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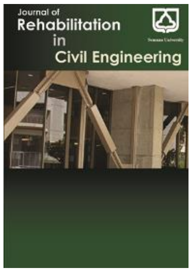

Seismic Retrofitting of Steel Frames With Buckling Restrained and Ordinary Concentrically Bracing Systems with Various Strain Hardening and Slenderness Ratios

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ABSTRACT

The present study assesses the seismic performance of steel moment resisting frames (SMFs) retrofitted with different bracing systems. Two structural configurations were utilized: ordinary concentrically braces (OCBFs), buckling-restrained braces (BRBFs). A 7-story and 18-story steel perimeter SMFs were designed with insufficient lateral stiffness to satisfy code drift limitations in high seismic hazard zone. The frames were then retrofitted with OCBFs with 30, 60, 90, 120 slenderness ratios and BRBFs. Inelastic time-history analyses have been carried out using OPENSEES software for strain hardening from 1 to 10 percent to assess the structural performance under earthquake ground motions. Inter story drifts were employed to compare the inelastic response of the retrofitted frames. It is shown that the distribution of maximum story drifts in the height of BRBFs is more uniform than OCBFs with various slenderness ratios and with increasing strain hardening, the inter story drift and P-Δ effects is decreased. In addition, normal buckling braces with low slenderness ratio behave similar to the BRBFs to control inter story drift, but the cycling behavior in dissipation the energy can't be changed, and finally the suitable performance from BRBF can't be obtained.

1. Introduction

Observing structures behavior in the last earthquakes, e.g. 1994 Northridge (California), 1995 Kobe (Japan) and 1999 Chi-Chi (Taiwan), have shown that conventional steel frames undertake large levels of lateral deformation when subjected to strong ground motion. If this deformation is excessive, structural and nonstructural damage is evident, compromising the structural integrity. Damage becomes severe as P-Δ effects take place, caused by large deformations. These observations shown that in moderate-to-severe earthquake ground motions, the majority of damaged buildings had un-braced SMFs as earthquake-resistant system (Disarno et al., 2008; Asgarian and Shokrgozar, 2009). To override such deformations, various types of elements and devices have been used for seismic retrofitting of steel frames. Braces as lateral load resistant systems are one of the most commonly used methods to resist lateral loads such as earthquakes. These diagonal elements increase the stiffness and energy dissipation, and they control relative inter story deformations effectively, thus protecting the structures against damage and improving the overall behavior. However, the energy dissipation capacity of a steel braced structure is limited due to the buckling of the braces (Kim and Seo, 2004; Kim and Choi, 2005). Considering this limitation, some efforts have been made to develop new CBF systems with stable hysteretic behavior, significant ductility as well as large energy dissipation capacity. One such CBF system with an improved seismic behavior is the Buckling Restrained Braced Frame (BRBF) that not only enhances the energy dissipation capacity of a structure but also decreases the demand for inelastic deformation of the main structural members. Di Sarno et al. (2007; 2010) found that the seismic performance of typical reinforced concrete (RC) existing framed structures that retrofitted with buckling resistant brace. They demonstrate that both global and local lateral displacements are notably reduced after the seismic retrofit of the existing system. The computed inter storey drifts are 2.43% at Collapse Prevention limit state (CP) and1.92% at Life Safety limit state (LS) for modal distribution of lateral forces. Conversely, for the retrofitted structure, the estimated values of inter storey drifts (d/h) are halved; the maximum d/h are 0.84% at CP (along the Y-direction) and 0.65% at LS (yet along the Y-direction). Furthermore, lateral drifts are uniformly distributed along the height; in turn, damage localizations are inhibited, especially at ultimate limit states, i.e. LS and CP. Asgarian and Amirhesari (2008) investigated the differences in performance between Ordinary Brace Frames (OBF) and BRBFs. They concluded, through nonlinear dynamic analysis, that BRBFs are superior in performance and behavior than OBFs. The OBFs are limited in performance and behavior, since they experience bracing member buckling, while BRBFs do not buckle but instead show stable hysteretic behavior. Comparing concrete structures, having concentric steel bracings with those having BRB systems, Rahai and Alinia (2008) found that the concentric X bracing laterally creates rigid structures but the BRB system produces a concurrent suitable rigidity, ductility and maximum overstrength factors for structures; so it confirms a better performance of the BRB system in the nonlinear range. Chang and Chiu (2011) show that the BRBFs can provide a high level of confidence, ensuring the building to achieve the performance objectives of immediate occupancy and life safety. So this study focuses on the evaluation of the seismic performance of SMFs retrofitted with different bracing systems. In accordance with Iranian code of practice for seismic resistance design of buildings (BHRC 2005), Iranian National Building

