Performance of Story-Drift-Controlled R/C Frames Equipped with Hysteretic Dampers Subjected to Earthquake Motions

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SUMMARY
This paper investigates the performance of story-drift-controlled reinforced concrete (R/C) frames equipped with hysteretic dampers subjected to ground motions. For this purpose, nonlinear time-history analyses are carried out on a series of frame models that include a wide range of mechanical properties of dampers. Key to damper installation is yielding the dampers prior to the main structure. Thus, unlike previous studies, the mechanical properties of dampers are defined according to a proportion rule to explicitly control the yield story drift of dampers and ensure their early yield. The results of analysis show that the seismic performance of the entire structure is noticeably improved after installing dampers according to the proposed proportion rule. This is because the lateral deformation demand and seismic damage in the R/C frame after damper installation decreases uniformly over the building height; which clearly indicates a controlled protection to the R/C frame.

Keywords: R/C frame, hysteretic damper, story-drift control, seismic response reduction

1. INTRODUCTION

To date, earthquake disasters still occur with a significant number of casualties and tremendous economic losses. Due to the destructive effect of earthquakes on building structures, the scientific community has been working on developing systems and structural members for the improvement of the seismic performance and protection of the structural integrity of buildings. Seismic response-control techniques have demonstrated through numerous applications worldwide to be efficient in reducing lateral deformation and seismic damage in buildings (Higashino and Okatomo 2006, Bozorgnia and Berterto 2004, Soong and Spencer 2002). Among those techniques, hysteretic dampers (passive control) are the most prevalent structural members installed into a building structure (main structure) to improve its seismic performance through dissipating most of the vibration energy imposed by ground motions, and therefore, reducing the share of vibration energy to be dissipated by the structural members of the main structure.

Hysteretic dampers (damper system) are generally designed to yield before the main structure. This is usually achieved by setting the lateral yield strength of dampers to be smaller than that of main structure. Thus, most analytical studies on building structures with hysteretic dampers have defined the geometry of dampers based on a required yield strength and stiffness (e.g., Inoue and Kuwahara 1998, Nakashima et al. 1996); however, this work scheme does not provide direct control over the yield deformation of dampers, and does not necessarily lead to the early yield in the damper system (Oviedo et al. 2010). Fig. 1.1 shows that if the stiffness of the damper system is much smaller than that of the main structure, the damper will yield at a larger lateral deformation than that required for yielding the main structure. This situation clearly suggests a loss of effectiveness of dampers.

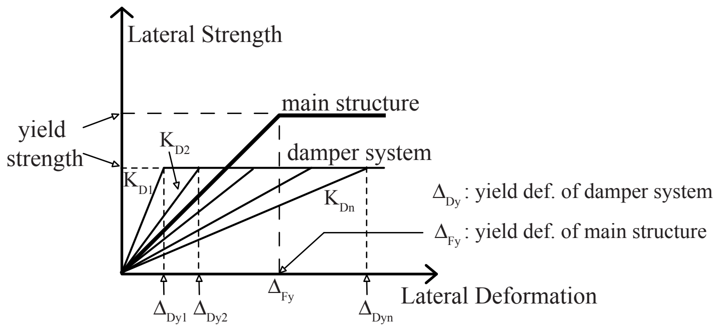

Figure 1.1. Schematic restoring force of main structure and dampers

This paper presents a methodology aimed at explicitly controlling the yield story drift of damper system in order to ensure its early yield. The methodology bases on a proportion rule in which the yield story drift and strength of damper system are proportionally smaller that the respective values of the main structure. Thus, the study evaluates through nonlinear dynamic analysis the seismic response of a series of low- and mid-rise reinforced concrete (R/C) frames equipped with hysteretic dampers that are defined according to the proposed proportion rule.

