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INITIAL PARAMETER DEVELOPMENT FOR MULTI-PHASE PERFORMANCE-BASED PASSIVE CONTROL SYSTEMS

Justin D. Marshall[1]

ABSTRACT

A Multi-phase Passive Control System (MPCS) combines two types of passive control elements into a single system. The configuration is designed to provide phased behavior that can be essentially pre-programmed to respond effectively to different magnitude seismic events or other potential hazards. Some work has been completed previously to determine the effect of the various design parameters and demonstrate the potential of MPCS systems as a performance-based seismic protection system. An initial single-degree-of freedom (SDOF) non-linear dynamic parametric study was completed to verify fundamental assumptions about behavior and determine which parameters are critical. The results demonstrate the importance of the initial gap size, the strength ratio of the moment-frame to displacement-dependent energy dissipation element and the formulation of the SDOF model. The results from this study will be used to formulate a comprehensive parametric study on multi-phase protective systems.

Introduction

Developing effective seismic protective systems for structures requires striking a balance between stiffness, strength and energy dissipation. The primary options to successfully strike the necessary balance are to allow the structure to dissipate energy through inelastic deformation of the structural members, to seismically isolate a structure at the foundation, or to provide a structural control device or system to dissipate energy and reduce deformations. A conventional system, where the structure yields or buckles to dissipate energy, designed according to a prescriptive approach results in significant structural and non-structural damage at the end of an event. This fact was highlighted by the 1994 Northridge, California and 1995 Kobe, Japan earthquakes. The damage resulting from these events initiated a re-examination of connection details and a transition to performance-based seismic design (FEMA 2000; FEMA 2006). The key to improved structural performance and more predictable levels of damage during seismic events is to provide a protective system such as base isolation or passive control within the framework of performance-based design.

Passively controlled structures use displacement between device attachment points to generate control forces or energy dissipation. The two classes of passive control are rate-independent and rate-dependent devices. Several references with details about design and

[1]Assistant Professor, Civil Engineering Department, 238 Harbert Engineering Center, Auburn University, Auburn, AL 36849.

implementation of passive control in seismic protection are available (Constantinou, Soong et al. 1998; Hanson and Soong 2001; Symans, Charney et al. 2008). Rate-independent, also called displacement-dependent, passive devices provide both stiffness and energy dissipation. The added stiffness reduces displacement while increasing base shear and acceleration prior to yielding. Energy dissipation does not occur until the slip or yield force is exceeded. The benefits include large energy dissipation capacity and reduced displacements.

Viscous fluid dampers are rate-dependent devices, also called velocity-dependent devices, which dissipate energy by deforming a viscous fluid. VFDs can also be used in various configurations to increase their effectiveness. Unique configurations, which amplify the velocity across the device, include the scissor-jack and toggle-brace systems (Constantinou, Tsopelas et al. 2001; Sigaher and Constantinou 2003). Viscoelastic (VE) solid dampers are velocity-dependent devices that dissipate energy when deformed. These materials dissipate energy for all levels of deformation and provide some static stiffness. High-Damping Rubber (HDR) is a viscoelastic material used in seismic protection systems. HDR was initially utilized in base isolation bearings, but has also transitioned into dissipative braces in structural frames (Fujita, Furuya et al. 1995; Lee, Sause et al. 2003; Bartera and Giacchetti 2004; Ragni, Dezi et al. 2009).

A small body of work exists on using combinations of passive control elements. One example used a metallic yielding device in parallel with a VE damper (Tsai, Chen et al. 1998; Chen, Chen et al. 2002). These studies found a beneficial effect from the combination. A single degree of freedom study was completed using yielding braces supplemented by viscous dampers (Vargas and Bruneau 2007). The results found improved response although the VFDs reduced the effectiveness of the metallic devices. These studies show that simple combination may not be sufficient to unlock the potential. The combination of partially restrained (PR) moment connections and a viscoelastic damper provided a considerable reduction in response (Amadio, Clemente et al. 2008). The lower stiffness of the PR connections allows the damper to be effective. Additionally, the PR connections yield and dissipate energy without damage to the structural frame.