Code (Part 10) for Structural Steel Design (MHUD 2009) and seismic provision of AISC (2005), the SMFs were designed with insufficient lateral stiffness to satisfy code drift limitations in high seismic hazard zone. Therefor OCBFs with various slenderness ratios and BRBFs were used to retrofit. At last, the inelastic structural response has been expressed in terms of inter story drifts that are derived by 84 percent occurrence and using time-history nonlinear analyses for five earthquake ground motions.

2. Buckling restrained braced frames

With respect to the conventional concentrically braced frames, since much of the potential difficulties arise from differences between tensile and compression capacity of the brace as well as the degradation of brace capacity under compressive and cyclic loading, a considerable research has been conducted to develop braces with ideal elast-o-plastic behavior (Sabelli et al., 2003). The idea of Buckling Restrained Brace (BRB) frames was borne out of need to enhance the compressive capacity of braces without affecting its stronger tensile capacity in order to produce a symmetric hysteretic response. The BRB is composed of a ductile steel core, designed to yield during tension and compression both. To prevent the buckling phenomenon, the steel core is first placed inside a steel casing before it is being filled with mortar or concrete. Prior to mortar casting, an unbinding material or a very small air gap is left over between the core and mortar to minimize or possibly eliminate the transfer of axial force from steel core to mortar and the hollowness of structural section components of BRB (Fig. 1).

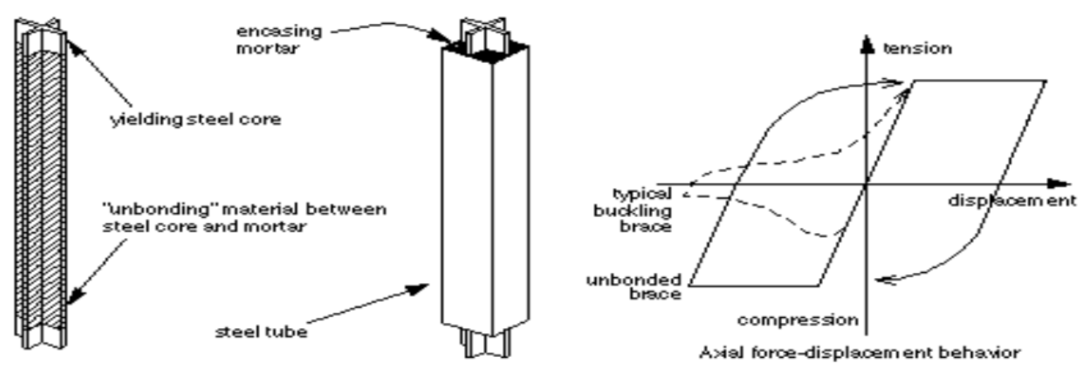


Fig.1. Typical cross section of a BRB and its hysteretic curve (Disarno et al., 2008)

Thus, the core in BRB under both tension and compression can undergo a considerable yielding, and absorb energy unlike conventional bracing. On the other hand, the basic structural framework in BRBF is designed to remain elastic and all of the seismic damage occurs within the braces (Sabelli et al., 2003).

