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The Economic Justification of Semi-Active Damping Systems for Civil Structures

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The economic justification of semi-active damping systems for civil structures

by

Steven T. Pritchett

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Civil Engineering (Structural Engineering)

Program of Study Committee:
Simon Laflamme, Major Professor
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Iowa State University
Ames, Iowa
2014

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ABSTRACT

The upfront costs of the installation of a vibration damping system in a structure can be significant with respect to total structural costs. A detailed life-cycle cost analysis of the benefits of incorporating a damping system in a structure can show that much of the upfront costs are offset by savings occurring either at the time of construction or over the life of the structure. Semi-active dampers are a modern type of vibration damping system that has received increasing amount of attention in the structural community for its increased performance capabilities with respect to passive systems and significantly lower power requirements with regards to active damping systems.

Currently, there is a gap in the research community between the performance and cost of semi-active dampers. This study aims at closing this gap by evaluating the current performance of passive systems and existing data on semi-active systems. First, we discuss cases where researchers proved that passive dampers can be cost effective while providing significant structural benefits. Secondly, we discuss how other research has shown that semi-active dampers can perform better than passive dampers and in some cases with fewer dampers, which could imply a lower-cost, better-performing damping system than those currently used in practice. Thirdly, we discuss the possible shortcomings and the unknown characteristics of semi-active damping systems, including lack of testing on the resiliency of semi-active dampers and sensors over time, the power requirements for semi-active dampers, the over-idealized testing procedures with control algorithms greatly optimized for a predetermined excitation sequence and the future of codified structural design with regards to structural resiliency in addition to life safety guidelines. The research indicates the possibility of semi-active damping

being a more effective damping solution with regards to performance and cost savings compared to passive damping, but more research on semi-active damping is required to affirm the aforementioned claim.

CHAPTER 1: INTRODUCTION

1.1. INTRODUCTION

Motion of civil structures via unpredictable loading has been a topic of concern and research for decades, because wind and seismic loading on structures can induce displacements with magnitudes and dynamic properties sufficient to cause discomfort to occupants or even critically damage the structure. In an effort to increase occupant comfort while increasing the safety and performance of structures during seismic and wind loading events, several solutions have been proposed, many of which have been practically and effectively deployed. Increasing the damping ratio of a structure is one of many possible ways to mitigate displacement and acceleration due to various types of excitation; adding mass or adding stiffness to a structure are viable alternatives, but may be less effective than damping. As shown in Figure 1, even the addition of 30% mass or 30% stiffness to a structure is significantly less effective at reducing building accelerations and base moments than even a modest increase in the energy damping properties of a structure (Irwin, Kilpatrick, Robinson, & Frisque, 2008). The upfront cost of many of the vibration damping systems used in the design and retrofitting of structures can be significant with respect to the total construction costs, however when life-cycle cost analyses are performed the benefits provided by passive damper systems produce reduced upfront costs and in many cases actually pay for themselves entirely, as discussed in Chapter 3.

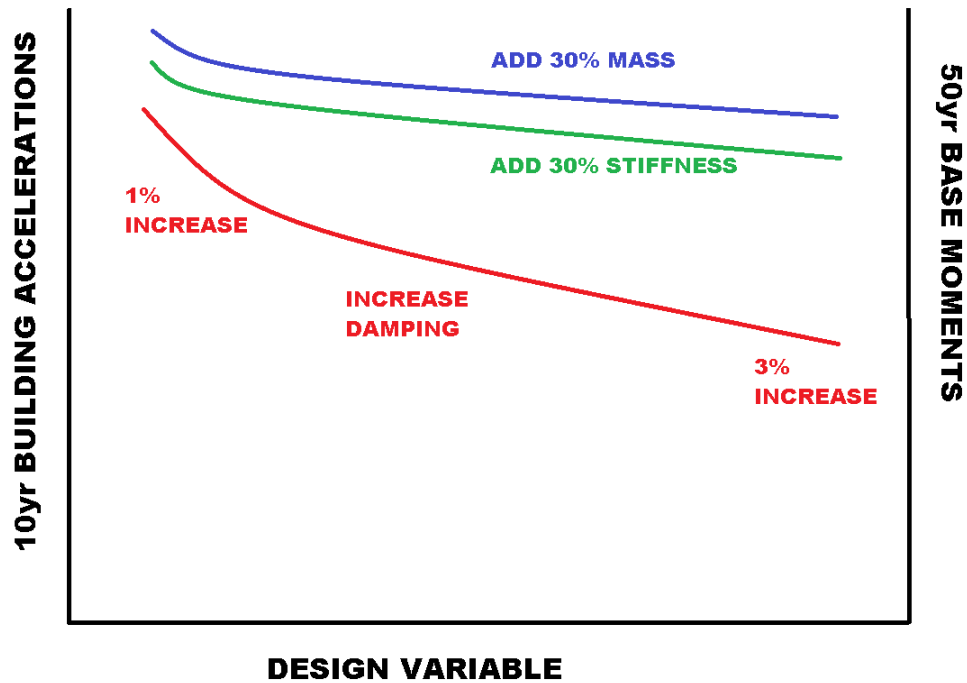


Figure 1 - Relative Effects on Building Motion of Changing Damping

Adapted from (Irwin, Kilpatrick, Robinson, & Frisque, 2008)

1.2 PROBLEM STATEMENT

Recent research has shown that semi-active dampers can outperform passive dampers, sometimes even while using as few as one third the number of damper units. There is a gap in the research community between what is known about the performance and cost of semi-active dampers. This study aims at closing this gap by evaluating the current performance of passive systems and existing data on semi-active systems. Factors that influence the cost of semi-active dampers and require additional research will also be evaluated and tabulated.

CHAPTER 2: BACKGROUND

Consideration must be given to the type of loading expected on the structure, because some damping systems can excel at mitigating vibration from some loading types while being less effective at mitigating with others. An explanation of various loading types and their behaviors are discussed herein, followed by an overview of the various types of damping systems and classifications.

2.1. TYPES OF LOADING

Humans begin to feel discomfort when the lateral acceleration to which they are exposed reaches approximately 0.02g. Loads that affect civil structures include harmonic, periodic, transient and impulsive load (Bachmann & Ammann, 1987). Some damping systems excel at mitigating a few types of loading but are ineffective or significantly less effective at others. Typical time functions of dynamic loads are shown in Figure 2.

2.1.1. Harmonic loading

Harmonic loading varies with time according to a sinusoidal function, and affect the structure such that a steady-state vibration response is possible (Bachmann & Ammann, 1987). Harmonic loading is typically caused by machine operation.

2.1.2. Periodic loading

Periodic loading produces random excitation over the course of one load cycle or period, which is repeated for a long enough time for a steady-state response to develop (Bachmann & Ammann, 1987). Periodic loading can be caused by machine operation, human motion or wind.

2.1.3. Transient loading

Transient loading produces random excitation over a random amount of time, with no periodicity. Transient loading can be caused by wind, water waves and earthquakes (Bachmann & Ammann, 1987).

2.1.4. Impulse loading

Impulsive loading is a special case of transient loading that occurs over a very short amount of time, which can be caused by construction, impact, blast waves (via explosions) or a loss of support or earthquakes with very short durations (Bachmann & Ammann, 1987).

