Probabilistic Analysis and Non-Linear Semi-Active Base Isolation Spectra for Aseismic Design

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ABSTRACT:

Semi-active resetable actuators can significantly improve seismic structural response and customise structural hysteresis loops using novel devices. However, no one has yet examined their use as base isolators despite recent results that show the hysteretic (force-displacement) response for optimally controlled base isolation stiffness is similar to a novel 1-3 resetable device response, particularly if including non-ideal, realistic non-linearities encountered when accounting for non-zero reset times and practical friction. Hence, non-linear semi-active resetable devices should be able to optimally base isolate structures by providing non-linearly increasing resistance to excursions and smooth sliding behaviours with friction back towards equilibrium – matching analytical optimal control results that provide significant isolation and reduce isolated structure acceleration responses. This paper presents the non-linear device models and uses them to analyse semi-active isolated structures over 3 suites of 20 probabilistically scaled ground motions. Results are compared to realistic passive isolation systems and show significant isolation that meets or exceeds passive solutions and closely match optimal isolation results presented in the literature. Overall, this study shows that their may be significant application potential for non-linear semi-active devices in structural isolation.

1 INTRODUCTION

Base isolation systems are used to reduce seismic structural response by reducing the fundamental frequency of the structure on its foundation. Seismic isolation technology has been developed for decades. It has also been proven to be one of practical and effective means for seismic protection of structural systems (Lu and Yang 1997; Naeim and Kelly 1999; Skinner et al. 1993). However, its limitations include the inability to dramatically reduce some peak response values.

A typical isolation system usually consists of a flexible or sliding mounting system to decouple the structure from the ground. A resilient mechanism is used to reduce the residual displacement of the isolation layer. As a result, an isolation system usually possesses a constant isolated frequency that is typically designed to be well below those expected in typical seismic ground motions. However, recent studies show that conventional isolation systems subjected to near field earthquakes can suffer more extensive damage than expected as these events can possess a long-period (low frequency) wave (Lu et al. 2006a; Yang and Agrawal 2002). This wave can induce resonance in this otherwise relatively low-frequency isolated structure, thus amplifying the motion input to the structure. The result is greater response of the structure and greater damage or risk to occupants and equipment.

To overcome these near field resonance problems, some researchers suggested using modified passive isolation systems, such as sliding isolators with variable curvature (Pranesh and Sinha 2000) or supplementary passive damping (Makris and Chang 2000). These modified passive isolation systems perform well when they are subjected to earthquakes below the design level but are limited in their capability and require specific design and/or tuning as with any passive response control system.

To improve the adaptability of any control or isolation system, some researchers have proposed using active control. These solutions, in the context of base isolation, usually consists of an isolation system augmented with an active device (Barbat et al. 1995; Feng 1993; Feng et al. 1993). An active isolation system usually performs better than a passive system due to its use of sensor feedback to adapt its behaviour to the response based on the model used in its design. However, an active system will also require a large amount of control energy or control force, in comparison to an energy free passive isolation design. Moreover, active systems can introduce significant issues with complexity and the need for maintenance that passive systems don't require.

Due to the concern of control energy, the concept of semi-active control has been proposed for controlling seismic structural response. This concept has been adapted to the base isolation problem as well (Lu et al. 2006b; Nagarajaiah and Narasimhan 2006; Nagarajaiah and Narasimhan 2007; Narasimhan and Nagarajaiah 2005; Narasimhan and Nagarajaiah 2006; Narasimhan et al. 2006; Ramallo et al. 2002; Spencer et al. 2000; Yang and Agrawal 2002). These full and/or semi-active isolation systems usually involve a semi-active device, such as an MR damper, a variable friction damper, semi-active variable stiffness, or similar. These semi-active devices are essentially passive devices with some controllable internal parameters, such as a variable orifice damper. The control force provided by a semi-active device is actually a resistant force that is exerted by the relative motion of the device. Therefore, the direction of the control force is always in opposite to the direction of the relative motion of the device, thus ensuring a measure of stability via purely dissipative control. Due to its passive origins and control, a semi-active device usually requires much less control energy, although complexity can be quite high with devices like variable friction damper and MR devices.

