Structural Design for Passive Seismic Control Utilization

Wenshen Pong, Ph.D., P.E.
School of Engineering | San Francisco State University

Abstract

A special steel moment frame building with supplemental damping devices was designed to achieve immediate occupancy performance levels for Design Basis Earthquakes (DBE). In order to protect the valuable contents in this building, seismic fluid dampers were chosen to reduce the lateral accelerations and displacements during earthquakes. The primary seismic frames, without dampers, were designed to meet the 1997 Uniform Building Code (UBC). The frames, without dampers, were designed to remain elastic under a DBE. The goal was to limit the lateral drift to 1% of the story height and the demand-to-capacity ratio of the moment connections within 1 under a DBE. Under this design criteria, buildings should sustain minimal or no damage to their structural elements and only minor damage to their nonstructural elements. In addition, business interruption after a major earthquake should be low.

Introduction

The addition of an Energy Dissipation System (EDS) in structures provides a new and innovative option to enhance seismic resistance. With the implementation of such a system, the demands on main structural elements would be reduced significantly during an earthquake. Currently, the UBC does not provide criteria for an EDS, but it does address design procedures for base isolation. Therefore, buildings with an EDS require specific design criteria and procedures. This study investigates steel moment frame structures, with and without seismic dampers, as they are subjected to various site-specific earthquake records. The EDS chosen for this study was a Fluid Viscous Damper because the damper forces are out of phase with axial loading of the columns, and the structural period does not alter due to the addition of fluid dampers.

Building Frames Description

A 4-story office building with supplemental damping devices was designed for better seismic performance. The beam members are typical W24 and column members are W27. The frame elevation is shown below in Fig.1. Approximately 20% of critical damping was provided. The brace with a damper and the brace connection are shown in Fig. 2. The gap between the gusset plate and the beam is designed to ensure that additional forces due to the dampers does not impact the existing axial forces on the beams. Because of the change from a moment frame to a braced configuration, load paths were altered to produce substantial axial loads in the columns. As a result, the number of piles and the size of the pile cap were significantly increased. Fig. 3 shows additional reinforcement that was added to compensate for peak column axial forces. As a result of the addition of seismic dampers, foundation design and construction become of significant concern.

Site Specific Ground Motion Records

Site specific ground motion records are required for time-history dynamic analyses for buildings with passive control utilization. Probabilistic hazard levels used in this design and their corresponding mean return periods (the average number of years between events of similar severity) are shown in Table 1. Response spectra should be developed for an equivalent viscous damping ratio of 5%. Additional spectra are also developed for other damping ratios. One pair of MPE and three pairs of DBE and MCE were prepared by geotechnical engineers. The time histories used in spectral matching are shown in Table 2, and the peak acceleration for level three earthquakes is shown below in Fig. 4. The time histories used in spectral and spectral accelerations at various damping ratios are shown below in Fig. 5.

Fluid Viscous Dampers

The simplest model to simulate the mechanical behavior of fluid viscous damper is the Maxwell model (Bird, et. al., 1987) given by where is the relaxation time, is the damping constant at zero frequency, is the damping force, and is the damper position velocity. Constantino & Symans (1992) and Pong, Tsai & Lee (1994) also investigated the mechanical behavior of fluid
Fig. 1. Frame Elevation

Fig. 2. Brace Connection
Fig. 3. Base Plates and Foundation
function of the damping constant and velocity, the damper force can be defined as $F = CV\alpha$ where $C$ is the damping constant, $V$ is the velocity, and $\alpha$ is a velocity exponent. The cyclic response of the damper is dependent on the velocity of motion. The mechanical behavior of the damper is dependent on the frequency and amplitude of motion (Constantionu & Symans, 1992). The addition of fluid viscous dampers should be detailed so that the period of the damped structure does not change in comparison to that of bare frames without dampers.

Design Criteria

Special steel moment frames without dampers were designed to conform to the UBC of 1997 requirements for strength and drift. Per the UBC static force procedure, the seismic design parameters are as follows.

The maximum inelastic response displacement under the UBC earthquake design force was limited to 0.02 times the story height. The structural period was found to be about one second. As a result, the static base shear force equals 7.2% of total story weight. The stress on members was found to be relatively small using the Load and Resistance Factor Design method. However, the final design of moment frame members was governed by the time-history analyses for the damped structure. Steel moment frames with dampers were designed to remain elastic under a DBE. The goal was to limit the lateral drift to 1% of the story height and the Demand-to-Capacity ratio (DCR) of the moment frame members and connections to within 1 under the DBE events. In case of a larger earthquake such as a MCE, plastic hinge formation and some structural damage would be expected. Therefore, the post-Northridge moment frame connections were designed to provide the ductility to minimize the structural and nonstructural damage in the event of a MCE. Reduced beam section connections

<table>
<thead>
<tr>
<th>Earthquake Definition</th>
<th>Earthquake Having Probability of Exceedance</th>
<th>Mean Return Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Level Earthquake (MPE)</td>
<td>50%/50 year</td>
<td>72</td>
</tr>
<tr>
<td>Design Basis Earthquake (DBE)</td>
<td>10%/50 year</td>
<td>474</td>
</tr>
<tr>
<td>Max. Credible Earthquake (MCE)</td>
<td>10%/100 year</td>
<td>950</td>
</tr>
</tbody>
</table>