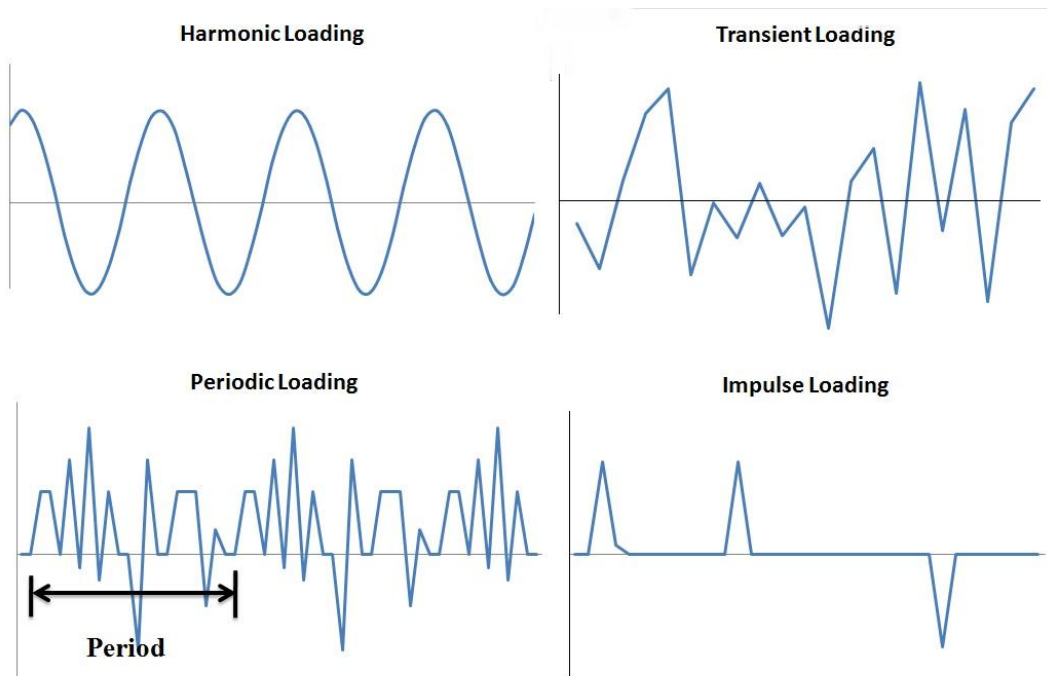


Figure 2 - Loading Types

2.2. TYPES OF DAMPING SYSTEMS

There are many methods proposed to accomplish the task of reducing occupant discomfort due to lateral accelerations and reduce structure damage due to excessive vibration and displacement. Varying the mass or the stiffness characteristics of a structure are effective, but not as efficient, as changing damping characteristics, as shown in Figure 1. Damping systems are primarily separated into three types: active, semi-active and passive systems.

Several common passive damping systems include but are not limited to viscous, tuned mass, and base isolation damping. Passive damping systems have set parameters based on an expected loading envelope for a given area and an expected structure self-weight and are not designed to react effectively outside of that range, which results in a conservative design. Passive damping types are described in the following sections.

2.2.1. Viscous dampers

Viscous damping can be subdivided into two categories, fluid and solid material damping. The amount of energy dissipated by viscous *fluid* damping is dependent on the *rate* of deformation, while the energy dissipated by solid material damping is dependent on the total displacement of the system as well as the rate of deformation. A viscous damping system utilizing both fluid and solid damping methods is shown in its most simplistic of idealizations in Figure 3, represented by a spring “k” and a dashpot “c” within the member oriented in the direction of the expected axial forces “F” and deformation, “x”.

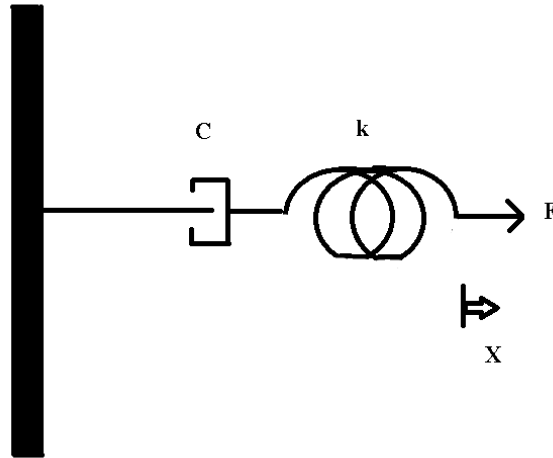


Figure 3 - Viscous Damping Approximation

2.2.2. Tuned mass dampers

A Tuned Mass Damper is a device which consists of a mass attached to a structural system and is used to reduce the dynamic response of a structure to a predetermined loading. A simplified figure illustrating the use of a Tuned Mass Damper is shown in Figure 4, where natural damping properties of the structure are approximated as one set of spring and dashpot and natural methods of attaching the tuned mass to the structure create damping properties on the mass approximated by the second set of spring and dashpot. The properties of the Tuned Mass Damper, including the exact mass and the precise location of the mass are calibrated with the dynamic properties of the structure such that when any of the predetermined frequencies of excitation are reached, the mass will vibrate out of phase with the structure, reducing overall displacement and energy in the structure (Connor, 2003).

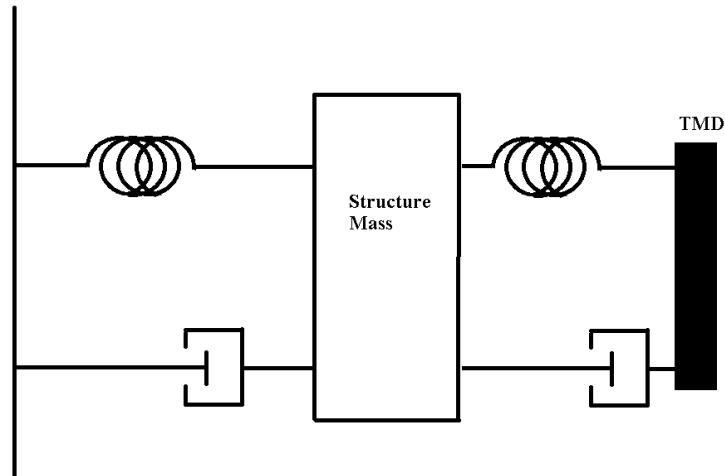


Figure 4 - Tuned Mass Damping Approximation

2.2.3. Base isolation

The concept of base isolation as it relates to mechanical equipment has been used for over a hundred years to prevent harmonic or periodic loading from machines from being transferred to their supports. The same idea relates to civil structures by employing various materials to create a pseudo-discontinuity between a foundation and a superstructure such that during a seismic event the load induced on a structure is significantly reduced (Naeim & Kelly, 1990). Many modern structural base isolation systems utilize steel-reinforced elastomeric rubber bearing pads, but while bearing pads alone are adequate for seismic loading, they allow excessive deflection from wind loads imposed directly on the structure and other low-level loads. A common solution is to pair rubber bearing pads with springs or steel rods designed to behave elastically up to a certain point and offer increased lateral stiffness, but yield when loading exceeds a certain threshold so as not to counteract the benefits of the rubber pads (Connor, 2003). One widely-utilized example of a solid elastic damper is the lead-core elastomeric bearing pad, as shown in Figure 5.

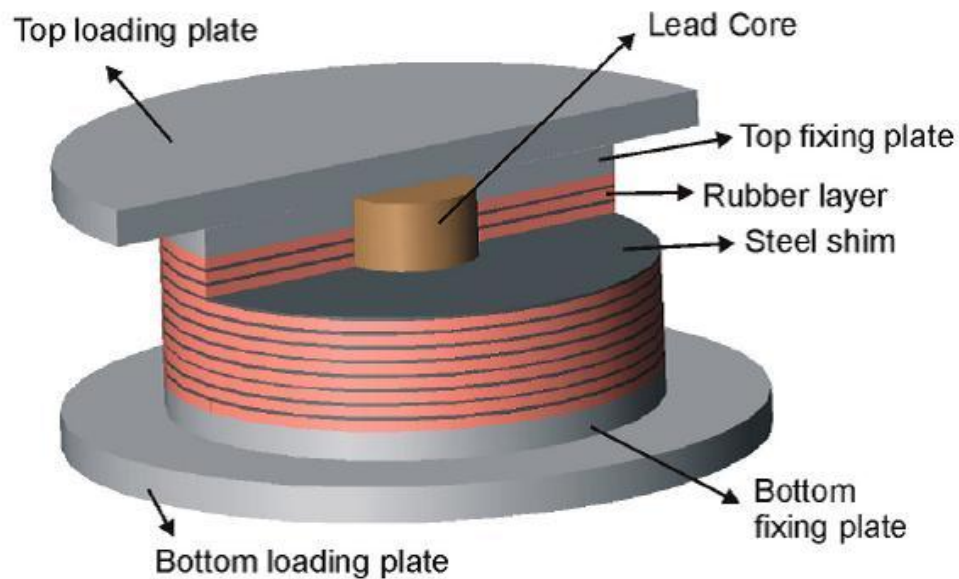


Figure 5 - Elastomeric Bearing Pad with Lead Core
(Base Isolation: The Seismic Zone, 2013)

2.2.4. Active damping

The concept of Active Damping control is vastly different than the previous damping solutions discussed. Active Damping systems use external sources of energy to optimize their system properties for a wide envelope of loading. Active Damping integrates three main components: a Monitor, which acquires data from sensors placed throughout the structure a Controller, which is a data processing unit that decides on a course of action for the given circumstances and Actuator(s), which carry out the commands imposed by the Controller (Connor, 2003). Active control involves monitoring the system input and the structural response so that changes can be made to the input to optimize a system response for the real-time situation. The act of optimizing a system response can be achieved in many ways, depending on the design selected by the structure owner; actuators may be used to move a large mass or

masses on the structure, or even expand or contract cross-bracing elements in a structural framework to dissipate energy.