Another recent development in semi-active control involves a relatively very low complexity device, the resetable damper (Bobrow et al. 2000; Jabbari and Bobrow 2002). These systems have been studied extensively for use in structures for seismic response mitigation (Barroso et al. 2003; Chase et al. 2004; Chase et al. 2005; Chase et al. 2006; Jabbari and Bobrow 2002; Rodgers et al. 2007). Recently, these devices have been used to create novel methods of reshaping hysteretic behaviour of the total structural response (Chase et al. 2006; Rodgers et al. 2007). These works have recently been validated in a series of large-scale experiments (Franco-Anaya et al. 2006; Mulligan et al. 2007).

More interestingly, the novel 1-3 resetable device control law that provides only dissipative resistance against motion away from equilibrium (Chase et al. 2006; Mulligan et al. 2007), with moderate controllable friction on return motion, has the same approximate hysteresis loop behaviour as a recently reported actively controlled optimal variable stiffness base isolation control design (Lu et al. 2006a). Therefore, this paper investigates the use of resetable devices as semi-active base isolation elements. Resetable devices also offer low power consumption, but with much lower complexity and potential need for maintenance than many of the other semi-active devices proposed to date. Overall, the focus is on proof of concept feasibility analyses for resetable base isolation (RBI) with comparison to typical passive base isolation (PBI) solutions, in terms of efficacy and ease of design or tuning.

2 SYSTEM MODELS

2.1 Structural System Model

This study uses the same simplified two degree of freedom model shown in Figure 1, as defined:

$$\mathbf{M}\cdot\{\ddot{v}\}+\mathbf{C}\cdot\{\dot{v}\}+\mathbf{K}\cdot\{v\}=-\underline{\mathbf{M}}\cdot\ddot{x}_g \tag{1}$$

Where the mass (**M**), stiffness (**K**) and damping (**C**) matrices are defined in Tables 1-2 to match the model from the study by Lu et al (Lu et al. 2006a) for easy comparison of some results. The ground motion is represented by $\ddot{x}_g$ and v is the vector of displacements, where the dots indicate differentiation with respect to time to obtain the velocity and acceleration respectively.

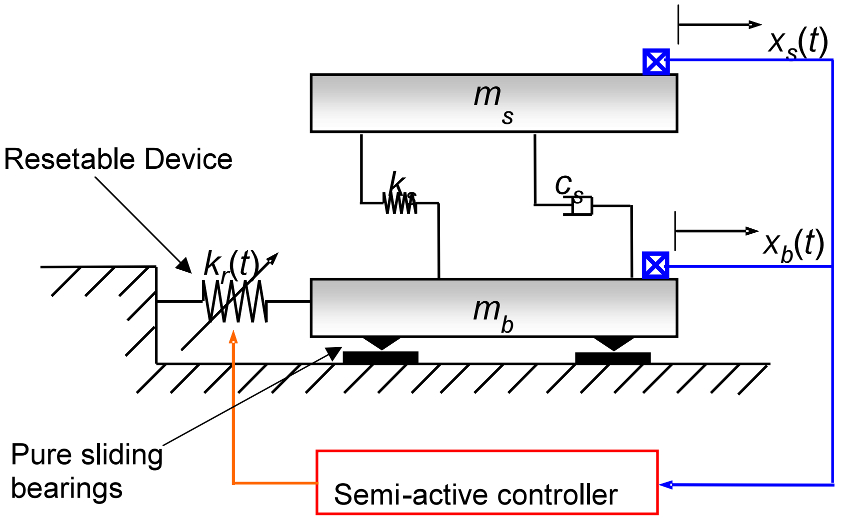

Figure 1: Model system schematic where subscripts “b” and “s” represent the base and structure respectively and measurements of relative or total responses are available as shown.

Table 1: Values of parameters for numerical simulation.

System	Item	Value
Super-structure	Structural mass (m_s)	300 ton
	Structural stiffness (k_s)	3.289×10^4 kN/m
	Damping coefficient (c_s)	3.141×10^2 kN-sec/m
	Frequency (f_s)	1.67 Hz (fixed-base)
	Damping ratio (ζ_s)	5 % (fixed-base)
Isolation system	Mass of base mat (m_b)	100 ton
	Friction coefficient (μ)	0.03
	Range of controllable stiffness (k_r)	0.0 - 3.79×10^3 kN/m

Table 2: Matrices of **M**, **C** and **K**.