3. Design of the models

3.1. Description of the sample frames

A 7-story and 18-story SMF building was designed by lateral stiffness that does not comply with inter story drift limitation imposed for structural systems in earthquake-prone regions, based on Iranian code of practice for seismic resistance design of buildings (BHRC 2005). Based on this code and Uniform Building Code 1997 (UBC 97), the maximum relative story displacement (Δ_m) is limited to:

$$\Delta_m < 0.025h \text{ , For For } \mathbf{T} < 0.7\, s \quad (1)$$

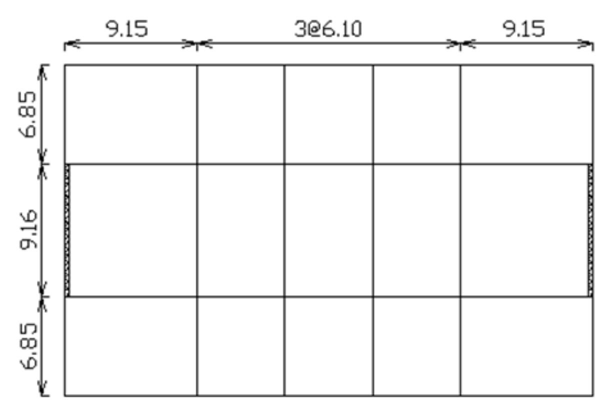
$$\Delta_m < 0.020h \text{ , For } \mathbf{T} \geq 0.7\, s \quad (2)$$

In which h and T are the inter story height and the fundamental period of the frame, respectively.

The multi-story frames have three bays. The length of left, right and middle bays is 6.85, 6.85 and 9.15 meter, respectively. The inter story height is 3.51 meter for all but the first floor which is 3.81 meter height. The dead and live loads of 3.21 and 0.958 KN/m^2 for roof, and 4.072 and 2.395 KN/m^2 for all floors, respectively, were used for gravity load. For member design subjected to earthquake, equivalent lateral static forces were applied on all the story levels. These forces were calculated following the provisions stated in Iranian code of practice for seismic resistance design of buildings (BHRC 2005). In this code, the design base shear was computed as follows:

$$\mathbf{C} = \frac{\mathbf{ABI}}{\mathbf{R}} \rightarrow \mathbf{V} = \mathbf{CW} \quad (3)$$

For this study, the importance factor of $\mathbf{I} = \mathbf{1.2}$, preliminary response modification factors of $\mathbf{R} = \mathbf{6}$ and seismic zone factor of $\mathbf{A} = \mathbf{0.35}$ (in areas with high earthquake hazard) were considered for frame design. The behavior factors B=2.75 and 1.86 were used for computing the fundamental period of structure T=0.89 s and 1.8 s, respectively, for 7 and 18 story frames constructed in soft soil. By computation of the equivalent weight of the 7 and 18 story building, the base shear of 7 and 18 story frames were resulted V=2707 KN and 3706 KN. For all frames, the equivalent viscous damping is assumed 5%. For both frames, the beam-column connection were assumed to be rigid at both ends and allowable stress design method was used to design frame members in accordance with part 10 of Iranian National Building Code for Structural Steel Design (MHUD 2009). To retrofit the SMFs with inadequate lateral stiffness, bracing was utilized. Reduction of inter story drift at third story of un-braced frames, which had maximum inter story drift among all stories, was the design target. To do so the inverted V braces in terms of ordinary concentrically brace and buckling-resistant brace were employed. These braces were connected to beams by pin joints (Fig. 2).



