Multi-Phase Passive Control Systems for Performance-Based Design

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LISBOA 2012

SUMMARY:
A Multi-phase Passive Control System (MPCS) combines two types of passive control devices in a single system in order to offset the inherent weaknesses of the individual devices and improve overall structural performance. Performance-based design of a MPCS in structures would allow the system to respond effectively to varying levels of lateral loading. Previous work indicates the effectiveness of MPCS but the fundamental knowledge of the system is lacking. A single-degree-of-freedom (SDOF) non-linear dynamic study was performed in order to more clearly define multi-phase behaviour. Parameters such as seismic hazard, system arrangement, system strength, system components, and material properties were all varied in order to fundamentally understand the effects on response. An incremental dynamic analysis was performed on the SDOF systems for a suite of scaled strong ground motions. The response quantities of interest included acceleration, base shear, element ductility demand, and drift.

Keywords: Multi-phase, Performance-based, Seismic, Passive Control, SDOF

1. INTRODUCTION

This study seeks to find a solution to seismic design that provides life safety in addition to damage control, utilizing a multi-phase passive system, which allows for varying response without an external power source. The solution proposed in this work combines two different passive control devices working together to create multi-phase behavior that utilizes the strengths of each device. There are three primary elements of a multi-phase passive control system: 1) a velocity-dependent damper, 2) a displacement-dependent energy dissipation device, and 3) a phase transition mechanism. Combining these elements with a moment frame creates two-phased behavior. The first phase involves the velocity-dependent damper paired with a special moment frame for initial stiffness which utilizes supplemental damping for severe wind events and low to moderate seismic events. The second phase involves the transition mechanism which engages at a displacement less than the yield displacement of the moment frame. After the transition, the displacement-dependent device adds significant stiffness and energy dissipation capability. This phase would be utilized in moderate to severe events, limiting damage to replaceable elements and minimizing non-structural damage.

Multi-phase devices have demonstrated beneficial behavior in many different applications (Weidlinger & Ettouney, 1993; Motlagh & Saadeghvaziri, 2001; Ibrahim et al. 2007). In particular, a multi-phase passive control system (MPCS) was developed, analyzed, and experimentally tested that combined a viscoelastic high-damping rubber sandwich damper and a buckling restrained brace in series in order to utilize the strengths of each system (Marshall 2007; Marshall & Charney, 2010). Another arrangement involving a viscous fluid damper, instead of a rubber damper, was proposed and analytically evaluated. Arrangement of the phases in parallel, which would allow the supplemental damping to be present throughout the duration of excitement, was also investigated. Nonlinear dynamic analyses were carried out on a 9-story, code compliant building. Response parameters such as acceleration, base shear, drift, and residual displacements all showed marked improvement over conventional systems.

Although the previous research demonstrates the effectiveness of combining passive control systems, the fundamentals of system behavior are unclear. In order to identify the more important variables influencing response, an exhaustive single-degree-of-freedom (SDOF) study had to be performed (Marshall 2007). This SDOF non-linear dynamic analysis is meant to more clearly define multi-phase behavior. The research was completed in three main stages: 1) parametric development and analysis plan, 2) model development and nonlinear dynamic SDOF analytical study, and 3) interpretation of results.

2. PARAMETRIC DEVELOPMENT

Numerous factors are involved in each multi-phase control system: a velocity-dependent damping device, displacement-dependent energy dissipation device, system arrangement, hysteretic-device-to-moment-frame strength ratio, seismic hazard, natural period, and transition gap size. The large range of potential values for each variable had to be investigated in order to narrow down the scope of the research. This was accomplished by looking at each variable in detail and deciding on an appropriate range of values. Furthermore, a preliminary analysis reduced the scope of the study even further by identifying the better performing systems and providing a direction for the rest of the research.

Two main types of velocity-dependent damping devices were reviewed and considered for a multi-phase system: linear viscous fluid dampers (VFD) and viscoelastic dampers (VED) with respective total damping values of 16% and 10% of critical damping (Occhiuzzi 2009). Although the VED damping value is less than that of the VFD, the stiffness added to the system by the high-damping rubber is potentially advantageous. Many options were also considered for the displacement-dependent device but, for simplicity, only a buckling-restrained brace (BRB was chosen due to a reliable hysteretic behavior, large energy dissipation capability, and proven effectiveness in multi-phase configurations.

