INTRODUCTION

In the passive control of building structures, hysteretic dampers are the most prevalent structural members installed into a building to improve its seismic performance through dissipating most of the vibration energy imposed by ground motions.

Hysteretic dampers (damper system) are generally designed to yield prior to the main structure. This is generally achieved by setting the lateral yield strength of damper system to be smaller than that of main structure. However, attention must be paid to the stiffness of damper system because if this stiffness is much smaller than that of the main structure, the dampers do not yield before the main structure, as seen in Figure 1.

To date most research efforts on buildings with hysteretic dampers have focused on steel frames, and have defined the configuration of dampers based on a required yield strength and stiffness. This scheme used for defining the mechanical properties of hysteretic dampers does not provide control over the yield deformation of dampers. Thus, one way of ensuring dampers to yield before the main structure is through the explicit control of their yield story drift. A deformation-controlling scheme is presented for such a purpose, in which the mechanical properties of dampers are defined according to a proportion rule in order to explicitly control the yield story drift of dampers.

The main objective of this study is to examine the seismic performance of R/C frames with hysteretic dampers (installed according to the proposed scheme) through nonlinear dynamic analysis.

Figure 2 shows how addition of dampers may alter the story shear versus story drift response of the original R/C building. The damper system yields prior to the R/C frame and dissipates most of the hysteretic energy, whereas the R/C frame is expected to remain essentially elastic. In Figure 2, $Q_S$, $Q_{Fy}$, and $Q_{Dy}$ are the yield shear strength of the entire system, R/C frame and damper system, respectively. $\Delta_{Fc}$, $\Delta_{Fy}$, $\Delta_{Dy}$, and $\Delta_{max}$ are the cracking story drift, the yield story drift of the R/C frame, the yield story drift of the damper system and the maximum story drift, respectively. $Q_{Fc}$ is the shear at the cracking point and $K_{eq}$ is the equivalent stiffness of the R/C frame. $K_T$ is the total stiffness of the entire system.

**Figure 1.** Schematic restoring force of main structure and dampers

**Figure 2.** Restoring force of R/C frame with dampers

**Description of Analyzed R/C Frames**

R/C frames with 5, 10 and 20 stories are investigated under similar design parameters. The symmetric plan is shown in Figure 3a, and Frame C is selected to represent the response of the whole building. Hysteretic dampers are installed into the R/C frames at each story and at the center bay of the Frame C, as shown in Figure 3b.

The gravity loads (dead and live) per unit area were assumed to be the same for all stories. Prior to installing the dampers, the structural designs of the three R/C frames were established based on the Building Standard Law of Japan (BSLJ) [1], originating three code-based reference R/C frames into which dampers are installed afterwards. A strong-column and weak-beam philosophy (typical for ductile moment-resisting frames) was followed to avoid any soft stories. The natural period of the 5-, 10- and 20-story models are 0.73 s, 0.87 s and 1.54 s, respectively.
Mechanical Properties of Hysteretic Dampers

As previously mentioned, the mechanical properties of the damper system—yield story drift and yield shear strength—are adjusted proportionally to those of the bare R/C frame. The yield shear strength $Q_i^S$ and yield story drift $\Delta_i^S$ (see Figure 2) at the $i$-th story of each R/C frame were determined by tracing the corresponding story shear-story drift curve obtained from pushover analysis (with a vertical distribution of lateral load proportional to the story shear distribution factor $A_i$ described in BSLJ [1]) with a trilinear skeleton curve.

The damper’s yield story drift is determined from the ‘constant yield story-drift ratio’ scheme. This scheme uses the drift ratio $\nu$ (yield story drift of the damper system normalized by that of the R/C frame) to define the damper’s yield story drift in proportion to that of the R/C frame, as shown in Figure 5. If damper’s strength increases from $Q_{Dy}$ to $2Q_{Dy}$, as a result of a larger $\beta'$, the damper’s stiffness $K_D$ also increases to meet $2Q_{Dy}$ and keep $\nu$ constant over the building height.

