EVALUATION OF WALL DAMPER EFFECTIVENESS ON THE SEISMIC PERFORMANCE OF BUILDINGS

A. Dilsiz¹, M.S. Mohammed², A.R. Özuygur³, and M.A. Moustafa⁴

ABSTRACT

Energy dissipation systems, e.g. viscous linear and wall dampers, are effective solutions for enhancing the seismic performance of buildings through reducing the dynamic and seismic demands. These systems are particularly beneficial for high-rise buildings for controlling accelerations and motion comfort under wind loading as well. For high-rise buildings, dynamic behavior is the primary issue in the design process. As a result of developing technology, many new energy dissipation systems have been developed and used for four decades. In this paper, the effects of wall dampers on the dynamic performance of the high-rise buildings under seismic loads are evaluated. Wall dampers have been used in many projects mainly in Japan, and recently, a new hospital building in California in the United States has been equipped with wall dampers for seismic mitigation. A readily available computational model for wall dampers is implemented and used in this study to analytically investigate the seismic response of high-rise buildings with and without wall dampers. A 30-story reinforced concrete buildings that is located in Turkey and use core shear walls as lateral resistance systems is considered with and without wall dampers for this study. For a target interstory drift of 1.5% as in case of special or important buildings, the analysis here considered maximum credible earthquake level to check whether wall dampers can satisfy the target drift requirements. Nonlinear response history analysis was carried out for the two cases: with and without wall dampers, and the wall dampers were shown to effectively reduce maximum interstory drift ratios from more than 2% to less than the 1.5% target performance objective.

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ABSTRACT

Energy dissipation systems, e.g., viscous linear and wall dampers, are effective solutions for enhancing the seismic performance of buildings through reducing the dynamic and seismic demands. These systems are particularly beneficial for high-rise buildings for controlling accelerations and motion comfort under wind loading as well. For high-rise buildings, dynamic behavior is the primary issue in the design process. As a result of developing technology, many new energy dissipation systems have been developed and used for four decades. In this paper, the effects of wall dampers on the dynamic performance of the high-rise buildings under seismic loads are evaluated. Wall dampers have been used in many projects mainly in Japan, and recently, a new hospital building in California in the United States has been equipped with wall dampers for seismic mitigation. A readily available computational model for wall dampers is implemented and used in this study to analytically investigate the seismic response of high-rise buildings with and without wall dampers. A 30-story reinforced concrete buildings that is located in Turkey and use core shear walls as lateral resistance systems is considered with and without wall dampers. A target interstory drift of 1.5% as in case of special or important buildings, the analysis here considered maximum credible earthquake level to check whether wall dampers can satisfy the target drift requirements. Nonlinear response history analysis was carried out for the two cases: with and without wall dampers, and the wall dampers were shown to effectively reduce maximum interstory drift ratios from more than 2% to less than the 1.5% target performance objective.

Introduction

Energy dissipation systems, e.g., viscous linear dampers and viscous wall dampers (VWD), are effective solutions for enhancing the seismic performance of buildings through reducing the dynamic and seismic demands, especially interstory drifts. These systems can be particularly beneficial for high-rise buildings that are subjected to different lateral loads and multi hazards such as earthquakes and winds. For instance, a high-rise building in San Francisco in the United States
is designed to maintain certain motion comfort criteria under wind loading while being located in a seismically active area. In this case, devices such as VWD can be useful in controlling accelerations and motion comfort under wind loading as well as reducing drift ratios to satisfy high standards of performance based seismic design (PBSD). In signature tall and high-rise buildings around the world, such as the Taipei 101 tower, commonly used damping devices are tuned mass dampers or in some other instances conventional linear viscous dampers. On the other hand, devices like VWD are less commonly used especially and more research might be needed to identify the limitations and optimal design cases for VWD.