The baseline systems considered consisted of conventional lateral force resisting systems; a special moment frame and a braced frame combined into a dual frame. The range of stiffness ratios for the dual systems were limited to 5 values: Moment frame resisting 40% of the lateral force and BRB resisting 60% of the lateral force (M40B60), M50B50, M60B40, M70B30, and M80B20. The inherent behavior of a moment frame coupled with a buckling restrained brace creates different strength-to-stiffness ratios for each baseline system. The overall strength of these elements will equal the required design strength, yet the overall stiffness will vary depending on the baseline ratios. The arrangements of phases can be in series and parallel, both potentially advantageous. Utilizing the variables defined previously (two arrangements, two velocity-dependent devices, and one displacement-dependent device), creates 4 possible multi-phase systems. In addition, a device with a transitional gap but no supplemental damping was introduced to capture the importance of the adding a damping device. Table 2.1 details the system arrangements and the corresponding abbreviations.

Table 2.1. MPCS System Abbreviations and Descriptions

Abbreviation	System Description
MPCS-S-VE	Special moment frame with a multi-phase passive control device utilizing a BRB and high-damping rubber sandwich damper in series
MPCS-S-VFD	Special moment frame with a multi-phase passive control device utilizing a BRB and linear viscous fluid damper in series
MPCS-None	Special moment frame with a multi-phase passive control device with no damper
MPCS-P-VE	Special moment frame with a multi-phase frame configuration utilizing an BRB and compressed elastomeric device in parallel
MPCS-P-VFD	Special moment frame with a multi-phase frame configuration utilizing a BRB and viscous fluid damper in parallel

Problems arise when dealing with the high damping rubber in the parallel arrangement which does not cap the displacement of the viscoelastic device. The ability to model and utilize a high-damping rubber for large displacements and corresponding strains is not very practical due to the highly nonlinear behavior of rubber for large strains. The SDOF study demands simplicity to understand the fundamental behavior of the multi-phase systems, therefore a new system was investigated for parallel action of damping and yielding for the MPCS-P-VE configuration in order to improve the behavior of the model. This device consists of pre-compressed high-damping rubber wrapped around a longitudinal bar and enclosed in a steel tube. The rubber is bonded to the central longitudinal bar, which is subsequently wrapped in a steel tube but not bonded to the steel tube (Karavasilis 2010). At a "slip force," the steel tube displaces with minimal resistance until the load is reversed, providing similar behavior to a friction device, with the added benefit of VE damping prior to slipping. Since the rubber remains elastic, a simple linear model gives a reasonable approximation. The BRB element of this arrangement has a specified gap size before the yielding takes place. Similar to the MPCS-S-VE, the damping and stiffness provided could significantly reduce response except the MPCS-P-VE high-damping rubber can be utilized throughout the duration of excitement. Fig. 2.1 details all the multi-phase arrangements considered.

