Comparison of Dynamic Characteristics and Response Analysis of Building Structures Incorporating Viscous Fluid Dampers and Buckling Restrained Braces

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ABSTRACT

The use of viscous fluid dampers (VFDs) and buckling restrained braces (BRBs) are common in seismic regions. These devices are very successful in robust energy dissipation and they use different mechanism in preventing damage to structural systems. These devices are not used together very often but a hybrid system may act more efficiently for a wider range of earthquake magnitudes. The building benefits more from VFDs at low magnitude earthquake, for a moderate event both VFDs and BRBs come into action, and for extreme events VFDs may help when BRBs tend to exhibit large maximum and residual drift. This paper presents a study using varying configuration of VFD and BRB in a reference test model. These devices are employed in alternate-diagonal configuration at each story and the number of these devices is varied. A series of nonlinear time history analysis is performed and various analysis responses are captured. The results from the study are used to understand dynamic characteristics and response analysis of such a hybrid system and how it may be employed to get the optimum response.

INTRODUCTION

Energy dissipating devices can adequately control seismic performance of structures during moderate and high intensity ground motions. There are two main groups of these devices: (1) displacement dependent devices (such as metallic-yielding braces, buckling restrained braces) that add initial stiffness to the structure which may be degrading or non-degrading; (2) velocity dependent devices (such as viscous fluid dampers or visco-elastic dampers) that may or may not add initial stiffness to the structural system on which they are deployed but always provide some dynamic stiffness which is frequency dependent.
These devices are commonly used to improve building performance under seismic and wind events by effectively reducing displacements and damages in structures. Energy dissipation is accomplished by these devices based on different energy dissipating mechanisms. For instance, damping force in a VFD element is velocity-dependent and it is out of phase with structural motion, which introduces an effective restoring force into the structural response. On the other hand, a BRB element is displacement-dependent and dissipates energy through yielding of its steel core while buckling is effectively prevented. Idealized force-displacement loops of VFD and BRB are shown in Fig. 1.

![Force-displacement loops](image)

**Figure 1.** Force-displacement loop of (a) a viscous fluid damper, and (b) a buckling restrained brace

In this study, velocity-dependent viscous fluid dampers (VFD) and displacement-dependent buckling restrained braces (BRB) are selected and deployed on a moment resisting frame to create a hybrid system. The main objective is to utilize these elements in such a way that the new structural system controls and limits further damages under a wider variety and range of ground motions. To accomplish this, a series of hybrid models is created from a reference model using various permutations and combinations of VFDs and BRBs applied on different stories in an alternate diagonal configuration. The performances of hybrid models are compared to those of regular moment resisting frames containing only VFDs or only BRBs as energy dissipating devices. Several engineering demand parameters are selected as performance measures in these comparisons. Nonlinear time history analyses are carried out with a selected suit of ground motions. A software solution is developed to conduct nonlinear analysis and to manage and collect analysis results. The results from this study are used to understand dynamic characteristics and response analysis of such hybrid systems and how they may be employed to get the optimum response.

**MODELING OF VISCOUS FLUID DAMPERS**

A viscous fluid dampers (VFD) used in a building structural system is like any shock absorber deployed on an automobile, but it is larger in size and can withstand higher forces. A typical VFD is shown in Fig. 2, which consists of a stainless steel cylinder and a piston rod. A VFD provides damping by the flow of silicone fluid across the
piston head. The force developed in the device during a damper stroke is velocity-dependent and it is expressed as follows:

\[ F = C \, \text{sgn} \left( \frac{du}{dt} \right) \frac{du}{dt}^\alpha \]  

in which \( C \) is the damping coefficient, \( \frac{du}{dt} \) is the velocity and \( \alpha \) is a velocity exponent. The damper is called a linear damper if \( \alpha = 1 \), otherwise it is called a nonlinear damper.

