Evaluation of proper supplemental damping for a multi-story steel frame using capacity spectrum method

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Abstract

In this study a straightforward procedure was developed without carrying out time-consuming dynamic nonlinear analysis to obtain the required amount of viscous dampers to meet given performance objectives. To this end nonlinear static response of a structure was obtained first using capacity spectrum method, and the required effective damping ratio was computed from the difference between the analysis result and the target displacement. Then the amount of required viscous damping was obtained using the effective damping ratio. Three different types of seismic story force were considered. The procedure was applied to a 10-story steel frame with added viscous dampers. According to the earthquake time history analysis results, the maximum displacement of the model structure with the added viscous damping determined from the proposed method corresponds well with the target displacements.

1 Introduction

Analysis of a structure with added velocity-dependent damping devices, such as viscous dampers, subjected to a strong ground motion generally requires dynamic nonlinear time-history analysis to evaluate the dynamic response characteristics. This procedure, however, is quite sophisticated and highly time-consuming. Therefore a more simple but reliable alternative method is needed for preliminary design purposes. Performance-based seismic design provides insight into the actual performance of structures during earthquakes, and requires engineers to design a structure to meet performance objectives for multi-level seismic loads. For performance-based seismic design the capacity of a structure to resist seismic loads needs to be evaluated first. This can efficiently be carried out by the capacity spectrum method.
method (CSM). To enhance seismic performance of a structure ATC-40 [1] and FEMA-273 [2] propose technical strategies which include such approaches as increasing strength, altering stiffness, and reducing demand by employing base isolation and energy dissipation devices. Specifically the energy dissipation devices directly increase the ability of the structure to dampen earthquake response.

The selection and design of supplemental dampers should be based on the dynamic characteristics of the structure, including its mass and stiffness, the effective damping desired to satisfy the performance levels of the structure, etc. With these informations, the preliminary determination of the required damper size and the damping force is possible. Once the size of the dampers is estimated, the adequacy of the structure for the given seismic loads can be checked by dynamic analysis. However the nonlinear dynamic analysis of structural systems with supplemental dampers requires a lot of computation time, and a series of iterative process should be employed to find out an appropriate number of dampers to meet the required performance point.

In this study a simple procedure based on CSM was developed to obtain the amount of supplemental viscous dampers required to satisfy the given performance objectives without iterative process. The procedure was applied to a multi-degree-of-freedom (MDOF) system to verify the applicability of the method. Three different types of seismic story forces were applied in the pushover process. After the required supplemental damping was estimated in an equivalent single-degree-of-freedom (SDOF) system, it was redistributed to each story of the MDOF structure. Finally nonlinear dynamic time history analysis was carried out for the structure with the added dampers to evaluate the preciseness of the proposed method. For simplicity, the viscous dampers were modeled by a linear dashpot.

2 Seismic performance evaluation by CSM

2.1 Formation of a pushover curve

The relationship between the base shear and the top story displacement, which is generally called pushover curve or capacity curve, is obtained by gradually increasing the lateral loads appropriately distributed over the stories. There are many alternatives for the distribution of the lateral load. In this study the capacity curve was obtained by applying three different types of lateral seismic loads:

1) Forces are applied in proportion to the product of story masses and the fundamental mode shape of the elastic model structure [1]:

\[ F_i = \frac{m_i \phi_{i1}}{\sum_j m_j \phi_{j1}} V \]

where \( F_i \) is the seismic story force in the \( i \) th floor, \( m_i \) is the mass of the \( i \) th floor, \( \phi_{i1} \) is the \( i \) th component of the mode shape vector for the fundamental mode, \( V \) is the base shear, and \( N \) is the number of floors.

2) The effect of the higher modes are considered by means of combination of the
story force of all modes using the SRSS method [3]:

\[ F_j = \sqrt{\sum_{i=1}^{N} \left( \frac{\sum_{j=1}^{N} m_i \phi_{ij} \cdot S_{aj}}{\sum_{i=1}^{N} m_i \phi_{ij}^2} \right)^2} \]  

where \( \phi_{ij} \) is the \( i \)th component of the \( j \)th mode shape vector and \( S_{aj} \) is the spectral acceleration corresponding to the \( j \)th mode.