Passive control is achieved by yielding the dampers prior to the yield in the R/C frame, in other words by setting the value of $\nu$ smaller than unity. Thus, the value of $\nu$ varied by an interval of 0.2, ranging from 0.2 to 1.0, to define the damper’s yield story drift $\Delta_i^D$ and lateral stiffness $K_D$ at the $i$-th story as in Equations 3 and 4. The drift ratio $\nu$ can be further expressed in terms of $\beta'$ and stiffness ratio $k$ as in Equation 5.

$$\nu^i = \frac{\Delta_i^D}{\Delta_i^S}$$  
$$K_i^D = \frac{Q_i^D}{\Delta_i^D}$$  
$$\nu = \frac{\beta'}{k}$$

Dampers add stiffness and strength to the bare R/C frame. Figure 6a shows the variation of natural vibration period $T$ of the entire system obtained from modal analysis with respect to $\beta'$ and $\nu$. The natural period varies highly with $\beta'$ and is sensitive to $\nu$ (especially for $\nu \leq 0.6$). This behavior is mainly due to the relatively small variation of the total stiffness $K_T$ within the same range of $\nu$, as seen in Figure 6b. The shortest natural period after installing...
dampers is 0.49 s, 0.66 s and 1.20 s, for the 5-, 10- and 20-story model, respectively.

Figure 6. Variation of: (a) natural period $T$ and (b) total stiffness $K_T$

ANA\LYSIS METHODOLOGY

Numerical analyses were conducted on the frame models shown in Figure 3b over a range of earthquake motions and structural parameters. The series of analyses correspond to the following cases: (1) three numbers of stories ($n=5,10$ and $20$), (2) eight damper-frame strength ratios ($\beta=0,0.1$ to $0.7$), (3) five drift ratios ($\nu=0.2,0.4,0.6,0.8$ and $1.0$), and (4) the input motions in Table 1. In total, 1200 nonlinear time-history analyses were performed.

Table 1. Input ground motions

<table>
<thead>
<tr>
<th>Original record</th>
<th>Year</th>
<th>Designation</th>
<th>PGA (m/s$^2$)</th>
<th>PGV (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Centro NS</td>
<td>1940</td>
<td>ElCentro50</td>
<td>5.05</td>
<td>0.51</td>
</tr>
<tr>
<td>El Centro NS</td>
<td>1940</td>
<td>ElCentro100</td>
<td>9.87</td>
<td>0.98</td>
</tr>
<tr>
<td>BCJ-L2</td>
<td>-</td>
<td>BCJ50</td>
<td>3.55</td>
<td>0.50</td>
</tr>
<tr>
<td>BCJ-L2</td>
<td>-</td>
<td>BCJ100</td>
<td>6.45</td>
<td>1.00</td>
</tr>
<tr>
<td>JMA-Kobe NS</td>
<td>1995</td>
<td>Kobe50</td>
<td>4.50</td>
<td>0.50</td>
</tr>
<tr>
<td>JMA-Kobe NS</td>
<td>1995</td>
<td>Kobe100</td>
<td>9.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Taft NS</td>
<td>1952</td>
<td>Taft50</td>
<td>4.84</td>
<td>0.50</td>
</tr>
<tr>
<td>Taft NS</td>
<td>1952</td>
<td>Taft100</td>
<td>9.70</td>
<td>1.00</td>
</tr>
<tr>
<td>Hachinohe EW</td>
<td>1968</td>
<td>Hachi50</td>
<td>2.51</td>
<td>0.50</td>
</tr>
<tr>
<td>Hachinohe EW</td>
<td>1968</td>
<td>Hachi100</td>
<td>4.96</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Five different acceleration records were selected. Four well-known recorded ground motions in the United States and Japan: El Centro NS, Taft NS, Hachinohe EW and JMA-Kobe NS. And a synthesized motion (BCJ-L2 motion) widely used in Japan to check and ensure safety in the building design against Level-2 earthquakes. The Japanese seismic design practice specifies a Level-2 earthquake as a ground motion with a probability of exceedance of about 10% in 50 years and with a peak ground velocity (PGV) of 0.50 m/s. The ground motions listed in Table 1 were scaled to meet this level of seismic intensity. In addition, a higher value of PGV (1.0 m/s) was also investigated to represent an earthquake motion with a PGV value similar to that of Kobe earthquake in 1995 (about 0.91 m/s). Finally, it should be noted that the acceleration records listed in Table 1 are very frequently used in the structural design practice in Japan.