Parameters	Matrix Definitions
Mass	$\mathbf{M} = \begin{bmatrix} m_s & 0 \\ 0 & m_b \end{bmatrix} = \begin{bmatrix} 300 & 0 \\ 0 & 100 \end{bmatrix}$ *ton*
Damping	$\mathbf{C} = \begin{bmatrix} c_s & -c_s \\ -c_s & c_s \end{bmatrix} = \begin{bmatrix} 314.1 & -314.1 \\ -314.1 & 314.1 \end{bmatrix}$ *k*N/(m/s)
Stiffness (without considering controllable stiffness	$\mathbf{K} = \begin{bmatrix} k_s & -k_s \\ -k_s & k_s \end{bmatrix} = \begin{bmatrix} 32890 & -32890 \\ -32890 & 32890 \end{bmatrix}$ *k*N/m

2.2 Resetable Devices for Base Isolation and Customised Device Hysteresis

The resetable device stiffness, and thus force, $k_r(t)$, is modelled as a variable stiffness spring element based on the relative motion between the base and the ground. The ideal device acts like a linear pneumatic or hydraulic spring and develops force due to displacement and the resulting compression of a working fluid. At any specified point of device reset the compressed working fluid is released, thus dissipating energy, and resetting the effective spring length to zero.

In this case, Figure 2 shows how these devices can be used in a novel two-valve configuration to resist selected motions while providing only minimal air damping for other motions (Chase et al. 2006; Mulligan et al. 2005a; Mulligan et al. 2005b; Mulligan et al. 2005c). The end result is customised hysteretic behaviour of the device. For this analysis the 1-3 control law is chosen due to its similarity to the optimal hysteretic device behaviour reported by Lu et al (Lu et al. 2006a).

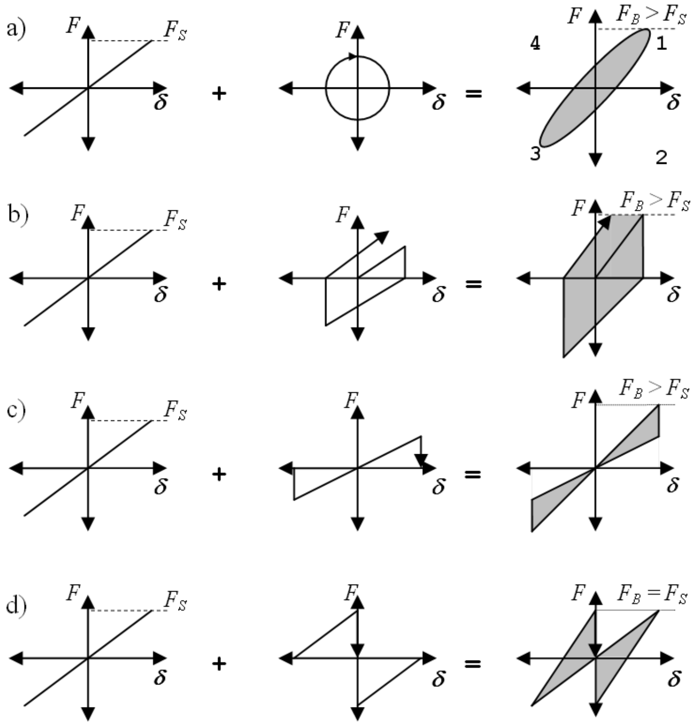

Figure 2: Schematic hysteresis for a) viscous damping for comparison, b) a 1-4 device, c) a 1-3 device, and d) a 2-4 device. Quadrants are labelled in the first panel, and F_B = total base shear, F_S = base shear for a linear, undamped structure. $F_B > F_S$ indicates an increase due to the additional damping.