2. HYSTERETIC DAMPERS INSTALLED INTO AN R/C FRAME

Hysteretic dampers are commonly installed in an R/C frame in the form of braces, walls or shear links, connecting two consecutive floors to control the relative displacement between them. Fig. 2.1 shows how supplemental damping (damper installation) may change the force-displacement (story shear-story drift) response of the original R/C frame by adding stiffness and strength. 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 Fig. 2.1, Q_S, Q_{Fy} and Q_{Dy} are the yield shear strength of the entire system, R/C frame and damper system, respectively. Δ_{Fc}, Δ_{Fy}, Δ_{Dy}, Δ_{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

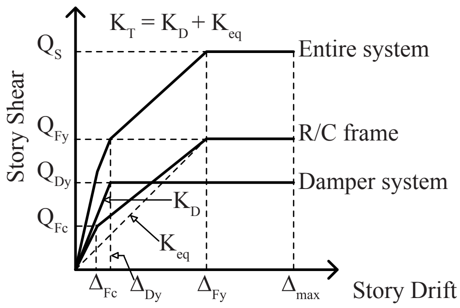

Figure 2.1. Influence of supplemental damping by hysteretic dampers

2.1. Studied R/C frames

In this study, R/C frames with 5 and 10 stories are studied as representative of low- and mid-rise building structures. The symmetric plan is shown in Fig. 2.2a. Frame C is selected to represent the response of the whole building, and hysteretic dampers are installed into the R/C frames at each story and at the center bay of the Frame C, as shown in Fig. 2.2b.

The gravity loads (dead and live) per unit area were assumed to be the same for all stories, with a typical floor load of 8.80 kN/m^2 and 10.02 kN/m^2 for the 5- and 10-story frames, respectively. Prior to installing the dampers, the structural designs of the R/C frames were established based on the Building Standard Law of Japan (BSLJ) (BCJ 2000). This was to originate two code-based reference R/C frames into which dampers were installed afterwards. The design of R/C frame was kept unchanged whereas the damper system was changed systematically to observe the influence of the mechanical properties of dampers on the seismic performance of the entire system. A strong-column and weak-beam philosophy (typical for ductile moment-resisting frames) was followed to avoid any soft stories. Table 2.1 summarizes the building properties of the bare R/C frames. The natural period T_0 of the 5- and 10-story models is 0.73 s and 0.87 s, respectively.

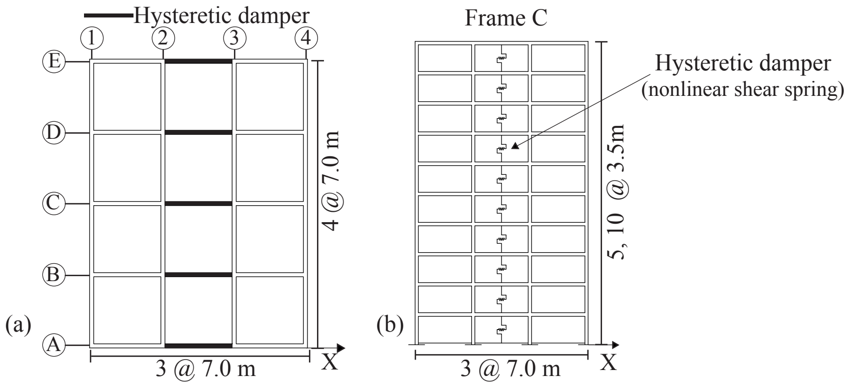

Figure 2.2. Analyzed R/C frames with hysteretic dampers: (a) typical plan and (b) elevation

Table 2.1. Structural Properties of Studied Bare R/C Frames

n floors	Element	Cross-section (m)	Concrete strength (MPa)	Natural period T_o (s) Total weight W (kN)
5	All columns	0.80 x 0.80	30	T_o = 0.73
	All floor beams	0.40 x 0.50	27	W = 6480
10	1st – 2nd story columns	0.90 x 0.90	36	
	3rd – 10th story columns	0.90 x 0.90	30	T_o = 0.87
	2nd – 6th floor beams	0.45 x 0.80	27	W = 14730
	7th floor – roof beams	0.45 x 0.75	27	