The non-liner time-history analyses were carried out using the computer program STERA-3D [2]. The analytical model of hysteretic damper is a line element with a nonlinear shear spring whose deformation is linked to the nodal displacements of the frame to which it is connected. Further details on modeling assumptions can be found elsewhere [2]. The hysteresis rule for bending in columns and beams is the degrading trilinear Takeda model [3], and the hysteresis model for dampers is of bilinear type with kinematic hardening. For all numerical analyses, integration time step of 0.005 s and a post-elastic bilinear type with kinematic hardening. For all numerical analyses, integration time step of 0.005 s and a post-elastic

RESULTS OF EARTHQUAKE RESPONSE

Figure 7 shows the mean of maximum story drift $\Delta$. The mean is taken over the values obtained from the five input motions of the PGV50 seismic intensity group. The following trends and aspects are identified: (1) the maximum story drift after damper installation tends to be smaller than that of the R/C frame without dampers. This reduction of story drift demand tends to increase with decreasing values of $\nu$ and increasing values of $\beta$. However, some increase in the story drift demand is observed in the upper stories of the 20-story model. This increase becomes more significant with increasing values of $\beta$ and is attributed to the essentially elastic behavior of the damper system in the upper stories caused by the effect of global flexural deformation of the damper-installed bay and to the effect of higher modes. It is worth mentioning that the increase in the story drift demand at the upper stories of the 20-story model after installing dampers does not necessarily indicates an inadequate performance of the building. This is because the story drift demand at this part of the building is not high, as seen in Figure 7.

(2) It is observed for the 5- and 10-story models and for $\nu > 0.6$ that the story drift demand after installing dampers is close to that of the R/C frame without dampers and that is almost independent of the value of $\beta$. This indicates that dampers are practically not effective for this range of $\nu$.

(3) It is important to note that the distribution over the building height of story drift demand after installing dampers tends to be proportional to that of the R/C frame without dampers. In other words, the reduction in proportion of story drift demand is fairly constant over the building height. This clearly indicates a controlled protection to the R/C frame with damper installation.
Hysteretic Energy Dissipated by R/C Frame

Figure 8 shows the total hysteretic energy dissipated by the R/C frame $E_{IH}$ normalized by that of the frame without dampers $E_{IH0}$. Moreover, shown in Figure 9 is the participation of the R/C frame into the total input energy $E_i$. In Figure 8, it can be clearly seen that the amount of hysteretic energy dissipated by the R/C frame (i.e., cumulative seismic damage) tends to decrease for increasing values of $\beta$ and for values of $\nu$ lower than or equal to 0.6. However, some increase in the seismic damage in the R/C frame is observed in the 5- and 10-story models (under the PGV50 seismic intensity) after installing a damper system with a value of $\beta$ larger than 0.6. It is also evident that the $E_{IH}/E_{IH0}$ ratio is affected slightly by $\beta$ in most analysis cases and for $\nu > 0.6$. Here, the choice of a low value of $\beta$ would be preferable in terms of economy. By comparing the results among the three numbers of stories, it seems that increasing values of $\beta$ will lead to larger reductions in the seismic damage in the 5-story model. On the other hand, the $E_{IH}/E_{IH0}$ ratio tends to be relatively constant with respect to $\beta$ in the 10- and 20-story models, for $\beta \geq 0.3$. Values of $\nu$ lower than or equal to 0.4 led to the most reduction in the seismic damage in the R/C frame.

In Figure 9, it is evident that the participation of the R/C frame into the total input energy decreases as $\beta$ increases and $\nu$ decreases, and that it is always smaller than that of the R/C frame without dampers. This certainly demonstrates that the damper system absorbs vibration energy, and thereby protects the members of the R/C frame.

Shown in Figure 10 is the story $E_{IH}/E_i$ ratio. It can be seen for the 5- and 10-story models that the $E_{IH}/E_i$ ratio at each story is always smaller than that of the R/C frame without dampers, and that its vertical distribution tends to be proportional to that of the bare R/C frame. This clearly indicates a uniform control over the protection of the R/C frame. On the other hand, the $E_{IH}/E_i$ ratio tends to be larger than that of the R/C frame in the upper stories of the 20-story model. Despite this increase, the damage distributed better over the building height after installing dampers, compared to the original R/C frame where damage concentrated more at lower stories.