As Figure 2 shows, used in a structure this form of re-shaping hysteresis does not increase base shear in some forms. However, for base isolation, the 1-3 format is ideal as it resists motion away from centre or equilibrium, but allows easy re-centering on return motion, with only minimal friction forces. In this study two added non-linearities are included in the ideal model to better represent the physical reality of these devices:

1. **Non-linear Reset**: The device reset is not instantaneous or vertical as in Figure 2. Instead the device loses 5% of its force every 0.01 seconds based on experimental data (Mulligan et al. 2005b; Mulligan et al. 2007). The result is that some energy or force is returned to the system aiding re-centering and creating a sweeping or curved reset line on the hysteresis loop.
2. **Return Friction**: A constant return friction or sliding friction force of 10kN is used, which is approximately 3-5% of the peak device force seen in initial simulations. This level is based on experimental device data to date (Mulligan et al. 2005b; Mulligan et al. 2007). It also serves to limit base and thus structural velocities at the cost of some increased transfer of forces.

Overall, these two non-linearities are based on experimentally observed data from full size devices. They also provide a more optimal base isolation result. Note that friction force could readily be controlled via using more than one valve per chamber or variable orifice valves, thus creating an active air damper from the device when it was not resisting motion (Mulligan et al. 2007).

3 ANALYSES

The research utilises three earthquake suites from the SAC project (Sommerville et al. 1997), with 10 different time histories and two orthogonal directions for each history. The three suites represent ground motions having probabilities of excedance of 50% in 50 years, 10% in 50 years, and 2% in 50 years in the Los Angeles region, and are referred to as the low, medium and high suites, respectively. Response statistics can thus be generated from the results of each probabilistically scaled suite.

Passive and semi-active base isolated structures are compared. Two passive isolated structures are designed for isolated frequencies of 0.1 and 0.2 Hz (T = 10 and 5 secs respectively). Two resetable device stiffnesses are utilised. One is set to match passive isolation stiffness for the 0.2Hz while the other is 1.5 times larger.

Similar and larger semi-active isolation stiffnesses are chosen because they will generate more isolation forces and thus dissipate more energy (Chase et al. 2006). In addition, stiffer semi-active devices will also limit the base displacement more than other choices. Hence, the comparison is between typically tuned passive solutions and stiffer semi-active solutions. Hypothetically, the stiffer isolation system will transmit more motion. However the semi-active adaptability may still provide equal or superior isolation, creating a unique tradeoff comparison.

Results are presented for a variety of metrics including:

1. **Absolute peak acceleration of the base** (normalised to the PGA of the ground motion record): indicates the level of isolation in terms of input accelerations
2. **Absolute peak acceleration of the structure** (normalised to the PGA of the ground motion record): indicative of isolation, as well as damage to contents or fixtures.
3. **Absolute peak displacement of the structure relative to the base**: indicative of structural damage and efficacy of isolation from the input acceleration.
4. **Absolute peak displacement of the base relative to the ground**: indicates the required travel
5. **Absolute final base displacement**: indicates any resulting offset displacement

All results are presented as the median value over each suite of 20 ground motions. The inter-quartile range (IQR) or middle 50%, and the 90% range are also presented to show the distribution of responses over each suite.

4 RESULTS

The results are presented in Tables 3-4 for the passive and semi-active systems respectively. All results show significant reductions in peak displacement response from what might be expected for a solid structure, even one resetable device controlled (Rodgers et al. 2007). Hence, it is clear that from a damage perspective, at least in terms of peak structural story drift, both systems provide significant protection. Similarly, for accelerations, the passive and semi-active systems both provide significant reductions from PGA. However, the semi-active structural accelerations are 40-70% lower than those for the passive system indicating significantly improved damage protection.

Finally, the max and final base displacements are important considerations. In all cases they are within acceptable limits for the low and medium suites. Given that the medium suite is a maximum design event size earthquake this result is significant for indicating the feasibility of the semi-active approach. The high suite results, representing 1 in 2400 year return period events, are all relatively excessive for both cases. Finally, it should be noted that the final displacements are larger for the semi-active case.