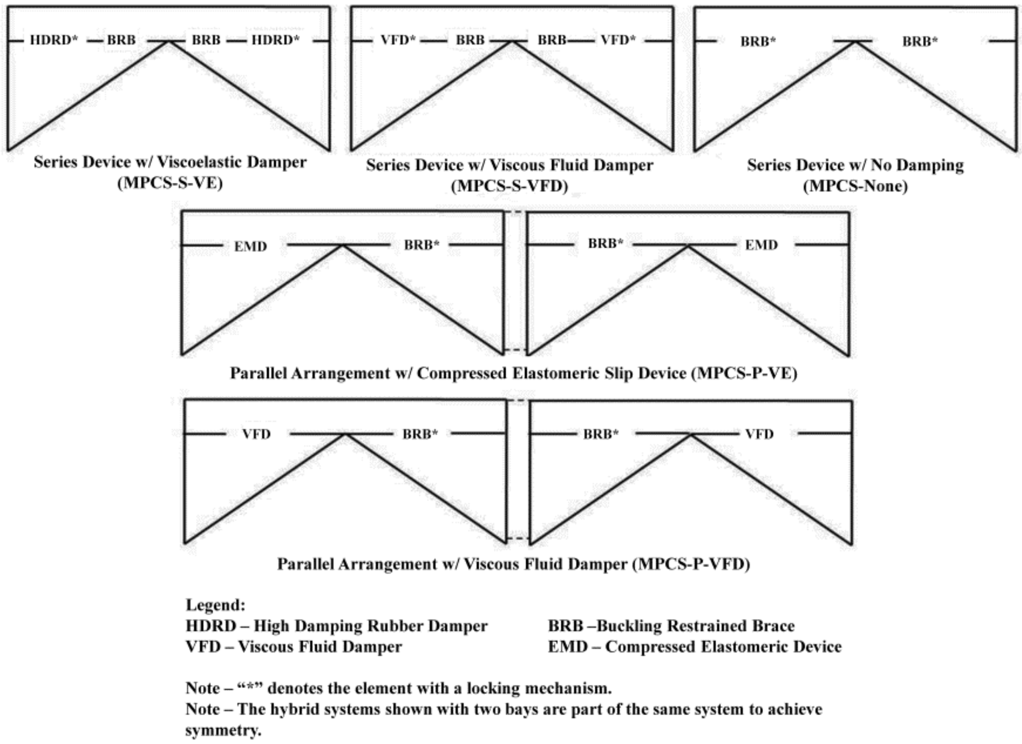

Figure 2.1. Multi-Phase Systems Considered

As stated before, each multi-phase system has a transition before the second phase (BRB) becomes active. The transition displacement or "gap" needs to be less than the yield displacement of the moment frame in an attempt to limit yielding to the replaceable BRB. The gap also has to be large enough to allow damping to be effective before the mechanism locks out. This research looks to strike a balance in order to increase damping of the system and reduce moment frame yielding, which is designed to first occur in the beam element. These gaps are specified as a percentage of the moment frame yield displacement: 20%, 40%, 60%, 80%, and 100%. A gap in a high-damping rubber system has a stiffness that is a function of the damper size while the VFD has no initial stiffness. All of the gap properties are a function of the design strength, which is dependent on the seismic hazard.

The systems were initially designed for two different seismic hazard levels: Los Angeles, CA (34.05°,-118.25°) and Memphis, TN (35.65°, -90.22°). The systems were designed with an Occupancy

Importance Factor of II, on Site Class D soil, and were considered vertically and horizontally regular. The periods chosen were: 0.25 s, 0.5 s, 1 s, 2.5 s, and 4 s. These natural periods are representative of most buildings within these seismic locations and were chosen to test the feasibility of multi-phase behavior in both long and short periods. Given the seismic hazards and possible multi-phase arrangements, there were 1250 possible systems.

3. MODEL DEVELOPMENT

Since this research is intended to identify the fundamental behavior of multi-phase systems, an approximation into a single degree of freedom model was made. All the analyses were carried out in SAP2000 and the details of the modelling are in the succeeding sections (CSI 2009). The baseline systems consist of the dual seismic resisting system without added multi-phase capabilities. The multi-phase systems also contain the baseline elements, but included the addition of other elements representing transition gap, rubber, and damping behavior, depending on the system arrangement. The baseline systems were analyzed to demonstrate the benefits of MPCSs. Backbone curves were developed in accordance with ASCE Standard 41-06 for the nonlinear link elements representing moment frame and buckling restrained brace elements (ASCE/SEI 2007). The basic model for the baseline systems is represented in Fig. 3.1.

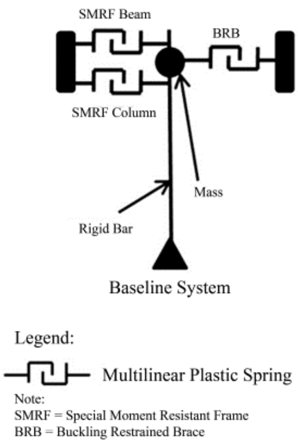

Figure 3.1. Baseline System

The series systems included the elements from the baseline systems with the addition of a gap element with a VE or VFD. The gap element for the MPCS-S-VE system is represented with a multilinear elastic link element that accounts for the high-damping rubber stiffness and lockout mechanism. The stiffness during the transition action is dependent on the damper size but after the desired displacement is reached, the element essentially becomes infinitely stiff when the mechanism locks out. The MPCS-S-VFD and MPCS-None systems also have a multilinear gap link with a small stiffness to account for friction in the slotted connection. Damping in the high-damping rubber and viscous fluid damper was modeled using a linear viscous dashpot element, modifying the damping coefficient, c, as appropriate for the system of concern. In the series systems, viscous or viscoelastic damping is only present while the gap is active; therefore the linear viscous dashpot element is placed in parallel with the gap. The details of these system arrangements are shown in Fig. 3.2.