2.2.5. Semi-active damping

Semi-Active Damping systems offer the adaptability of active damping systems without requiring the requisite large power source. A semi-active system cannot increase the energy in the system (which includes the damping system and the structure) but has properties that can be dynamically varied. Semi-active damping systems are effective because of their mechanical simplicity, robustness, low power requirements and a level of effectiveness similar to fully active damping systems (Dyke, Spencer Jr., Sain, & Carlson, 1996).

There are an ever-growing number of semi-active damping devices and an even greater number of applications for those devices. One example is the magneto rheological damper, which functions similarly to viscous fluid dampers, with a fluid of a given viscosity absorbing energy in the form of heat as it is forced from one position in the damper casing to another by a plunger rod. The main difference between standard viscous dampers and magneto rheological dampers is that magneto rheological dampers utilize a damping fluid that contains very small particles suspended hydraulic oil that are reactive to magnetic fields. The damping characteristics of magneto rheological dampers can be quickly varied by changing the viscosity of the magneto rheological fluid by exposing them to magnetic fields of varying intensities (Wilson & Abdullah) (Li & Tao, 2011). A schematic of a magneto rheological damper is shown in Figure 6.

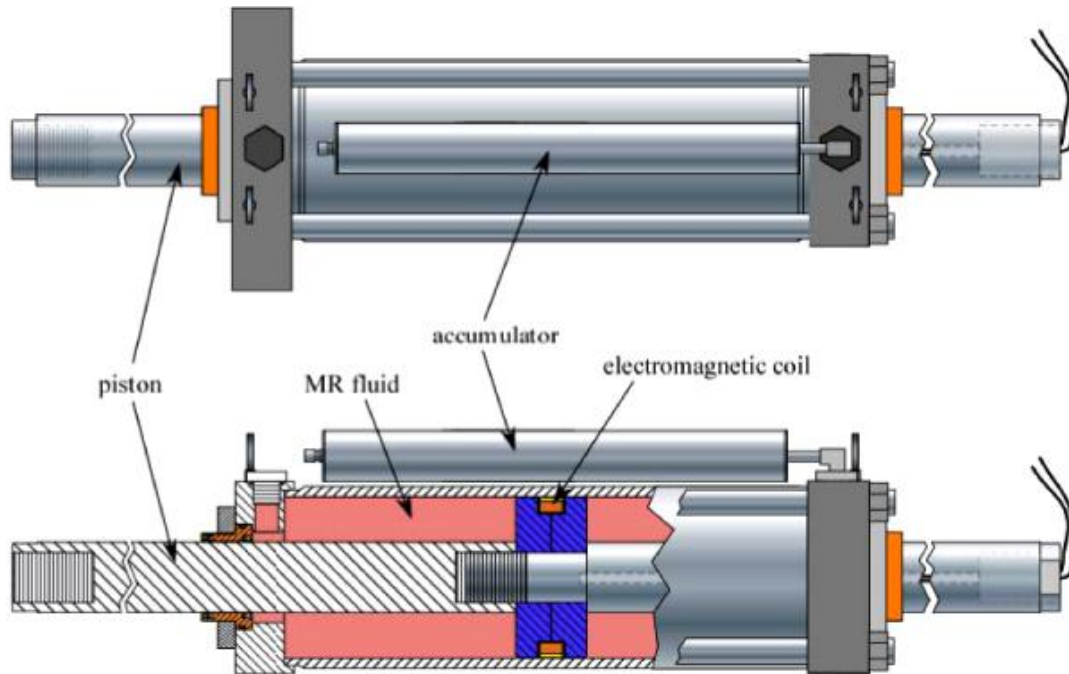


Figure 6 - Viscous Magneto rheological Damper

(Jiang & Christenson, 2012)

Another innovative concept useful for semi-active damping is a regenerative force actuation network. Regenerative force actuation networks are groups of actuators that produce controlling forces while requiring very small amounts of external power. They are also capable of generating small amounts of power, which can then be used to power other dampers in the network so as to create a pseudo self-sustaining system of actuators (Scruggs & Iwan, 2005). There is a significant amount of research required on the topic before a regenerative force actuation network is ready for implementation in a full scale structure, but the concept itself shows merit (Scruggs & Iwan, 2005).

CHAPTER 3: MONETARY COSTS AND BENEFITS

In some cases, direct cost-benefit analysis data was made available on various projects such that a project owner would know with certainty that installing a certain type and size of vibration damping system on their structure would save a certain amount of money compared to the undamped equivalent structure based on the material and labor prices of the day.

Unfortunately these analyses are uncommon, likely because of the significant extra work involved in generating cost data for the structure. A designer would be required to design a structure once without damping and then add damping in with all the changes to structural and dynamic properties required and redesign the entire structure. For this reason, the quantity of data available in this most direct format is extremely limited. Nonetheless, a significant cache of data on the direct savings from the installation of structural damping systems is shown in the following chapter. Chapter 3 identifies the cost saving capabilities of passive damper systems in real world applications so that a starting point can be made by which to measure the potential cost savings of semi-active damping systems. In this way, once additional research is completed and accurate cost benefit analyses are carried out for semi-active dampers, there is a comprehensive list of passively damped structure for comparison.

3.1. SAVINGS FROM DAMPING SOLUTIONS

250 West 55th Street, New York, NY

In the example of the building constructed at 250 West 55th Street, New York, NY, the structure itself would have required an additional 500 tons of steel in added stiffness of members to adequately comply with acceleration and drift limitations based on wind tunnel testing. The use of the damped outrigger system meant that the additional stiffness was no longer necessary

and an additional 500 tons of steel could be removed from the structure because of the capabilities of the damping system. Material cost savings therefore summed to 1000 tons of steel, which at the time of construction equated to an approximate savings of \$800,000. Total savings on the project because of the damping system were “several million dollars” (Jackson & Scott, 2010). A photograph of the aforementioned structure is shown in Figure 7.



Figure 7 - 250 West 55th Street Building

(Fedak, 2013)

Probabilistic Life-cycle Cost Analysis of 3-story Concrete Structure

A report on the findings of a study on the effects of damping on the life-cycle cost of buildings [in a seismically active area] stated that retrofitting a structure with viscous dampers would lead to a 22% reduction of the total life-cycle cost of the structure without dampers. The quantitative results of the simulation-based, probabilistic study of life-cycle costs of a building in

a seismic hazard zone with and without dampers installed are shown in Figure 8, where the total cost without dampers was \$555,700 and the total cost with dampers was \$115,710, which represented an 80% savings in the total life-cycle costs for the structure, totaling \$440,000 (Taflanidis & Gidaris, 2013). Damper life-cycle cost is dependent on the type of damper selected for use, but costs can be generated by factors like fluid seal leakage, possible debonding of solid damper layers due to limited deformation capacity and temperature dependency and degradation of materials (Symans, et al., 2008).