Table 3: Passive isolation results

	0.1 Hz Passive					0.2 Hz Passive				
Low Suite	**Median**	**90% Range**		**IQR**		**Median**	**90% Range**		**IQR**	
peak base accel / PGA	0.32	0.20	0.44	0.27	0.38	0.32	0.20	0.49	0.27	0.41
peak struct accel / PGA	0.19	0.11	0.39	0.15	0.26	0.21	0.10	0.47	0.16	0.27
peak struct disp (mm)	5.8	3.9	14.4	4.8	7.6	6.3	4.7	15.1	5.3	7.3
max base disp (mm)	63.3	47.1	140.7	55.8	91.4	67.7	49.6	149.4	60.6	100.2
final base displ (mm)	1.1	0.1	5.7	0.3	2.6	1.2	0.2	6.6	0.9	3.6
Medium Suite	**Median**	**90% Range**		**IQR**		**Median**	**90% Range**		**IQR**	
peak base accel / PGA	0.33	0.24	0.43	0.30	0.35	0.34	0.24	0.49	0.31	0.36
peak struct accel / PGA	0.24	0.17	0.39	0.21	0.28	0.26	0.17	0.47	0.22	0.31
peak struct disp (mm)	11.8	8.2	16.0	10.0	15.0	13.2	9.4	17.0	10.9	15.6
max base disp (mm)	218.3	121.8	325.0	180.9	234.9	218.4	131.4	314.1	191.8	248.3
final base displ (mm)	2.6	0.0	6.7	1.4	3.2	2.9	0.2	6.9	1.6	4.9
High Suite	**Median**	**90% Range**		**IQR**		**Median**	**90% Range**		**IQR**	
peak base accel / PGA	0.35	0.21	0.47	0.32	0.38	0.38	0.23	0.51	0.32	0.42
peak struct accel / PGA	0.30	0.22	0.41	0.26	0.34	0.32	0.22	0.47	0.27	0.39
peak struct disp (mm)	23.6	12.6	30.4	19.6	26.7	26.3	13.5	34.2	23.0	28.8
max base disp (mm)	366.2	225.5	729.7	251.6	537.3	379.5	222.2	842.6	292.2	535.6
final base displ (mm)	1.2	0.2	7.6	0.6	2.2	1.0	0.1	15.0	0.4	2.5

Table 4: Semi-active resetable isolation at 0.2Hz passive device stiffness and 1.5x stiffness

	Resetable 1					Resetable 2				
Low Suite	**Median**	**90% Range**		**IQR**		**Median**	**90% Range**		**IQR**	
peak base accel / PGA	0.06	0.03	0.38	0.04	0.18	0.07	0.04	0.53	0.05	0.22
peak struct accel / PGA	0.04	0.02	0.27	0.03	0.16	0.06	0.03	0.50	0.04	0.23
peak struct disp (mm)	1.6	1.0	4.9	1.3	2.3	2.7	1.7	7.2	2.0	4.4
max base disp (mm)	105.3	64.3	337.1	85.3	193.3	107.1	70.6	338.3	86.0	199.4
final base displ (mm)	43.4	14.1	106.6	18.3	72.9	19.3	0.3	75.6	12.2	38.6
Medium Suite	**Median**	**90% Range**		**IQR**		**Median**	**90% Range**		**IQR**	
peak base accel / PGA	0.15	0.04	0.36	0.08	0.25	0.22	0.05	0.53	0.14	0.38
peak struct accel / PGA	0.14	0.03	0.36	0.08	0.26	0.20	0.05	0.51	0.13	0.38
peak struct disp (mm)	5.8	2.5	11.1	4.5	8.2	9.5	4.2	16.7	7.4	13.0
max base disp (mm)	407.7	192.3	776.0	320.3	577.6	432.0	203.3	771.1	351.6	612.7
final base displ (mm)	27.1	4.5	127.7	12.6	65.2	18.6	3.8	70.3	9.6	32.3
High Suite	**Median**	**90% Range**		**IQR**		**Median**	**90% Range**		**IQR**	
peak base accel / PGA	0.17	0.07	0.30	0.09	0.26	0.26	0.11	0.53	0.16	0.41
peak struct accel / PGA	0.17	0.06	0.31	0.10	0.27	0.28	0.10	0.53	0.15	0.41
peak struct disp (mm)	10.1	5.2	22.9	7.1	17.4	15.3	10.1	37.3	11.6	26.4
max base disp (mm)	739.7	423.5	1621.5	575.9	1192.3	678.1	512.4	1832.5	588.4	1409.1
final base displ (mm)	94.9	22.7	232.6	44.4	152.6	52.1	10.7	124.1	20.2	76.1