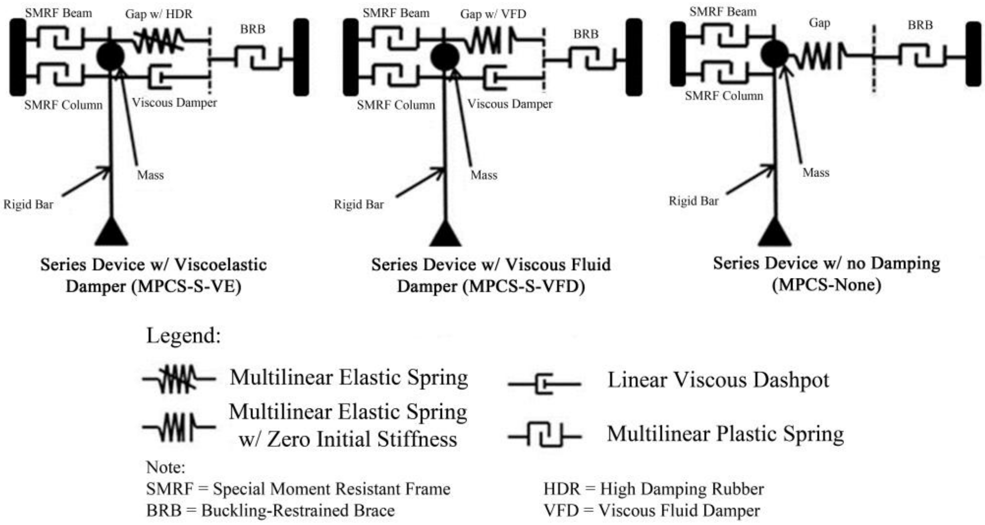

Figure 3.2. Series Arrangements

The parallel systems were a little more complex to model and had to allow for damping during all phases of excitation. The MPCS-P-VE system included the SMRF elements in parallel with a BRB and gap element in series on one side of the system. The other side included the compressed elastomeric device (EMD) described earlier. The slip behavior is represented with a multilinear plastic link element that does not become active until the slip force is reached. The MPCS-P-VFD system utilizes a VFD placed in parallel with a BRB and gap element acting in series. The other side of the system is the typical moment frame configuration seen in all the other systems. The modelling schematics for the parallel systems are represented in Fig 3.3.

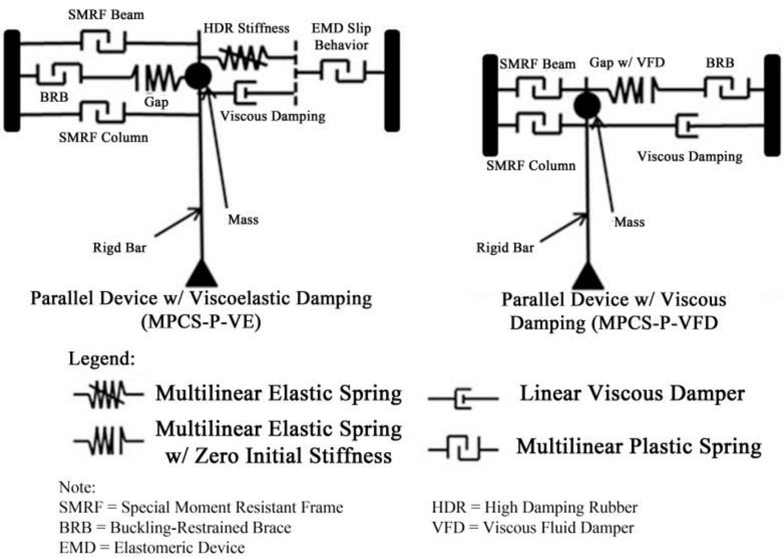

Figure 3.3. Parallel Arrangements

Eleven ground motions were chosen for each seismic hazard location representing 5 far field records, 3 near field with acceleration pulse records, and 3 near field without acceleration pulse records (Engineering Seismic Laboratory, 2010; Fernandez, 2007; Applied Technology Council, 2009; PEER, 2010). In the scope of this research, the incremental dynamic analyses (IDAs) were created by 1) scaling the ground motions appropriately for the periods of concern, 2) scaling the ground motions further by factors of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0 (DBE), 3) running each scale factor for the model, and 4) plotting the maximum absolute value for each response quantity (Vamvatsikos and Cornell, 2002). The values used in the IDAs were an average response of the 11 ground motions at each scale factor. General trends, such as yielding of an element, were noticed as the IDA plots changed shape. Comparing multi-phase system IDAs to baseline system IDAs was also a useful means of analysis. The four primary response quantities used to evaluate the systems were total acceleration, base shear, moment frame ductility, and buckling restrained brace ductility. These response quantities were changed into unitless or normalized quantities.