A Multi-phase Passive Control System (MPCS) combines two types of passive control elements into a single system. The configuration is designed to provide phased behavior that is essentially pre-programmed to respond effectively to different magnitude seismic events or other potential hazards. The two types of energy dissipation are velocity-dependent devices including viscous fluid or viscoelastic solid dampers and displacement-dependent components including hysteretic yielding or friction devices. An MPCS is typically used as part of a dual system with a Steel Moment-Resisting Frame (SMRF). The structure is designed so the MPCS elements dissipate the seismic energy and protect the gravity load members. The key to the performance-based nature is the phased behavior. The initial phase relies on the damping provided by the velocity-dependent device to reduce structural response for small to moderate events with no damage. The hysteretic or friction device provides the additional stiffness and supplementary energy dissipation needed for severe seismic events. The performance-based aspect originates from the transition between phases. The displacement prior to transition determines the severity of event before the phase change. Secondarily, multiple system parameters are available to control response. In lieu of a standard seismic resisting system attempting to meet multiple performance-based objectives, an MPCS provides the ability to tailor a steel structure to meet the desired combination of objectives. The added damping in the initial phase improves performance during severe wind events in areas where multi-hazard response is requisite.

Several previously developed innovative control device configurations have been found to be effective at improving structural response (Murthy 2005; Ibrahim, Marshall et al. 2007; Marshall 2008). One example of an MPCS configuration is the hybrid passive control device which is shown in schematic form in Figure 1. The previous work has analytically and experimentally demonstrated potential but has not fully explored the fundamental nature of multi-phased protective systems (Marshall 2008).

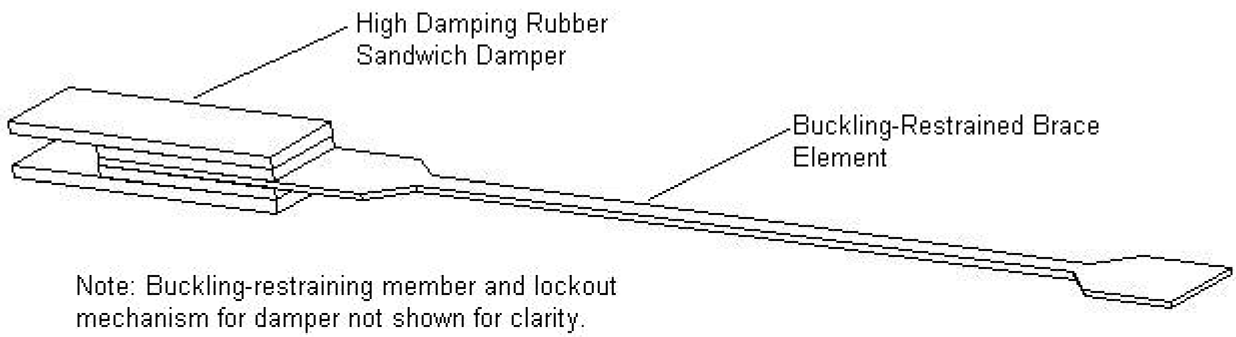

Figure 1. Schematic Drawing of a Hybrid Passive Control Device

Analysis Plan and Model Description

The previous work on multi-phase passive control devices has laid the foundation for further development. The previous analytical study (Marshall 2008) used a 9-story steel moment- frame and compared the response of a special steel moment-resisting frame and a dual SMRF-BRB system to several MPCS configurations. The results demonstrated a benefit from the unique control systems, but also highlighted the need for a better fundamental understanding of MPCS protected structures and the parameters affecting response. While some individual parameter effects could be discerned from the 9-story structure, it was difficult to identify individual parameters within the complex non-linear structural model. In order to drill down into the behavior of multi-phase control systems a step back to a simple single-degree-of-freedom model (SDOF) non-linear model will be used. The SDOF model will be used to determine the effect of the different parameters on structural response to seismic loads. The work presented here is the result of an initial phase of the full effort needed to develop and understanding of MPCS systems.