The results in Tables 3-4 represent significant reductions for these suites of earthquakes. The reduction factors versus a normal fixed two degree of freedom structure are significant. In particular, a normal structure would experience some plastic deformation under these ground motions, especially with the medium and high suites. A semi-active resetable device controlled spectral analysis indicates that for this type of structure displacement reductions would be on the order of 30-50% from the uncontrolled case (Rodgers et al. 2007) with similar results seen for realistic structures like the SAC-3 or SAC-9 steel frames (Barroso et al. 2003; Chase et al. 2005; Hunt 2002). The values in Tables 3-4 represent significantly larger reductions and structures that remain essentially damage free and linear elastic

With respect too the resetable device itself, Figure 3 shows the hysteresis loops for the resetable isolation device for the 1989 Loma Prieta earthquake scaled for the high suite probability of occurrence. The results clearly show the two non-linear behaviours added to capture realistic behaviour and the optimal solution of Lu et al (Lu et al. 2006a). In particular, there is the gradual release of energy followed by the friction force on return motion towards the initial equilibrium. The 1-3 device behaviour is also clearly evident for this example, where the device stiffness is equivalent to the passive case tuned to a 0.2Hz isolated structural frequency. Finally, the peak forces of 150-200kN are reasonably achievable using either pressurised air based resetable dampers (Mulligan et al. 2007) or a higher bulk modulus working fluid.

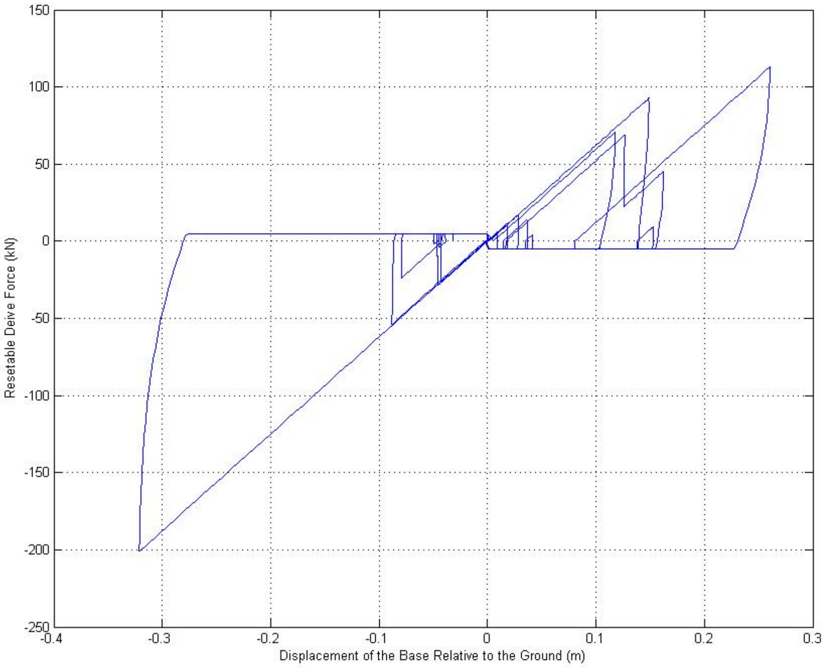

Figure 3: Hysteretic force displacement loop for a semi-active resetable device and the Loma Prieta (high suite) ground motion. Friction and delayed release of stored energy on reset are evident.

Hence, the device as modelled in Figure 3 is realistic based on experimental studies to date. In addition, the forces and displacements required are within achievable levels. The overall system developed outperforms the passive equivalents in terms of peak and (not shown) average responses. Hence, the feasibility of the system is clearly evident and full or large scale experimental studies would thus be justified as a next step in this research.