2.2. Description of damper system

The mechanical properties of damper system are changed systematically in a way that damper´s yield story drift and yield shear strength are proportionally smaller than those of the bare R/C frame. The yield shear strength Q^i_{Fy} and yield story drift Δ^i_{Fy} (see Fig. 2.1) 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 trilinear skeleton curve. The vertical distribution of lateral load in the pushover analysis was assumed to follow the factor A_i in the Japanese code. The factor A_i determines the distribution of story shear over the building height. Having defined Q^i_{Fy}, the yield shear strength of the entire system Q^i_S and damper system Q^i_{Dy} at the *i*–th story are determined by Eqns 2.1 and 2.2, where β' is the damper-frame strength ratio (yield strength of the damper system normalized by that of the R/C frame). Since a damper system with yield strength smaller than 80% of that of the R/C frame, i.e., $\beta' \leq 0.8$, is preferred to limit lateral displacement and reduce the seismic damage in the R/C frame (Oviedo et al. 2010), the value of β' varied by an interval of 0.1, ranging from 0.1 to 0.7, to define the damper's yield strength Q^i_{Dy}.

$$Q^i_S = Q^i_{Fy}(1+\beta') \tag{2.1}$$

$$Q^i_{Dy} = \beta' Q^i_{Fy} \tag{2.2}$$

The damper's yield story drift is determined from the 'constant yield story-drift ratio' scheme proposed by Oviedo et al. 2010. This scheme employs the drift ratio ν (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. The value of ν is constant over the building height in order to keep a uniform proportion of stiffness between the R/C frame and the damper system. Fig. 2.3 shows that when the damper's strength increases from ${}_1Q_{Dy}$ to ${}_2Q_{Dy}$, as a result of a larger β', the damper's stiffness K_D also increases to meet ${}_2Q_{Dy}$ and keep ν constant over the building height.

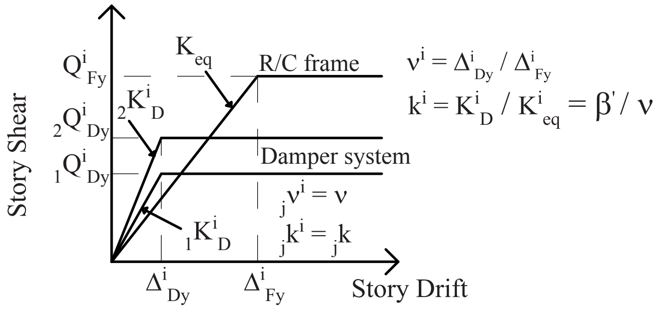

Figure 2.3. Story shear versus story drift relationship under the 'constant yield story-drift ratio' scheme

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 ν smaller than unity. Thus, the value of ν varied by an interval of 0.2, ranging from 0.2 to 1.0, to define the damper's yield story drift Δ^i_{Dy} and lateral stiffness K^i_D at the i-th story as in Eqns 2.3 and 2.4.

$$\Delta^i_{Dy} = \nu \Delta^i_{Fy} \tag{2.3}$$

$$K^i_D = Q^i_{Dy} / \Delta^i_{Dy} \tag{2.4}$$

As mentioned, supplemental damping adds stiffness and strength to an original R/C frame. Fig. 2.4a shows the variation of natural vibration period T of the entire system obtained from modal analysis with respect to β' and ν. The natural period varies highly with β' and is sensitive to ν (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 ν, as seen in Fig. 2.4b. The shortest natural period after installing dampers is 0.49 s and 0.66 s, for the 5- and 10-story model, respectively.

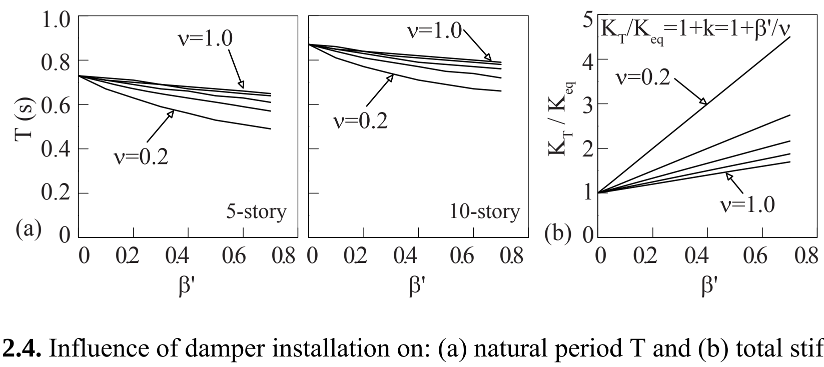

Figure 2.4. Influence of damper installation on: (a) natural period T and (b) total stiffness K_T