**MODELING OF BUCKLING BRACED BRACES**

A BRB device is a hybrid element that is composed of an interior steel yielding core placed within an exterior concrete and steel casing. The interior core and the exterior casing are separated by a bond-preventing layer and hence, load transfer between them is prevented or minimized (Fig. 3). The exterior casing prevents the interior core from buckling and the interior core can repetitively yield both in tension and compression without experiencing any significant strength and stiffness degradation.

The force-displacement relationship for buckling-restrained braces (BRB) is relatively more complex compared to a VFD. A rule based trilinear force-deformation relationship is used for modeling inelastic BRB element. This model is primarily composed of three zones: elastic, yielding and hardening zones. The model is capable of capturing strain hardening behavior, which adopts both isotropic and kinematic hardening effects. A total of 13 parameters are needed to define the trilinear model for a specific BRB element as shown in Fig. 4. These parameters are based on interior steel core area, length between pin-to-pin connection, length of the interior steel core, modulus of elasticity and yield strength of steel.
GROUND MOTION RECORDS

A total of eight ground motion records are selected for the current study. Table 1 provides information for the selected ground motions and data for these motions are obtained from PEER Strong Motion Database (http://peer.berkeley.edu/smcat/). There is no scaling applied to the ground motion data and the earthquakes M11, M12, M21 and M22 are near-field earthquakes whereas M31, M32, M41 and M42 are far-field. Elastic response spectra curves for these motions with 5% damping are shown in Fig. 5.

REFERENCE TEST MODEL

A six-story moment resisting frame is selected as a reference model, which is adopted from Ramirez, et. al. (2003). The frame is a part of a building with regular plan dimensions of 41.15 m by 41.15 m and it is designed to satisfy requirements according to 2000 NEHRP Provisions.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Station and Component</th>
<th>M</th>
<th>R (km)</th>
<th>PGA (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M11</td>
<td>Loma Prieta (1989)</td>
<td>15UCSC, 0</td>
<td>6.9</td>
<td>18.1</td>
</tr>
<tr>
<td>M12</td>
<td>Loma Prieta (1989)</td>
<td>15UCSC, 90</td>
<td>6.9</td>
<td>18.1</td>
</tr>
<tr>
<td>M21</td>
<td>Northridge (1994)</td>
<td>74 Sylmar – Converter, 052</td>
<td>6.7</td>
<td>6.20</td>
</tr>
<tr>
<td>M22</td>
<td>Northridge (1994)</td>
<td>74 Sylmar – Converter, 142</td>
<td>6.7</td>
<td>6.20</td>
</tr>
<tr>
<td>M31</td>
<td>Loma Prieta (1989)</td>
<td>58223 SF Intern. Airport, 0</td>
<td>6.9</td>
<td>64.4</td>
</tr>
<tr>
<td>M32</td>
<td>Loma Prieta (1989)</td>
<td>58223 SF Intern. Airport, 90</td>
<td>6.9</td>
<td>64.4</td>
</tr>
<tr>
<td>M41</td>
<td>Whitter Narrows (1987)</td>
<td>24436 Tarzana, Cedar Hill, 0</td>
<td>6.0</td>
<td>43.0</td>
</tr>
<tr>
<td>M42</td>
<td>Whitter Narrows (1987)</td>
<td>24436 Tarzana, Cedar Hill, 90</td>
<td>6.0</td>
<td>43.0</td>
</tr>
</tbody>
</table>
The structural details of the selected frame are shown in Fig. 6a. Various permutations and combinations of VFDs and BRBs are applied in the middle bay, locations of which are shown by the dash lines in the figure. Fig. 6b shows list of all possible configurations. In this list, the letters “V” and “B” are used for a VFD and BRB, respectively and the order of the letters indicate the floor number (for instance, “17:VBBVVV” stands for hybrid model 17 in which VFDs are positioned at the 1st, 4th, 5th and 6th floors and BRBs are at the 2nd and 3rd floors). The following series of analytical models are generated from the reference test model:

1. One model with only the bare frame (H0),
2. One model with only VFDs (H1),
3. One model with only BRBs (H65), and
4. 62 hybrid models with different combinations of VFDs and BRBs (H2-H64).

