The Efficacy of Seismic Control Algorithms in Semi-Active Energy Dissipation Systems

Bo André Lundqvist
Civil Engineering

Author

Bo Lundqvist wanted to get involved in research as a way to expand his knowledge of his major beyond what he was learning in the classroom. He discovered that Professor Zareian was working on research related to earthquakes, and was able to join one such project. Through his work, Bo developed a passion for Earthquake Engineering that he looks to pursue in his future education and career. After graduation, Bo intends to begin work on a Master's degree at Stanford University.

Abstract

Several algorithms have been proposed for use in conjunction with energy dissipation devices to mitigate damage to structures during earthquakes. Prior research has shown that these control algorithms have the potential to significantly reduce structural displacements during seismic events. The proposed energy dissipation devices, when paired with the appropriate control algorithm, hold promise for effective structural control as low-cost, low-maintenance, and low-energy solutions to damages caused by seismic events. While the algorithms had already shown desirable results in prior testing, the device and control methods had not yet been tested and analyzed for a broad range of ground motions and system settings. This study verifies existing research conclusions of the control systems' efficacy and also achieves a more comprehensive understanding of their respective strengths and weaknesses. Mathematical models were created to perform a thorough analysis of structural performance under applied earthquake conditions. Comparison of the two fundamental control algorithms for this research, known as 1&3 and 2&4, yields more favorable results for the former, due to its lesser reliance on high stiffness and its ability to resist pulse-like ground motions. The study concludes that the 1&3 algorithm is a more effective control method to apply through the proposed mechanical device.

Key Terms

- Control Algorithm
- Energy Dissipation
- Seismic Mitigation
- Semi-Active Control
- Structural Control
- Structural Design
- Variable-Stiffness

Faculty Mentor

Bo's research advances our understanding of a special class of structural control devices for protection of various components of civil infrastructure (*e.g.*, building and bridges) from destructive seismic events. This research is not only important to the Earthquake Engineering research community who are mainly focused on developing structural control devices and algorithms, it also serves the practicing engineers by introducing a simple and effective structural control concept. Bo was in the unique position to tackle this research. He developed the required knowledge for leading this project through coursework and research. I strongly encourage all talented undergraduate students to take advantage of the research opportunities at UCI.

Farzin Zareian
Samueli School of Engineering

Introduction

Earthquakes pose a threat for which it is difficult to prepare. Although many areas of the world have building codes that require a certain degree of seismic analysis in the design of their structures, the unpredictable nature of seismic events often results in large communities getting hit off-guard and important facilities being rendered temporarily, if not permanently, non-operational. Research regarding seismic mitigation systems has therefore become increasingly prominent, especially in countries that frequently face the destructive nature of earthquakes. In the expanding field of seismic mitigation, semi-active structural control has become an increasingly popular research focus due to its balance between passive and active control traits. Passive control systems, such as tuned mass dampers, are characterized by the lack of a need to input energy for them to function and act only when prompted by outside forces—more importantly, they are always ready to act without having to be artificially turned on. However, this condition means that passive systems are unable to adjust to specific seismic motions as they occur. Active control systems, on the other hand, are characterized by a need to apply energy to damp a building, in doses based on measured responses, often from sensors. Unfortunately, inserting energy into a structural system can be costly, despite also accomplishing the desired task of damping structural response motions. Semi-active control is a blend of both in that it requires a control algorithm and sensors to determine when to damp the system, as with active control, but does not add any additional energy to the system, thus being strictly dissipative (Chase J. G., et al., 2006). Such a system provides a theoretically cost-effective, potent way to protect buildings against seismic events, given the correct algorithm and device to provide the semi-active control.

Energy Dissipation Device

To capitalize on the benefits of semi-active structural control, Professors Faryar Jabbari and James Bobrow of the University of California, Irvine introduced a mechanical pneumatic device which mitigates adverse effects of structural vibrations by dissipating energy through timed and controlled alterations of structural stiffness (Jabbari & Bobrow, 2002). This device operates and can be modeled as a non-linear spring which is capable of "resetting" its theoretical length—thus altering its stiffness—to dissipate energy from the system to which it is attached, as shown in Figure 1. Essentially, the device functions like a pneumatic spring, a chamber filled with air alters the structural stiffness of its brace.[1] As the mass stretches the spring, the piston device attached to the mass builds pressure and adds additional stiffness to the system. Once the mass reaches a point designated by its corresponding control algorithm, the valve on the piston opens and releases the built-up pressure, effectively reducing the stiffness of the system back to that of the spring alone and dissipating energy in the process. This manner continues as directed by the applied control algorithm until the mass does not move anymore. Therefore, depending on the efficiency of the applied control algorithms, this device is capable of softening the violent responses that structures experience during seismic events through regular dissipation of energy in the resetting actuator.

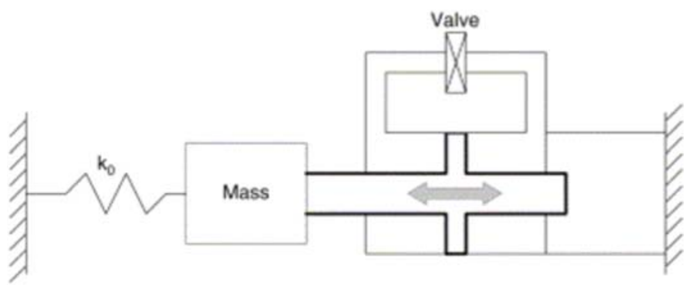

Figure 1

Schematic of a single-valve, semi-active resettable actuator attached to a single-degree-of-freedom system. The right side of the system fills with either air or fluid to build stiffness and act as a second spring to the mass system (which damps the motion of the existing spring). The valve allows the device to release its stiffness for optimized dissipation (Jabbari & Bobrow, 2002).

For larger structures, the damping piston would be attached to both the brace and frame of a structure, as seen in Figure 2. The brace provides additional stiffness to the frame of the structure through the intermediate device whenever it activates. When the device deactivates, the brace disengages from the frame and thus does not contribute any stiffness to the frame. The structure then returns to its original stiffness until the device is activated again to add the brace stiffness to the system.

Control Algorithms

Between research at the University of California, Irvine and the University of Canterbury, four control algorithms have been proposed as compatible with the resettable control device's unique mechanical capabilities for energy dissipation. These methods are known as the 1&3, 2&4, 1–4, and

1. Though the device is mainly introduced as a pneumatic spring in the literature, it would also be possible to implement it as a hydraulic system without sacrificing any of its functionality or benefits as a control device, as both gas and water are well understood in terms of their application to these kinds of devices. In fact, for a structural scale version of the device, hydraulics may be necessary as they can release pressure much quicker than gas.