MPCS systems posses several design parameters that can be used to control structural response. The driving principle is to use two different types of energy dissipation configured in a multi-phase system. The phasing is designed to utilize the individual devices in a way that takes advantage of the element strengths and offsets weaknesses. The three primary components of the system are the moment-frame, the velocity-dependent damping device and the displacement-dependent energy dissipation element. The initial phase of the system consists of the moment-frame in conjunction with the velocity-dependent damper. The initial phase must posses sufficient stiffness and damping for service level wind loads as well as small to moderate seismic events. The transition to the second phase is determined by the size of the initial gap. The initial gap is the amount of displacement provided before the displacement-dependent device is engaged. Once engaged, the stiffness is increased until the device slips or yields. The second phase has the capability for significant energy dissipation for significant earthquakes. The energy dissipation devices are designed to protect the moment-frame from inelastic behavior with the exception of the most severe seismic events. The increase in stiffness at the phase transition changes the primary frequency of vibration preventing resonant build-up. The number of design parameters available in these systems essentially provide a mechanism to pre-program the response to various levels of lateral loads.

An SDOF study is an efficent way to evaluate the effect of the large number of design parameters. The following variables were considered in the development of the full test matrix:

- Velocity-dependent damping: the two possibilities for this variable are a viscous fluid damper and a high-damping rubber device.
- Displacement-dependent energy dissipation: some possibilities for this element include a buckling-restrained brace, slotted-bolted friction device and steel plate shear wall.
- Initial gap: the size of the initial gap is key to determining when initiation of the supplemental energy dissipation occurs. It is also important to ensure that the displacement-dependent device engages and yields before the moment-frame.
- Critical damping value: the damping ratio of the first phase effects the response. The expected range for a viscous device is between 10% and 20%. Because of the stiffness of the HDR, a lower level of damping is required to achieve the desired performance.
- System strength or stiffness ratio: the second phase is essentially a dual system. The ratio of concern is the strength of the moment-frame to the displacement-dependent device. The minimum strength of the weaker element must be 25% of the total base shear (ASCE 2006). The range will extend from the moment-frame being the weaker element and the displacement-dependent the stronger, up to the other extreme. Another possibility is that the stiffness ratio will be more important than the design strength.
- System configuration: the arrangement of the damping and energy dissipation elements can be in parallel or series. The response of the system is different for the two options. With the device in parallel, the damper is still active during the final phase. With the elements in series the damper is locked out after the transition.
- Structure geometry: the size of the structure will likely have an effect on the design of MPCS system. Different heights will be simulated by a range of periods.
- Seismic hazard: this system could easily be modified for any significant seismic hazard. Three different geographic locations will be used to evaluate various MPCS configurations and which ones are effective for the various degrees of hazard.

The number of parameters considered in the full study requires a large number of models to determine the effect and interaction of the various parameters. Statistical methods will be employed to determine the appropriate number of models and value of the variables for the full study. In order to get an approximation of the desired range for the critical variables, this initial study was used to develop a better understanding and verify initial assumption. The intial study includes a small sample of the parameters needed for the full study.

Three earthquake records were selected for the initial analyses. The records were scaled to the design acceleration at the system period of vibration. The earthquake records are shown in

Table 1. Two MPCS systems were selected for analysis, one with a high-damping rubber device and one with a viscous damper. A buckling-restrained brace system was used for the displacement-dependent energy dissipation. The critical damping ratio for both damping systems was set at 10%. The size of the initial gap and the strength ratio of the dual system were varied to determine interaction and effect. The strength ratio had three different values. The first was 25% of the base shear carried by the moment frame and 75% carried by the BRB frame, denoted by M25B75 in the model title. The second value had equal strength for the moment-frame and BRB. The final value is the inverse of the first value with the BRB designed for 25% of the required shear strength (M75B25). The structures were designed to have a period of 0.5 seconds and designed for the seismic hazard of Los Angeles, California on soil site class D. Three different gap sizes were selected for the initial analyses. The gap sizes are 0.15 in., 0.35 in., and 0.5 in. Gap 1 is the smallest gap. A list of the models is shown in Table 2. The analyses were done in the form of an Incremental Dynamic Analysis (IDA) (Vamvatsikos and Cornell 2002) with the design basis earthquake being at a scale factor of 1.0. The focus of this portion of the study is in the smaller scale factors to see the effect of gap size and strength ratios on response.