A total of 65 analytical models (including the bare frame) is created. In these models, beams and columns are assumed to be elastic and nonlinear response is only allowed for BRBs. All the VFDs in this study are assumed to be linear (i.e., $\alpha = 1$ in Eq. (1)). The panel zone deformations, beam-column connection yielding and P-Delta effects are ignored.

A plot of the first three periods of vibration (using initial BRB stiffness and ignoring non-classical damping property wherever it is applicable) for all the test models is shown in Fig. 7. It should be noted in the figure the results are ordered such that those on the left are from models with predominantly VFDs (except the first one, which is from the bare frame model), while those on the right are from models with predominantly BRBs, as listed in Fig. 6b.

The VFDs are modeled with a damping constant of $C = 2.3$ kN-s/mm. A comparable BRB element is obtained by trial and error. For this purpose, two models are created: one model containing only VFDs and another one with only BRBs. A nonlinear time history analysis is performed for these models using normalized El-Centro earthquake record scaled to 1.0g. The parameters for the BRB elements are calibrated such that both models yield similar top-story drift within 2 percent error margin.
It should be noted that a different ground motion is used for calibration as opposed to one of the eight being used for parametric study to avoid any bias in results generated towards or against that ground motion. It is also intended that a significant amount of energy dissipation is captured in VFDs as well as BRBs during the calibration process. Table 2 shows calibrated BRB properties for this example. Coincidentally, the calibrated BRB properties match with a prefabricated BRB component manufactured by StarSeismic (Powercat PC160).

A 2% Rayleigh damping is assumed in 1st and 3rd vibration mode of all the models. It is realized that this damping does not stay constant for these modes or as a matter of fact for all the modes as the nonlinear time history analysis proceeds. This is due to change in vibration period when BRBs yield or when VFDs comes in action (introducing non-classical damping). However, it is expected that this nominal Rayleigh damping does not change significantly for the 1st three modes which covers 95% of modal participation for all the models.

Figure 6. (a) Reference frame, (b) Configuration list
Table 2. Modeling Parameters for a BRB element

<table>
<thead>
<tr>
<th></th>
<th>$K_0$ (kN/mm)</th>
<th>$F_y$ (kN)</th>
<th>$F_{u0}$ (kN)</th>
<th>$D_{u0}$ (mm)</th>
<th>$F_{uh}$ (kN)</th>
<th>$K_f$ (kN/mm)</th>
<th>$D_{ouh}$ (mm)</th>
<th>$D_{uh}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>74.7</td>
<td>600.5</td>
<td>742.9</td>
<td>17.8</td>
<td>1000.8</td>
<td>1.36</td>
<td>76.5</td>
<td>113.4</td>
</tr>
<tr>
<td>Compression</td>
<td>74.7</td>
<td>578.3</td>
<td>734.0</td>
<td>17.8</td>
<td>1112.1</td>
<td>2.72</td>
<td>76.5</td>
<td>113.4</td>
</tr>
</tbody>
</table>

PARALLEL COMPUTING PLATFORM

Nonlinear time history analysis generally produces huge amount of analysis results. Considering the number of models used for the present study and the amount of enormous data generated during analyses, an efficient way to handle this process necessitated development of a suitable software solution. To serve this need, a software platform named SimFEA is developed. Briefly, SimFEA is designed to run multiple input files and it generates requested output files for analysis results. Problem definitions (geometry definition, member properties, loading, analysis parameters, etc.) are specified in input files that are driven by pre-defined keywords (i.e. commands).