5 CONCLUSIONS

Overall, the results indicate the feasibility of semi-active base isolation utilising novel resetable devices that can sculpt hysteresis response. The results indicate that for suites of ground motions the semi-active system provides significantly improved isolation and damage protection even when compared to a typical passive isolation approach. The only major drawback to date is potentially excessive base and final displacements, relative to accepted passive solutions, for the very largest ground motions. These issues may be overcome with enhanced design and analysis of the devices used. Alternatively, systems utilising a mixture of passive and resetable isolation elements will ensure better re-centering behaviour. Finally, the 1-3 resetable device behaviour utilised in this research is easily obtained via careful valve control in using the device as has already been demonstrated in prior studies. Hence, there is existing potential and feasibility for this approach to augment or replace passive isolation solutions in special cases requiring extended protection, such as hospitals or critical lifeline infrastructure.

REFERENCES:

Barbat, A. H., Rodellar, J., Ryan, E. P., and Molinares, N. (1995). "Active Control of Nonlinear Base-Isolated Buildings." *Journal of Engineering Mechanics-Asce*, 121(6), 676-684.

Barroso, L. R., Chase, J. G., and Hunt, S. (2003). "Resettable smart dampers for multi-level seismic hazard mitigation of steel moment frames." *Journal of Structural Control*, 10(1), 41-58.

Bobrow, J. E., Jabbari, F., and Thai, K. (2000). "A New Approach to Shock Isolation and Vibration Suppression Using a Resetable Actuator." *ASME Transactions on Dynamic Systems, Measurement, and Control.*, 122, 570-573.

Chase, J. G., Barroso, L., and Hunt, S. (2004). "The impact of total acceleration control for semi-active earthquake hazard mitigation." *Journal of Engineering Structures, Elsevier Science*, 26(2), 201-209.

Chase, J. G., Mulligan, K. J., Barroso, L. R., and Hunt, S. J. (2005). "Actuator-Actuator Interaction and Instability in Decentralised Semi-Active Control of Non-Linear Seismically Excited Tall Structures,." *Proc. 9th International Conference on Structural Safety and Reliability (ICOSSAR 2005), Rome, Italy, June 19-22, 8-pages, ISBN 90-5966-040-4.*

Chase, J. G., Mulligan, K. J., Gue, A., Alnot, T., Rodgers, G., Mander, J. B., Elliott, R., Deam, B., Cleeve, L., and Heaton, D. (2006). "Re-shaping hysteretic behaviour using semi-active resettable device dampers." *Engineering Structures*, 28(10), 1418-1429.

Feng, M. Q. (1993). "Application of Hybrid Sliding Isolation System to Buildings." *Journal of Engineering Mechanics-Asce*, 119(10), 2090-2108.

Feng, M. Q., Shinozuka, M., and Fujii, S. (1993). "Friction-Controllable Sliding Isolation System." *Journal of Engineering Mechanics-Asce*, 119(9), 1845-1864.

Franco-Anaya, R., Carr, A., Chase, J., Mulligan, K., and Mander, J. "Seismic Protection of a Model Structure Using Semi-Active Resetable Devices." *19th Australasian Conference on Mechanics of Structures and Materials (ACMSM)*, Christchurch, New Zealand, 379-384.

Hunt, S. (2002). "Semi-active smart-dampers and resetable actuators for multi-level seismic hazard mitigation of steel moment resisting frames." *Master of Engineering (ME) thesis, Dept of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand.*

Jabbari, F., and Bobrow, J. E. (2002). "Vibration Suppression with a Resetable Device." *ASCE Journal of Engineering Mechanics*, 128(9), 916-924.

Lu, L.-Y., Kuo, T.-C., and Lin, G.-L. "Base Isolation with Controllable Stiffness for Mitigating Response of Near-Fault Seismic Structures." *4th World Conference on Structural Control and Monitoring*, San Diego, CA, USA, 4-pages.

Lu, L. Y., Chung, L. L., Wu, L. Y., and Lin, G. L. (2006b). "Dynamic analysis of structures with friction devices using discrete-time state-space formulation." *Computers & Structures*, 84(15-16), 1049-1071.

Lu, L. Y., and Yang, Y. B. (1997). "Dynamic response of equipment in structures with sliding support." *Earthquake Engineering & Structural Dynamics*, 26(1), 61-77.

Makris, N., and Chang, S. P. (2000). "Effect of viscous, viscoplastic and friction damping on the response of seismic isolated structures." *Earthquake Engineering & Structural Dynamics*, 29(1), 85-107.