Table 1. Earthquake records

Abbreviation	Record Description	Scale Factor
KB	Kobe, Japan, 01/16/1995 - Takarazu-090	0.71
NR	Northridge, California, 01/17/1994 - Newhall-360	0.97
TB	Tabas, Iran, 09/16/1978 - Tabas - LN	1.19

Table 2. SDOFModels for Initial Study

High-Damping Rubber Models	Viscous Fluid Damper Models
HDR10-1-M25B75	VFD10-1-M25B75
HDR10-2-M25B75	VFD10-2-M25B75
HDR10-3-M25B75	VFD10-3-M25B75
HDR10-1-M50B50	VFD10-1-M50B50
HDR10-2-M50B50	VFD10-2-M50B50
HDR10-3-M50B50	VFD10-3-M50B50
HDR10-1-M75B25	VFD10-1-M75B25
HDR10-2-M75B25	VFD10-2-M75B25
HDR10-3-M75B25	VFD10-3-M75B25

Analytical Results

The results of the analyses are shown in a combination of IDA and response history plots. Figure 2 is an IDA plot showing the effect of the gap size on displacement response. What is interesting here is that the traces are grouped based on the earthquake record rather than the gap size. Even though the maximum response is controlled more by the acceleration record than the gap, the difference in response history can be significantly different. This difference can be seen in Figure 3, a displacement response history of model HDR10-M25B75 with gap size 1 and 3 to the Kobe earthquake record at a scale factor of 0.2. For this model and earthquake record, the larger gap provides a similar maximum response but a reduced response in the later part. Other models and earthquake records display the opposite trend with a smaller gap size resulting in smaller displacements near the end of the record.

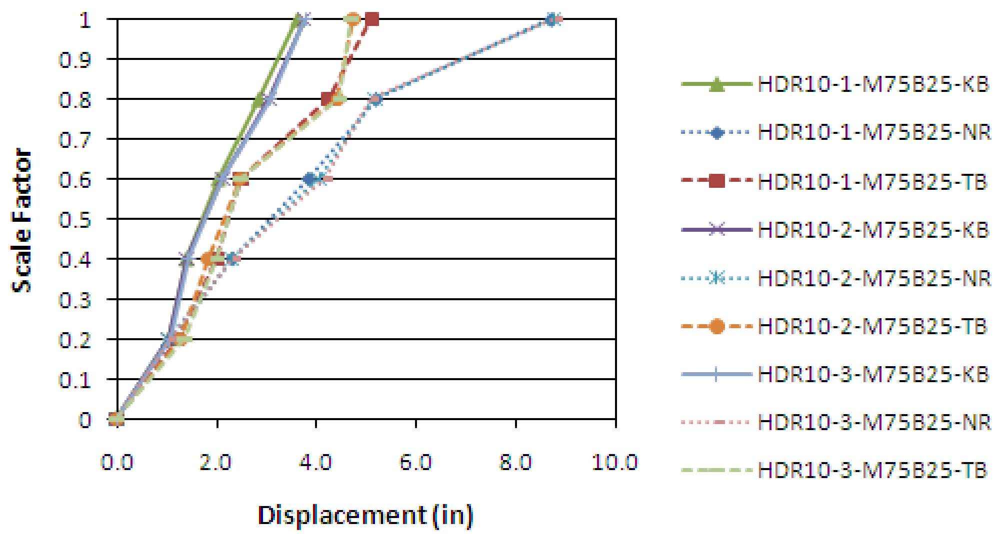

Figure 2. IDA displacement plot with HDR dampers and strength ratio M75B25.

