OPTIMUM STRENGTH RATIO OF BUCKLING-RESTRAINED BRACES AS HYSTERETIC ENERGY DISSIPATION DEVICES INSTALLED IN R/C FRAMES

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ABSTRACT :

This paper focuses on the application of buckling-restrained braces (BRB) to reinforced concrete (R/C) framed structures in order to reduce the seismic damage in the main frame components. An attempt for a new direction in defining the mechanical properties of hysteretic dampers is evaluated in which the deformation of dampers is directly controlled. The range of strength levels required to be given to the dampers to minimize the damage in the main frame is investigated. A parametric study was carried out on 10-story R/C building structure with damper strength ratio β and yield drift ratio ν as main parameters. Equivalent single-degree-of-freedom (ESDOF) model is also discussed. Based on the numerical results it has been concluded that there is not a unique value that minimizes the damage in the main frame; on the contrary, there is an applicable range. The range is found to be dependent on the seismic input level and time-dependent characteristics of ground motions. Earthquake response shows the significant improvement of the structural performance and the implication of the yield drift ratio on the reduction of maximum floor displacements and damage in the main frame. ESDOF model demonstrated to provide sufficiently accurate estimations of floor displacements.

KEYWORDS: buckling-restrained brace, equivalent SDOF system, hysteretic damper, optimum strength of hysteretic dampers, reinforced concrete structure

1. INTRODUCTION

Conventional structural design focuses on the deformation capacity of buildings in the inelastic range, taking as condition the ductility capacity in the structural components. This approach allows certain extent of damage in the case of severe earthquake motions. The damage is accepted as long as does not endanger the human lives and user's properties. Seismic response control techniques have been implemented as new methodologies of earthquake-resistant design in order to reduce the seismic demand in the structural members by controlling their deformation; therefore, the damage. These techniques complement the conventional approaches introducing additional structural components which are to dissipate most of the energy exerted by earthquake motions. In the case of hysteretic dampers such BRBs, seismic response control stands for the attempt to keep the main frame in either its elastic range or within low inelastic response and, in the mean time, the secondary structure given by the BRBs undergoes in the inelastic range (Bozorgnia and Bertero 2004, Wada and Nakashima 2004).

Since the first application of BRBs nearly 30 years ago in Japan, recently in USA and other countries, the use of this type of hysteretic dampers has become very popular in the engineering practice. This popularity is mainly caused by the remarkable economical benefits in the fabrication process and on-site installation, and relatively simple modeling. Up to present, most of the application cases of BRBs, steel members in the main structural system have been used; in contrast with the number of projects applied to reinforced concrete structures. Moreover, some studies have been reported with the aim of estimating a unique value of damper strength that minimizes the seismic damage in the main frame (Inoue and Kuwahara 1998, Yamaguchi and El-Abd 2003).

This study is motivated by the need to observe the effect of additional strength and stiffness given by BRBs on the structural performance and protection of R/C main frames. An attempt for a new direction in defining the mechanical properties of hysteretic dampers is evaluated in which the deformation of dampers is directly controlled. This attempt is meant to observe its direct implication on possible reductions of structural response. ESDOF model proposed by Oviedo et al. (2008) for R/C buildings with hysteretic dampers is also investigated.

2. R/C BUILDING WITH BUCKLING-RESTRAINED BRACES

The structure investigated is a 10-story moment-resistant reinforced concrete building with a pair of BRBs installed at each story at the center bay as illustrated in Figure 1. Frame-C was analyzed representing the behavior of the building. As seen in Figure 1a, the symmetric plan consists of 3 by 4 bays of 7 meters and typical height of 3.5 meters. BRBs (damper system) are installed in the R/C structure (main frame). Figure 1c summarizes the structural properties of the main frame. Unlike common practice, structural design of the R/C main frame was done prior installation of BRBs to observe the influence of the strength level of BRBs on the structural performance of the entire system (main frame + damper system), while R/C main frame was intentionally kept unchangeable. Required design seismic loads were defined according to the Building Standard Law of Japan (BSLJ) (The Building Center of Japan 2000). Vertical distribution of equivalent forces was defined according to the seismic lateral strength at *i*-th story C_i and the seismic lateral strength distribution factor at *i*-th story A_i (The Building Center of Japan 2000). The story drift under the design loads was limited to 1/200. Structural design of the R/C main frame represents the strong-column-weak-beam collapse mechanism. Floor load was assumed to be the same at each story and proportional to the tributary area of Frame-C. The total weight for this 2-dimension frame model is 14720 kN.