VWD were first developed more than two decades ago in Japan and since then, have been used in over a hundred projects [1]. VWDs consist of a stiffened steel tank filled with viscous “fluid” and one or more steel vanes that extend into the tank of viscous fluid. The VWD is typically installed between two rigid girders. The tank is connected at one level while the vanes are connected at the level above such that the interstory drift and interstory velocity result in in-plane movement of the vane within the tank as illustrated in Figure 1. Viscous shearing of the fluid relative to the tank wall and vane (Figure 1) provides damping and energy dissipation. To characterize the behavior of VWD and define modeling parameters, Newell et al. [1] conducted full-scale testing of the Dynamic Isolation Systems Inc. devices [2, 3] at the University of California, San Diego to establish expected wind and seismic performance and determine appropriate properties for modeling the devices. One 7 ft wide by 12 ft tall double vane prototype specimen was tested (Figure 2) under a variety of displacements and velocities (sinusoidal and earthquake motion) in single and bi-directional loading conditions. Tests were done according to ASCE7-05 [4] to establish device performance and to determine VWD properties, i.e. force at zero displacement ($F_0$), force at maximum device displacement ($F @ D_{max}$), effective stiffness ($K_{eff}$), and area of hysteresis loop ($E_{loop}$) as defined in Figure 2.

![Figure 1. Schematic representation of VWD components and concept as adopted from Dynamic Isolation Systems Inc. [2, 3]](image-url)

As previously mentioned, most of the VWD applications originated in Japan and only recently, a large VWD project has been completed in the US. This project is a new 15 story hospital that is part of the California Pacific Medical Center and located in San Francisco, CA, only 11 km from...
the San Andreas Fault. In this project, the design team opted to use innovative VWD technology to help achieve stringent structural and nonstructural performance goals. The lateral force resisting system for the new hospital consists of steel moment resisting frames with 153 supplemental VWDs, provided by Dynamic Isolation Systems, Inc. Figure 3 shows the field installation of VWD and construction of the new hospital.

Figure 2. Full-scale VWD prototype test at UC San Diego and VWD property definitions [2]

Figure 3. VWD installation and construction of the new California Pacific Medical Center (photo credit: Dynamic Isolation Systems Inc.)

The previously presented application of VWD for an important structures (hospital) in a seismic active areas (California) indicates that this technology is promising and can be attractive to a variety of stake holders. However, more research is needed to further understand the structural response of different structural systems equipped with VWD under different hazards, conduct life cost benefit analysis, and determine best configurations for optimized VWD efficiency for instance. Accordingly, exploring the applicability of VWD to taller buildings in seismic active
areas that are designed using different international codes (e.g. European or Turkish design standards) and exploring the efficiency of the VWD technology with reinforced concrete (RC) lateral resistant systems can be of interest and in turn, is the focus of this study.

This exploratory study presented herein is a collaboration between academics and structural engineers from Turkey and the United States as well as the Dynamics Isolation System Inc. The objective of this paper is to evaluate the effects of wall dampers on the dynamic performance of high-rise RC buildings under seismic loads. A readily available computational model for VWD [3] was implemented and used in this study to analytically investigate the seismic response of high-rise buildings. A 30-story RC building that is located in Turkey and use core shear walls as lateral resistance systems is considered with and without wall dampers for this study. This building represents a typical case of an older building that is not satisfying more recent codes or rigorous performance objectives usually assigned for important buildings, such as governmental buildings, hospitals, etc. and is subject to retrofit. For a target interstory drift of 1.5%, the analysis here considered maximum credible earthquake level to check whether retrofitting the building using VWD can satisfy the target drift requirements. The model was developed using the ETABs CSI Package [5] and nonlinear response history analysis (NRHA) was carried out for the two cases with and without wall dampers as discussed in the following sections.

Model Description

In this section, a brief description of the prototype building, ETABS model development and characteristics along with a background on VWD modeling are presented.