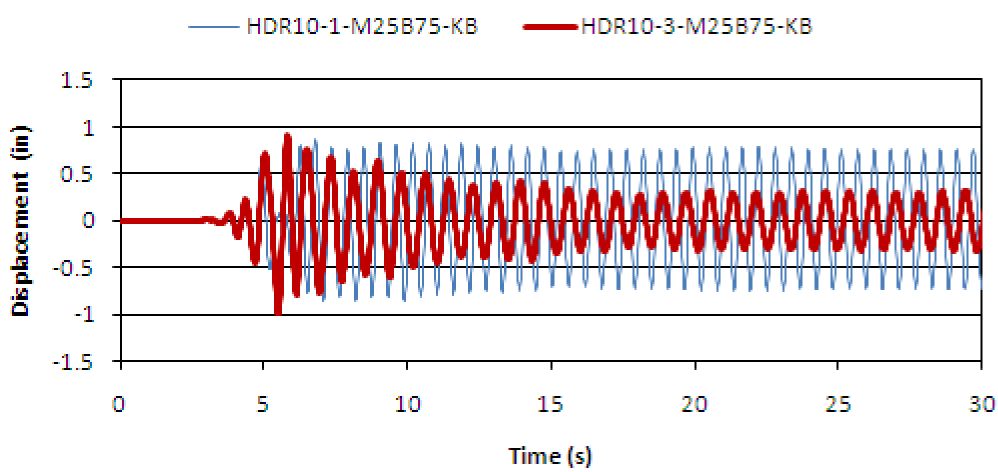

Figure 3. Displacement response history plot – Kobe record (Scale Factor = 0.2).

Figure 4 shows an IDA displacement plot comparing gap size effect for models with viscous fluid devices. It also shows grouped traces based on the earthquake record rather than gap size. The two IDA plots (Figs. 2 and 4) show that the earthquake record has a larger effect than the gap size on maximum response. The response history plot (Fig. 3) shows that the gap size can have a significant effect on the response history. Because the viscous and HDR results are similar, this demonstrates that the size of the gap was not sufficient to allow the initial phase to be effective. This behavior could also indicate a need for more supplemental damping from the viscous or HDR damper.

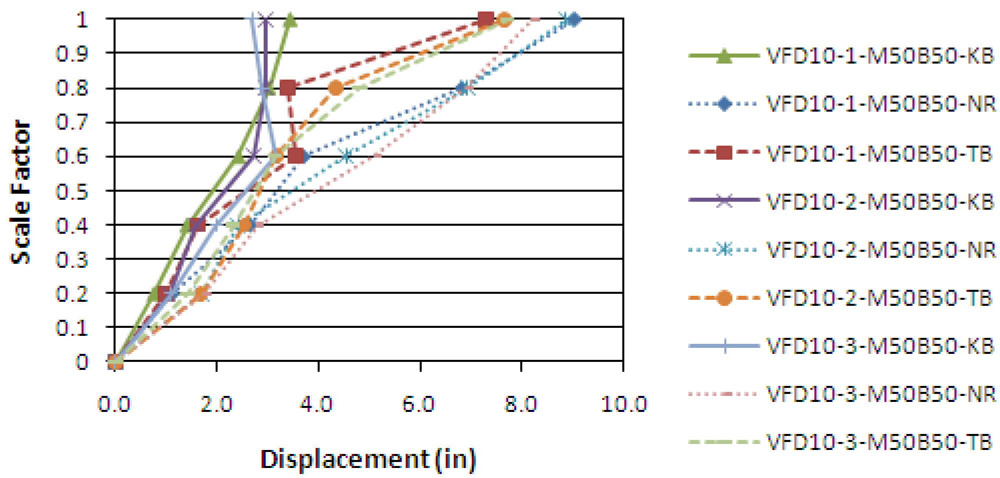

Figure 4. IDA displacement plot with viscous fluid dampers and strength ratio M50B50.

The next parameter of interest in the initial study is the strength ratio. This parameter is critical for these systems. One issue that needs to be resolved is if there is a problem with acceleration shocks due to the change in stiffness at the phase transition. Figure 5 is an IDA base shear plot with a constant gap size to evaluate the difference in strength ratio on maximum response for models with high-damping rubber dampers. Figure 6 shows the same IDA base shear graph for systems with viscous dampers. Both systems show a similar shape to the IDA trace with a difference in the base shear value. The difference in the base shear is due to the design. Because a moment-frame design is controlled by stiffness rather than strength to meet drift requirements, the moment-frame strength is greater than the BRB. Because of this, the system with stronger moment-frame component has a higher ultimate strength. In this case, the response is controlled based on the strength ratio rather than the earthquake record. The base shear levels off after initial yield for an SDOF system, because the only remaining stiffness is strain hardening.