3. ANALYSIS PROCEDURE

The mechanical properties of the frame models shown in Fig. 2.2 are varied systematically and the seismic response of the models is obtained through nonlinear dynamic analysis. The series of analyses correspond to the following cases: (1) two numbers of stories (n = 5 and 10), (2) eight damper-frame strength ratios (β' = 0, 0.1 to 0.7), (3) five drift ratios (ν = 0.2, 0.4, 0.6, 0.8 and 1.0), and (4) the input motions listed in Table 3.1. In total, over 800 nonlinear dynamic analyses were performed.

Five different acceleration records very frequently used in the design practice in Japan were selected and scaled to two levels of seismic intensity: peak ground velocity (PGV) of 0.50 and 1.0 m/s. 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 PGV of 0.50 m/s. 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 the severe Kobe earthquake in 1995 (about 0.91 m/s). The nonlinear dynamic analyses are carried out by the computer program STERA-3D (Saito 2010), used for the frame analysis of R/C buildings. 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, as shown in Fig. 2.2b. The hysteresis rule for bending in columns and beams is the degrading trilinear Takeda model (Takeda et al. 1970), 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 stiffness ratio of 0.01 were used, and initial stiffness proportional damping was assumed with a damping ratio of 3% of the critical for the first mode.

Table 3.1. Input ground motions

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

4. RESULTS OF EARTHQUAKE RESPONSE ANALYSIS

Fig. 4.1 shows pushover curves after damper installation for some analysis cases. It can be observed, especially for the 5-story model, that the yield story drift of the damper system at each story agrees very well with the assumed values from Eqn 2.3. For the 10-story model, however, it can be observed a difference between the assumed and the actual yield story drifts, which increases as β' increases and is more evident at the upper stories. This is because the global flexural deformation of the damper-installed bay reduces the effective stiffness of the damper system. The global flexural deformation of the damper-installed bay is caused by the extension and contraction of the columns that support the damper. These columns are subjected to additional axial stresses induced by the story shear resisted by dampers and its associated overturning moment.