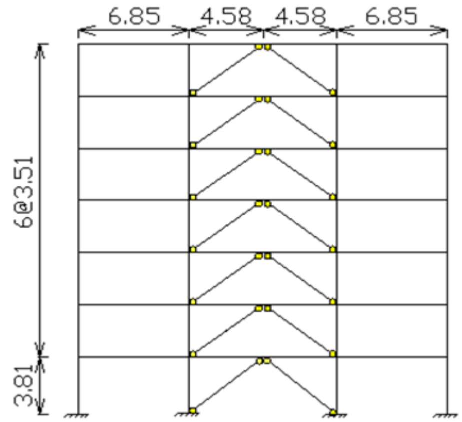


Fig.2. Typical plan and configuration of braced frame

One of the methods for increasing frame stiffness is increasing the strain hardening parameter for steel. To evaluate the effect of such parameter, the different strain hardening includes 1, 3, 5, 7 and 10 percent have been used in bilinear hysteretic model for all structural models in all analysis. According to UBC 97 (UBC 97) and Iranian National Building Code (MHUD 2009) the maximum slenderness ratio in bracing members is limited to $\frac{720}{\sqrt{F_y}}$, which, for normal A36 steel ($F_y = 36ksi$) is equal to 120. To assess the effect of this parameter, slenderness ratio is chosen prior to the design stage. Therefore, following the described requirements, slenderness ratios of 30, 60, 90 and 120 were selected for OCBFs. Also for example Sectional properties of seven story model structures with ordinary braces (Y=60) and buckling resistant braces is shown in Table 1.

Table.1 Sectional properties of seven story model structures with ordinary braces(Y=60) and buckling resistant braces.

Story	*Interior col.*	*Exterior col.*	*Conventional concentric braced*	*Buckling restrained brace*	*Beam*
1	Box150×150×10	Box150×150×10	2UNP120	PL50 × 15	IPE360
2	Box150×150×10	Box150×150×10	2UNP160	PL50 × 15	IPE360
3	Box150×150×10	Box150×150×10	2UNP180	PL50 × 18	IPE360
4	Box250×250×15	Box150×150×10	2UNP180	PL50 × 20	IPE360
5	Box250×250×15	Box150×150×10	2UNP200	PL50 × 20	IPE360
6	Box300×300×20	Box150×150×10	2UNP200	PL50 × 20	IPE360
7	Box300×300×20	Box150×150×10	2UNP220	PL60 × 20	IPE360

3.2. Ground motion records

By employing five severe Iranian earthquake ground motions with different frequency content, response- time history analyses were carried out. The seismological properties of the records used for this study are summarized in Table 2.

Table 2. Characteristics of selected earthquakes

Earthquake name	Date	Record//Component	Ms	PGA(g)	Duration(sec)
Bam	26/12/2003	Bam , LN	6.7	0.8	80
Roodbar	20/06/1990	Ab-bar, LN	7.7	0.65	46

Tabas	16/09/1978	Tabas , LN	6.7	0.86	33
Golbaf	14/03/1998	Kerman1, LN	6.9	0.37	43
Avaj	22/06/2002	Abgarm , LN	6.6	0.318	28

All earthquakes recorded in far-field conditions. These earthquakes have different levels of seismic hazard, between 10% and 2% probability of exceedence in a 50-year period. And also they were scaled Based on Iranian Instruction for Seismic Rehabilitation of Existing Buildings (MPO 2007) that is according to FEMA 356 (2000) for two levels of seismic hazards (life safety and collapse prevention).

3.3. Structural performance criteria

Based on Iranian Instruction for Seismic Rehabilitation of Existing Buildings (MPO 2007) three main structural performance levels, i.e. Occupiable, Life Safety and Near Collapse limit states are considered for the system assessment carried out in the present research. The relationship between overall seismic performance and maximum transient inter-story drifts is shown in Table 3.

Table 3. Structural performance levels

Performance level	Qualitative description	Damage type	Recommended transient drift (%)
SP-1	Occupiable	Light	0.7
SP-2	Life safety	Moderate	2.5
SP-3	Near collapse	Severe	5.0

Based on this Instruction, under design earthquake, with 10% probability of exceedence in a 50-year period (hazard level 1), the structures should have life safety performance level by maximum transient inter story drift 2.5% and under severe earthquakes with 2% probability of exceedenc in a 50-year period (hazard level 2), the structures should have near collapse performance level by maximum transient inter story drift 5.0%

3.4. Modeling the structures in software OPENSEES:

The computational model of the structures was developed using the modeling capabilities of the software framework of OpenSees. This software is finite element software which has been specifically designed in performance systems of soil and structure under earthquake. For modeling the members in nonlinear range of deformation, following assumptions were assumed:

• For the dynamic analysis, story mass were placed in the story levels considering rigid diaphragms action.

• For the modeling of braces, nonlinear beam-column element with the material behavior of steel02 was used.