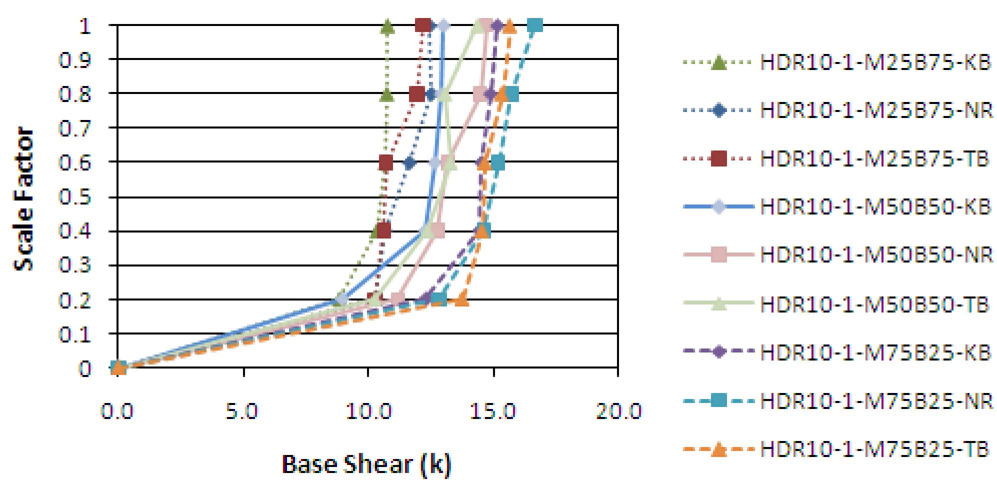

Figure 5. IDA base shear plot with high-damping rubber dampers and gap size 1.

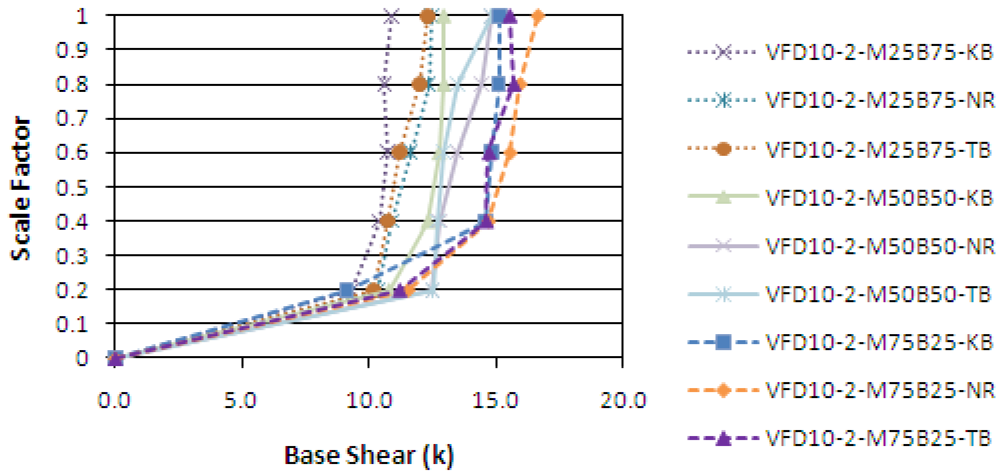

Figure 6. IDA base shear plot with viscous fluid dampers and gap size 2.

Figures 7 and 8 show the displacement and base shear response history difference for different strength ratio systems with viscous dampers. The M75B25 system has an initially higher stiffness which is apparent in both the plots with a lower displacement and base shear initially. The higher initial stiffness system performs better in both plots in the later portion of the earthquake response. The challenge to optimization of an MPCS system is to provide an initial phase with sufficient stiffness to meet serviceability requirements but is flexible enough to allow the damping system to be effective at dissipating energy. These findings indicate the range of strength ratios should be limited to where the moment-frame is designed at a minimum of 50% of the design base shear.