Hysteretic Energy Dissipated by Dampers

Shown in Figure 11 is the ratio of the hysteretic energy dissipated by the damper system $E_{ID}$ to the total dissipated hysteretic energy $E_{IH}$. The vertical axis depicts the mean of the $E_{ID}/E_{IH}$ ratio. For the 5-story model, the contribution of dampers to the total hysteretic energy dissipation increases with increasing values of $\beta$ regardless of the drift ratio $\nu$. The largest contribution of dampers is given for the smallest $\nu$. This is to be expected as the damper system yields and starts to dissipate hysteretic energy much before the R/C frame. A similar aspect is observed for the 10-story model under the PGV100 seismic intensity. For the 10- and 20-story models, however, the contribution of dampers follows a mountain-shape variation with respect to $\beta$. The contribution of dampers tends to decrease for large values of $\beta$ because the global flexural deformation of the damper-installed bay reduces the energy dissipation of dampers. This reduction is more significant in the 20-story model.

A higher seismic intensity tends to decrease the contribution of dampers for $\nu \leq 0.6$. Such behavior is because the deformation demand in the R/C frame increases with increasing levels of seismic intensity. In terms of practical application, the contribution of dampers with $\nu \leq 0.6$ seems to be more significant than that with $\nu > 0.6$.

Effect of Global Flexural Deformation on Inelastic Response of Dampers

The story drift at the $i$-th story caused by global flexural deformation $\delta A_i$, as shown in Figure 12c, can be reasonably obtained from Figures 12a and b. As a result of the expansion and contraction of columns of the damper-installed bay due to the additional axial force $N'$ generated by the addition of dampers, the rotation angle $\theta^i$ at the $i$-th story is given by Equations 6 and 7 [4]. Where $L$ is the span length of the damper-installed bay and $E$ is the axial deformation in the columns. $A_i$ and $E_c$ are the cross-sectional area and the modulus of elasticity of column, and $h$ is the story height.

$$\theta^i \equiv \sin \theta^i \equiv \frac{2e^i}{L}$$  \hspace{1cm} (6)

$$e^i = \frac{N'h^i}{A_iE_c^i}$$  \hspace{1cm} (7)

Assuming that the story shear resisted by the dampers causes the overturning moment and the associated axial forces in the columns of the damper-installed bay, $N$ and the relationship between the rotation $\theta^i$ and story drift $\delta A_i$ are given by Equations 8 and 9 for the $i$-th story of Figure 12c, respectively. Here, $n$ is the total story number and $Q_{00}$ is the story shear of the damper system. From Equations 6 to 8, Equation 9 can be rewritten as in Equation 10. Figure 12d shows the effect of global flexural deformation on the damper’s story shear-story drift relationship.

The actual yield story drift of the damper system at the $i$-th story $\delta A_{00}^i$ is given by Equation 11; where $\delta A_{00}^i$ and $\delta A_{00}'$ are the story drift of damper system due to shear and global flexural deformation, respectively.

$$N^i = \frac{L}{I} \sum_{k=i}^{n} Q_{h_k}^i h^k$$  \hspace{1cm} (8)

$$\delta A = \sum_{k=1}^{i-1} \theta^k h^{k+1}$$  \hspace{1cm} (9)

$$\delta A = \sum_{j=0}^{i-1} \left[ \frac{2}{L A_iE_c^i} \left[ \frac{L}{I} \sum_{k=j+1}^{n} Q_{h_k}^i h^k \right] \right] h^{j+1}$$  \hspace{1cm} (10)
As seen in Figure 12d, the apparent stiffness of the damper system decreases from $K_y$ to $K_{Deq}$ due to the additional deformation $b\Delta D_y$. Because of this reduction in the stiffness of the dampers system, the yield story drift of the damper system initially assumed to be equal to $\nu_2\Delta y$, (Equation 3) increases and the damper system will require a larger story drift to reach its yield point and start to dissipate hysteretic energy. The larger the global flexural deformation is, the larger the reduction in the stiffness and effectiveness of the damper system.