4. RESULTS

An exploratory preliminary design reduced the overall scope of the research from 1250 systems to 144 systems by eliminating poor performing levels of each variable. The end result allowed for a full factorial analysis to be completed on the 144 systems outlined in Fig. 4.1.

Once the scope of the study was reduced, the resulting systems were all analyzed and compared. First, the systems were compared to their corresponding baseline system to demonstrate the benefits of multi-phase control systems. Fig. 4.2 shows the performance of all the multi-phase systems for a 1 second natural period with a M50B50 dual frame. This is a representative selection of multi-phase systems but similar observations were made across all of the multi-phase systems evaluated in this analysis. The responses of the baseline systems were represented with a solid line. Box plots were used to depict the spread in the multi-phase system responses. Using the five number summary (minimum value, lower quartile, median, upper quartile, and maximum value), variability and skewness in the responses were readily identified. Since these comparisons included all of the multi-phase systems, large error bars or a high level of skewness may be apparent in some system combinations, indicating poor performance. Initially, this was a useful means to evaluate the multi-phase performance, but more detailed analyses were used to further evaluate system behavior.

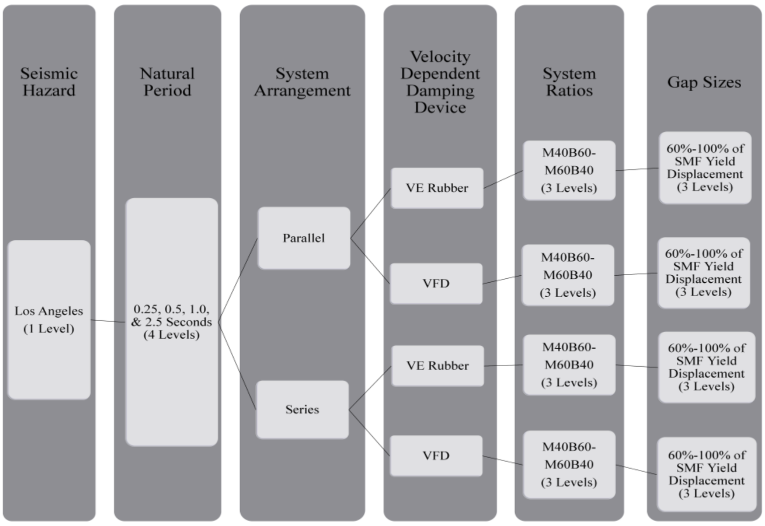

Figure 4.1. 144 Systems Analyzed

As seen in Fig. 4.2, relative to the baseline system (solid line), poor performance was seen for the upper scale factors with 40% more acceleration for the median multi-phase system. This poor performance is probably partially due to larger second phase stiffness present once the gap is closed and yielding of the displacement device takes place. The mid-scale factors exhibited a tremendous amount of variability in acceleration response, depending on the system arrangement. This is due to the transition of phases as the gap locks out and the system becomes stiffer. The most evident and convincing benefit of the multi-phase systems is present in the lower scale factors. Regardless of the multi-phase arrangement, improved performance was observed from 10% to 40% of the DBE. The supplemental damping and lower stiffness present in the initial phase of the multi-phase arrangements is responsible for the improved behavior. Base shear performance for the multi-phase systems in comparison to the baseline dual frame, was very similar to that for the acceleration performance.