Building and ETABS model
The building considered in this study is an older building located in Istanbul, Turkey, where the tall building inventory has rapidly grown further in recent 10 to 15 years. During these years, the valid Turkish Earthquake Code [6] was not implying any special design requirements for tall buildings. However, current buildings assessment using recent PBSD frameworks, e.g. the PEER tall Building Initiative (TBI) [7], or current Turkish updated codes and seismic hazards definitions according to the Turkish Building Seismic Code, TBSC [8] may render existing building uncompliant or unsafe. It is noted that the current TBSC is significantly different from earlier codes especially for hazard definitions where newer procedures as adopted by ASCE 7 [4] are now implemented, which dictates larger seismic demands. Accordingly, many of existing building require immediate attention and retrofit, and VWD is one potential technology for retrofitting as investigated in this study. On the other hand, some buildings are considered important or vital buildings and requires immediate operations following earthquakes for enhanced resiliency such as governmental buildings or hospitals for instance. In such cases, more rigorous performance objectives are required.

In this paper, we consider a governmental building that requires retrofitting to satisfy current seismic demands in addition to limiting the interstory drifts to a 1.5% for enhanced performance. The building is located 10 km away from North Anatolian Fault (NAF) where the current seismic demands can be expressed using the 1-sec and short-period spectral accelerations as \( S_1 = 1.3g \) and \( S_s = 2g \), respectively, according to TBSC [8]. The building is an RC 30-story building with core shear walls used as the main lateral force resisting system as illustrated in Figure 4. The building
has 4 basement stories with a larger footprint area and specified concrete of 50 MPa strength is used throughout the entire structure. More details about the prototype building used in this study is given in Table 1.

A three-dimensional (3D) model for the building was developed using ETABs [5] as shown in Figure 5. Beam-column elements were used for the gravity system, while 2D shell elements were used for floor slabs and the shear walls modeling. All elements used linear elastic materials except for the structural shear walls within the lower $h/6$ parts that used nonlinear material for concrete and Grade 420 reinforcing steel as well. The same model was modified to include VWD as discussed in the next section. Because of the nonlinear model capabilities, NRHA was conducted using seven different ground motions as also explained in a following section.

Figure 4. Plan and elevation views of the building (dimensions in meter)

Figure 5. General 3D view of ETABS model of the building
Table 1. Dimensions and geometry of the building

<table>
<thead>
<tr>
<th>Stories</th>
<th>Basement</th>
<th>S1 - S4</th>
<th>S5 - S12</th>
<th>S13 - S20</th>
<th>S21 - S30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story Height (m)</td>
<td>4.0</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Wall Thickness (m)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.2</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>Columns (m)</td>
<td>1.2 * 1.2</td>
<td>1.2 * 1.2</td>
<td>1.0 * 1.0</td>
<td>0.8 * 0.8</td>
<td>0.8 * 0.8</td>
</tr>
<tr>
<td>Beams (m)</td>
<td>1.0 * 0.6 (perimeter) &amp; 0.8 * 0.6 (inner)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab Thickness (m)</td>
<td>0.35</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Dead Load (kN/m$^2$)</td>
<td>2.0</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live Load (kN/m$^2$)</td>
<td>5.0</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Viscous Wall Damper (VWD) Modeling
The modeling details of VWD have been applied in this case study according to the modeling guide provided by the Dynamic Isolation Systems Inc. [3]. Note that such modeling procedure was previously applied [1] for the full design of the CA 15-story hospital building mentioned in the first section. With VWDs, both displacements and stresses in the superstructure are aimed to be reduced for lower structural costs, and to obtain better performance for both structural and nonstructural components under seismic hazards. Besides the design of the new buildings, VWDs are also recommended as an ideal retrofit and strengthening solution for the existing buildings [3].