• Considering idealized elastic-plastic behavior of steel material, compressive and tensile yield stresses were considered equal to the steel yield stress.

• The maximum ductility ratio of 4 was considered for member behavior in inelastic range of deformation.

• To evaluate the effect of strain hardening, the values of 1, 3, 5, 7 and 10 percent were considered for strain hardening in inelastic behavior of members.

• Geometric nonlinearities, i.e. P-Δ effects, were included in the elastic and inelastic analyses.

4. Statistical analysis of results

A statistical analysis considering the 84th percentile criterion was used. The 84th percentile means that the chance to exceed this value is 16%. If $\boldsymbol{X_1}, \boldsymbol{X_2}, \boldsymbol{X_3}, \ldots, \boldsymbol{X_n}$ are the results obtained from the analysis of models, then the logarithmic median can be obtained as follows:

$$\boldsymbol{\mu = e^{\ln \bar{X}}} \tag{4}$$

Where lnX⁻ is the average of the natural logarithm of response and is computed as,

$$\boldsymbol{\ln \bar{X} = \frac{1}{n} \sum_{i=1}^{n} ln X_i} \tag{5}$$

That n is the total number of cases analyzed which in this study it is equal to 5, $\boldsymbol{n = 5}$ It means five ground motions were adopted. The standard deviation, σ, is computed by following equation:

$$\boldsymbol{\sigma = [\frac{1}{n-1} \sum_{i=1}^{n} (\ln X_i - \ln \bar{X})^2]^{1/2}} \tag{6}$$

The 84th percentile is obtained in the following way,

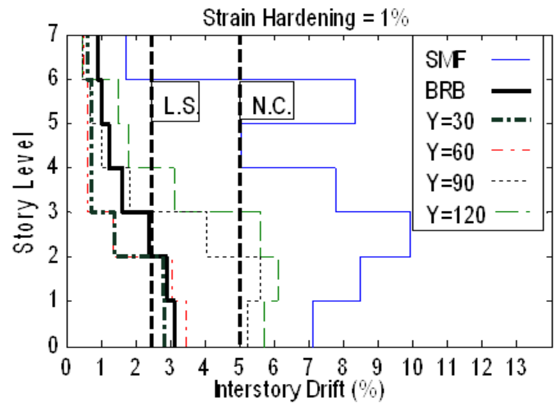
$$\boldsymbol{P_{84} = \mu . e^{\sigma}} \tag{7}$$

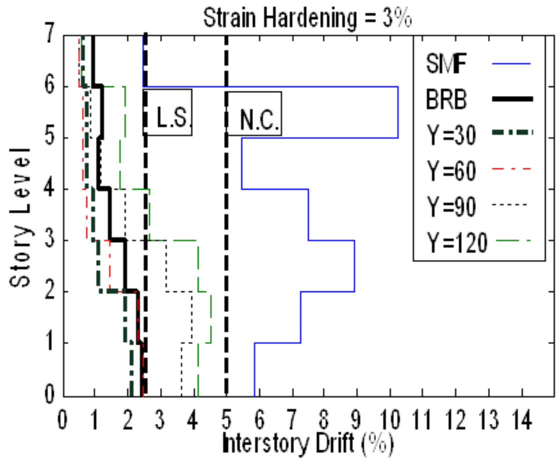
In this study, the maximum inter story drift under ith record was supposed X_i and consequently P_84 percentile shows the maximum response interstory drift with probability of occurrence of 84% in each story.