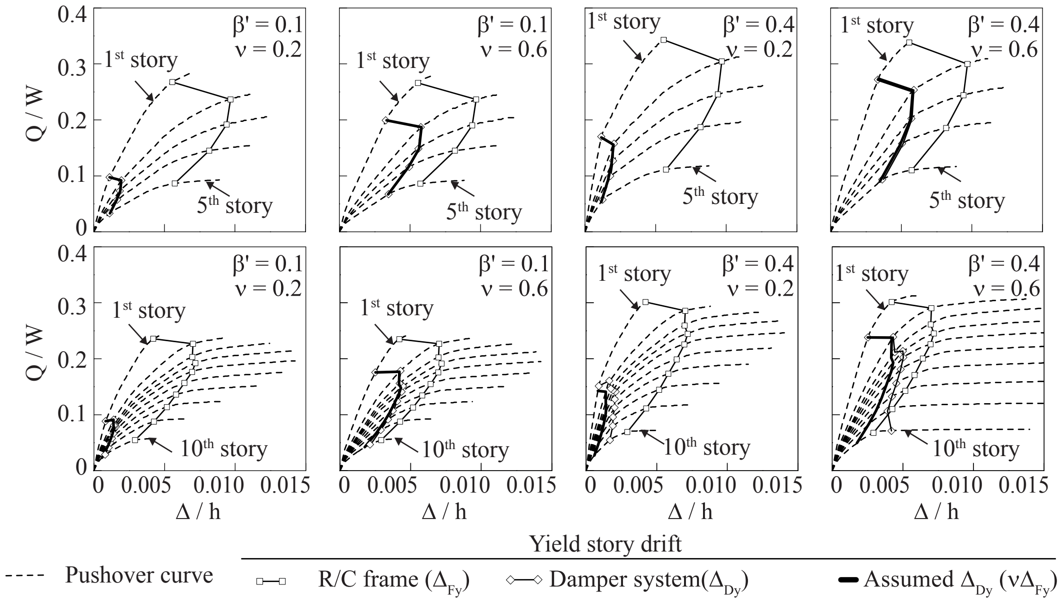

Figure 4.1. Pushover curves after damper installation

4.1. Axial deformation of columns

Fig. 4.2 shows the maximum axial deformation of the first story columns in both compression and tension side. As indicated in Fig. 2.2a the interior columns C2 and C3 form the damper-installed frame. From Fig. 4.2, it is evident for the columns C2 and C3 that the difference in the maximum axial deformation between the compression and tension side increases with β', regardless of the value of ν. The small variation of the envelope of maximum axial deformation with respect to ν is because the additional axial stresses (induced by dampers) in the columns C2 and C3 depend mainly on the damper's strength. With regard to the exterior columns C1 and C4, as expected, the axial deformation response is not influenced by the installation of dampers.