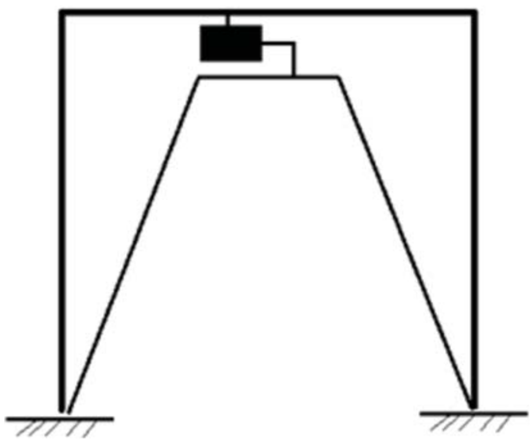

Figure 2

Example of the semi-active resettable device's implementation in a brace-frame system

Diamond methods (Corman, Chase, MacRae, & Rodgers, 2012). In the 1&3 method, the control device activates when the frame experiences lateral deformation in the same direction as its motion. Upon activation of the device, the brace stiffness is added to the frame stiffness to reduce the system's response displacement. Once the system begins to move back to its point of zero displacement, mathematically indicated by opposite signs on velocity and displacement, the device deactivates and the total stiffness becomes only the frame stiffness. In the 2&4 method, the device activates when the sign of velocity does not match the sign of displacement. This means that the device activates when the structure is returning from its maximum displacement, operating under the complete opposite activation theory from its counterpart 1&3 method. Once the structure returns to its original position, the device deactivates and the stiffness returns to being only the frame stiffness once again. The 1–4 method employs a similar control theory to that of the 1&3 method, adding brace stiffness to the system when displacement and velocity are in the same direction (have matching signs); however, once the device reaches maximum displacement, the "spring" resets by releasing pressure and then re-activates to add stiffness once again. As seen in Figure 3, this causes the device to dissipate more energy at a greater frequency by adding some of the theory from the 2&4 method to the 1&3 control algorithm as well. The Diamond method, the most recently developed of the proposed control algorithms, seeks to improve upon the 2&4 method by adding more stiffness resets to release built-up pressure and energy from the device, similar to the means by which the 1–4 method improves upon the 1&3 algorithm's framework.

The Mechanical and Civil Engineering Departments at the University of Canterbury in New Zealand have performed precursory testing with all of these control methods in order to determine the possible reductions in system responses to seismic events, reporting reductions as great as 60% for modeling of the most effective method, the 1–4 (Chase J. G., et al., 2006). However, while reductions of that scale are immensely promising for seismic mitigation methods and corroborate that continued research on the topic is worthwhile, modeling of these control algorithms as executed

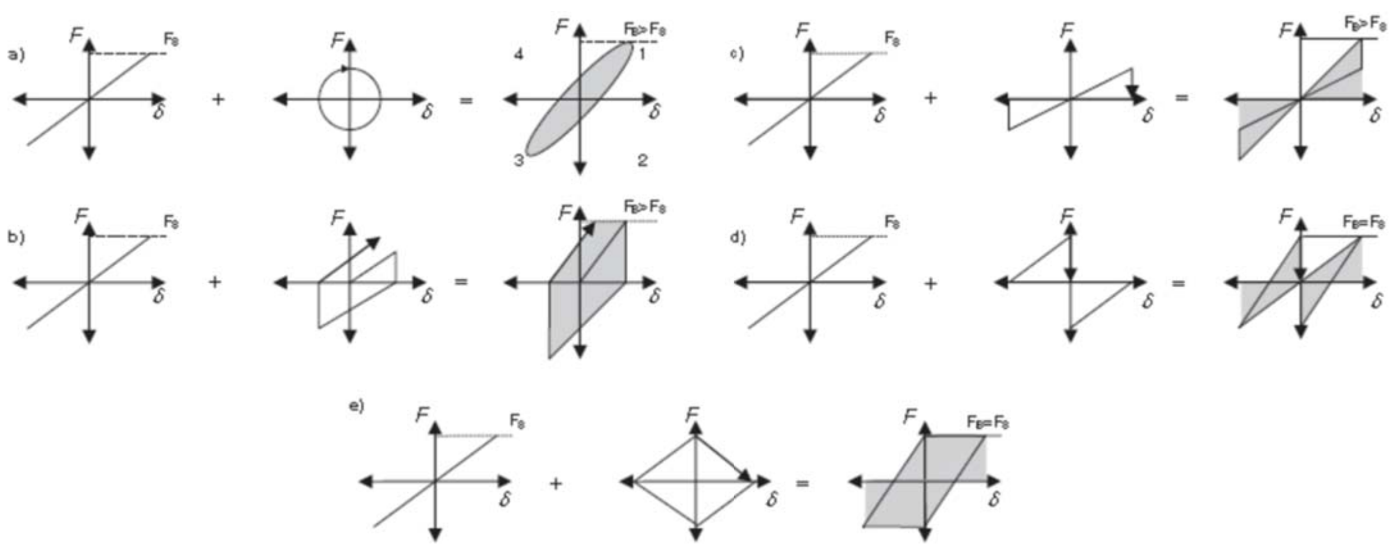

Figure 3

Schematic hysteresis for: a) viscous damping, b) a 1–4 device, c) a 1&3 device, d) a 2&4 device, and e) a diamond shaped device. FB = total base shear, FS = base shear for a linear, undamped structure. FB > FS indicates an increase due to the additional damping (Corman, Chase, MacRae, & Rodgers, 2012).

through the proposed resettable device in previous studies has not been complete in terms of thorough modeling for a wide range of seismic events. Limited ground motion testing has prevented the functional understanding of this device and its proposed algorithms from being entirely comprehensive, particularly in terms of the algorithms' strengths and weaknesses for a variety of ground motion scenarios.

The current study completes an expanded analysis of the two most fundamental control algorithms, 1&3 and 2&4, as applied through the energy dissipation device to a single degree-of-freedom brace-frame system for an extensive set of ground motion data in order to both confirm modeling results from antecedent studies and fill knowledge gaps of the methods' respective strengths and weaknesses. This study also compares the results of each of the tested control algorithms to determine their relative capabilities in structural response mitigation and to ascertain whether or not certain ground motions can be more adequately reduced by one algorithm or the other.