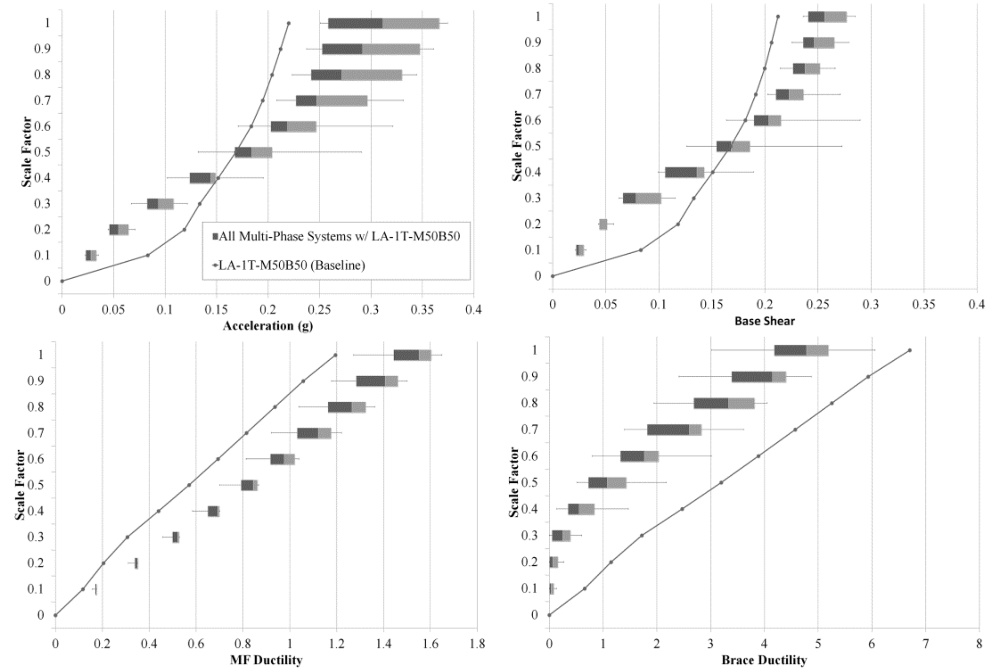

Figure 4.2. Comparison to Baseline Systems

Although the variability in moment frame ductility response was relatively low, overall performance of the multi-phase systems for moment frame ductility was worse than the baseline performance across all of the scale factors. Ductility values ranged from 20% to 70% higher than the baseline, with the multi-phase systems remaining elastic up to a 60% DBE, as opposed to 80% of the DBE with the baseline system. The response is sensitive to the frame stiffness ratio and gap size pairing, but even if optimized in this regard, moment frame ductility was worse than baseline values.

The brace ductility performance in comparison to the performance of the baseline system is by far the most appealing aspect of the multi-phase systems. Unfortunately, this outstanding performance comes at the cost of moment frame ductility. Every system remained elastic at 40% of the DBE, and about half of them remained elastic up to 50% of the DBE which is much better than the baseline system, which yields before 20% of the DBE. Even beyond the elastic range, brace ductility was still markedly improved in comparison to the baseline system, with median ductility values of only 70% of the baseline value at the DBE.

This comparison demonstrates the obvious advantages and disadvantages of the multi-phase system but the particular variables controlling response were still not evident. The multi-phase systems offer many advantages in comparison to the baseline dual frames. This better performance comes at the cost, though, of higher accelerations and base shears in the mid to high scale factors, and of poor moment frame ductility response. Since the displacement device is the replaceable link in the system, more investigation into limiting the moment frame ductility will need to be performed. Before solutions could be developed for these systems, it was important to identify the best performing systems within the remaining 144 systems.

Generally speaking, it was noticed that performance improved across all scale factors as the natural period increased. Overall performance of the shorter period systems did not offer many benefits in contrast to the baseline systems making the multi-phase systems an undesirable option. This is best explained by Fig. 4.3, which shows a comparison of the gap element behavior of two of the same multi-phase arrangements designed with different natural periods and subjected to the same ground motion. Each plateau represents the changing of phases as the gap element locks out and the secondary phase begins. The 0.25 second period system experiences about 50 phase transitions throughout the duration of the 90 second ground motion, compared to 8 phase changes for the 2.5 second period multi-phase system. The poor performance could be a result of large acceleration spikes that may occur as the multi-phase systems transition from the first to second phase. These acceleration spikes were evaluated in more detail in Rawlinson (2011).