Fig. 8a shows abstraction layers of SimFEA. One can launch SimFEA to run multiple input files in sequence or one can exploit an interactive (i.e., command driven) layer (Console) of SimFEA. The Parser layer reads and interprets input files and feeds this information into Console that communicates with a finite element library (FELib) through an Engine layer. The FELib is a COM-based object-oriented nonlinear finite element analysis library that is developed for nonlinear static and dynamic analysis of structures and it is used in several commercial products (Bentley Systems, Inc., 2012). SimFE generates output files and provides a plotting utility layer (PLOT) to
draw analysis results. It is also worth mentioning that the Console layer provides functionality to extract specific information (such as base-shears, story drifts, nodal displacements, etc.) from the output files. This feature is extremely useful because it significantly reduces the effort to extract specific information from hundreds (or thousands) of files generated during multiple analyses. To take the advantage of modern computers’ multi-core hardware structure, a parallel execution process is adopted. In this approach, multiple copies of SimFEA are launched at the same time while each SimFEA runs multiple input files (see Fig. 8b).

The aforementioned concepts implemented in SimFEA significantly reduce overall analysis time and the amount of effort to harvest output data. For instance, the six story example includes 520 different models and it generates over 8 GB of output data written to more than 17 thousand files. It takes about 90 minutes to run all models in parallel on a typical desktop computer with 8-cores (Windows 7), and it only takes a few minutes to extract and plot base shears and inter-story drifts.

![SimFEA Software Solution Platform](a)

![Parallel Execution Process](b)

**Figure 8. SimFEA Software Solution Platform**

**ANALYSIS RESULTS**

In the discussion below, the following naming convention is used: FRM refers to bare frame model, VIS refers to model with only viscous fluid dampers, and BRB refers to model with only buckling restrained braces. The term “HYBRID” is used for the best performing hybrid frame in the corresponding categories. Furthermore, some plots refers to frame model number given in Fig. 6b (for instance, H4 refers to 4:VVVBVV in Fig. 6b).

Fig. 9 shows a bar chart for percentage of base shear with respect to structural weight as noted for eight ground motion records. It is observed that there is at least one hybrid frame that produces lower base shear for all earthquakes except for M32 where the purely viscous damper model is only slightly better. In general, it is observed that the BRB frame returns higher base shears compared to the VIS frame, which can be attributed to stiffness contribution of BRB components to overall performance of structure. One may also note that base shear is relatively higher for all the models subjected to M21 and M22 ground motions compared to other motions. The main reason for this behavior is attributed to relative high spectral acceleration in between 1.5 sec to 3.0 sec period range which also envelopes the first fundamental
period of all the models. In a separate analysis (not presented in the paper), it is shown that in general 80% of the participation is coming from the first fundamental mode of vibration. As a result, for these high intensity earthquakes (M21 and M22), it is found that BRB elements in the best performing hybrid frames are all yielded as they are subjected to larger cyclic deformations.

Fig. 10 includes maximum inter-story drift ratio envelope plots for all earthquakes. It is immediately observed that the hybrid models as well as models with only VFDs or BRBs are very effective in reducing inter-story drifts. There is again at least one hybrid model that outperforms VIS, BRB and bare frames in regards with reducing inter-story deformations.

Figure 9. Base Shear relative to Structural Weight for different Systems

Figure 10. Maximum Inter-Story Drift Ratio Envelopes
Fig. 11 includes plots of analysis results per selected engineering demand parameters (EDP). Due to limited space, the results for only two ground motions (M11 and M21) are portrayed graphically. In the plots, as mentioned earlier, the models with more VFDs are placed at left and the models with more BRBs are placed at right. The selected EDPs are maximum story drift ratio among all stories (Fig. 11a), base shear (Fig. 11b), summation of all column axial forces at the base (Fig. 11c) and dissipated energy in VFDs and BRBs (Fig. 11d). Note that the response ratio given in the plots is the ratio of the response of the specified model with respect to the response of the bare frame, for the given EDP.

One immediate observation noticed in the plots is that BRB elements mostly respond elastically with minimum energy dissipation in earthquake M11 (i.e., the energy dissipated by BRBs are almost zero as shown in Fig. 11d). On the other hand, they are forced into their nonlinear range, dissipating significant amount of energy as observed in M21. The axial force demand (Fig. 11c) in the columns is significantly higher for those models with more BRBs (as high as 8 times of the bare frame as observed in M11), which can be attributed to their stiffness contribution to overall response of the frames. Once these braces are yielded (as observed in M21), this demand is reduced (i.e., approx. 80 percent of the bare frame). A similar trend is observed for the base shear, in which it is almost halved for earthquake M21.