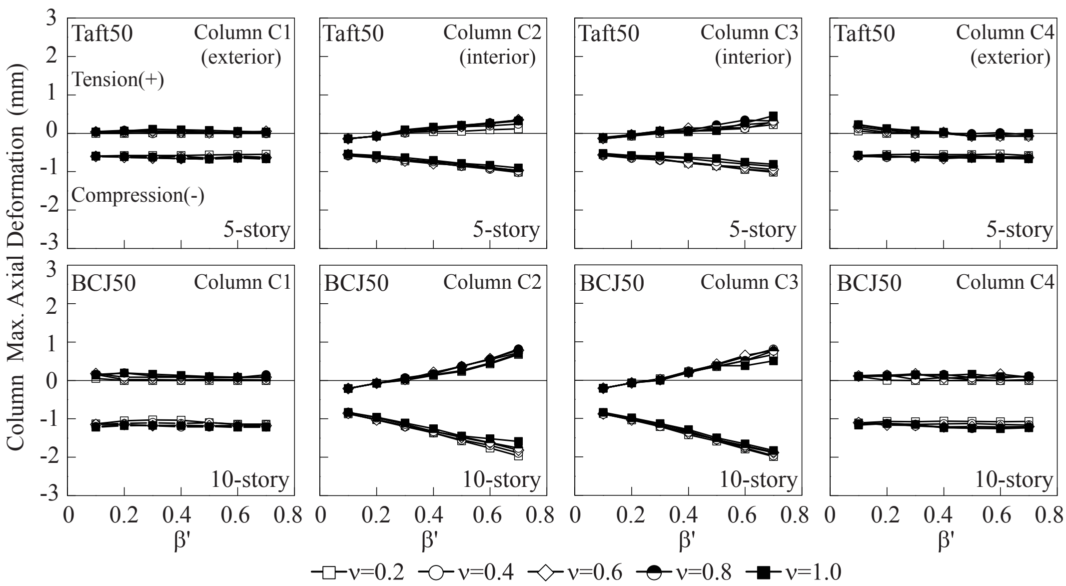

Figure 4.2. First story column maximum axial deformation

4.2. Story drift response

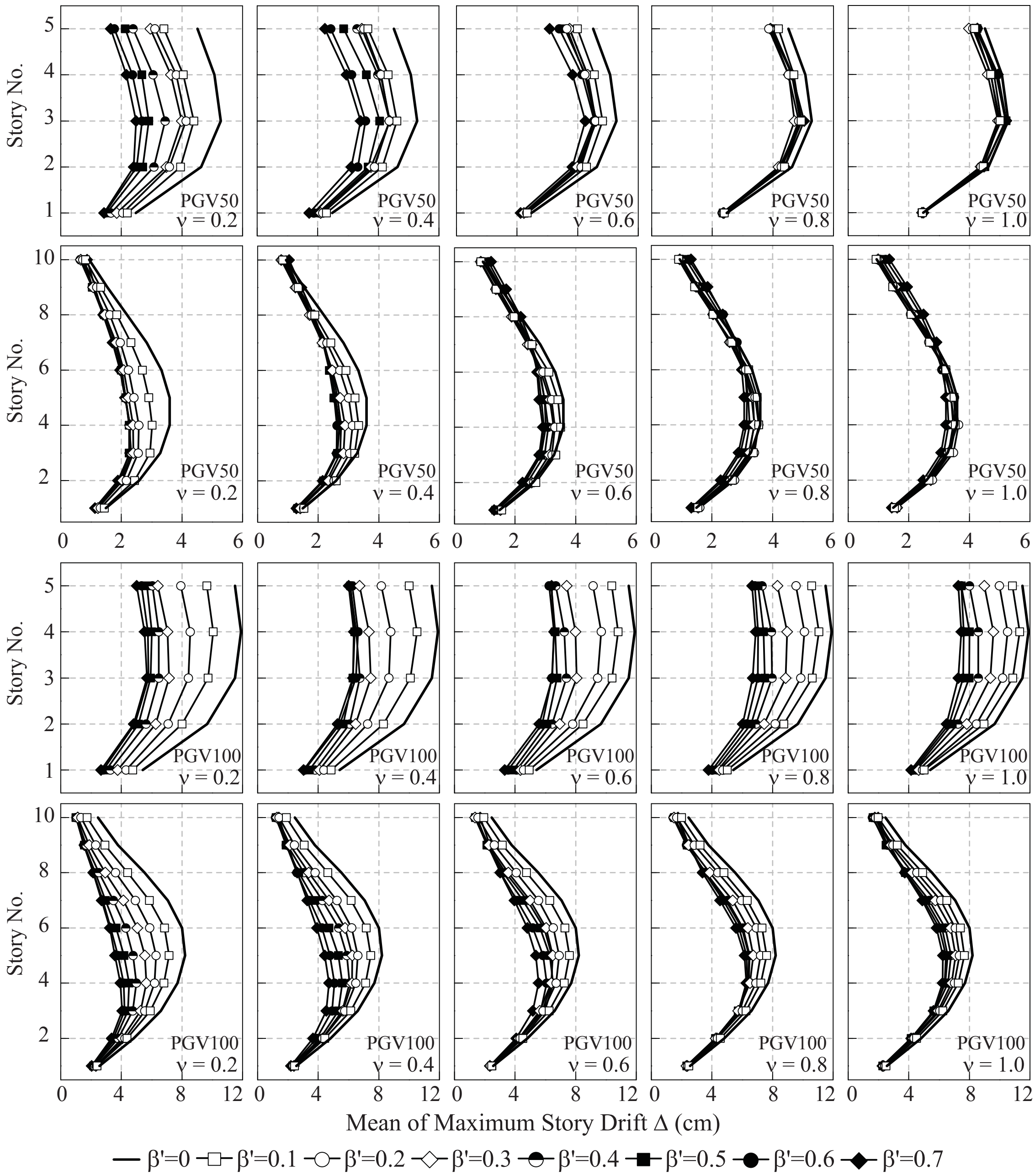

Figure 4.3. Story drift response

Fig. 4.3 shows the mean of maximum story drift Δ. The mean is taken over the values obtained from the input motions of each seismic intensity group. A reduction in the story drift demand after damper installation can be observed clearly. This reduction tends to increase with decreasing values of ν and increasing values of β'. However, some increase in the maximum story drift is seen in the upper stories of the 10-story model for $\nu \geq 0.6$ and for the PGV50 group. This increase becomes more significant with increasing values of β'. This response trend is mainly 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. Moreover, it is observed for $\nu > 0.6$ and the PGV50 group 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 β'. This indicates that dampers are not effective for this range of ν. On the other hand, it is observed a better participation of the damper system in reducing story drift demands for the PGV100 group.

It is important to note here 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.

4.3. Energy response

Shown in Fig.4.4 is the hysteretic energy dissipated by the R/C frame E_{HF} (i.e., cumulative seismic damage) normalized by the total input energy E_I. It is evident that the participation of the R/C frame into the total input energy decreases as β' increases and ν decreases, and that the E_{HF} / E_I ratio at each story 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 structural members of the R/C frame. Moreover, the vertical distribution of the E_{HF} / E_I ratio tends to be proportional to that of the bare R/C frame; response characteristic that again clearly indicates a uniform control over the protection of the R/C frame.