Model & Algorithm Methodology

Tested Algorithms

Of the four control algorithms developed and researched by faculty at the University of California, Irvine and the University of Canterbury, the 1&3 and 2&4 structural control algorithms are the most fundamental methods. Though these are not necessarily the most effective algorithms in structural response reduction according to existing research, the control principles on which each is based serve as the foundations for both the 1–4 method (based on the 1&3 method) and the Diamond method (a modification of the 2&4 method). For this reason, the 1&3 and 2&4 algorithms were chosen as the damping algorithms which would be applied to the brace-frame structural system in the modeling process. Positive results from these fundamental models would confirm the general efficacy of all of the developed control algorithms and general congruence with previous research results would also confirm the validity of the current study's modeling methods. Additionally, modeling the 1&3 and 2&4 algorithms allows for the best comparison between the core semi-active control theories, as these algorithms add stiffness to the structure at exactly opposite times in the spring cycle. This study's mathematical model was therefore developed for the discussed brace-frame system under each of the fundamental control algorithms, set to output data for maximum acceleration, velocity, and displacement, given an input ground motion set.

Variable Parameters

A critical factor in determining the feasibility and cost of implementing the proposed damping device on a large scale brace-frame system will be how much stiffness needs to be added to the system by the device in order to be effective to a desired damping level. The maximum added stiffness from the device was characterized in the model as the Brace-to-Frame Stiffness Ratio (BFS), ranging from a factor of .0001 to 2.0. A BFS factor of 2 would indicate a system where the device can triple the initial stiffness of the system when activated, whereas a BFS factor of .0001 essentially represents a system without a device (as virtually no stiffness is added when the device engages). More likely feasible from an economic standpoint than the extreme of 2.0, BFS factors of 0.5 and 1.0 were also considered in all conditions to ensure that even adding half of the system's original stiffness would be effective in damping displacements. Although the modeling process focused on verifying and comparing the theoretical effectivity of the 1&3 and 2&4 control algorithms, testing the degree of seismic mitigation across a range of added stiffnesses is equally critical for determining the viability of a structural-scale device and what method should be implemented in the device for maximum cost efficiency. It is reasonable to assume that larger values for the BFS factor could represent a higher device cost, creating a greater barrier for its applicability in a real-world setting. Initial predictions were that a BFS factor of 0.5 would already provide a significant value of desired damping, with diminishing returns for values above 2.0.

The need for general applicability of the current study's findings to many building types required that the brace-frame system model also be tested using varying structural periods, with a range between 0.5 and 3.0 being used for the model analysis. Data for a variety of structural periods could point to possible incentives for using one method over the other in certain buildings, which would allow the study to better recommend certain control algorithms for buildings within a specific period range. A concern regarding the 1&3 method expressed in prior research was that the algorithm could cause increases in total base shear experienced by a structure, limiting the applicability of the device mostly to new buildings (Chase J. G., et al., 2006).[2] The current study sought to test this claim by analyzing output acceleration data to check the severity of any base shear increases under a variety of possible structural and device conditions, to clarify trade-offs in terms of structural resistance.

2. Significant increases in base shear due to the control algorithm could push an existing structure beyond its design parameters, particularly in terms of leaving an adequate factor of safety. Therefore, if the control method were to cause great amounts of base shear, buildings using the device would have to be designed for it to begin with.

Ground Motion Data

Though past research has convincingly introduced the possible benefits of the proposed control algorithms, testing through physical and computerized models has been limited in the scope of earthquakes applied to the system. Though one might assume that the type of earthquake experienced is largely irrelevant to the system's damping capabilities using the device and control algorithm, as with the building period, it is imperative that the device be tested for a large variety of ground motions in order to ascertain its universal success, as well as any nuances under certain conditions, and to determine if a certain control method exceeds the performance of another.

Initially the model began with an input of forty random ground motion records in order to determine relative device success for a wide and non-uniform variety of seismic events, scaled to meet Design Basis Earthquake (DBE) levels. After establishing a precedent for the system's abilities under these conditions, the model system was tested under a significantly larger number of ground motions drawn from research done by Stanford University's Professor Jack Baker for the Pacific Earthquake Engineering Research Center under the "Ground Motions Studies for Transportation Systems" project (Baker, Jayaram, & Shahi, n.d.). These additional ground motion sets are divisible into three groups: Broadband Soil, Broadband Rock, and Pulse-Like ground motions. Each of these ground motion categories consisted of forty fault-normal and forty fault-parallel ground motion sets (strike-normal and strike-parallel for Pulse-Like motions) that were analyzed with the modeled brace-frame system. In addition to analyzing the Engineering Demand Parameters (EDPs) of the system (displacement, velocity, and acceleration), the base earthquake's recorded values were similarly analyzed to provide a frame of reference between varying earthquakes. Additionally, the activity of the device was analyzed for the duration of the ground motion in order to determine activation of the device with respect to the motions of the earthquake throughout the duration of the seismic event. This comprehensive analysis provides a broader perspective on the applicability of the device, as well as providing new insight into its functionality in unique scenarios, such as Pulse-Like ground motions, which are often difficult for seismic resistant systems due to the initial pulses' "shock" on the systems. Modeling the device and associated control algorithms for these approximately 320 ground motion sets under a variety of added stiffness and structural period conditions provides a more thorough understanding of the behavior of the device-mounted system under both tested control algorithms, along with their full capabilities and limitations.

Model Theory

The modeling infrastructure for the device-mounted brace-frame system jointly relies on MATLAB® and Simulink® software to generate the desired outputs. The developed MATLAB script begins by reading an input set of ground motion acceleration data with an associated data collection time interval. The acceleration data with respect to time is plotted as the ground motion acceleration and then integrated to develop similar plots for velocity and displacement, as seen in Figure 4. These ground motion output plots provide a foundation for analyzing the brace-frame system to which they are then applied because they allow for direct comparisons between various earthquake scenarios.

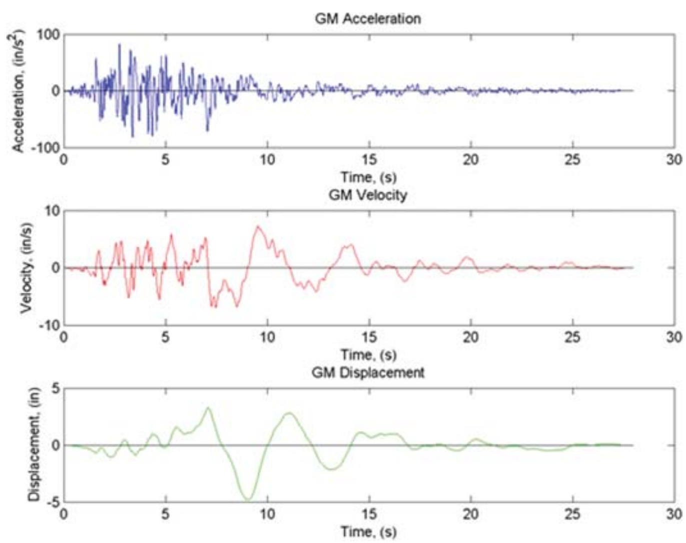

Figure 4

Ground motion plots of acceleration, velocity, and displacement produced by the modeling script using data from the Broadband Soil ground motion set.