3. PARAMETRIC ANALYSIS

The restoring force of the entire system can be idealized as the combination of two systems (main frame and damper system) connected in parallel as shown in Figure 2. Main frame can be considered as elastic or plastic meanwhile the damper system is always considered inelastic. Both systems and the entire system share the same deformation. The skeleton curve for the damper system is regarded as bi-linear type, and for R/C main frame, it should include the effect of stiffness reduction due to section cracking corresponding to a tri-linear curve or bi-linear approximation with reduced stiffness as in Figure 2. Mechanical properties of the hysteretic dampers have been usually defined in terms of strength and stiffness in order to comply with certain required stiffness of the entire system. However, this definition does not allow a direct control over the deformations. Therefore, unlike previous studies (e.g., Inoue and Kuwahara 1998), mechanical properties of BRBs are defined from the yield story drift and strength level. Damper strength ratio β (hereafter strength ratio) and yield story drift ratio ν (hereafter drift ratio) are the main parameters varying upon a fixed R/C main frame; defined from Figure 2 as:

$$Q_S = Q_{Fy} + Q_{Dy} \tag{3.1}$$

$$\beta = Q_{Dy} / Q_S \tag{3.2}$$

$$Q_{Fy} = (1-\beta) Q_S \tag{3.3}$$

$$k = K_D / K_{eq} \tag{3.4}$$

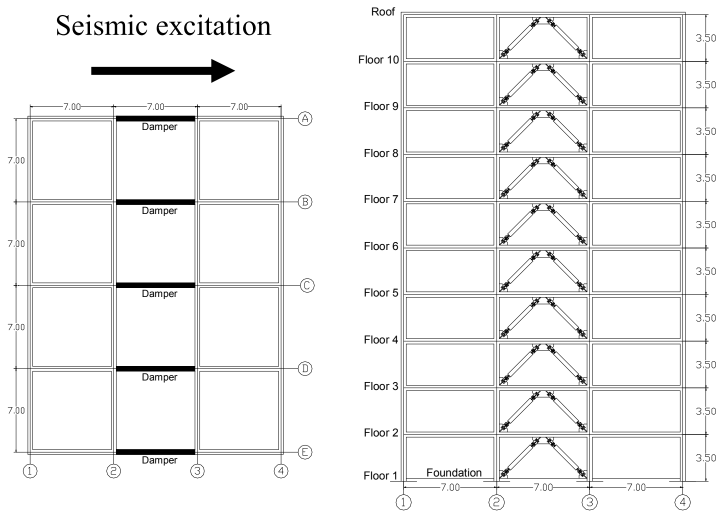
Where, Q_S, Q_{Fy}, Q_{Dy}, β, k are the yield shear strength of the entire system, the yield shear strength of the main frame, the yield shear strength of the damper system, the strength ratio and the stiffness ratio, respectively. Δ_{Fc}, Δ_{Fy}, Δ_{Dy}, Δ_{max}, μ_F, μ_D are the cracking story drift, yield story drift of the main frame, yield story drift of the damper system, maximum story drift of the entire system, main frame's ductility and damper system's ductility. α and ρ define the shear at cracking point Q_{Fc} and the equivalent stiffness for the main frame K_{eq}, respectively.

The stiffness at each story was determined and confirmed by pushover analysis; Δ^i_{Fy}, K^i_{eq} were determined. Then, value of β was varied by intervals of 0.1 ($0<\beta<1.0$), in order to modify the strength level of dampers. At each value of β, the total shear resisted by the damper system βQ_S was distributed along the height alike the horizontal force distribution used for the main frame's design to determine the story shear resisted by the damper system at *i*-th story Q^i_{Dy}. Drift ratio ν is introduced by Eqn. 3.5 and Figure 3 within the range of [0-1] and is intended that the value of ν is constant for all stories and strength ratios; ν=1.0 means that both damper system and main frame will yield at the same story drift level. ν=1.0 can be understood as the lowest protection provided to the main frame now that the damper system will have the lowest stiffness and require more displacement to start to dissipate energy. Therefore, control over the story drift and uniform distribution of stiffness ratio is automatically granted. Then the horizontal stiffness and story drift at yield level at the *i*–th story for the damper system given by K^i_D and Δ^i_{Dy}, respectively, are defined as follows:

$$\Delta^i_{Dy} = \nu\Delta^i_{Fy} \tag{3.5}$$

$$K^i_D = Q^i_{Dy} / \Delta^i_{Dy} \tag{3.6}$$

In Figure 3, it can be clearly seen that when the damper strength increases from ${}_jQ^i_{Dy}$ to ${}_{j+1}Q^i_{Dy}$, product of a larger β, the stiffness of the damper system increases to meet ${}_{j+1}Q^i_{Dy}$ and the drift ratio is kept constant for all stories and strength ratios; yet the stiffness ratio remains the same for all stories under a certain β.