Mulligan, K., Chase, J., Barroso, L., and Hunt, S. (2005a). "Impact of Control Architecture in the Reliability of Resetable Device Controlled Tall Structures." *Proc. 9th Intl Conf on Structural Safety and Reliability (ICOSSAR 2005) Rome, Italy, June 19-22, 8-pages, ISBN 90-5966-040-4.*

Mulligan, K., Chase, J., Gue, A., Mander, J., Alnot, T., Deam, B., Rodgers, G., Cleeve, L., and Heaton, D. (2005b). "Resetable Devices with Customised Performance for Semi-Active Seismic Hazard Mitigation of Structures." *Proc of NZ Society for Earthquake Engineering 2005 Conference (NZSEE 2005), March 11-13, Wairakei, New Zealand.*

Mulligan, K., Chase, J., Mander, and Elliott, R. "Semi-active Resetable Actuators Incorporating a High Pressure Source." *Proc New Zealand Society of Earthquake Engineering 2007 Conference (NZSEE 2007)*, Palmerston North, NZ, 8-pages.

Mulligan, K. J., Chase, J. G., Gue, A., Alnot, T., Rodgers, G. W., Mander, J. B., Elliott, R. B., Deam, B. L., Cleeve, L., and Heaton, D. (2005c). "Large Scale Resetable Devices for Multi-Level Seismic Hazard Mitigation of Structures." *Proc. 9th International Conference on Structural Safety and Reliability (ICOSSAR 2005), Rome, Italy, June 19-22.*

Naeim, F., and Kelly, J. M. (1999). *Design of Seismic Isolated Structures: from theory to practice*, John Wiley & Sons.

Nagarajaiah, S., and Narasimhan, S. (2006). "Smart base-isolated benchmark building. Part II: phase I sample controllers for linear isolation systems." *Structural Control & Health Monitoring*, 13(2-3), 589-604.

Nagarajaiah, S., and Narasimhan, S. (2007). "Seismic control of smart base isolated buildings with new semiactive variable damper." *Earthquake Engineering & Structural Dynamics*, 36(6), 729-749.

Narasimhan, S., and Nagarajaiah, S. (2005). "A STFT semiactive controller for base isolated buildings with variable stiffness isolation systems." *Engineering Structures*, 27(4), 514-523.

Narasimhan, S., and Nagarajaiah, S. (2006). "Smart base isolated buildings with variable friction systems: H-infinity controller and SAIVF device." *Earthquake Engineering & Structural Dynamics*, 35(8), 921-942.

Narasimhan, S., Nagarajaiah, S., Johnson, E. A., and Gavin, H. P. (2006). "Smart base-isolated benchmark building. Part I: problem definition." *Structural Control & Health Monitoring*, 13(2-3), 573-588.

Pranesh, M., and Sinha, R. (2000). "VFPI: an isolation device for aseismic design." *Earthquake Engineering & Structural Dynamics*, 29(5), 603-627.

Ramallo, J. C., Johnson, E. A., and Spencer, B. F. (2002). ""Smart" base isolation systems." *Journal of Engineering Mechanics-Asce*, 128(10), 1088-1099.

Rodgers, G. W., Mander, J. B., Chase, J. G., Mulligan, K. J., Deam, B. L., and Carr, A. (2007). "Re-shaping hysteretic behaviour - spectral analysis and design equations for semi-active structures." *Earthquake Engineering & Structural Dynamics*, 36(1), 77-100.

Skinner, R. I., Robinson, W. H., and McVerry, G. H. (1993). *An introduction to seismic isolation*, Wiley, Chichester ; New York.

Sommerville, P., Smith, N., Punyamurthula, S., and Sun, J. (1997). "Development of Ground Motion Time Histories For Phase II Of The FEMA/SAC Steel Project, SAC Background Document Report SAC/BD-97/04."

Spencer, B. F., Johnson, E. A., and Ramallo, J. C. (2000). ""Smart" isolation for seismic control." *Jsme International Journal Series C-Mechanical Systems Machine Elements and Manufacturing*, 43(3), 704-711.

Yang, J. N., and Agrawal, A. K. (2002). "Semi-active hybrid control systems for nonlinear buildings against near-field earthquakes." *Engineering Structures*, 24(3), 271-280.