The complimentary Simulink model then takes the input ground motion and applies it to three theoretical systems—one with a 1&3 controlled device, one with a 2&4 controlled device, and a control system without any device. The system using the 1&3 algorithm follows the control theory described in the Introduction, adding device stiffness (brace stiffness) when the displacement of the spring system and system velocity have the same sign and disengaging as soon as either sign changes. The 2&4 system, on the other hand, adds device stiffness to the system when displacement and velocity have opposing mathematical signs (as the system returns to its neutral position) and disengages as soon as that is no longer the case. The system's accelerations and displacements for the duration of the seismic event are then recorded and output as a data set with values collected at the same time intervals as the data from the input ground motion. For each ground motion, this process is repeated for a set of brace stiffness factors and structural periods until all considered combinations of these variables have been exhausted.

Once this data has been output from Simulink, a MATLAB script takes the response data—acceleration, velocity, and displacement—from the theoretical device and adds it to the original ground motion data to determine total EDP responses of the system. Once this has been done for each brace stiffness and period, graphs are generated to compare how the EDP responses vary with BFS factor for a fixed period, as in Figure 5. Such a plot is generated for both control algorithms, which can then be compared to determine relative effectiveness between the two, with particular interest in the acceleration and displacement graphs.

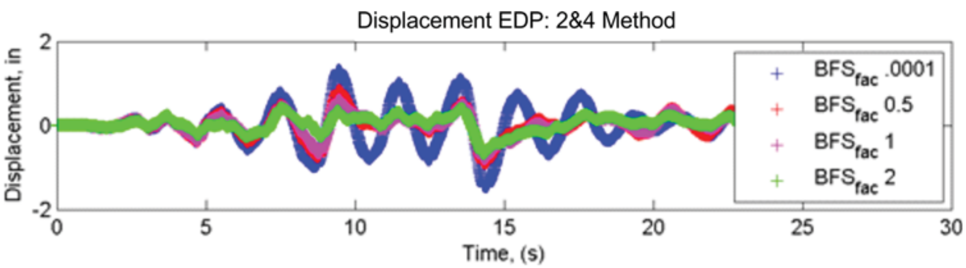

Figure 5

Comparison plot of total Displacement EDP response from the brace-frame system under varying BFS factors. Note that a BFS factor of .0001 is essentially equivalent to a system without the energy dissipating device, operating only under an assumed natural structural damping of 5%.

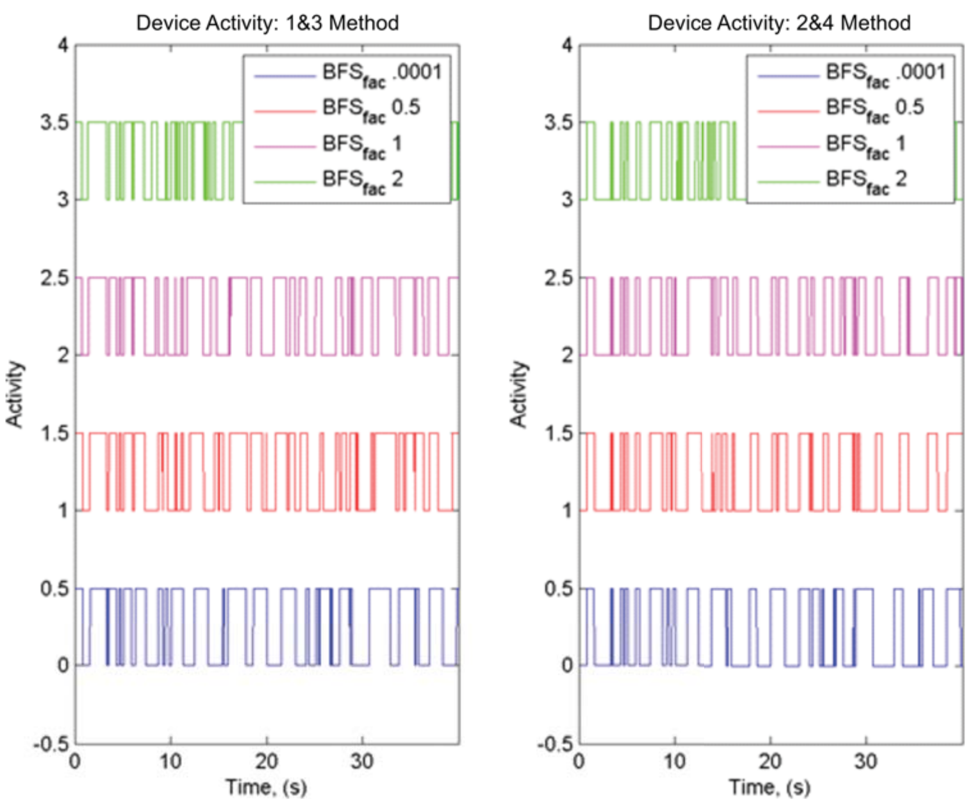

Figure 6

Activation graph for a Pulse-Like ground motion; values at 0.5 intervals represent an active device, while integer intervals represent a dormant device. As a check, the activity for the device under the 1&3 and 2&4 control algorithms should be opposite at similar temporal points during the seismic event.

Finally, the script reviews the output data and determines when the device was active or inactive and plots activations of the device with respect to time. This is useful for comparison to the timeline present in the EDP plots as another check that the device and control algorithm are being applied to the device. The density of the lines also provides an idea of the frequency of activations, which is interesting data to analyze for various structural periods. A sample of this output plot can be seen in Figure 6.

Results

Expected Results

Given the theoretical force-displacement plots of the different algorithms seen in Figure 3, a system using these methods would necessarily dissipate energy and reduce a seismic event's capabilities to displace the modeled brace-frame system. Given correct modeling of the device and algorithm in the brace-frame system, displacements should also necessarily diminish. However, the scale of response reductions and possible increases in base shear would likely still vary based on the selected control algorithm, BFS factor, and structural period.