R/C building with BRB:

*Columns 1floor: (0.80x0.80) m^2
Concrete strength: 35MPa. Reinf.ratio: 3.05%
*Columns 2floor: (0.80x0.80) m^2
Concrete strength: 35MPa. Reinf.ratio: 1.60%
*Columns 4floor-roof: (0.80x0.80) m^2
Concrete strength: 28MPa. Reinf.ratio: 1.22%

*Beams 2-6 floors: (0.40x0.75) m^2
Concrete strength: 28MPa
*Beams 7-roof: (0.40x0.70) m^2
Concrete strength: 28MPa

*Elastic modulus for concrete:
28000MPa for concrete strength of 35MPa
25100MPa for concrete strength of 28MPa

a) b) c)

Figure 1 Reinforced concrete frame with BRB. a) plan b) elevation c) structural properties

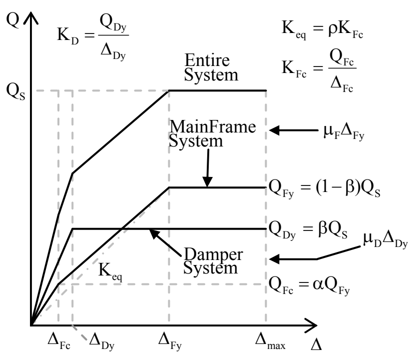


Figure 2 Scheme of restoring force characteristics

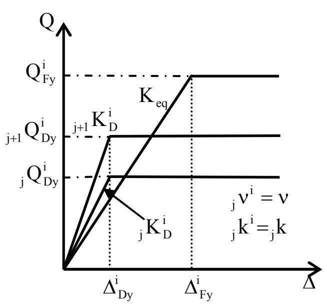


Figure 3 Scheme for the constant yield story drift ratio of *i*-th story

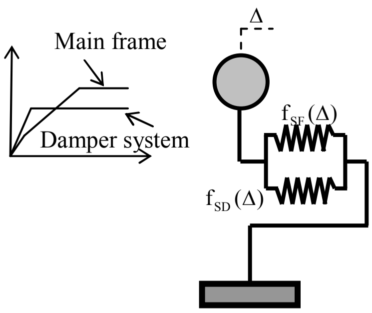


Figure 4 ESDOF model (Oviedo et al. 2008)

Oviedo et al. (2008) carried out an analytical study on the floor displacement prediction of R/C buildings with hysteretic dampers and proposed an ESDOF model which differentiates the hysteresis behaviors and skeleton curves for the main frame and damper system. They showed good correspondence of the floor displacement prediction by the proposed ESDOF model. Therefore, the model proposed by Oviedo et al. (2008) was used for the non-linear time-history analyses as shown in Figure 4, where $f_{SF}(\Delta)$ and $f_{SD}(\Delta)$ are the restoring force for the main frame and damper system, respectively. Extended details can be found in Oviedo et al. (2008).

4. NON-LINEAR ANALYSIS PARAMETERS AND INPUT GROUND MOTIONS

Input ground motions were defined and scaled to meet different levels of seismic intensity, characterized by peak ground velocity (PGV), from three sources: El Centro NS (1940), JMA-Kobe NS (1995) and synthesized BCJ-L2. Table 1 summarizes the characteristics of the input motions used for the non-linear time-history analyses. A total of 290 (145 MDOF and 145 ESDOF) non-linear time-history analyses were performed. All analysis cases correspond to the combination of strength ratios [0.2-0.8], drift ratios [0.4, 0.6, 0.8, and 1.0] and the input motions in Table 1. MDOF time-history analyses were carried out by the program Drain-2DX with element type 2 for columns, element type 7 for beams and element type 1 for BRBs (Prakash et al. 1993). Bi-linear skeleton curve was used as approximation to tri-linear skeleton curve for R/C members. Consequently, stiffness reduction coefficients were applied according to the provisions and recommendations given by FEMA-274 (FEMA 1997). For the ESDOF model, degrading tri-linear Takeda model and bi-linear model were used for the R/C main frame and damper system, respectively. Inherent viscous damping ratio was taken as 0.02 and integration time step is 0.005. Post-elastic stiffness ratio is 0.01 for MDOF.