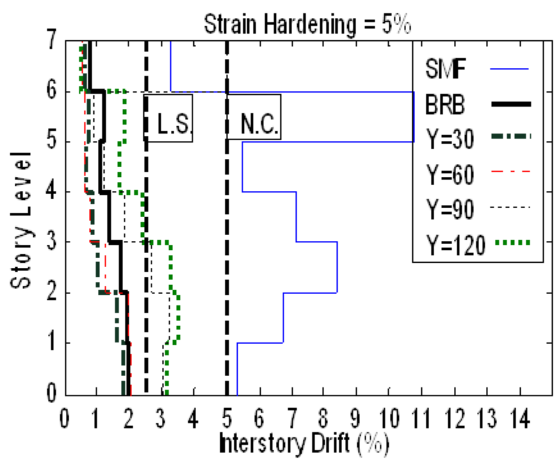
5. Structural performance assessment

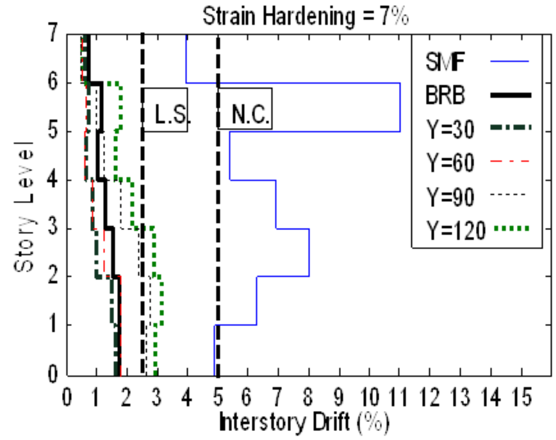
The maximum inter story drift experienced by the SMFs under the selected earthquakes exceeds the target inter story drift (5%), recommended by Iranian Instruction for Seismic Rehabilitation of Existing Buildings (MPO 2007) for near collapse performance level. The maximum inter story drifts were found for Bam earthquake. Bracing is the simplest solution to reduce these large drifts and therefore these poorly behaved SMFs were retrofitted by various types of braces. In total 55 cases were analyzed using OPENSEES for frames with 7 and 18 stories, with different slenderness ratios (Y=30, 60, 90 and 120), BRB configuration and various strain hardening parameters (1%, 3%, 5%, 7% and 10%). Each of them was analyzed for the five different ground motions. Fig.3 and Fig.4 present the results corresponding to 84th percentile of the maximum inter story drift associated with the different strain hardenings for each of the analyzed models. In this figure the lines corresponding to 2.5% (Life Safety) and 5% (Near Collapse) drifts have been included in the plots as benchmarks.

Fig.3 and Fig.4 show that frames with conventional braces show irregular patterns of deformation under earthquake excitation, with tendency to concentrate large deformation levels in one or more stories. It is shown that BRBFs exhibit a more stable behavior than conventional braces. This does not necessarily mean that the relative displacements will be smaller, but the response will be more uniform along the frame height.