Prior research performed at the University of Canterbury indicated that the 2&4 method increases structural damping without increasing base shear, on the basis that the method operates solely on opposing motion towards the center (in terms of a spring) (Chase J. G., et al., 2006). The 1&3 method, on the other hand, adds stiffness while motion of the system is away from its center, which would theoretically increase the base shear that the system experiences. Expected results of the modeling were therefore that the 1&3 algorithm would exceed the 2&4 in terms of effectiveness in reducing response displacement but, in turn, significantly increase the acceleration of the system. The degree to which acceleration and base shear would increase under the 1&3 conditions was unclear at the initiation of the modeling process but was noted as an important result to analyze, as too large a multiplier could greatly limit its use in retrofit applications.

With regards to the effect of the BFS factor on structural damping, it is intuitive that greater stiffness would imply greater damping, as more resistive force could be added to the system. Of greater significance to the study, however, was the point at which the added structural damping would become significant and the point of diminishing returns where further added stiffness would become insignificant. Both results would provide critical insight into what degree of added stiffness would be most economical as the design value. The point of significance was predicted to be around 1.5 times the original stiffness and the point of diminishing returns for structural damping was assumed to be between two and three times the original stiffness. These predictions dictated the chosen values of 0.0001, 0.5, 1.0, and 2.0 for the BFS factor values.

As with device stiffness, predicted results dictated chosen period values for testing in the model. Values of 0.5, 1.0, 2.0, and 3.0 were chosen for the system's period on the basis that seismic design, barring design of skyscrapers, is usually most critical for buildings with periods between 0.5 and 3.0 seconds (Chase J. G., et al., 2006). Thus, expectations held that the model would yield the greatest effects when the system's period was set within the critical range, with only incremental changes when the system's period was set to a value above 2.0. However, the current study predicted structural period to play a significantly less critical role in damping potential than the chosen control algorithm or the added stiffness. Nonetheless, it was set to be varied in the modeling process in order to ensure the universality of the results from the device and control algorithm to all building types.

Model Results

Running the first set of random scaled ground motions (referred to as LMSR-N) yielded initial plots of the maximum EDP response ratio (with device to without device) against structural period for each ground motion. In order to get a better idea of the variation in the device's effectiveness, trend lines and their associated standard deviations were drawn through the data. Trends shows that the 2&4 control method was fairly consistent across all periods,

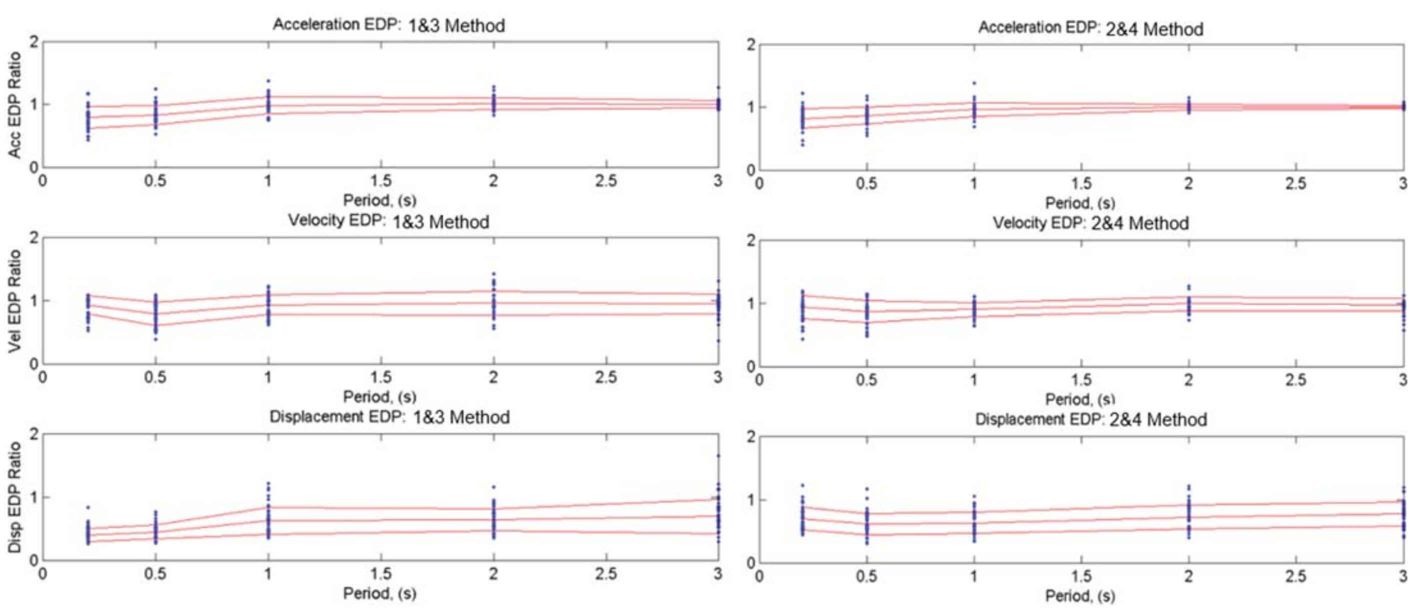

Figure 7

Response Ratios for LMSR-N Ground Motion set across a variety of periods. Maximum ratio values for each of the forty ground motions are denoted by the blue dots. The middle red line indicates the average of all of these values, while the upper and lower red lines indicate standard deviations from the average trend.

while the 1&3 method operated more optimally for low structural periods. In summary, the 1&3 method generally dominated the 2&4 method in terms of decreasing seismically induced displacement and neither algorithm significantly affected the acceleration of the system. These initial results implied that the 1&3 method would generally be preferable to the 2&4 method in terms of structural damping. Figure 7 typifies EDP response ratio results when the BFS factor is at a value of 1, but values of 0.5 and 2.0 also yielded similar results. Notably, the acceleration ratio of the 2&4 method during some earthquakes actually goes above 1.0, as initially predicted only for the 1&3 method. At least in terms of the LMSR-N Ground Motion Set, the 1&3 method was clearly superior, with the difference between the two methods diminishing as the structural period increases.