3) Equivalent mode shape considering modal participation factors is utilized [4]:

\[ F_i = \frac{\bar{m}_i \bar{\phi}_i}{\sum_{i=1}^{N} m_i \phi_{ij}} V \]

\[ \Gamma_j = \frac{\sum_{i=1}^{N} m_i \phi_{ij}}{\sum_{i=1}^{N} m_i \phi_{ij}^2} \]

\[ \bar{\phi}_i = \sqrt{\sum_{i=1}^{N} (\phi_{ij} \Gamma_j)^2} \]

The first method can be properly applied to a structure in which the first mode dominates the dynamic motion. The second and the third methods have advantage that higher mode effect can be included in the estimation of seismic lateral load.

2.2 Conversion to ADRS spectra

Application of the capacity spectrum technique requires that both the demand spectra and structural capacity curve be plotted in the spectral acceleration vs. spectral displacement domain, which is known as acceleration-displacement response spectra (ADRS). To convert a response spectrum from the standard \( S_a \) vs. \( T \) format to ADRS format, it is necessary to determine the value of \( S_d \) for each point on the curve, \( S_a \) and \( T \). This can be done with the equation:

\[ S_d = \left( T^2 / 4 \pi^2 \right) S_a \]

In order to develop the capacity spectrum from the capacity curve, it is necessary to do a point-by-point conversion to the first mode spectral coordinates. Any point \( V, \Delta_R \) on the capacity curve is converted to the corresponding point \( S_a \) and \( S_d \) on the capacity spectrum using the equations:

\[ S_a = \frac{V}{M_1^*} \]

\[ S_d = \frac{\Delta_R}{\Gamma_1 \phi_{R1}} \]

where \( \Gamma_1 \) is the modal participation factor for the first natural mode of the structure, \( M_1^* \) is the modal mass coefficient and \( \phi_{R1} \) is the roof level amplitude of the first mode.
2.3 Estimation of the equivalent viscous damping ratio

A bilinear representation of the capacity spectrum, as described in Fig. 1, is needed to estimate the effective damping and appropriate reduction of spectral demand. ATC-40 recommends that the area under the original capacity curve and the equivalent bilinear curve be equal so that the energy associated with each curve is the same.

When the bilinear system undergoes inelastic action at displacement \( S_{ap} \) with corresponding acceleration equal to \( S_{ap} \), the effective period, \( T'_{eff} \), is determined from the secant (or effective) stiffness at maximum displacement.

\[
T'_{eff} = 2\pi \sqrt{\frac{S_{ap}}{S_{dp}}} 
\]  

(7)

The equivalent viscous damping ratio for the yielding structure is determined from the energy dissipated by the hysteretic behavior, \( E_D \), which is the area enclosed by the hysteresis loop at maximum displacement, and the stored potential energy corresponding to the area of the shaded triangle, \( E_S \).

When additional energy dissipation devices are added, the effective viscous damping ratio becomes [2][5]

\[
\beta_{eff} = \frac{1}{4\pi} \left( \frac{E_{DN} + E_{DE}}{E_S} \right) + \beta \\
= \frac{E_{DE}}{2\pi m S_{ap} S_{dp}} \left( \frac{2\kappa (S_{ay} S_{dp} - S_{ay} S_{ap})}{\pi S_{ap} S_{dp}} \right) + \beta 
\]

(8)

where \( E_{DN} \) is the energy dissipated by the dampers. \( \beta \) is the inherent viscous damping of the structure and \( \kappa \) is called the efficiency factor or damping modification factor which is equal to the actual area enclosed by the hysteresis loop divided by the loop area of the corresponding perfect bilinear hysteretic system. The factor is selected on the basis of experience with particular structural systems. In this study the factor is taken to be 1.0 because perfect bilinear system is assumed in the analysis. The first term in the right hand side is the additional damping ratio contributed from the added dampers. The energy dissipated from
the added viscous dampers for a cycle of harmonic motion can be computed as follows:

\[ E_{DE} = \int f_D du = \int (cu) \dot{u} dt = \pi \omega \omega_n^2 = 2\pi \beta_v \frac{\omega}{\omega_n} k u_0^2 \]  

(9)

If eqn (9) is substituted to eqn (8) and solved for \( \beta_v \), then the damping contributed from the devices can be obtained as follows after some manipulations:

\[ \beta_v = (\beta_{eff} - \beta) - \frac{2\kappa (S_{dy}S_{dp} - S_{dy}S_{dp})}{\pi S_{ap}S_{dp}} \frac{T_e}{T_{eff}} \]  

(10)

where \( T_e \) is the initial elastic stiffness.