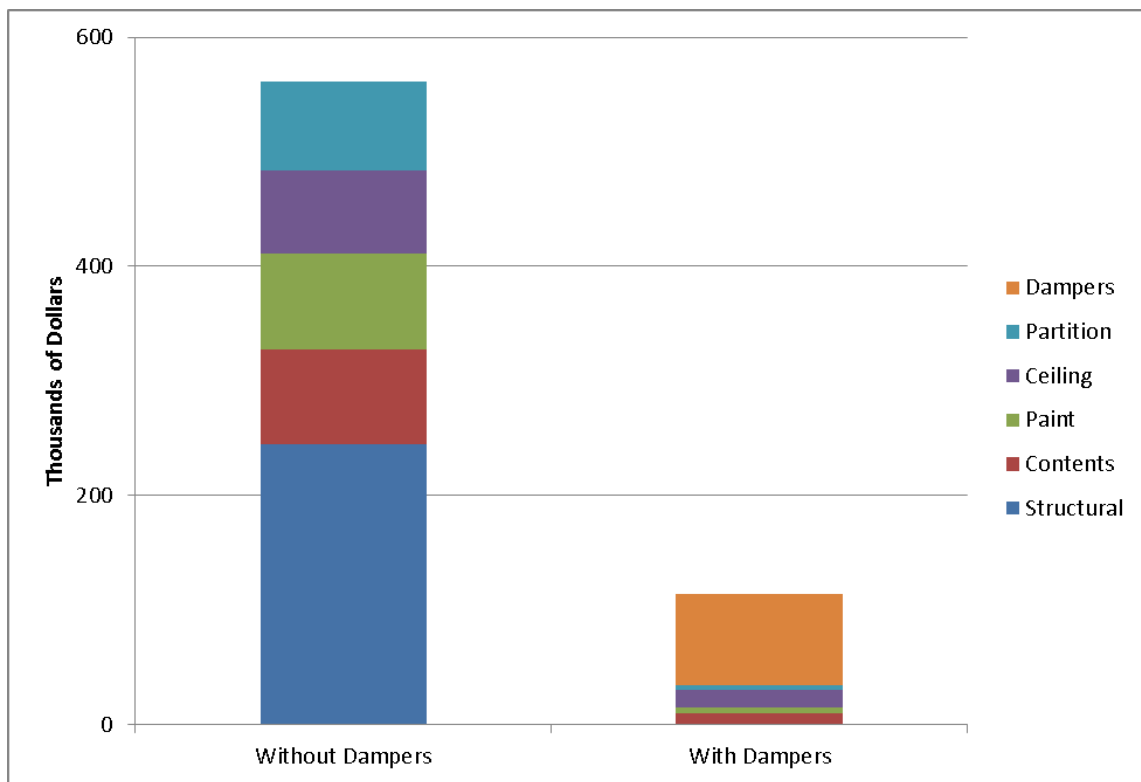


Figure 8 - Structure Life-Cycle Cost Comparison

Adapted from (Taflanidis & Gidaris, 2013)

Life-cycle Cost Analysis of 26-story Steel Structure, Palo Alto, CA

Another life-cycle cost analysis of damping for buildings was completed, this time using a simulated 26-story steel high-rise moment frame structure located in Palo Alto, California. The

estimated building cost and contents of the structure were \$52.67 million each. 10,000 simulations were carried out to measure the sensitivity of the model to various intensities and frequencies of excitation, time periods over which the simulation ran (from 5 to 100 years), damping ratios in the structure (which ranged from 5% to 30%) and thresholds used to determine the type and extent of damage, as well as the estimated cost of repair. Conceding that the study was somewhat limited in scope, the results are shown in Table 1, Table 2 and Table 3 and show that as the damping ratio was increased the average expected loss over the life of the structure decreased. There came a point, due to the law of diminishing return, when the cost of additional damping to the structure would not have been worthwhile. Table 2 shows the data from Table 1 averaged over the expected life of the structure, while Table 3 shows the potential cost savings of additional damping over the 5% case. The data from Table 3 shows that it would be economical to increase damping to 10% if and only if the cost associated with the additional damping is \$4.9 million, to 20% if the additional cost is \$8.3 million and to 30% only if the added cost is \$10 million. Similarly, if \$3.25 million is spent to increase damping to 20%, the cost would be recovered from loss reduction in only 15 years (King, Jain, & Hart, 2001).

Table 1 - Total Overall Expected Loss (millions of 2001 US Dollars)

Time Period (years)	Damping Ratio (% of critical)			
	5	10	20	30
5	1.03	0.58	0.31	0.16
15	4.34	2.79	1.07	0.62
30	11.45	6.55	3.15	1.45
50	21.36	12.99	6.03	3.69
100	50.31	30.81	15.46	9.93

(King, Jain, & Hart, 2001)

Table 2 - Average annual overall expected loss (thousands of 2001 US dollars)

Time Period (years)	Damping Ratio (% of critical)			
	5	10	20	30
5	20.6	11.6	6.2	3.1
15	28.9	18.6	7.2	4.1
30	38.2	21.8	10.5	4.8
50	42.7	26.0	12.1	7.4
100	50.3	30.8	15.5	9.9

(King, Jain, & Hart, 2001)

Table 3 - Percentage reduction in total expected loss with respect to 5% damping

Time Period (years)	Damping Ratio (% of critical)			
	5	10	20	30
5	0	43.4	69.8	84.7
15	0	35.6	75.2	85.7
30	0	42.8	72.5	87.3
50	0	39.2	71.8	82.7
100	0	38.8	69.3	80.3
Average	0	40	71.7	84.1

(King, Jain, & Hart, 2001)

San Bernardino Justice Center, San Bernardino, CA

A case study was completed in 2013 regarding the use of damping systems in a courthouse in San Diego, California and the San Bernardino Justice Center as it relates to the rate of return of an initial investment for a damping system in the form of reduced annual loss as well as reduced cost of business relocation after a seismic event. The study compared the cost-effectiveness of a standard steel moment frame design to a moment frame design enhanced with

viscous damping devices in chevron, reverse toggle and scissor-jack configuration in the case of the San Diego Central Courthouse, and base isolation in the San Bernardino Justice Center case.

The results of this study are shown in Table 4 and Table 5 (Sarkisian, Lee, Hu, Garai, Tsui, & Reis, 2013). A rendering of the Justice Center is shown in Figure 9.

Table 4 - San Diego Central Courthouse Damping Comparison

Structural System	Additional Initial Cost	Average Annual Loss	Average Annual Return	Business Relocation	Annual Return on Investment
Normal	Baseline	\$804,000	Baseline	140 days	Baseline
Viscous Damping	\$5.5m	\$346,000	\$458,000	0 days	+6.7%

(Sarkisian, Lee, Hu, Garai, Tsui, & Reis, 2013)

Table 5 - San Bernardino Justice Center Damping Comparison

Structural System	Additional Initial Cost	Average Annual Loss	Average Annual Return	Business Relocation	Annual Return on Investment
Normal	Baseline	\$1.5m	Baseline	210 days	Baseline
Base Isolation	\$6.5m	\$0.27m	\$1.23m	0 days	+18.5%

(Sarkisian, Lee, Hu, Garai, Tsui, & Reis, 2013)



Figure 9 - San Bernardino Justice Center Rendering

(Ruano, 2011)

Hotel Stockton, Stockton, CA

The Hotel Stockton in Stockton, California was retrofitted with viscous dampers in 2003 to improve the survivability of the historic structure during a seismic event, to reduce soft-story effects, and to provide better torsional seismic response without sacrificing floor space. After 20 viscous fluid dampers and some column reinforcement were installed, the maximum seismic response was reduced by more than a factor of five, with a total cost of \$1.3 million. The total construction budget was \$24 million, so the seismic upgrade constituted only 0.5% of the budget (Miyamoto, Determan, Gilani, & Hansen, 2003). A photograph of Hotel Stockton is shown in Figure 10.



Figure 10 - Hotel Stockton

(Peterson, 2011)

Citicorp Center, New York, NY

The Citicorp Center in New York, New York was designed with tuned-mass dampers that cost \$1.5 million dollars at the time of completion, but were estimated to have saved 2800 tons of structural steel that would have been otherwise required to satisfy deflection constraints on the structure. This steel savings equated to about \$4 million in savings at the time of construction, which was saved 1.4% of the total structural cost overall (Connor, 2003). A photograph of the Citicorp Center is shown in Figure 11.



Figure 11 - Citicorp Center

(Hevesi, 2006)

Crystal Tower, Osaka, Japan

The Crystal Tower in Osaka, Japan utilizes a pendulum tuned mass damper in the form of six thermal storage tanks hung from 13-foot-long cables on the top of the structure. The added energy dissipative properties cost the building owner only \$350,000 to add to the structure, which was less than 0.2% of the total structure cost. The damping system reduced the wind-induced structure response by about 50% (Connor, 2003). A rendering of the Crystal Tower is shown in Figure 12.