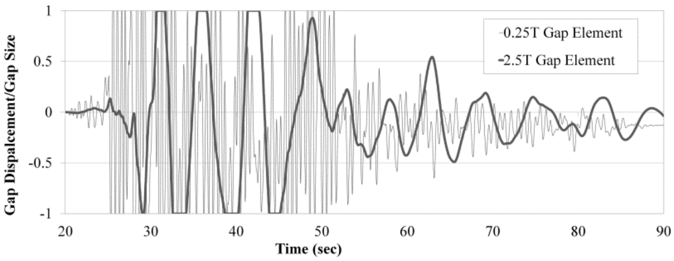

Figure 4.3. Natural Period Comparison of Gap Elements

In order to reduce the scope even farther, an in-depth look at each arrangement had to be completed. Because there were four response quantities and good performance in one quantity was often offset by poor performance in another, a selection criterion was developed to create a consistent, more systematic way of analyzing the data. The first, and most important criteria, is moment frame protection. As stated earlier, the goal of a multi-phase system is to efficiently dissipate energy as well as to limit yielding to a replaceable element. Damage to the moment frame requires expensive and time-consuming repairs after an event. Another important criterion is good performance in the low-to-mid scale factors for the acceleration and base shear responses. Protection of acceleration and shear sensitive elements in the low-to-mid scale factors could mean immediate occupancy after an event. Lastly, the BRB ductility performance must be checked. Most of the multi-phase systems showed great performance in this regard, remaining elastic anywhere from 30%-70% of the design basis earthquake allowing immediate occupancy in low-to-midscale factor events. Although this type of performance is ideal in regards to occupancy, as the ground motion intensity increases, it becomes important to strike a balance between brace ductility and other response quantities. Higher brace ductility values in the mid-to-upper scale factors would be acceptable because of the extensive energy dissipation capabilities and the ability to replace the device after an event.

Following this systematic approach to evaluating the performance of the multi-phase systems, the better performing systems could be identified for each arrangement. Fig. 4.4 shows a representative comparison of the preferred system (LA-1T-1.0-M40B60-S-VE), all 1T-S-VE systems, and the baseline system with no multi-phase capabilities. A comparison of four of the better performing systems, one from each arrangement, is seen in Fig. 4.5. The moment frames in all four systems were observed to yield anywhere from 60% to 70% of the DBE, with the MPCS-P-VE system exhibiting the best performance. Acceleration and base shear exhibited the most variability in response from the four systems. The parallel systems both experienced higher responses in the upper scale factors. Brace performance for all of the systems remained elastic until at least 50% of the DBE.

Overall, the systems offer many benefits in relationship to the baselines. The one major drawback is the poor moment frame ductility behavior, which could be resolved by adding more damping. This was investigated further, adding damping to the VFD systems to see if it would better protect the moment frame. The overall critical damping value was increased from 16% to 25% for the VFD systems. Improved performance was seen across all response quantities with a marginal improvement in moment frame ductility. The parallel arrangement saw the most improvement from the additional damping, remaining elastic up to 80% of the DBE.

In addition to the four primary response quantities, it is also important to analyze residual drifts for the different system arrangements. Inelastic behavior of the buckling-restrained brace element or the moment frame could lead to permanent residual deformation in the system. Although residuals may not be directly applicable to a real structure as a SDOF system, the relative residuals for each system