3 Distribution of supplemental damping in MDOF system

In a SDOF system the additional damping required to achieve the target displacement can simply be added to the system. In a multi-story structure, however, the damping should properly be distributed over the stories. If the dampers are placed as diagonal members with the inclination of \( \Theta \), then the energy dissipated by the dampers are formulated as follows:

\[ E_{DE} = \frac{2\pi^2}{T} \sum_j C_j \cos^2 \Theta_j \Delta_{ij}^2 \]  

(11)

Where \( T \) is the fundamental natural period, \( C_j \) is the damping coefficient of the \( j \) th story, and \( \Delta_{ij} \) is the relative displacement between the \( i \) th and the \( j \) th stories. Using the modal displacement instead of the displacement response, the required damping of the dampers can be obtained as [2]

\[ \beta_{device} = \frac{E_{DE}}{4\pi E_S} = \frac{T \sum C_i \cos^2 \Theta_i (\phi_i - \phi_{i-1})^2}{4\pi \sum m_i \phi_i^2} \]  

(12)

where \( m_i \) is the mass of the \( i \) th story and \( \phi_i \) is the modal displacement at floor level. If it is assumed that the same amount of dampers are used in every story, the damping coefficient of the damper in the \( i \) th story, \( C_i \), can be easily computed from eqn (12).

4 Application to a multi-story structure

4.1 Model structure

The two-dimensional analysis model frame is a part of a 10-story steel framed structure designed to resist gravity and wind loads. The structure has 3 bays with the story height of 4m for all stories. Uniform dead load of 540kgf/cm² and live load of 250kgf/cm² were applied throughout the stories. Basic wind speed of 35 m/sec was used for lateral static wind load. The dynamic modal characteristics of
the model frame are shown in Table 1. Fig. 2 shows the mode shapes obtained for the three methods for lateral load distribution mentioned above, where it can be found that the mode shape obtained from SRSS and the equivalent mode shape is almost identical. However Fig. 3 indicates that the story forces resulting from the SRSS method are higher than those from the other methods in the lower stories, but are smaller in the higher stories.

Table 1. Dynamic characteristics of the model structure.

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period (sec)</td>
<td>1.41</td>
<td>0.49</td>
<td>0.28</td>
<td>0.19</td>
<td>0.14</td>
</tr>
<tr>
<td>Period ratio ($T_l/T_m$)</td>
<td>1.00</td>
<td>2.87</td>
<td>4.98</td>
<td>7.49</td>
<td>10.14</td>
</tr>
<tr>
<td>Modal participation factor</td>
<td>1.34</td>
<td>0.51</td>
<td>0.30</td>
<td>0.22</td>
<td>-0.16</td>
</tr>
<tr>
<td>Effective mass (%)</td>
<td>77.54</td>
<td>11.68</td>
<td>4.28</td>
<td>2.23</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Figure 2: Mode shapes. Figure 3: Seismic story forces.

### 4.2 Design spectrum and earthquake time history record

Site-specific elastic design response spectrum was constructed in accordance with Fig.16-3 of UBC-97 with the values $C_g$ and $C_s$ as suggested in the *Korean Seismic Design Guidelines* [6] for earthquakes with recurrence period of 2,400 years and soil type of $S_E$. Based on the design spectrum time history record shown in Fig. 4 was generated using the program SIMQKE [7] for comparison of the static procedure with the nonlinear dynamic time history analysis. The response spectrum constructed from the time history record generated from the design spectrum is plotted in Fig. 5 along with the design spectrum.

Figure 4: Ground excitation generated from the design spectrum.
4.3 Capacity spectrum

The base shear-top story displacement relationship shown in Fig. 6 was obtained with the lateral static load gradually increased until the top story displacement reached 4% of the total structure height. In this study, pushover analysis was carried out using DRAIN-2D+ [8]. Then this force-displacement relationship was transformed into the capacity spectrum of an equivalent SDOF system in ADRS format using the procedure mentioned previously. This is plotted in Fig. 7.