The VWDs were modeled using nonlinear link elements in ETABs as an “Exponential Maxwell Damper” model, which is given by Eq. 1 [3, 5]. The model is schematically shown in Figure 6 and it consists of a linear spring, K, in series with an exponential damper characterized by C and α, such that the force in the damper is related to the velocity across the damper through the force-velocity relationship given in Eq. 1:

$$ F = C V^\alpha $$

(1)

Since the story height is 3.6 m, the readily available 7-foot (2.13 m) wide by 12-foot (3.65m) tall VWD [3] was selected here, and centered in the bays where they are modeled. For this type of VWD, the nominal properties $K = 71802$ kN/m; $C = 3014.35$ kN*(sec/m)$^\alpha$, and $\alpha= 0.5$ have been used which also agrees with what was previously found from the UC San Diego test results [1].

![Figure 6. Schematic representation of VWD model based on [3]](image-url)

The nonlinear links are located at the mid-height of the story (Figure 7) and connected to the upper and lower beams – which are modeled as rigid link elements – using appropriate frame sections. In each orthogonal direction of the building, two VWDs were used and attached to the structural...
system of the existing building in the bays which are adjacent to the existing walls as shown in Figure 4 above. The locations of the VWDs were determined in such a way that it does not cause any torsional irregularity in the building. Since the aim of the study is to control drifts and other displacement-related response, the building has been analyzed by multiplying the nominal properties by the minimum property modification factor of “0.80” as suggested in [1, 3].

![Figure 7. Model close up from ETABs wall damper to shear wall connection](image)

### Ground Motions

The response history analysis is usually carried out using the certain number of earthquake ground motion pairs properly scaled to the target acceleration spectrum. In this study, the maximum credible earthquake (MCE) is defined for the site of the building according to TBSC 2016 [8] and was used as the target acceleration spectrum. The ground motions were selected from the NGA-West2 Database of the Pacific Earthquake Engineering Research Center, PEER [9]. All selected ground motions have the strike slip mechanism and a distance to fault within 10 km, in order to reflect the fault characteristics of NAF. The scaled response spectra of the selected ground motions are shown in Figure 8 and compared to the two MCE spectra for the site of the building that represent the older code [6], i.e. 2007 requirements, and the TBSC [8] 2016 requirements. Note that both earthquake code [6, 8] have no specific MCE definition and accordingly, a multiplier of 1.5 was used to amplify the design-based earthquake (DBE) spectrum to obtain an equivalent MCE. A list of the selected and scaled ground motions used in this study is also given in Table 2.

![Figure 8. Comparison of selected ground motions and code-based MCE target response spectra](image)
### Table 2. List of selected ground motions for this study

<table>
<thead>
<tr>
<th>Record Number</th>
<th>Scale Factor</th>
<th>Pulse Period (sec)</th>
<th>Earthquake Name</th>
<th>Year</th>
<th>Station Name</th>
<th>Magnitude</th>
<th>Vs30 (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>161</td>
<td>3.2873</td>
<td>4.396</td>
<td>Imperial Valley-06</td>
<td>1979</td>
<td>Brawley Airport</td>
<td>6.53</td>
<td>209</td>
</tr>
<tr>
<td>179</td>
<td>1.6677</td>
<td>4.788</td>
<td>Imperial Valley-06</td>
<td>1979</td>
<td>El Centro Array #4</td>
<td>6.53</td>
<td>209</td>
</tr>
<tr>
<td>1148</td>
<td>4.6904</td>
<td>7.791</td>
<td>Kocaeli_Turkey</td>
<td>1999</td>
<td>Arcelik</td>
<td>7.51</td>
<td>523</td>
</tr>
<tr>
<td>1605</td>
<td>1.3314</td>
<td>-</td>
<td>Duzce_Turkey</td>
<td>1999</td>
<td>Duzce</td>
<td>7.14</td>
<td>282</td>
</tr>
<tr>
<td>5825</td>
<td>1.8381</td>
<td>-</td>
<td>El Mayor-Cucapah, Mexico</td>
<td>2010</td>
<td>Cerro prieto</td>
<td>7.2</td>
<td>242</td>
</tr>
<tr>
<td>6906</td>
<td>1.0349</td>
<td>6.23</td>
<td>Darfield, New Zealand</td>
<td>2010</td>
<td>GDLC</td>
<td>7.0</td>
<td>344</td>
</tr>
<tr>
<td>6911</td>
<td>1.2994</td>
<td>9.919</td>
<td>Darfield_New Zealand</td>
<td>2010</td>
<td>HORC</td>
<td>7.0</td>
<td>326</td>
</tr>
</tbody>
</table>