Table 1 Input ground motions

Earthquake Source	Input Motion	PGA (cm/s^2)	PGV (cm/s)	Td (s)
ElCentro NS 1940	ElCentro	344	35	54
ElCentro NS 1940	ElCentro50	505	51	54
ElCentro NS 1940	ElCentro100	987	98	54
BCJ-L2	BCJ-L2	355	50	96
JMA–Kobe NS 1995	Kobe	818	91	60

5. EARTHQUAKE RESPONSE AND DISCUSSIONS

Figure 5 presents the energy dissipated by main frame E_{HF} and damper system E_{HD} in relation to the total energy dissipated by hysteresis behavior E_{HS}. Horizontal axis denotes the strength ratio. Almost all input motions present a relatively flat region at which participation of main frame is minimized. For ElCentro, for $\nu = 0.4$, the lowest participation of main frame is about 10% and it increases up to nearly 70% for $\nu = 1.0$; on the contrary, in the damper system, the participation decreases from 90% to 30%. For BCJ-L2, the lowest participation of main frame is about 10% and the largest about 50% when ν changes from 0.4 to 1.0. In the case of Kobe, the participation of main frame is kept from 20% to 40%. PGV level for ElCentro tends to increase the participation of main frame for low drift ratios and decrease it for large drift ratios; PGV also tends to shift the relatively flat range to the right. The aforementioned clearly shows that for low drift ratios, the participation of main frame in the total hysteresis energy dissipation is also low independently on the input motion for $\beta \leq 0.7$. In this sense, lower drift ratios would grant more protection. For strength ratios on the right of the relatively flat range, the damper system is less efficient in protecting the primary structure.

Figure 6 illustrates the ratio of total input energy E_i to the total input energy without BRBs E_{io}. It is clearly noticed that there is not much relevant influence of drift ratio within the same input ground motion for strength ratios lower than 0.5. The input energy ratio almost always increases with the strength ratio. Moreover, it is also seen a remarkable influence of input motion characteristics rather than influence of PGV level. Input energy ratio is found to be mainly dependent on characteristics of ground motions and strength ratio.

Figure 7 shows the ratio of cumulative plastic strain energy dissipated by the main frame ω_F normalized to which the structure experiences without dampers ω_{Fo}. The cumulative plastic strain energy ratio is calculated by Eqn. 5.1, where E^i_{HF}, Q^i_{Fy}, Δ^i_{Fy} and ω^i_F are the hysteresis energy dissipated, yield shear strength, yield story drift and cumulative plastic strain ratio at *i*-th story in the main frame, respectively.

$$\omega^i_F = E^i_{HF} \big/ Q^i_{Fy} \Delta^i_{Fy} \tag{5.1}$$

Reduction of damage in the main frame characterized by ω_F is no less than 50% for $\beta \leq 0.5$, except in Kobe for which is no less than 60%; this is a very attractive reduction. For $\nu = 0.4$ and 0.6, the reduction of the damage in the main frame is larger comparing to the reduction given for $\nu = 0.8$ and 1.0. The interval at which the protection of main frame is maximized tends to enlarge and become more uniform as ν decreases. This effect has remarkable meaning in the engineering practice; the concept of a "uniform" range for the strength ratio may be desirable as it would regard possible modifications of the real response due to uncertainties such as construction process and material strength reliability. Consequently, the strength ratio should be preferably chosen within this "uniform" range so that the protection to the main frame is less probable to be modified. Reduction of cumulative plastic strain energy in the main frame is more significant with decreasing drift ratios.

Figure 8 shows the floor displacement response. Horizontal axis represents the floor displacement δ normalized to the floor displacement without braces δ_o. Vertical axis represents the floor number. In general, floor displacements are lower than the displacements without braces. This reduction of floor displacements suggests lower story inelastic response and therefore less damage. For $\beta \leq 0.5$ and all drift ratios, there is always reduction; on the contrary, for higher strength ratios, there are some increase in the displacements for $\nu = 0.8$ and 1.0. Higher PGV tends to slightly increase the displacement ratios. It is important to mention that for moderate earthquakes, such as ElCentro and ElCentro100, the reduction of floor displacements tends to be relatively constant among all stories for $\beta \leq 0.6$ regardless the drift ratio. This behavior may suggest the likeliness of predefining a target displacement reduction of the floor displacements and therefore direct control over the maximum floor displacements could be achieved.