4.4 Estimation of performance point

To estimate the performance points the capacity spectrum and the demand spectra with various damping ratios are plotted simultaneously in ADRS format. Fig. 8 presents the process of estimation of the performance point. Fundamental mode shape was used to construct the capacity curve. The intersection of the capacity and demand curves corresponds to the performance point. Table 2 shows the displacement and acceleration obtained for the equivalent SDOF system and the displacement and base shear for the original MDOF structure induced from the results of the SDOF system using eqn (6). The results from the three different lateral story forces were also compared in the table, where it can be seen that the top story displacement obtained from the lateral load by SRSS combination of the mode shapes is the lowest while the base shear is the largest.
The opposite is true for the lateral loads constructed from the fundamental mode shape of the structure. The results from the equivalent mode are placed in the middle.

Figure 8: Estimation of performance point.

Table 2. Structural response for each method.

<table>
<thead>
<tr>
<th>Method</th>
<th>Equivalent SDOF system</th>
<th>MDOF system</th>
<th>Effective Damping ($\beta_{eff}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Displacement (cm)</td>
<td>Acceleration (g)</td>
<td>Displacement (cm)</td>
</tr>
<tr>
<td>Fundamental mode</td>
<td>18.59</td>
<td>0.167</td>
<td>24.85</td>
</tr>
<tr>
<td>SRSS combination</td>
<td>16.72</td>
<td>0.175</td>
<td>23.19</td>
</tr>
<tr>
<td>Equivalent mode</td>
<td>17.45</td>
<td>0.165</td>
<td>24.23</td>
</tr>
</tbody>
</table>

4.5 Comparison with the results from time history analysis

Fig. 9 and 10 represent the maximum inter-story drift and the maximum story displacements of the model structure obtained from the nonlinear static analysis and the nonlinear dynamic time history analysis. According to the results the displacements predicted from the SRSS mode combination for lateral load forms upper bound in lower stories, and forms lower bound in upper stories compared with those predicted by the other two forms of static lateral loads. This can be expected considering the shape of the static lateral load. It also can be noticed that the maximum story displacements predicted by CSM with three types of lateral load distribution are lower than those computed by time history analysis. However for inter-story displacements, although the results from the static nonlinear analysis are smaller than those from dynamic analysis in the lower stories, the opposite is true in the upper stories.

The inter-story drifts shown in the figure indicate that the structure satisfies the collapse prevention limit state prescribed in the reference [6], which is the maximum inter-story drift of 2.5% of the story height, but does not satisfy the functional limit state, which is 0.5% of the story height, except at the top two stories. The results are quite satisfactory considering the facts that the structure was designed only for wind load and that the seismic load used in the analysis corresponds to very severe earthquake.
The target displacement is set to be 0.5% of the structure height, which is 20cm. It can be seen in Fig. 10 that approximately 5cm of roof displacement needs to be reduced by installing viscous dampers to limit the maximum displacements within the target value. To find out the portion of the damping that should be provided by the dampers the required effective damping $\beta_{eff}$ corresponding to the target displacement is obtained first in the acceleration-displacement response spectrum. Then the amount of the additional viscous damping ratios required to restrain the top story displacement within the performance limit can be computed using eqn (10) and are presented in Table 3 along with the responses at the performance points, the effective damping ratios and the effective periods for each lateral loading pattern. Finally, assuming that the same dampers are used throughout the story, the damping coefficients of the supplemental dampers were evaluated using eqn (12), which are $C_{eff}=5100\text{ kg·sec/cm}$, $C_{SRSS}=4956\text{ kg·sec/cm}$ and $C_{eq}=5129\text{ kg·sec/cm}$ for the three story force distribution methods, respectively. The results indicate that the damping coefficients derived for each lateral story force pattern are very close, which demonstrates that the amount of the supplemental damping required to meet the given performance objectives does not depend significantly on the pattern of the lateral force for the pushover analysis. The maximum top story displacement of the model structure with the added damping computed by dynamic time history analysis turned out to be 16.44cm, which is about 3.5cm short of the target value.
5 Conclusion

In this study seismic performance of a multi-story steel frame was evaluated by capacity spectrum method and a simple procedure was proposed to determine the amount of supplemental viscous damping required to maintain the maximum response within a given target value. The results of the research show that with the addition of the supplemental damping evaluated by the proposed method the performance of the model structures are well restrained within the target point. Therefore it is concluded that the proposed process, which provides the amount of the required additional damping directly without carrying out time-consuming nonlinear dynamic analysis, can be a potential alternative for performance-based design of structures with supplemental dampers.

Acknowledgement
This research is funded by the Korea Science and Engineering Foundation under Grant No.1999-1-310-001-3. This financial support is gratefully acknowledged.

References