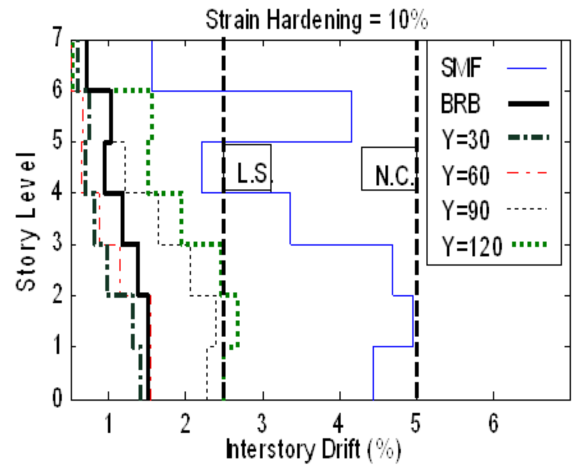
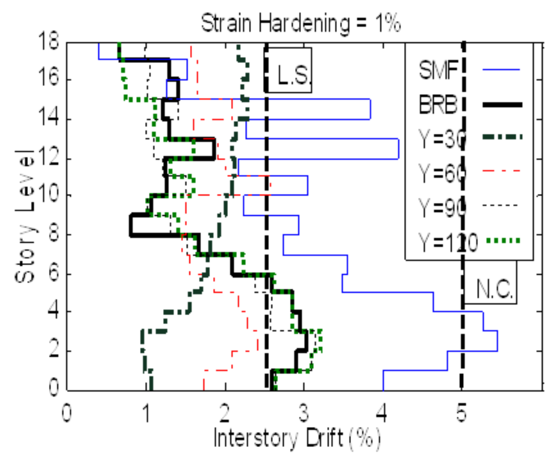
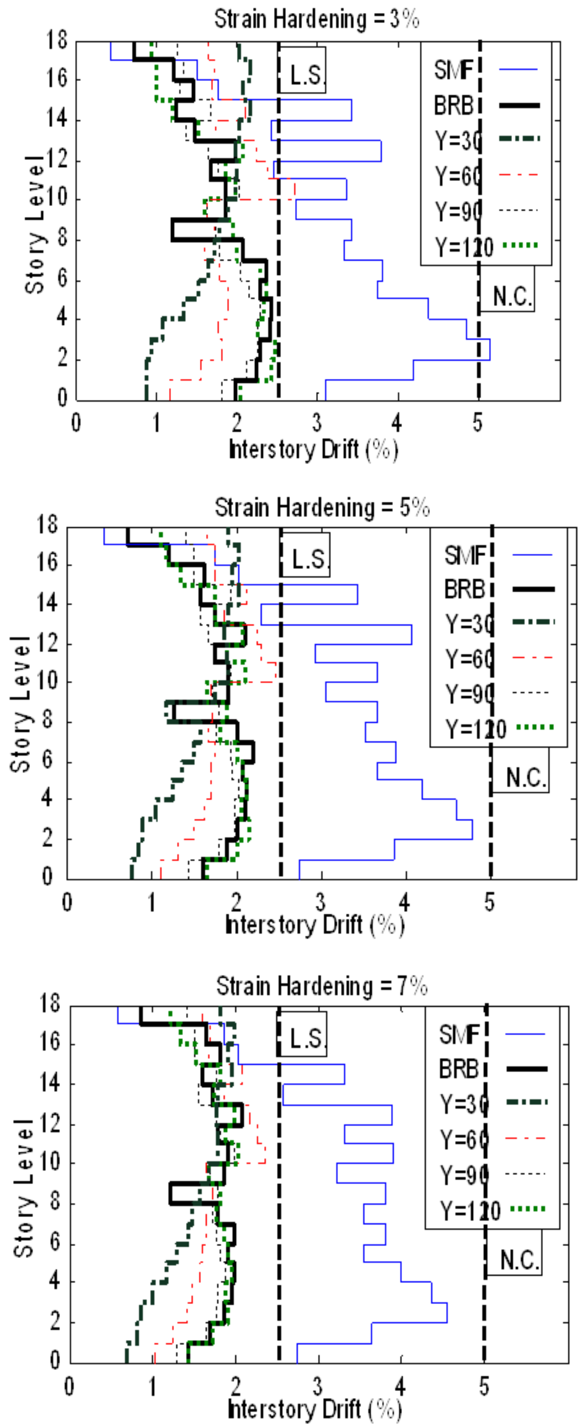


Fig.3. Inter story drifts for frames with seven-stories with different slenderness ratios and various strain hardening parameters





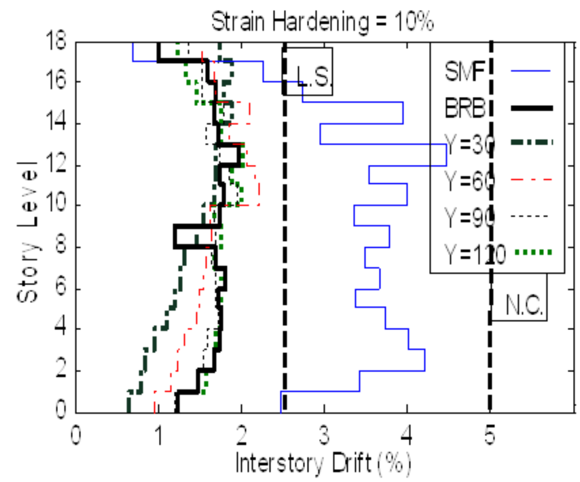


Fig.4. Inter story drifts for frames with eighteen-stories with different slenderness ratios and various strain hardening parameters