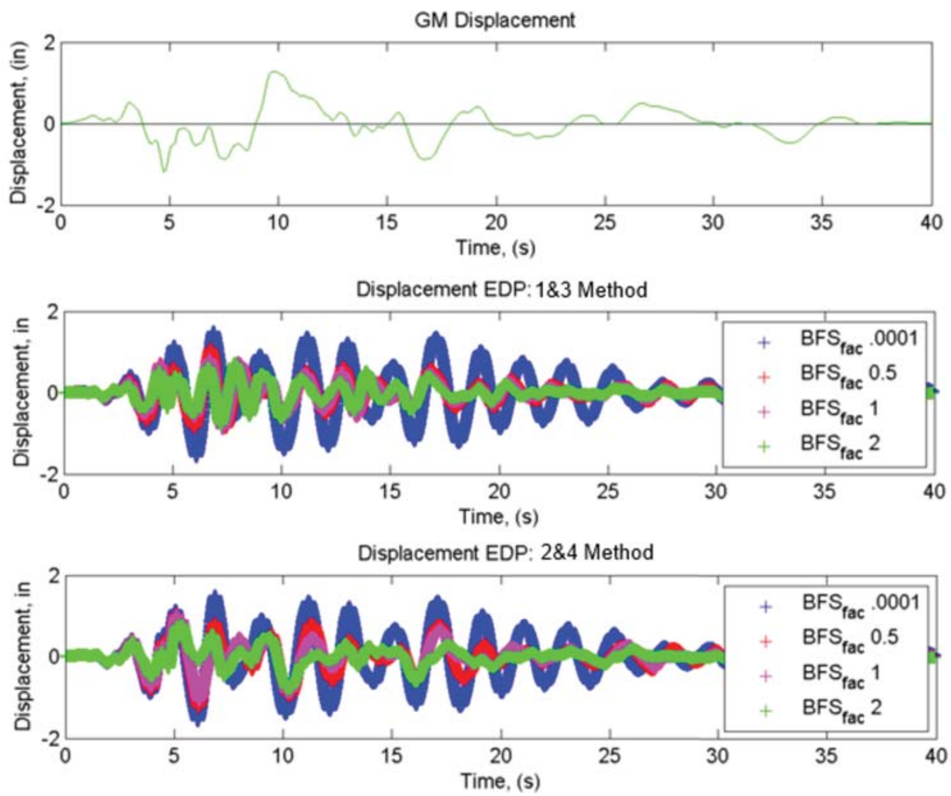

Figure 8

System Displacement comparison for each control method in a Fault-Normal simulation of the Loma Prieta earthquake (NGA Record # 748), classified in the Broadband Rock ground motion set.

In order for the current study to comprehensively fill the research gap for modeling results of the algorithms, the device methodology needed to be tested on a much more expansive assortment of ground motions—thus, a variety of structural periods and stiffness factors were tested on three sets of ground motions types. In order to determine which control method produced more desirable results, a number of factors were specifically observed from the model results, including increases or decreases in acceleration with respect to the "No Device" setting, magnitude of decrease in displacement due to each algorithm, response of the system to varying degrees of stiffness in each control method, and variations in the displacement across structural periods. Additionally, every set of ground motions was examined separately in order to determine if the control methods operate better for any particular kind or kinds of earthquakes.

The first set of ground motions from the PEER database, referred to as Broadband Rock, slightly favored the 1&3 method, although the 2&4 method also produced desirable results. One difference between the two control algorithms for this set of motions was that the modeled systems using the 1&3 algorithm generally benefitted more dramatically from increases in the device stiffness (BFS factor). When both modeled systems were at the maximum tested stiffness (BFS factor = 2.0), differences in displacement reductions were nominal, as seen by the small variation in their global and local maxima in Figure 8. However, at lower BFS factors of 0.5 or 1.0, the 1&3 method generated much better results than that of the 2&4 method in terms of displacement reductions. Though the 2&4 algorithm generally displayed a slightly greater reduction in maximum response acceleration, neither control method showed consistently potent increases or decreases in acceleration.

The modeled systems were also tested using two Broadband Soil earthquake records, the first of these sets being called M6R25 in the PEER database. Though Broadband Rock gave a good idea of what to expect from each control method for varying stiffness, it gave only a small insight into the effect of each method at varying structural periods. For this reason, Broadband Soil M6R25 was tested with a larger span of structural periods, ranging from 0.2 to 3.0 seconds. For small periods (0.2, 0.5, and 1.0), 2&4 is constantly worse in terms of displacement, again with only a small advantage over its 1&3 equivalent in terms of response acceleration. As the structural period increased (tested at 2.0

and 3.0), however, the difference in maximum displacement between the two control methods diminished. Up until the convergence of the methods' results at these high periods, the 1&3 method almost completely dominated the 2&4 method for damping EDP responses. These findings were mirrored in results from the second set of Broadband Soils, which more drastically showed greater reductions for the 1&3 method.

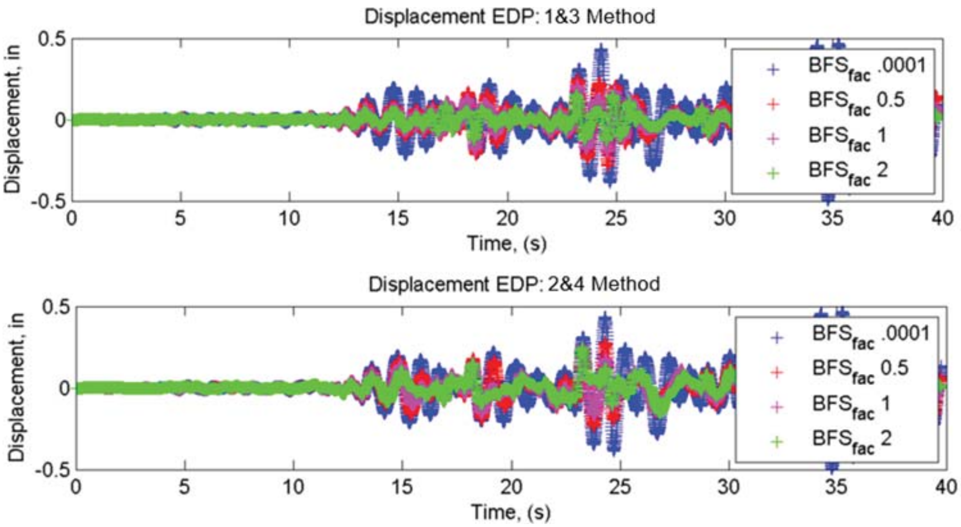

Figure 9

Displacement EDPs for both methods in Northridge-01 Earthquake (NGA Record #964) from 1994. Despite this earthquake having a magnitude of 6.7, the displacements for both algorithms are small because the measuring point was 50.6 km from the hypocenter. Nonetheless, the damping of the 1&3 method is seen to be more effective, particularly in the first few seconds of ground motion

The 1&3 method also reduced displacement EDP to a significantly greater degree than the 2&4 method for the final set, Pulse-Like ground motions. Not only do the results display greater damping for every increase in device stiffness, but the 1&3 algorithm also efficiently reduced the response from the initial pulse. The equivalent 2&4 method plots, on the other hand, reveal that that algorithm cannot effectively reduce the pulse of this unique set of ground motions.