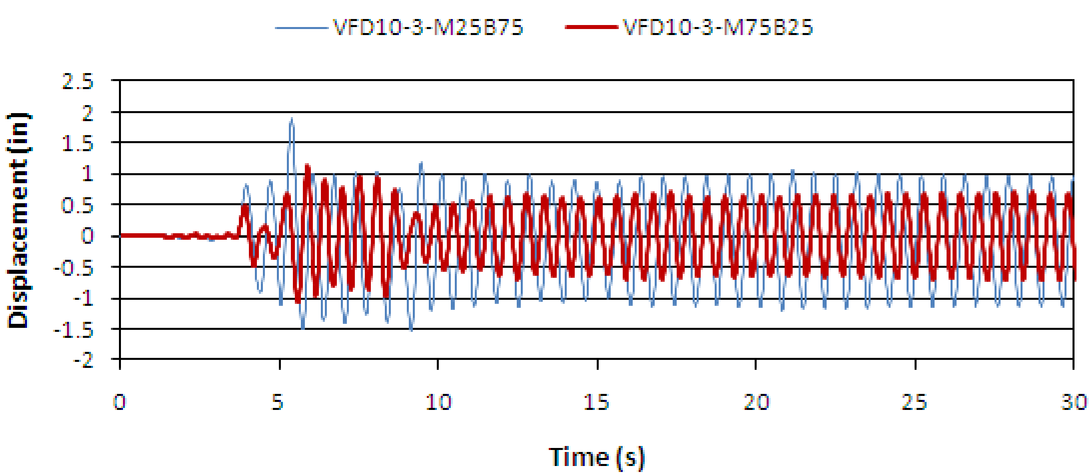

Figure 7. Displacement response history for Northridge earthquake record (Scale factor = 0.2).

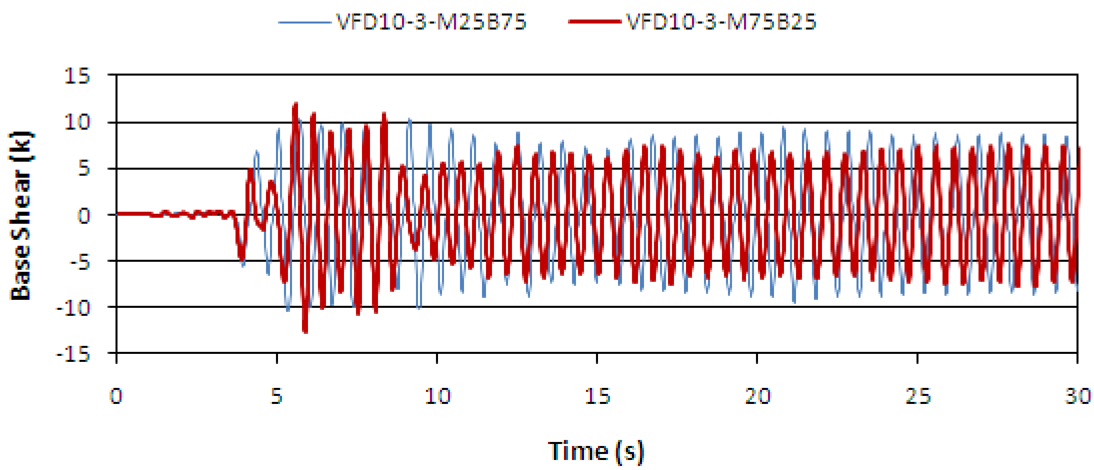

Figure 8. Base shear response history for Northridge earthquake record (Scale factor = 0.2).

Conclusions

The purpose of the study was to develop a better understanding of parameters critical to the response of MPCS systems. The results of this initial study have further developed an understanding of the system and narrowed the range of values of some critical variables. The groundwork laid during this work sets the stage for a complete SDOF study evaluating the different parameters inherent in multi-phase performance-based passive control systems. The following conclusions can be drawn from the results:

- The size of the gap has an effect on the response of systems, but the size selected in this study was not large enough to have a significant effect on the maximum response.
- The SDOF model needs a better representation of actual behavior. A single element yielding does not represent the more complex behavior of a single-story structure.
- The strength ratio utilized should limit the minimum strength of the moment-frame to 50% of the design base shear.
- A greater density of analyses should be run in the lower scale factors to provide a better indication of where initial yielding of the system occurs.

References

Amadio, C., I. Clemente, L. Macorini and M. Fragiacomo (2008). "Seismic Behaviour of Hybrid Systems Made of PR Composite Frames Coupled with Dissipative Bracings." Earthquake Engineering and Structural Dynamics **37**(6): 861-879.

ASCE (2006). Minimum Design Loads for Buildings and Other Structures. Reston, VA, American Society of Civil Engineers.