Since the damper system is intended to yield before the R/C frame does, the inequality in Equation 12 (represented by a $\Gamma$ index) should be satisfied. To determine the value of $\Gamma$ in Equation 12 when the damper yields, Equation 10 should be rewritten as in Equation 13. Assuming that all stories yield simultaneously, $Q_{\Delta y}$ is taken from Equation 2. It is worth mentioning that all parameters in Equation 13 are known prior to the analysis of the building with dampers, and that the $\Gamma$ index can be used for a preliminary estimation of the story number up to which the damper system yields before the R/C frame does. A practical implication of this $\Gamma$ index is that the designer, based on the value of $\Gamma$, could decide a suitable arrangement of dampers or column properties so as to achieve an adequate level of effectiveness of dampers.

$$\Gamma = \frac{\Delta D_y}{\Delta_{py}} \leq 1.0$$

Calculated values of $\Gamma$ are compared with those obtained from pushover analysis, as shown in Figure 13. As can be seen, there is a good correspondence of calculated values of $\Gamma$ to those from pushover analysis regardless of the building height, especially for $\nu \leq 0.4$ and $\beta' \leq 0.4$. It is also seen that Equation 13 tends to underestimate the value of $\Gamma$ in the upper stories in the 10- and 20-story models, especially for $\nu \geq 0.6$ and $\beta' \geq 0.5$. In general, there seems to be a relatively good correspondence up to the story number where the calculated value of $\Gamma$ is equal to unity. In the 5-story model, the correspondence is very good regardless of the values of $\nu$ or $\beta'$. It can be also seen that the difference between calculated values of $\Gamma$ and those from pushover analysis increases over the building height and as $\nu$ and $\beta'$ increases, and that is more noticeable for values of $\Gamma$ larger than unity. This difference is mainly because Equation 13 does not consider the progress of yielding in the R/C frame and dampers in the stories below the story at which $\Gamma$ is being calculated, which increases the story drift response. Moreover, the axial rigidity of columns is assumed to remain elastic in Equation 13.

CONCLUSIONS

The results indicate that by installing dampers according to the proposed scheme, the seismic performance of the structure is improved because the lateral deformation demand and seismic damage are reduced uniformly over the building height. Particularly, low values of $\nu$ and $\beta'$ lead to a fairly constant distribution over the building height of the reduction in proportion of story drift demand; which clearly indicates a controlled protection to the R/C frame. In high-rise frames, the seismic damage tends to distribute more uniformly over the building height after damper installation.

The global flexural deformation of the damper-installed bay reduces the contribution of dampers (installed at the upper stories of mid- and high-rise buildings) to the total hysteretic energy dissipation, particularly for values of $\beta'$ larger than 0.5. On the other hand, dampers installed in low-rise frames are scarcely affected by the global flexural deformation regardless of the strength of dampers. In general, the contribution of dampers to the total hysteretic energy dissipation increases with increasing values of $\beta'$ and decreasing values of $\nu$. However, this contribution tends to decrease for large values of $\beta'$ in mid- and high-rise buildings due to the effect of global flexural deformation of the damper-installed bay.

The proposed analytical procedure to account for the global flexural deformation through the $\Gamma$ index was shown to provide useful information for the preliminary estimation of the story number up to which the damper system yields before the R/C frame. The proposed index provides satisfactory results for values of $\Gamma$ as large as unity.

REFERENCES


Figure 8. Total R/C frame hysteretic energy
Figure 7. Maximum story drift for the PGV50 seismic intensity

Figure 8. Vertical distribution of the $\frac{E_{HF}}{E_{I}}$ ratio

Figure 9. Participation of R/C frame into the total input energy

Figure 10. Vertical distribution of the $\frac{E_{HF}}{E_{I}}$ ratio

Figure 11. Contribution of damper system to the total hysteretic energy dissipation

Figure 12. Global flexural deformation: (a) rotation of the first story, (b) rotation of the $i$-th story, (c) total deformed configuration, and (d) effect of global flexural deformation on the damper system

Figure 13. Comparison of $\Gamma$ index