The hybrid models with more VFDs follow a similar pattern. For instance, axial force demand on the columns for earthquake M11 is higher than those observed in the bare frame albeit no direct stiffness contribution from the VFDs. For the base shear, however, it is slightly lower than of the bare frame. For high intensity earthquake (M21), the hybrid models yield similar responses in a way that they effectively reduce both base shear and axial column forces.

It is also noted that the hybrid models as well as the models with VFDs or BRBs only are very effective in reducing inter story drifts (Fig. 11a). Interestingly, the models with more BRBs are more effective in reducing inter story drifts for high intensity earthquake (M21), but it is reversed for low intensity earthquake (M11), where the models with more VFDs are more efficient.

Table 3 shows the best performing models for different EDPs. As noted, there is no a single model that is referred to as the best configuration. Despite this observation, some conclusions are drawn as follows:

- For high-intensity ground motions, models with more BRBs (i.e., larger number models) generally tend to be more efficient in reducing displacement, column shears and column moments.
- For low-intensity ground motions, models with more VFDs (i.e., smaller number models) generally tend to be more efficient in reducing drift, drift ratio, column shears and column moments.
- Models with more VFDs (i.e., smaller number models) are more effective in reducing total base shear and column axial forces.
(a) Maximum story drift ratio among all stories

(b) Frame Base shear

(c) Summation of column axial forces at the base

(d) Dissipated energy in VFDs & BRBs

Figure 11 Comparison of EDPs from models undergoing motion M11 and M21
Table 3. Models with best EDP performance under 8 ground motions (high intensity
ground motions are highlighted)

<table>
<thead>
<tr>
<th></th>
<th>M11</th>
<th>M12</th>
<th>M21</th>
<th>M22</th>
<th>M31</th>
<th>M32</th>
<th>M41</th>
<th>M42</th>
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</thead>
<tbody>
<tr>
<td>Top story displacement</td>
<td>H52</td>
<td>H8</td>
<td>H64</td>
<td>H23</td>
<td>H19</td>
<td>H60</td>
<td>H1</td>
<td>H1</td>
</tr>
<tr>
<td>Max. story drift ratio</td>
<td>H58</td>
<td>H1</td>
<td>H63</td>
<td>H7</td>
<td>H1</td>
<td>H58</td>
<td>H15</td>
<td>H6</td>
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<tr>
<td>Base shear force</td>
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<td>(sum of shear forces of all</td>
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<tr>
<td>members at the base)</td>
<td>H16</td>
<td>H4</td>
<td>H13</td>
<td>H6</td>
<td>H9</td>
<td>H1</td>
<td>H17</td>
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<tr>
<td>Sum of column shears forces</td>
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<tr>
<td>at the base</td>
<td>H36</td>
<td>H9</td>
<td>H57</td>
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<td>Sum of column axial forces</td>
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<tr>
<td>at the base</td>
<td>H3</td>
<td>H1</td>
<td>H31</td>
<td>H1</td>
<td>H2</td>
<td>H2</td>
<td>H11</td>
<td>H1</td>
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<tr>
<td>Sum of column moments</td>
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<td>H17</td>
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CONCLUSIONS

Viscous dampers and BRBs are two of the most widely used performance improving
elements for structures in seismic regions. They are very effective in controlling story
deformations as well as in reducing column axial forces and frame base shears under
high intensity earthquakes. For moderate earthquakes, high demands in column forces
and frame base shears of BRB frames can be offset by using VFDs as observed in
some of the hybrid models in the present study. The results show that VFD-only or
BRB-only system may not be very effective for a wider range of earthquake
intensities and this is where utilizing a hybrid system can be beneficial. The
advantages of VFDs and BRBs could be utilized at DBE and MCE, respectively.

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