Figure 12 - Crystal Tower

(Photo Tour of Famous Attractions: Osaka Pictures, 2007)

Fire Department Command and Control Facility, Los Angeles, CA

The Fire Department Command and Control Facility in Los Angeles, California is a two-story, steel-framed structure that utilizes elastomeric bearing pads to isolate it from ground motion during a seismic event. Conventional and isolation designs were both considered with the stipulation that the functionality of the structure had to be maintained after an extreme design event. Utilizing base isolation was found to yield a cost savings of 6% over the conventional design, and expected losses were reduced by a factor of 40 (Connor, 2003). A photograph of the structure is shown in Figure 13.



Figure 13 - Los Angeles Fire Department Control Facility

(Building that use Base Isolation Technology, 2010)

Evans and Sutherland Manufacturing Facility

In Salt Lake City, Utah while designing the Evans and Sutherland Manufacturing Facility, the conservative approach taken by the engineers with regards to design loading offset the cost savings offered by the base isolation, so the total effect of the base isolation system and larger design loading was a net increase in the structure cost of 5%, or \$400,000. The owners deemed the added safety and damage reduction capabilities for the building important because the contents of the structure were valued at over \$100 million (Connor, 2003).

Proposed 80-story structure, Toronto, Canada

A structure was proposed in downtown Toronto that was to be 75 stories tall and the owner requested that the overall height be extended to 80 stories. Design engineers began studying possible damping solutions for the expected wind loading on the structure and determined that the most practical system was two tuned sloshing dampers each consisting of a large tank of a predetermined amount of water on the upper stories of the structure whose inertia would counteract the displacement and acceleration from the expected wind excitation. The tanks would also be used for an emergency fire suppression system. The increase in the damping characteristics of the structure due to the tuned sloshing dampers allowed designers to reduce the amount of concrete, steel and post-tensioning strands used in the remainder of the structure such that over 1400m³ of concrete, 88,000kg of reinforcing steel and 9,300kg of post-tensioning steel strand could be eliminated from the design, which summed to approximately \$500,000 of savings that could be used to offset the cost of the damping system. The reduction in building material was also estimated to have saved 670 tons of greenhouse gas emissions, which was the equivalent of removing 140,000 cars from the road for one day (Irwin, Kilpatrick, Robinson, & Frisque, 2008).

Comparison Study of Conventional versus Damped Construction, California

A structure constructed in 2007 in California was the first of its kind; engineers designed the steel moment resisting frames in the seismic region using conventional practice, and a separate design was completed using ASCE 7 guidelines with viscous Damping Devices. Comparison of the analyses of the expected performances for each design given 500-year and 2500-year return periods for seismic loading showed that the design that utilized the viscous dampers had superior seismic performance. The design that utilized dampers had a long period, low frequency structure with low acceleration, and a vastly reduced story drift ratio of 1%,

largely as a consequence of the dampers themselves. Table 6 presents a relative cost comparison between designs. The additional cost of the dampers was offset by the savings in reinforcing steel and foundation concrete volume, so the two designs have similar initial costs. Following a design-level earthquake, the conventional structure would provide life safety but would sustain significant damage requiring repair work; the cost of which would be in addition to the loss of operation of the structure while repairs were being made. Conversely, the structure designed with viscous Dampers would be expected to sustain very little damage and remain fully functional (Miyamoto & Gilani, Design of a New Steel-Framed Building Using ASCE 7 Damper Provisions, 2008). Analysis of Table 6 combined with material cost data from the year of construction, where concrete cost and steel cost were \$75 per cubic yard (Concrete Network, 2013) and \$545 per ton (Index Mundi) respectively shows a cost savings of \$28,000 in material from the implementation of the damper.

Table 6 - Initial Cost Comparison of Standard vs. Damper Design

	Conventional Design	Viscous Damper Design	Comments
Moment Resisting Frame Members	547,000 pounds	447,000 pounds	Savings of 100,000 lbs
Grade Beams	240 Cubic Yards	-	Savings of 240 Cubic Yards of concrete and 18 tons of reinforcing steel
Viscous Dampers	-	\$170,000	Additional Cost of Dampers

(Miyamoto & Gilani, Design of a New Steel-Framed Building Using ASCE 7 Damper Provisions, 2008)

Pall Dynamics Damper Projects

Pall Dynamics is a company founded in 1984, which specializes in the construction of Friction Dampers, which are a form of passive damping incorporated into the construction of cross bracing of conventional structural framing. Using specially treated metals and a unique manufacturing process, Pall Dynamics has used its friction dampers on dozens of projects to the benefit of their customers. Some examples are as follows: The Seismic Upgrade of a Boeing Commercial Airplane Factory saved the company \$30,000,000 compared to conventional structural seismic-resisting methods; The Moscone West Convention Center underwent an expansion and retrofit, and the owners saved \$2,250,000 over the cost of a viscous damper configuration; the Maison 1 McGill building utilized Friction Dampers in lieu of concrete shear walls, which resulted in a savings of \$500,000 over the cost of a conventional design (Projects: Pall Dynamics).

Earthquake Protection Systems Base Isolation Projects

Earthquake Protection Systems designs and manufactures a base isolation system for structures using proprietary “triple pendulum” technology. Base isolation bearings produced by Earthquake Protection Systems have been installed on many structures to the financial advantage of the structure owners, including but not limited to the following: The San Francisco International Airport Terminal was outfitted with a base isolation system that saved 680 tons of structural steel, which equates to a savings of \$370,000; The Benicia-Martinez Bridge in the San Francisco Bay Area was outfitted with a base isolation system from Earthquake Protection Systems, which saved over \$30,000,000 over conventional rubber base isolation pads. (Earthquake Protection Systems, 2011)

CHAPTER 4: SUPERIOR PERFORMANCE FROM SEMI-ACTIVE DAMPING

Although structural damping systems can have direct monetary benefits, there are other benefits inherent in structural damping that may have a profound effect on the performance and life cycle cost of a structure. Semi-active damping systems have an improved overall performance as well as a wider range of excitation spectra over which they are effective when compared to passive damping and even more so over undamped structures. Chapter 4 aims to demonstrate the superior performance capabilities of semi-active damping systems over passive damping systems. Combined with Chapter 3, which illustrates how passive damping can reduce structure costs, Chapter 4 illustrates the possibility of a better performing and potentially lower cost damping solution.

4.1. PERFORMANCE BENEFITS OF SEMI-ACTIVE DAMPING SYSTEMS

Reasoning for the separation of Chapters 3 and 4 are because structural damping systems may influence the response of a structure to extreme loading by reducing the overall story drift by a certain percentage, which is an important factor to take into consideration while designing the structure and choosing which motion damping system to utilize, however if the reduction in story drift for a given excitation causes the behavior of the members in the structure to shift from plastic response to elastic response the potential cost savings would be monumental and easily quantifiable with regards to savings of damaged members, etc. If the behavior of the members in the structure is reduced from plastic deformation to a smaller magnitude of plastic deformation, however, the reduction in overall structural damage may be significantly reduced with regards to production time lost due to displacement of occupants for building repairs, non-structural damage, and personal injury law suits from structure occupants, etc. While the overall cost

savings from the aforementioned reduction in plastic deformation in the event of a given design excitation can be calculated using a large number of assumptions and a host of Monte Carlo simulations to test for the sensitivity of the cost to a variation of the assumptions made, the entire process is lengthy, complicated and somewhat arbitrary given the amount of information that varies depending on minute factors. For these reasons the author has decided to make note of the advantages that semi-active damping systems can provide over passive devices with regards to the life-cycle cost of a structure, albeit separately from the more explicitly defined monetary advantages discussed in Chapter 3.

Semi-Active Damping of a 39-Story Office Building

A case study was completed in 2004 for a 39 story office building in an urban environment that was situated immediately adjacent to a 52 story tower. During wind tunnel testing, vortex shedding from the geometry of the 52 story tower was expected to create accelerations in the 39 story building that were double the industry standard for office buildings. Several possible solutions were investigated, including adding stiffness to the structure, using tuned mass dampers, tuned sloshing dampers and viscous dampers. Tuned mass dampers and tuned sloshing dampers were found to be quite effective, but also required the use of valuable office space near the top of the tower and were very expensive; viscous dampers were cost prohibitive at that time because there was a shortage of manufacturers in the US. Viscous dampers were chosen for the project along with motion amplification devices in the form of toggle braces to compliment the large force output to small displacement characteristics of viscous dampers and to reduce the required number of dampers in the structure. A total of 30 viscous dampers were used on the structure, which changed the effective damping ratio of the structure to around 3% and reduced the dynamic behavior of the structure by 30%. The cost of

the dampers and toggle braces was less than \$1 million, without which the structure as designed would not have been feasible (McNamara, Huang, & Wan, 2004).