Figure 9 shows the estimation of maximum floor displacements of MDOF by the ESDOF model of Figure 4. Horizontal axis denotes the estimated floor displacements by the ESDOF model and vertical axis denotes the floor displacements of MDOF. Solid line represents the linear regression among all estimated values for a certain ν; the slope is indicated. For ElCentro input motion, it can be seen that the average line has a slope very close to 1.0 meaning reasonable good correspondence of the predicted displacements to those of MDOF. Displacement ratio (δESDOF/δMDOF) is very close to 1.0 for all β and ν. For Kobe input motion, a higher variability is seen especially for upper floors where higher mode effect is more significant; however, most of the predicted values fall in the conservative side. In general, low drift ratios allow better estimations.

The variation of the total hysteresis energy demand is illustrated in Figure 10. Vertical axis denotes the ratio of hysteresis energy demand E_H over the hysteresis energy demand without BRBs E_{Ho}. It can be seen that there is not a significant influence of drift ratio for strong input motions such as ElCentro100 and Kobe. On the contrary, for ElCentro, ElCentro50 and BCJ-L2, high variability is presented with increasing strength ratios. Another remarkable situation presented for ElCentro100 and Kobe is that the hysteresis energy demand always increases along with the strength ratio and is kept relatively invariable in terms of drift ratio for $\beta \leq 0.5$. This suggests that in the case of strong ground motions, the demand of hysteresis energy does not vary in relation to the drift ratio and mainly depends on the strength level given to the damper system. On the other hand, no clear trend is observed for ElCentro, ElCentro50 and BCJ-L2 input motions; a high variability is presented for β approaching to 1.0. It is important to highlight that low drift ratios provide hysteresis energy demands as large as or lower than the demands in the case without BRBs for $\beta \leq 0.5$. This reduction is even more relevant for higher drift ratios within the same range of strength ratio.