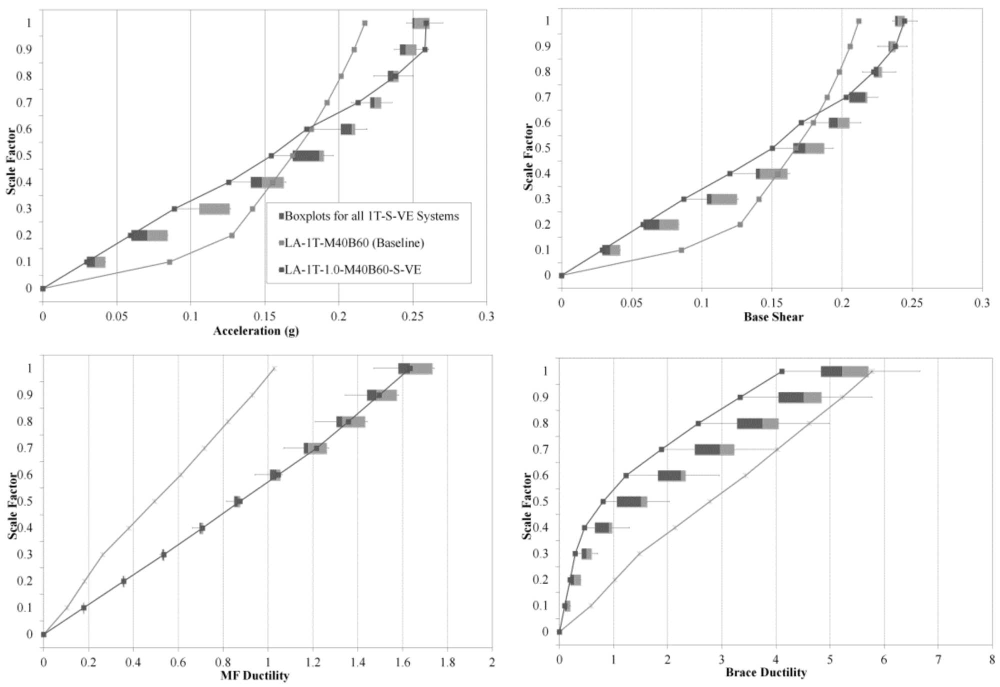

Figure 4.4. Identification of the Better Performing Systems

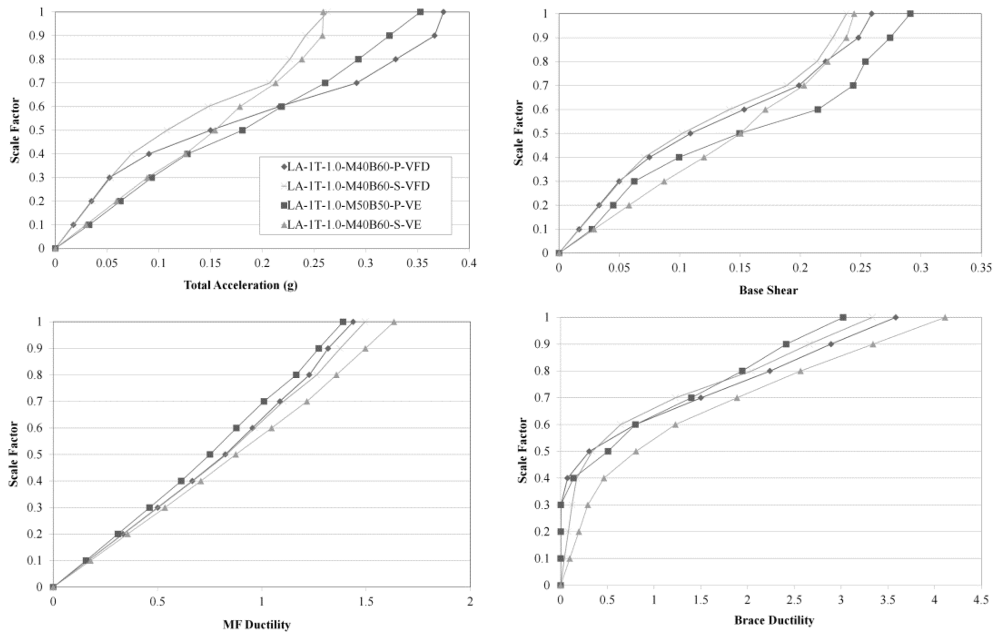

Figure 4.5. Comparison of the Best Performers for Each Arrangement

can still be compared to demonstrate which multi-phase systems perform the best. The MPCS-P-VE system, which included the parallel arrangement paired with the high-damping elastomeric device, demonstrated self-centering capabilities. This is evident in all of the ground motions by observing the relatively small residual deformations for this system when compared to the other systems. This system is also the most effective at damping out the energy after the duration of the ground motion. The MPCS-S-VFD and MPCS-P-VFD behaved very similarly in response to all four ground motions, while the MPCS-S-VE exhibited the highest overall residual deformations. More research should be performed regarding the minimization of residual deformations in the MDOF system study but this brief study was useful to demonstrate another possible advantage of using a multi-phase device.

5. CONCLUSIONS

The goal of this research was to understand the fundamental behavior of multi-phase passive control devices. This was accomplished by splitting the research into three primary sections: parametric development, model development, and interpretation of results. Compared to the baseline systems, multi-phase passive control devices offer many benefits, especially in the higher periods (1 second to 4 seconds). The first phase provides a significant decrease in acceleration and base shear in the lower scale factors. The brace behavior is another appealing aspect of the multi-phase devices, remaining elastic up to 60%-70% of the DBE in some cases. As the period decreases (0.25 seconds and 0.5 seconds), the beneficial multi-phase behavior decreases and therefore the extra costs associated with a multi-phase system may not be justified. More research needs to be done to investigate the feasibility of a multi-phase system in lower natural periods.

The major drawback of the multi-phase behavior lies in the protection of the moment frame. The beneficial protection of the brace element is only appealing if the moment frame remains elastic. Variability was not very large for moment frame ductility but was consistently poor in comparison to the baseline systems. Even in the best performing systems, yielding occurs as early as 60% of the DBE compared to 90%-100% for the baseline systems. The two VFD arrangements were analyzed with larger damping ratios for extra moment frame protectionwhich proved to be very beneficial.

Multi-phase systems provide an interesting aspect to structural design in that they allow the structure to be more resilient and essentially pre-programmed for ground motion excitation. The work provided in this research provides significant groundwork for multi-phase research in the future. Using the range of variables from this analysis, an MDOF system can be developed and evaluated further. Once the system performance is verified analytically, the study can be tested experimentally and implemented in design.

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