A study in 2011 simulated the same 39-story office tower to compare the performance of semi-active and passive control devices as compared to an undamped case. One simulation compared the semi-active case to the fluid dampers installed by limiting the capacity of the semi-active modules to the same level as the fluid dampers. The performance semi-active damping system with the capacity reduced to the level of the existing fluid damper system is shown in Table 7. The study goes on to demonstrate that the performance of the 30 currently installed passive fluid dampers could be matched by as few as 10 semi-active dampers, which would represent significant cost savings with regards to maintenance and initial cost of installation, while simultaneously allowing more freedom to the owner with regards to the use of the floor-space in the structure (Laflamme, Taylor, Maane, & Connor, 2011). Another study continued work from previous studies on the application of a new kind of semi-active damper known as a “Modified Friction Device” yielded data shown in Table 8. This data validates that as few as 10 semi-active dampers were needed to accomplish the same level of structural damping as 30 viscous dampers in the same direction. The study also goes on to demonstrate the cost-effectiveness of semi-active dampers by showing an itemized cost of damper installation on the structure, where the case utilizing semi-active damping achieved a cost of installation \$180,000 lower than the viscous damping alternative, which represented an 18% savings (Laflamme, Control of Large-Scale Structures with Large Uncertainties, 2011).

Table 7 - Comparison of Semi-Active System with Passive System Performance

	X-direction reduction		Y-direction reduction	
	Displacement	Acceleration	Displacement	Acceleration
Semi-Active	42%	59%	33%	27%
Passive	28%	50%	22%	23%

(Laflamme, Taylor, Maane, & Connor, 2011)

Table 8 - MFD Compared to Viscous Cost

Damping Strategy	Direction	# of Devices Required	Device Cost	Brace Cost	Total
Viscous	X	30	\$5,000	\$9,000	\$975,000
	Y	30	\$5,000	\$13,500	
MFD	X	10	\$15,000	\$9,000	\$795,000
	Y	30	\$5,000	\$13,500	

(Laflamme, Control of Large-Scale Structures with Large Uncertainties, 2011)

3-Story Single-bay Structure Comparing Passive to Semi-Active Damping

A study that took place as early as 1996 highlights the potential for advancement of the use of semi-active control of structural damping. The study used the structural input from the El Centro earthquake to compare passive damper performance to semi-active, magneto rheological damper performance. The tests were conducted on a scaled-down model of a 3-story, single-bay steel structure that used chevron-style bracing controlled by dampers while varying the strategies for acceleration feedback of the semi-active damper and results were conclusive; while the passive damper performed significantly better than the undamped case, the semi-actively damped structure showed a 24.3% reduction in peak 3rd floor displacement and a 29.1% reduction in maximum story drift *over the passively damped case*. The semi-active damping was capable of reducing the peak 3rd floor displacement by 74.5% and the peak acceleration by 47.6% over the undamped case, and the authors of the study admit that with further research into control algorithms a higher level of performance could have been possible. It is reasonable to assume

that while semi-active damping showed promise as a prominent damping system relative to passive damping in 1996 the technology has advanced significantly since that time, and performance levels are even higher (Dyke S. J., Spencer Jr., Sain, & Carlson, 1996).

3-story Semi-Active versus Passively Damped Comparison

A study in 2013 used a simulated 3-story, single-bay structure with a single chevron-style damper configuration subjected to seven different earthquake excitations to yield accurate performance records for a magneto rheological damping system with varied control algorithms. A reduction in peak displacement, inter-story drift and acceleration of 34%, 24% and 12% respectively versus the passively damped case was averaged from the seven excitations, and the results of the study illustrated that the quality of a control algorithm was important; even utilizing magneto rheological dampers with a sub-optimal control algorithm would yield better results than a passive damping system (Pohoryles & Duffour, 2013).

Semi-Active Dampers Used in Rail Transportation

A study was completed in 1998 describing the development of a semi-active damping system for use in rail vehicles to improve ride comfort for passengers. Rail cars were outfitted with a multitude of dampers, potentiometers, accelerometers and stroke sensors to provide feedback data at near-real-time to fine tune the performance of the ride control as conditions and excitations varied, due to passenger movement, imperfections in the track surface or tilt due to angular acceleration while rounding a corner. High pass filters were used during data processing to filter out low frequency noise in the signal caused by gravitational and angular accelerations to more accurately determine the requirements of the damping system. Evaluation of the performance for the semi-active magneto rheological damping system for railway cars showed that an improvement of up to 15% in ride quality, including displacement and acceleration experienced by passengers, could be obtained at the time and it is reasonable to assume that

advances in technology since that time are sufficient to produce even better results (Stribersky, Kienberger, Wagner, & Muller, 1998).

Semi-Active Dampers Used in the Damping of Cables on Bridges

Another example of how structural damping systems could be utilized in somewhat unorthodox ways was discussed in a paper published in 2007 on the topic of damping of steel stay cables used in cable-stay bridges. The paper stated that cables used for cable-stay bridges were prone to vibration due to weather effects like wind and precipitation. The vibration would cause reduced service life of the cables over time because of premature breakdown of corrosion protection, and public confidence in the structure was diminished. The use of a semi-active magneto rheological damper located 2% of the cable length from one support was found to reduce cable vibration by as much as 63% by adding as much as 8% equivalent modal damping of the first mode of vibration (Johnson, Baker, Spencer Jr, & Fujino, 2007).

Semi-Active Dampers to Suppress Rotational Forces

A study performed in 2012 showed the efficacy of using semi-active tuned mass dampers to suppress rotational and translational forces in structures. Semi-active tuned mass dampers work for a wide, varying frequency band by measuring the structural response to an excitation and varying the location of weights attached to a non-moving mass such that the moment of inertia of the entire damper effectively counteracts the structural response. Proper use of data feedback in conjunction with this rotational damper was found to reduce the peak values of rotation, angular velocity and angular acceleration by 73%, 75% and 78% respectively when compared to the performance of a standard tuned mass damper system. Because of the varying characteristics of the semi-active tuned mass damper, the frequency band over which the damper is effective is much larger than that of a standard tuned mass damper. The only restrictions on the frequency over which the damper could function were based on the length of the rails that the

weights were meant to slide on, as shown in Figure 14. The semi-active tuned mass damper provides a much simpler, less maintenance intensive solution for the problem of rotational response of structures when compared to that of a system of variable stiffness absorbers, which may be complicated and more difficult and expensive to maintain (Mohammadi-Ghazi, Ghorbani-Tanha, & Rahimian, 2012).

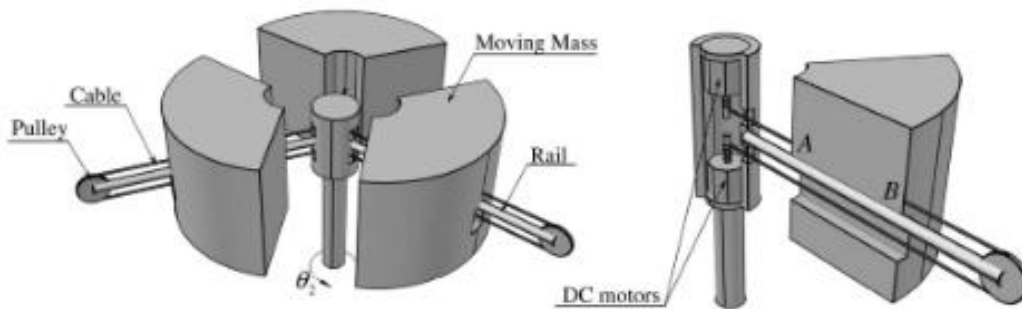


Figure 14 - Semi-Active Tuned Mass Damper for Rotation

(Mohammadi-Ghazi, Ghorbani-Tanha, & Rahimian, 2012)