Table 1. Earthquake Definition

<table>
<thead>
<tr>
<th>Design Earthquake</th>
<th>Earthquake</th>
<th>Magnitude</th>
<th>Time History</th>
<th>Dist. (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPE</td>
<td>Loma Prieta</td>
<td>7.1</td>
<td>Santa Teresa</td>
<td>18</td>
</tr>
<tr>
<td>DBE</td>
<td>Imperial Valley</td>
<td>6.7</td>
<td>El Centro</td>
<td>12</td>
</tr>
<tr>
<td>MCE</td>
<td>Imperial Valley</td>
<td>6.7</td>
<td>El Centro</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 2. Time Histories Used in Spectral Matching
(FEMA, 1995 and 1997) were selected to produce an intended plastic hinge zone. Steel moment frames with supplemental damping were designed to have a DCR of less than 1 under site-specific time-history dynamic analyses. Three DBE time-history analyses were performed and the maximum response of the parameter of interest was used for the final design. Each pair of site-specific time histories was applied simultaneously to the computer model, considering the most disadvantageous location of mass eccentricity (UBC 1997).

Diagonal braces were designed to ensure that DCR remains within 1/2 so that the braces would have higher safety factors. As a result, 10-inch (244-mm.) diameter extra strong pipes were selected to meet the design and construction requirements. Selecting stronger pipes ensures that the braces function properly under higher earthquake demands. Although the load paths are also changed, the seismic dampers can reduce the story drift and thus reduce the column bending moment. This alteration of load paths leads to substantial axial loads in the columns. As a result, demands on the foundation were significantly increased with the addition of dampers. More piles and larger pile caps were designed to keep the DCR to be less than 1 at strength level.

Structural Seismic Response

The DCR for beams at MPE, DBE, and MCE are tabulated in the Table 3. Figs. 6 and 7 show that both the story drift and story lateral acceleration are reduced significantly with the use of dampers during earthquakes.

Conclusions

Since the story drift ratio is limited to less than 1% during a DBE, the structural and nonstructural damage will be minimal. In the event of a MCE, the post-Northridge moment connections will yield to provide additional structural damping to reduce the demand on primary structural frames. More piles with increasing length and larger pile caps were designed to meet higher performance demands. In addition, collector forces were found to be much higher than originally expected. Therefore, larger connections and beam collector members were redesigned to meet this requirement.

Structural behavior is not much different during lower demand earthquakes such as a MPE or DBE, since the structure remains elastic under those events. However, structural behavior is quite different under a MCE because demands on the joints increase significantly. Table 3 shows that the DCR is larger than 1 under a MCE. Under MCE events, the primary structural members contribute larger energy dissipation, which reduces the role of the dampers as a major mechanism for energy dissipation. Due to the complexity of structural seismic response and the uncertainty of ground motion, the effects of inelastic behavior of frames with EDS become important. The effectiveness of seismic dampers is reduced when the structure experiences inelastic deformations. In such cases, force might be either increased or reduced when the structure is responding beyond its elastic range. The complexity of structural behavior during earthquakes makes it difficult to present a clear design

Table 3. Demand/Capacity Ratio for beams

![Fig. 6. Story Drift for Frames with and without Dampers at DBE.](image)

![Fig. 7. Story Lateral Acceleration (g) for Frames with and without Dampers.](image)
method for engineering professionals. Therefore, extensive verification of structural dynamic behavior is required.

In this study, the results show that the intensity of an earthquake is the primary factor affecting structural performance. For lower level earthquakes, such as a MPE, the structure has enough stiffness and strength to resist earthquake demands. Therefore, the addition of supplemental damping is relatively insignificant. At the DBE level, the added damping becomes a very important means of reducing structural response assuming the structure remains elastic. At the most severe level earthquakes, such as a MCE, the added damping may become insignificant if the structure undergoes inelastic action. Because of the characteristics of ground motion, such as its amplitude and frequency content, which will affect the amount of energy imparted to a structure, the time history analyses should be done wherever practical with many different ground motions. As a result, design parameters should be based on ground motion characteristics. It is also recommended that structural stiffness and strength are proportionally distributed to ensure structural regularity. Dampers should be arranged in such a way so that structural integrity and strength remain uninterrupted. Structural connections should be detailed properly so that they provide significant ductility in case of inelastic deformation during severe seismic excitations.

It is recommended that structural behavior is checked for a MCE. Under this earthquake level, the structural connections are likely to form plastic hinges and this will complicate the structural analysis.

Energy dissipation devices should be designed considering environmental conditions such as wind, fatigue, ambient temperature, operating temperature, and other damaging substances. A good quality control program should be implemented to ensure that the dampers consistently function properly after installation. A well-established maintenance document is a useful tool to ensure better long-run service. Supplemental damping devices are still new to many professionals. The seismic behavior of structures with dampers requires more research and testing to ensure reliability. Therefore, continuing research efforts and professional education and training are needed in this field.

References