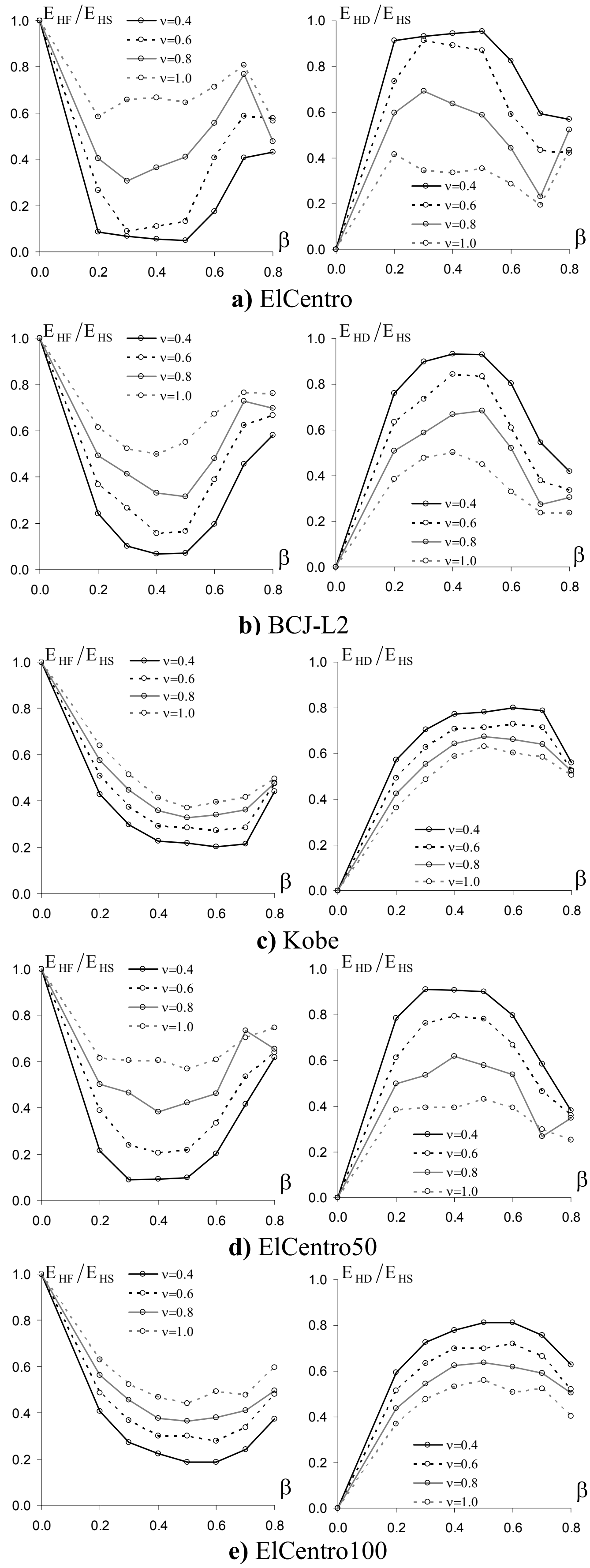


Figure 5 Hysteresis energy participation ratio

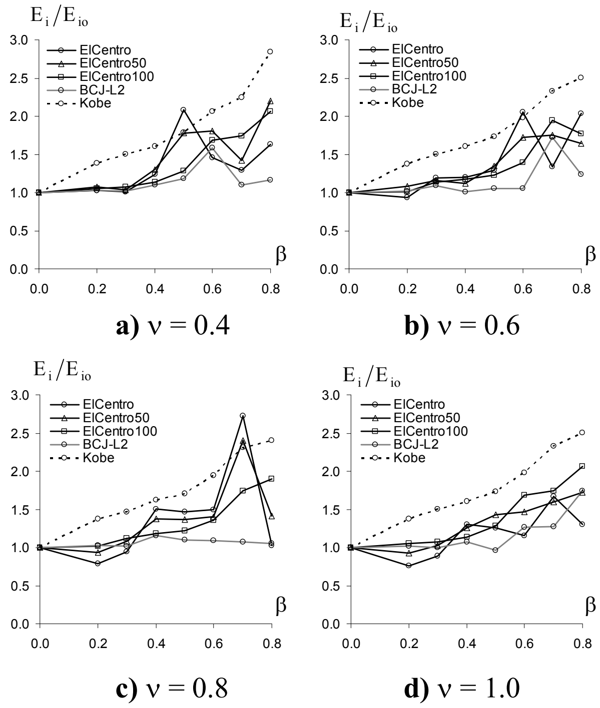


Figure 6 Input energy ratio

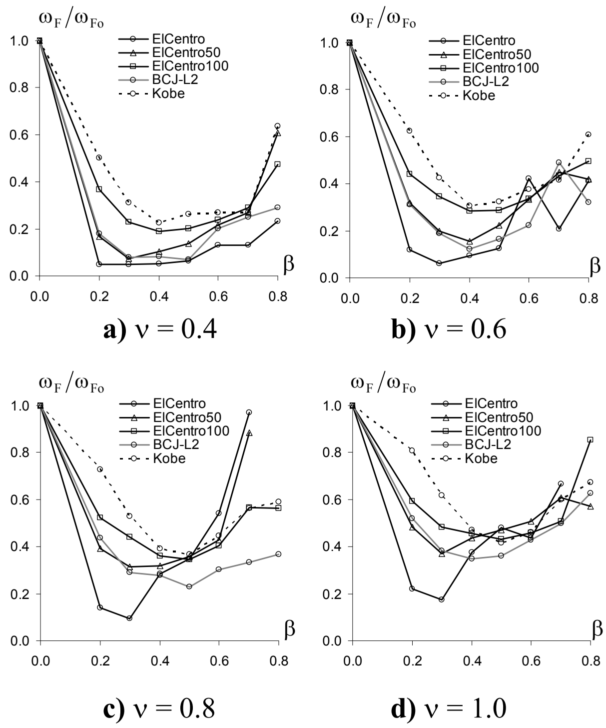


Figure 7 Normalized cumulative plastic strain energy ratio for the main frame

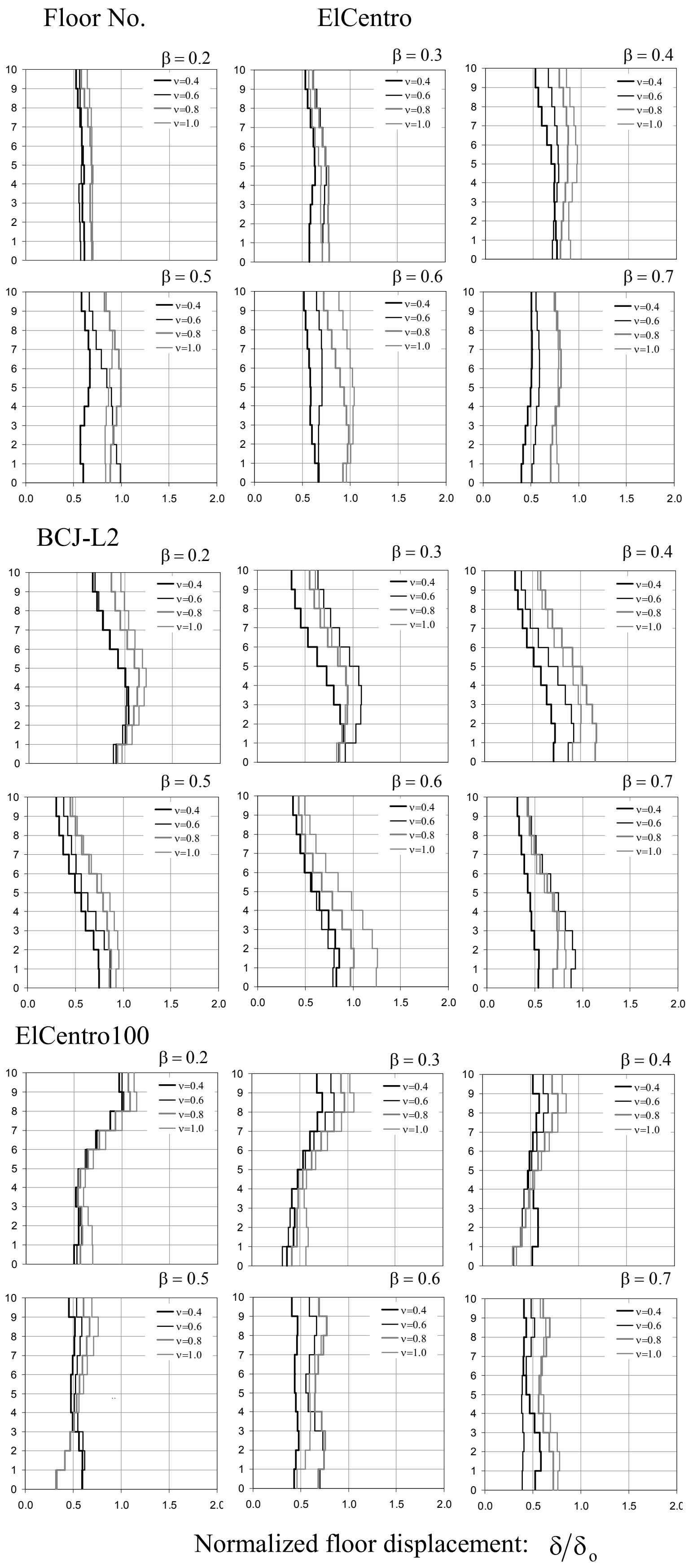


Figure 8 Distribution of floor displacement ratio

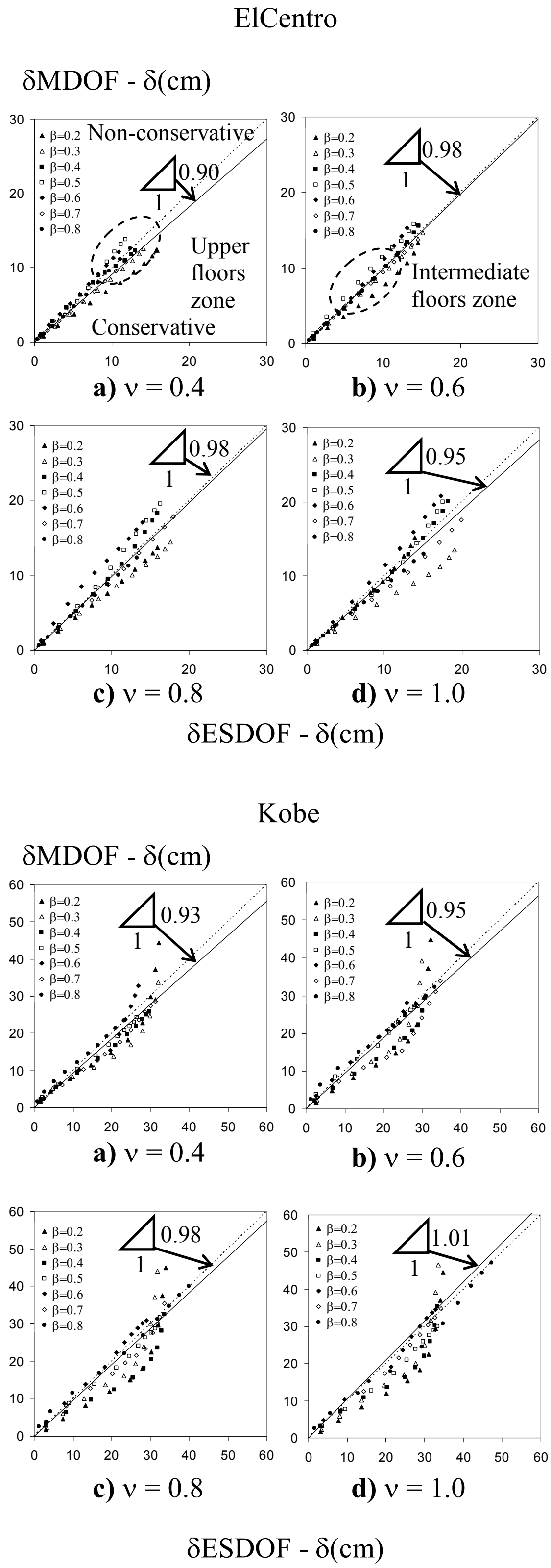
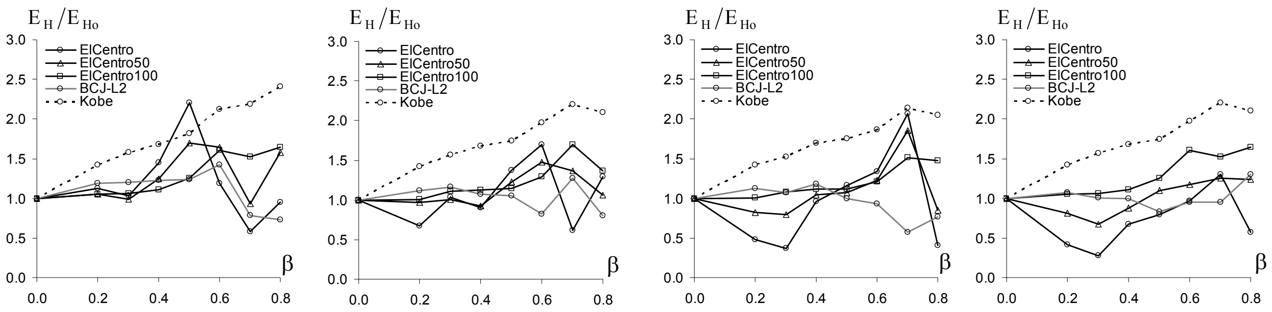


Figure 9 Comparison of maximum floor displacements between MDOF and ESDOF



a) ν = 0.4 **b)** ν = 0.6 **c)** ν = 0.8 **d)** ν = 1.0

Figure 10 Hysteresis energy demand ratio

6. CONCLUSIONS

The earthquake response of a 10-story weak-beam strong-column R/C building with buckling-restrained braces was evaluated by carrying out a series of non-linear time-history analyses for different cases according to the strength ratio and drift ratio. The analytical results have demonstrated the improvement of the structural performance when hysteretic dampers are installed. The following main findings are drawn from this study:

1) The damper strength that minimizes the damage in the main frame does not necessarily fall in a unique value; on the contrary, the damper strength ratio tends to keep a relatively stable range at which the reduction of the energy dissipated by the main frame is maximized and kept relatively constant.
2) Reduction of the inelastic work in the main frame was obtained for almost all strength ratios and drift ratios. However, lower strength ratios accompanied with low drift ratios demonstrated the best improvement to the structural response and protection to the main frame.
3) The simplified model proposed (Oviedo et al. 2008) for the prediction of floor displacements of R/C buildings with hysteretic dampers demonstrated to provide sufficiently accurate estimations when BRBs are installed. The model is considered useful for the seismic evaluation of R/C buildings with BRBs.

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