Bartera, F. and R. Giacchetti (2004). "Steel Dissipating Braces for Upgrading Existing Building Frames." Journal of Constructional Steel Research **60**(3-5): 751-769.

Chen, C.-S., K.-C. Chen, W. S. Pong and C. S. Tsai (2002). "Parametric Study for Buildings with Combined Displacement-Dependent and Velocity-Dependent Energy Dissipation Devices." Structural Engineering and Mechanics **14**(1): 85-98.

Constantinou, M. C., T. T. Soong and G. F. Dargush (1998). Passive Energy Dissipation Systems for Structural Design and Retrofit. Buffalo, NY, Multidisciplinary Center for Earthquake Engineering Research Center.

Constantinou, M. C., P. Tsopelas, W. Hammel and A. N. Sigaher (2001). "Toggle-Brace-Damper Seismic Energy Dissipation Systems." Journal of Structural Engineering **127**(2): 105-112.

FEMA (2000). Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings (FEMA 350), Federal Emergency Management Agency.

FEMA (2006). Next-Generation Performance-Based Seismic Design Guidelines (FEMA 445). Washington, D.C., Federal Emergency Management Agency.

Fujita, S., O. Furuya, T. Fujita, Y. Kasahara, Y. Suizu, S. Morikawa, T. Teramoto and H. Kitamura (1995). Research and Development of High-Damping Rubber Damper for Vibration Control of Tall Buildings. 1995 Joint ASME/JSME Pressure Vessels and Piping Conference. Honolulu, HI, USA, ASME, New York, NY, USA. **319:** 265-272.

Hanson, R. D. and T. T. Soong (2001). Seismic Design with Supplemental Energy Dissipation Devices. Oakland, CA, Earthquake Engineering Research Institute.

Ibrahim, Y. E., J. D. Marshall and F. A. Charney (2007). "A Visco-Plastic Device for Seismic Protection of Structures." Journal of Constructional Steel Research **63**(11): 1515-1528.

Lee, K. S., R. Sause, J. M. Ricles and L. W. Lu (2003). Seismic Behavior of Steel MRFs with UHDNR Structural Dampers. Stessa 2003, Behavior of Steel Structures in Seismic Areas. F. M. Mazzolani. Naples, Italy, Swets & Zeitlinger**:** 615-620.

Marshall, J. D. (2008). Development, Analysis and Testing of a Hybrid Passive Control Device for Seismic Protection of Framed Structures. Civil and Environmental Engineering. Blacksburg, VA, Ph.D. Dissertation, Virginia Tech. **Ph.D.**

Murthy, K. (2005). Application of Visco-Hyperelastic Devices in Structural Response Control. Civil and Environmental Engineering. Blacksburg, VA, M.S. Thesis, Virginia Polytechnic Institute and State University. **M.S.**

Ragni, L., L. Dezi, A. Dall'Asta and G. Leoni (2009). "HDR Devices for the Seismic Protection of Frame Structures: Experimental Results and Numerical Simulations." Earthquake Engineering and Structural Dynamics.

Sigaher, A. N. and M. C. Constantinou (2003). "Scissor-Jack-Damper Energy Dissipation System." Earthquake Spectra **19**(1): 133-158.

Symans, M. D., F. A. Charney, A. S. Whittaker, M. C. Constantinou, C. A. Kircher, M. W. Johnson and R. J. McNamara (2008). "Energy Dissipation Systems for Seismic Applications: Current Practice and Recent Developments." Journal of Structural Engineering **134**(1): 3-21.

Tsai, C. S., K.-C. Chen and C.-S. Chen (1998). Seismic Resistibility of High-Rise Buildings with Combined Velocity-Dependent and Velocity-Independent Devices. 1998 ASME Pressure Vessels and Piping Conference. San Diego, CA, ASME, Fairfield, NJ. **366:** 103-110.

Vamvatsikos, D. and C. A. Cornell (2002). "Incremental Dynamic Analysis." Earthquake Engineering and Structural Dynamics **31**(3): 491-514.

Vargas, R. and M. Bruneau (2007). "Effect of Supplemental Viscous Damping on the Seismic Response of Structural Systems with Metallic Damping." Journal of Structural Engineering **133**(10): 1434-1444.