### Results and Discussions

Using the developed ETABs model, NRHA and response spectrum analysis (RSA) were carried out using the selected earthquake ground motion pairs which were properly scaled to the target acceleration spectrum. Results are presented briefly in this section.

#### Global roof drift ratio

A summary of the computed values of global roof drift ratios are given in Table 3 for each type of analysis, i.e. NRHA and RSA, for both orthogonal directions of the building and for both with and without VWD cases. The fundamental periods of the building are also given in the table. The RSA results are similar and close to each other for both cases of with and without VWDs, which can be attributed to the RSA results mainly governed by the first mode. The NRHA results, on the other hand, exhibit the effect of the VWDs on the dynamic behavior of the building. It can be seen that the building with VWD experienced 20% less roof drift ratio than the building without VWD.

### Table 3. Summary of peak roof displacement and drift ratio for all analysis cases

<table>
<thead>
<tr>
<th>Analysis Case</th>
<th>Roof Disp. (mm)</th>
<th>Roof Drift (%)</th>
<th>Period (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Story without VWD</td>
<td>RSA X</td>
<td>1658.7</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>RSA Y</td>
<td>1675.4</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>NRHA X</td>
<td>1686.8</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>NRHA Y</td>
<td>1660.5</td>
<td>1.54</td>
</tr>
<tr>
<td>30 Story with VWD</td>
<td>RSA X</td>
<td>1623.3</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>RSA Y</td>
<td>1668.5</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>NRHA X</td>
<td>1360.7</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>NRHA Y</td>
<td>1354.5</td>
<td>1.25</td>
</tr>
</tbody>
</table>

#### Interstory drift

For the above analysis cases, the displacement response is also shown and presented in Figures 9 and 10 for the overall story displacements and Figures 11 and 12 for the interstory drift ratios for cases without and with VWD, respectively. In Figures 9 and 10, it can be seen that the maximum story displacements are approximately 18-20% less for the building with VWDs. Similarly, maximum interstory drift ratios, presented in Figures 11 and 12, show that lateral drift demands were decreased as low as 1.5% for the system with VWD, while the bare system was experiencing maximum interstory drift ratios of 2% or more. In other words, it is observed that VWDs reduced the interstory drift ratios by about 25% and can be considered as a potential solution for controlling drift ratios if implemented as a retrofit strategy.
Summary and Conclusions

In this paper, the effects of viscous wall dampers (VWDs) on the dynamic performance of the high-rise buildings under seismic loads were preliminarily evaluated. A readily available computational model for wall dampers was implemented and applied for a 30-story reinforced concrete building in Turkey with core shear walls as lateral resistance systems. NRHA was
conducted to compare the seismic response (mainly story displacements and interstory drift ratios) of the building with and without VWD. A target interstory drift of 1.5% that represents a typical performance objective for special or important buildings was desired to achieve using VWD. The analysis considered MCE earthquake level to check whether wall dampers can satisfy the target drift requirements. Overall, the wall dampers were shown to effectively reduce maximum interstory drift ratios from more than 2% to less than the 1.5% target performance objective, i.e. about 25% reduction, and thus, VWD can be considered as a potential solution for controlling drift ratios if implemented as a retrofit strategy.

![Figure 12. Maximum interstory drift ratios (%) the case with using any viscous wall dampers](image)

**Acknowledgment**

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