Semi-Active versus Passive Damping of Tall Structures

A paper published in 2012 presented research on the performance of “smart tuned-mass dampers” and their effectiveness at suppressing wind-induced lateral-torsional motion of tall structures. The authors of the paper worked with two damper construction companies throughout the design phase of the project to estimate the actual cost of the implementation of damping systems that are typically prejudiced as having exceptionally high upfront and maintenance costs. The advantage of smart tuned-mass dampers over standard tuned mass dampers is that they address the shortcomings of standard tuned mass dampers, such as their difficulty to optimize because of the uncertainties of the structural dynamic properties and the excitation, while incorporating the strengths of semi-active systems, such as their ability to adapt to a wide range of conditions like an active system would, but without the energy demands of a fully active

system. Averaging the expected costs of smart tuned-mass dampers from the two companies for various sizes of structures yielded the chart shown in Figure 15, where the generalized mass of the structure can be matched with the reduction in acceleration required to produce an estimation of the cost of a smart tuned-mass damper for the given configuration. After a series of wind tunnel tests were performed on a laboratory-scale model of a wind-sensitive structure with and without the use of smart tuned-mass dampers, and the smart tuned-mass dampers were found to decrease the peak response of the structure by 25%, while the damper system was estimated to only account for 2% of the total structure cost, with maintenance costs for 30 years after the initial installation only accounting for 0.2% of the total structure cost. The estimation of maintenance cost is especially relevant because of the perceived high maintenance costs of damping systems over the life of a structure, where the aforementioned study dispels that preconceived notion (Tse, Kwok, & Tamura, 2012).

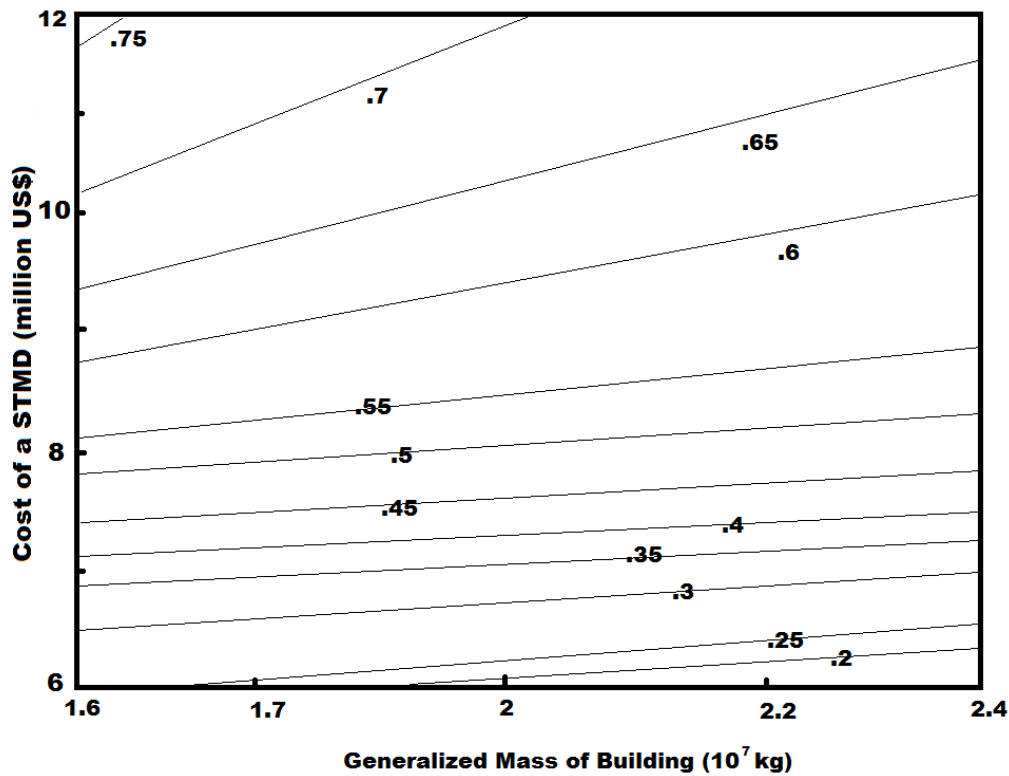


Figure 15 - Estimated Cost of a Smart Tuned Mass Damper

Adapted from (Tse, Kwok, & Tamura, 2012)

20-story Semi-Active versus Undamped Comparison

A study in 2004 performed a comparison of a 20-story undamped structural response to seismic loading with the same 20-story structure outfitted with semi-active magneto rheological dampers. Using 5 sensors to detect the response of the structure so that the characteristics of the magneto rheological dampers could be optimized in real time, the maximum acceleration of the structure was reduced by 48%, while the maximum drift ratio of the structure was reduced by 34% (Fukukita, Saito, & Shiba, 2004). Another study verified that structural response was limited by 46% for similar loading conditions (Wilson & Abdullah). Yet another study tested a 6-story structure outfitted with only two magneto rheological dampers excited with a scaled version of the El Centro earthquake and found a maximum reduction in structural response of

35% (Jansen & Dyke, 2000). Still another study tested a multiple degree-of-freedom structure subjected to the El Centro earthquake excitation and magneto rheological dampers reduced the displacement amplitudes by 78%, 47% and 39% for the first, second and third floors, respectively, and the interstory drift was reduced by 87% and 86% for the first-to-second and second-to-third story drifts, respectively (Gu & Oyadiji, 2008).

20-Story Semi-Active versus Undamped and Passively Damped

A 2004 study on the effectiveness of magneto rheological dampers deployed on a 20-story structure that was identical to one used in prior studies for viscous dampers. Using an identical structure allowed the researchers to accurately compare the behavior of the system against an undamped case and a passively damped case with a very small margin of uncertainty due to differences in damper and structure configuration. When the system was exposed to identical excitation in laboratory conditions, the MR dampers were found to reduce the structural response by 60%, and the number of plastic hinges that were formed during the loading phase was reduced by a significant amount (Yoshida & Dyke, 2004).

Semi-Active and Passive Damping Combination (Unoptimized)

A further study completed in 2012 found that the combination of viscous fluid dampers with an innovative new type of semi-active variable stiffness device was able to reduce acceleration and deformation by 20% for moderate ground motions, although optimization of the technology had yet to be completed (Pasala, 2012).

Semi-Active versus Passively Damped 4-story Structure

A study in 2007 was completed on a 4-story steel structure with a fixed base condition, base isolated condition, viscous dampers installed and a case with semi-actively damped condition under various seismic loading conditions. After many simulations to test the sensitivity to variation of the test results with regards to changes in device and structural parameters, it was

concluded that semi-Active damping reduced peak acceleration by 60% compared to a well designed viscous damper configuration. (Gavin & Zaicenco, 2007)

Cost-Effectiveness Evaluation of an Semi-Active Damper System based on a Life-Cycle Cost Concept

A study that took place in 2010 evaluated the cost-effectiveness of a magneto rheological damper system on cable-stayed bridges under earthquake loadings. The economic efficiency of the semi-active damper system is addressed by the concept of life-cycle cost analysis. To evaluate the expected damage cost the probability of failure was estimated using simulations of a parametric study, which varied the scale of the cost of damage to the structure and the cost of the damper to determine which combinations of variables were most and least conducive to the use of the semi-active damping system and under which circumstances a damping system would *not* be cost effective. The results of the study concluded that the scale of the damper cost had very little influence on the cost-effectiveness of the semi-active damping system; although the scale of the damage cost significantly influenced the cost-effectiveness of the damping system, it was found that the semi-active damping system was very cost-effective in regions with moderate to strong seismicity (Hahm, Ok, Park, Koh, & Park, 2012).

A related study regarding the cost-effectiveness of seismic isolation as it relates to life-cycle cost analysis found that although vibration damping measures can add to the safety of a structure and be cost effective, the costs of dampers relative to their vibration damping capabilities are not linear. As shown in Figure 16, the possibility of “over-designing” the damping system for a structure exists such that the addition of the damping system *will* add significant cost over the life of the structure, but with significant reduction in expected damage costs from seismic events (Park, Koh, & Song, 2004).