Discussion

Barring the results for Pulse-Like ground motions, both fundamental algorithms proved effective in reducing structural responses to seismic events. However, analysis of the two systems' responses to the ground motion sets shows that in a significant majority of ground motion scenarios the 1&3 method is better than or equal to the 2&4 method in terms of reducing system displacement, the most critical ground motion EDP to this study as it is often the most damaging to a structure during seismic events. Exemplified in Figure 10, the 1&3 reduction values were frequently 50% greater than their 2&4 counterparts', particularly for Pulse-Like ground motions. Strictly in terms of dissipating energy and mitigating response displacements, this makes the 1&3 method the obvious choice for structural control implementation. Previous research has correlat-

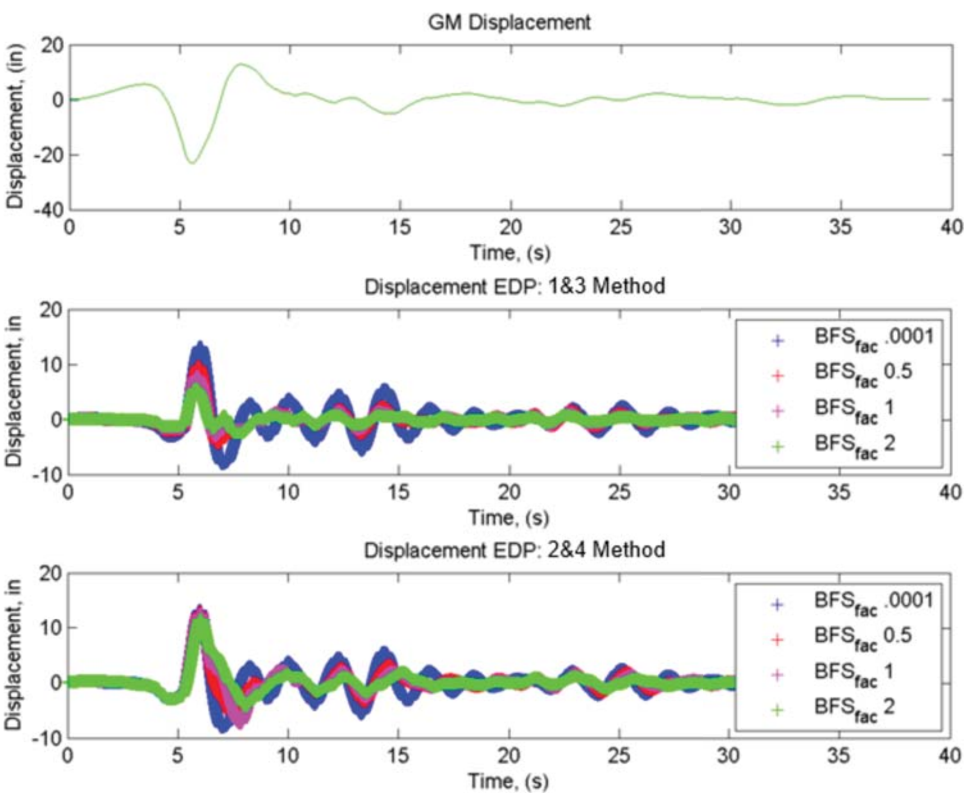

Figure 10

Variation in responses from systems undergoing data from Magnitude 6.53, 1979 Imperial Valley-06 Earthquake (NGA Record #: 179). Due to its particular control theory, the 2&4 device cannot damp the initial pulse as effectively as the 1&3 method, for all device stiffness values.

ed the 1&3 and 1–4 methods, claiming that the 1–4 method is simply an improved version of the 1&3 algorithm philosophy (Chase J. G., et al., 2006). This seems logical, given that the 1–4 method applies the same control philosophy as the 1&3 method, but also adds damping in the second and fourth quadrants. Continued research would be needed to more closely examine the feasibility of the 1–4 method, ensuring that it does not increase base shear (response acceleration) more than the 1&3 method. The efficiency demonstrated by the 1&3 method by significant response reductions, even with low BFS factors, indicates that it is likely also a more cost effective control option than its 2&4 counterpart.

Though the differences are generally small, it is worth noting that the 2&4 method, as suggested by research at the University of Canterbury, does surpass the 1–3 method in terms of reducing acceleration. Refraining from increasing acceleration is critical if a system is seeking to reduce displacements without increasing base shear, particularly if the intended use is for retrofit applications where it the design acceleration is already set. However, the current study's analysis of the 2&4 method indicates that it may not be as dependable as prior research indicates. A number of the modeled ground motions produced increased acceleration responses even for the 2&4 method—also mostly miniscule, but it puts into question the theoretical notion that the 2&4 method cannot produce increases in base shear.[3] This also casts some doubt on the Diamond method, as it is a derivative of the 2&4 method that also uses energy dissipation in the first and third quadrants. The 2&4 method may more consistently reduce acceleration and base shear throughout a ground motion, but it seems to have little effect on the global maxima, which are the most problematic consequence of ground motion accelerations for causing failures. Research previously done by Chase suggests that the Diamond method does not increase base shear at all, so the contradictory results of this study will require closer analysis in future research.

Overall, the study indicated that, while both structural control algorithms are viable, the 1&3 method (and, thus, possibly also the 1–4 method) is best suited for continued research using the proposed damping devices. The ideal control method is equally prepared for all ground motions and every set of modeled earthquake data favored the 1&3 method over its counterpart. The set that best defines the necessity for use of the 1&3 over 2&4 method is the Pulse-Like motions which begin with a quick pulse and then die off. The control theory for the 1&3 method allows it to resist motion away from its rest position, which enables it to provide resistance to this quick, initial pulse, while the 2&4 device only engages as it returns to the rest position. Thus, it does not engage until the building has felt the full initial displacement and only then begins to dissipate energy from the system. The 1&3 method should likely be the algorithm of choice for further study with the semi-active dissipation devices, as an unchecked Pulse-Like motion can be extremely destructive for any structural system.

3. Increasing base shear, even to a small degree, would greatly hamper the device and control method's ability to be used in retrofit applications, as calculations would have to be made to ensure that the existing building could handle any anomalous increases in base shear.

Limitations

Though this study thoroughly examines the proposed fundamental control algorithms for a wide range and large variety of ground motions, the results remain theoretical, as tests were conducted solely through computer modeling. Though the models' results certainly inform the physical tests that should be done to confirm the results, such tests have yet to be performed for such a wide variety of earthquake data. The efficacy of the 1&3 method is already supported by a number of previous physical tests on shake tables (though still using scaled buildings), but has yet to be physically tested on such a comprehensive set of ground motion data as presented in this study, particularly for the class of Pulse-Like motions it examined (Franco-Anaya, et al., 2007). Additionally, the mathematical model used in this study was a single-degree-of-freedom system; modeling using a multiple-degree-of-freedom system would need to be performed to verify the results for more complex building systems.