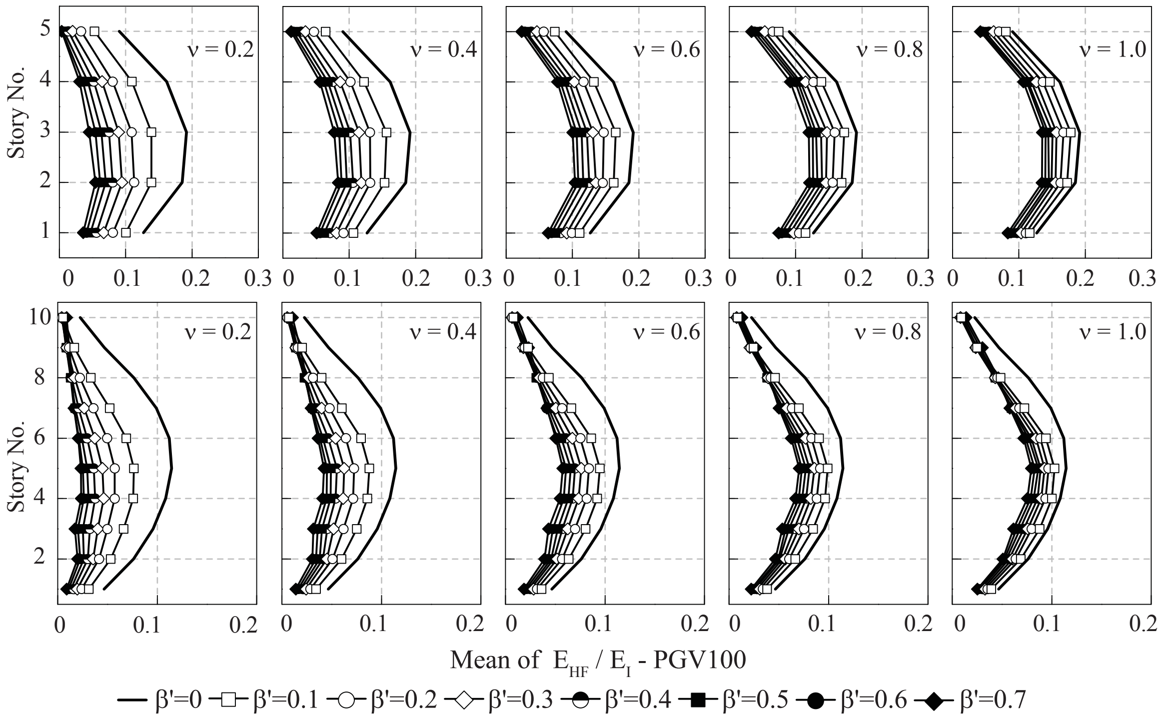

Figure 4.4. Participation of R/C frame into total input energy dissipation

5. CONCLUSIONS

The seismic performance of low- and mid-rise R/C frames with proportional hysteretic dampers was investigated through nonlinear dynamic analyses on a series of frame models that included a wide range of mechanical properties of dampers.

The analytical results have demonstrated a significant improvement of the seismic performance of an R/C frame when dampers are installed according to the proposed proportion rule. This is because the lateral deformation demand and seismic damage in the R/C frame are reduced uniformly over the building height; which clearly indicates a controlled protection to the R/C frame.

The global flexural deformation of the damper-installed bay has a significant influence on the response and effectiveness of dampers, especially on those with large yield strength and installed at upper stories of mid-rise frame.

Damper installation generates additional axial forces on the columns that support the dampers. These forces increase the axial deformation of such columns, and therefore, it is necessary to provide these columns with enough axial rigidity to accommodate such increased stresses.

AKCNOWLEDGEMENT

The authors would like to express their thanks to Dr. T. Saito, IISEE, Tsukuba, Japan, for his support with the computer program STERA-3D used in this study. The authors acknowledge the financial support given by the Ministry of Education, Culture, Sports, Science and Technology of Japan. This support is greatly appreciated.

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