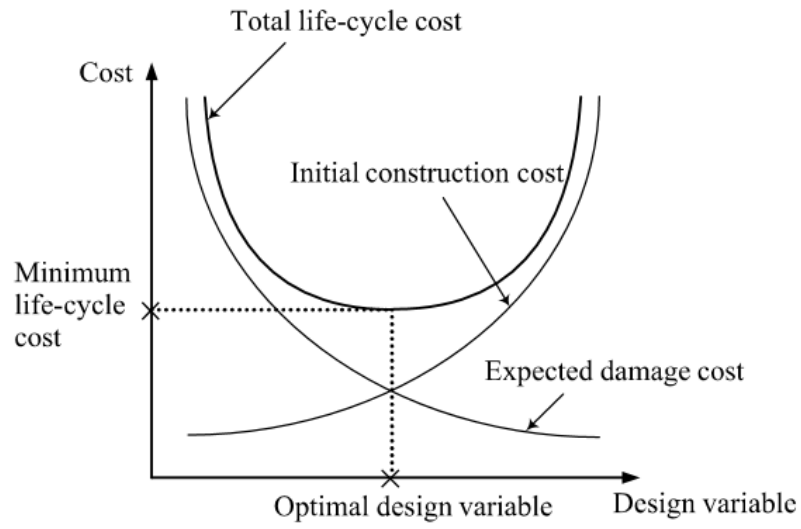


Figure 16 - Minimum Lifecycle Cost and Optimal Design
(Park, Koh, & Song, 2004)

CHAPTER 5: DISCUSSION

The previous chapters have described the various types of loadings and dampers, the benefits of passive dampers and the performance advantages of semi-active dampers over passive dampers, respectively, in order to portray the possible benefits of semi-active dampers over passive dampers. The conclusions drawn from the compilations of the aforementioned research topics are presented in section 5.1, including the discussion of the current research gap. The results show that there use of passive dampers can be effective at reducing structural cost and response and that semi-active dampers can out-perform passive dampers, possibly even at a lower cost.

5.1 ANALYSIS AND CONCLUSIONS

A compilation of the direct cost savings from the application of Passive dampers from Chapter 2 is shown in Table 9, where the median savings was \$800,000 and the average cost savings was \$5,800,000. These data show that while the possible savings from damping solutions can be significant, there are many factors that influence the available savings. Structure size and level of importance, seismicity of the region, and socioeconomic costs involved in repair of the structure heavily influence possible benefits of a damping system. Obtaining more data points would be useful for the validation of average and mean cost savings data. As previously mentioned, obtaining such data is difficult and time consuming. Engineers would be required to design the structure using conventional methods and obtain an estimated cost of construction, and then redesign the structure using the design considerations for the damping system properties and obtain another cost estimate, including life-cycle costs for the expected service life of the structure. The life-cycle cost analyses used in the determination of the monetary savings and

expenses of dampers were defined as the sum of the initial construction cost and the expected cost of the damage over the course of the lifespan of the structure including socio-economic effects of a collapsed structure (Hahm, Ok, Park, Koh, & Park, 2012).

Chapter 4 conclusively shows both the superior performance of semi-active dampers in similar test configurations as compared to the passively damped cases, as well as the ability of semi-active dampers to achieve similar performance levels as passively damped cases with as few as one third the number of dampers utilized which translated to as much as an 18% reduction in cost. Semi-active dampers could have the potential to generate significant reduction in the upfront cost of installing a structural damping system, which is a main deterrent to damping systems for structure owners. The enhanced performance of semi-active dampers could also reduce the cost of damage repairs over the life of the structure, thereby further reducing the life-cycle cost of a structure. Semi-active damping systems also share many of the same benefits as viscous damping, such as more freedom with regards to the configuration of floor space of the structure. This is particularly crucial when compared to tuned mass dampers, which tend to take up large amounts of space higher up in the structure where floor space is of higher value.

Unfortunately, at this time there is very little data on the reliability of semi-active dampers, or how the probability of failure of semi-active dampers and their associated sensors change with varying temperatures and levels of use over the life of the system. Semi-active dampers are also sensitive to loss of power, a condition which is likely given the catastrophic nature of seismic events that structural damping systems are predominantly designed to mitigate. Some types of semi-active dampers such as the magneto rheological damper have received attention over the last decades because of their exceptionally low power requirement and fail-safe nature in the event of a loss of power, but their level of applicability in structural systems is

inadequate for actual integration and adoption on a wide scale at this time (Laflamme, Taylor, Maane, & Connor, 2011). Another device, the MFD that has been mentioned previously, also requires very little power and even has some performance benefits (as high as 10% reduction in acceleration (Laflamme, Taylor, Maane, & Connor, 2011)) when in a completely unpowered state, however given the high likelihood of power failure and the significantly reduction in performance it is clear that reliability will be a concern of structure owners considering semi-active damping systems at this time.

Table 9 - Direct Cost Savings Summary

Type of Damper	Direct Savings	Structure Type
Viscous	\$ 800,000	Steel Moment Frame
Viscous	\$ 440,000	Multi-Story Concrete
Viscous	\$ 460,000	Steel Moment Frame
Viscous	\$ 28,000	Steel Moment Frame
Tuned Mass	\$ 4,000,000	Steel Moment Frame
Tuned Sloshing	\$ 500,000	Steel Moment Frame
Friction	\$ 30,000,000	Steel Moment Frame
Friction	\$ 2,250,000	Steel Moment Frame
Friction	\$ 500,000	Multi-Story Concrete
Base Isolation	\$ 370,000	Steel Moment Frame
Base Isolation	\$ 30,000,000	Cantilever Bridge
Base Isolation	\$ 1,200,000	Steel Moment Frame

5.2 RECOMMENDATIONS

Much work remains to be done on the topic of assessing true costs of semi-active damping systems.

- Factors such as electricity costs and requirements, and methods for ensuring the continued functionality of the damping system in the event that the structure loses electrical service from the main power grid must be researched. Without information on these factors, accurate life-cycle cost analyses cannot be completed.

- More data on the cost versus performance of semi-active damping systems are needed, including detailed life-cycle cost analyses and performance evaluation with regards to undamped and passively damped cases. A multitude of structural configurations should be tested so as to facilitate comparison between data from pretested configurations and real world applications.
- The topic of controller performance is also one of concern. Many tests have been conducted with sensors that are brand new, and with control algorithms that have been perfectly optimized for predetermined excitation ranges and amplitudes to be tested, which raises questions as to how performance may be affected by sensors that have been in service for many years in harsh conditions, and by excitations that are randomized and therefore possibly not within the range for which the system has been perfectly optimized. This is especially important because of the long expected service life of structures and their associated damping systems, which include the sensors required for operation. Also testing of randomized loading is an important step in the assessment of performance of semi-active damping because of the inherent unpredictability of the strength of the seismic or wind excitation that a structure may be exposed to in its lifetime.
- Further consideration must also be given to the codes by which engineers design structures. Structural damping systems were primarily developed as a means of protecting buildings from seismic and wind load damage. Owners expect structures equipped with structural damping systems to suffer only minimal damage during an earthquake, but this expectation is in conflict with current building codes that allow significant damage to damped structures. Building codes only ensure that structures equipped with damping systems “will be at least as safe as conventional buildings” and have the same *protection against collapse* as undamped structures (Zayas, Seismic Isolation Design for Continued Functionality, 2013). Over

the last 20 years, most of the economic losses caused by earthquakes have resulted from non-structural damage and loss of facility use from damage to non-structural building components during moderate ground shaking. The Federal Emergency Management Agency's "Seismic Performance Assessments of Buildings" (FEMA 58) is a computational tool that estimates expected earthquake damage to structures and non-structural components (Zayas, Seismic Isolation Design for Resilient Buildings, 2013). It was reported that for typical undamped structures, the damage expected in a seismically active zone over a 50 year period was equal to an additional 22% of the initial construction costs of a structure, while effective use of damping systems could lower earthquake losses by as much as 97% (Zayas, Seismic Isolation Design for Resilient Buildings, 2013).

- To satisfy owner expectations of minimal earthquake and wind damage, there is a movement toward codifying criteria for "Continued Functionality" where damage to structural and non-structural components will be limited to less than 2% of the building replacement cost. A "90% Reliability of Continued Functionality" is defined as limiting damage to less than 2% of the replacement costs for an earthquake with a less than 10% chance of being exceeded in 50 years (Arup & Arup, 2013). FEMA 58 methodology and software can be used to calculate the dollar value of the expected seismic damage, which can be used by the structure owner and design engineer to select the type and size of damping system that is most cost-effective for the project.

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