Conclusion

The proposed hydraulic semi-active control device presents a promising opportunity to improve structural damping through intelligently-crafted control systems. This study confirms that both fundamental control algorithms, the 1&3 and 2&4 methods, are effective in dissipating unwanted energy built up during seismic events, and designates the 1&3 method as the consistently more effective algorithm. Previous research on the methods lacked a thorough analysis of the methods under an array of ground motions; however, this study fills that gap to enable a more complete understanding of the strengths and limitations of each fundamental method. The sole limitation of the 1&3 method in comparison to its 2&4 counterpart is a slightly increased response acceleration shown in a number of model results. However, knowledge of this minor drawback beforehand can ensure that structural design is completed in such a way that it will not bring damage to the building once equipped with the device, and thus it is still the recommended method for structural control. Though it requires further research, the 1&3 method also implies the success of the 1–4 method, which theoretically improves on the same ideology but with more energy dissipation involved. Future research in structural control using semi-active devices should continue to use and explore the 1&3 and 1–4 methods in order to yield the most promising results and push at the research edge of structural control through energy dissipation.

Acknowledgements

I would like to thank Professor Farzin Zareian for all of his guidance as my faculty mentor for this project. This research has allowed me to gain a unique insight into and a passion for the fields of structural and earthquake engineering which I would not have otherwise gained solely through classroom learning. The passion with which Farzin approaches teaching his students to truly understand concepts, both in research and in course material, is infectious and has driven my desire to become more involved with the topics I have studied. I am eternally grateful to Farzin for teaching me both within and outside of the classroom.

I would also like to thank Kevin Nguyen, my friend and colleague, who was invaluable as my partner in this research effort. Though the steps to garnering successful results were not always clear when navigating this project, particularly at its onset, Kevin's intellectual contributions and willingness to explore new ideas always helped set our team on the right path. The products of this research are as much an indication of his success as they are my own.

Works Cited

Anaya, Roberto Franco. "Seismic Performance of Semi-Active Control Systems." Christchurch, April 2008.

Baker, Jack, Nirmal Jayaram and Shrey Shahi. Ground Motion Studies for Transportation Systems. n.d. 4 June 2014.

Chase, J. G., R. Franco-Anaya and A.J. Carr. "Seismic response reduction of a 12-storey reinforced concrete structure using semi-active resettable devices." Why Do We Still Tolerate Buildings That are Unsafe in Earthquakes? . NZSEE, 2009.

Chase, J. Geoffrey, et al. "Advanced Semi-Active Resetable Devices and Device Modeling Including Non-Linearities." 13th Asia Pacific Vibration Conference. Canterbury, 2009. 1-10.

—. "Development and Spectral Analysis of an Advanced Control Law for Semi-Active Resetable Devices." Building an Earthquake-Resilient Society. Auckland: Ninth Pacific Conference on Earthquake Engineering, 2011. 1-8.

—. "Probabilistic risk analysis of structural impact in seismic events for linear and nonlinear systems." Earthquake Engineering & Structural Dynamics (2014).

—. "Re-shaping hysteretic behaviour using semi-active resettable device dampers." Engineering Structures (2006): 1418-1429.

—. "Re-Shaping Semi-Active Structural Response via Simple Applications of Embedded Computation, Sensors and Valves." Proceedings of ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. Las Vegas: ASME, 2007. 1-10.

Chase, J.G., et al. "Resetable devices with customised performance for semi-active seismic hazard mitigation of structures." 2005 NZSEE Conference. NZSEE, 2005.

Chen, XiaoQi, et al. "Novel Controllable Semiactive Devices for Reshaping Structural Response." IEEE/ASME TRANSACTIONS ON MECHATRONICS, (2008): 647-657.

Chey, M. H., et al. "Design of Semi-Active Tuned Mass Damper Building Systems using Resetable Devices." (n.d.).

Chey, M.H., et al. "Resetable Tuned Mass Damper and its Application to Isolated Stories Building System." The 14th World Conference on Earthquake Engineering. Beijing, 2008.

Chey, Min-Ho, et al. "Semi-active tuned mass damper building systems: Design." Earthquake Engineering and Structural Dynamics (2010): 119-139.

Corman, Sylvain, et al. "Development and spectral analysis of an advanced diamond shaped resetable device control law." Engineering Structures (2012): 1-8.

—. "Nonlinear design and sizing of semi-active resetable dampers for seismic performance." Engineering Structures (2012): 139-147.

Franco-Anaya, R., A.J. Carr and J.G. Chase. "Semi-Active Resettable Devices For Seismic Protection of Civil Engineering Structures." Beijing: 14th World Conference on Earthquake Engineering, 2008.

Franco-Anaya, R., et al. "Seismic testing of a model structure with semi-active resetable devices." Performance by Design -- Can we predict it? Palmerston North, 2007. 1-8.

Jabbari, Fayar and James, E Bobrow. "Vibration Suppression with Resettable Device." Journal of Engineering Mechanics (2002): 916-924.

Johansen, Jeremy David. "Active Control of Frame Structures: A Decentralized Approach." A Dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Mechanical Engineering. Santa Barbara, June 2008.

Leavitt, John, et al. "Application of a high-pressure gas semi-active resettable damper to the benchmark smart base-isolated building." Structural Control and Health Monitoring (2006): 748-757.

Leavitt, John, James E. Bobrow and Faryar Jabbari. "Design of a 20,000 pound variable stiffness actuator for structural vibration attenuation." Shock and Vibration (2008): 687-696.

—. "Design of a 20,000 Pound Variable Stiffness Actuator for Structural Vibration Attenuation." Irvine, 1 October 2007.

Mulligan, K.J., et al. "Semi-active Resetable Actuators Incorporating a High Pressure Air Source." Performance by Design -- Can we predict it? Palmerston North, 2007.

Mulligan, Kerry J., et al. "Nonlinear models and validation for resetable device design and enhanced force capacity." Structural Control & Health Monitoring (2010): 301-316.

Rodgers, G. W., et al. "Spectral analysis for a semi-active–passive net-zero base-shear design concept." Earthquake Engineering & Structural Dynamics (2012): 1207-1216.

Rodgers, Geoffrey W., et al. "Customising Semi-Active Resetable Device Behaviour for Abating Seismic Structural Response." Bulletin of the New Zealand Society for Earthquake Engineering (2009): 147-156.