Also these figures show that, in all of the analyses, BRBFs present a more stable and uniform response along the frame height, especially in the cases that the P-Δ effect becomes less important in the final response. This result is the same as the one that was obtained by Di Sarno and Manfredi (2010). The responses obtained for all the configurations of normal braces depend on the selection of the slenderness ratio, Y, and it presents different behaviors. The most uniform behavior is obtained for Y=30, particularly in seven-story frame, and it becomes more fluctuating as the slenderness ratio increases. The response obtained for the two frames, seven-stories and eighteen-stories, shows the effect of the variation of the strain hardening parameter in the general response. As the strain hardening is larger, the inter story drift displacements will become smaller. For small values of strain hardening the displacement response varies significantly along the height and presents evident signs of immediate collapse. But for large strain hardening of all slenderness ratios, inter story drift remained smaller than 2.5% (life safety performance level) that it shows the stability of frames. On the other hand, for high values of strain hardening, i.e. 5% to 10%, variation on the relative displacements is small, and therefore the behavior of the frame in these cases is more similar.

From these results it is possible to infer the strong influence of the P-Δ effect on the general stability of the system. Low strain hardening does not provide the necessary stiffness to neutralize the P-Δ effects and therefore the entire stability is affected. While for large strain hardening, the P-Δ instability is overcome. Following this reasoning, it can be seen that the P-Δ effect is neutralized with a strain hardening about 3%, and it infers that the behavior of frame is determined mainly by the braces.

Fig.5 shows that BRBFs has the higher capacity and dissipate energy than OCBF, because of complete behavior hysteresis. Therefor it results in a better performance under nonlinear dynamic analysis, and better and more uniform responses in the stories. Also with considering the buckling ordinary brace in compression, the inter story drift in some stories will increase and finally there will be a total collapse in structure. With increasing the cross section area of ordinary braces, the inter story drift of all structure can be controlled, for example (the response of the normal buckling braces with slenderness ratio Y=30 are very similar to the BRBF, particularly for the seven-story frame) but the cycling behavior in dissipating the energy can't be changed, and finally the suitable performance from BRBF can be obtained.

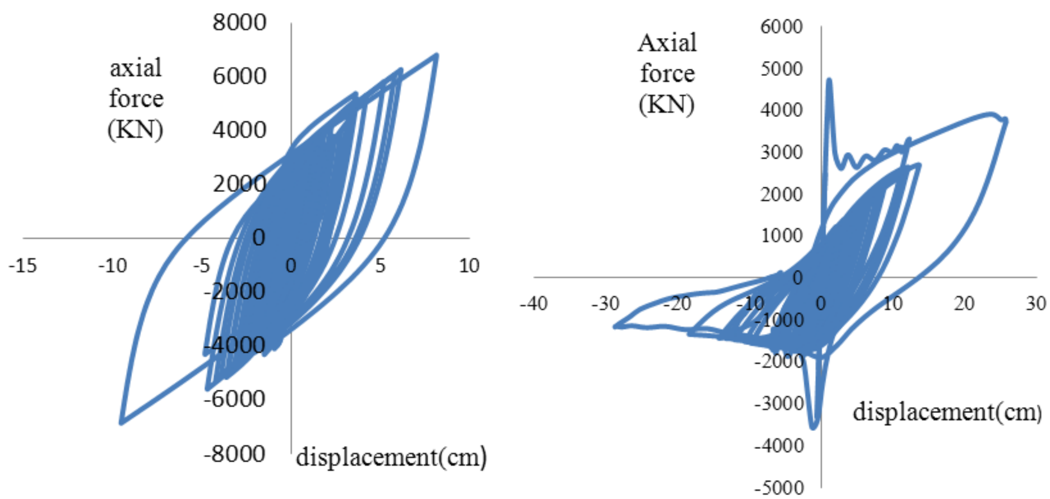


Fig.5. hysteresis behavior of ordinary brace (Y=60) in seven-stories (right) and buckling resistant brace (left)

6. Conclusions

1- The strain hardening parameter has a considerable effect on the response of the system, particularly when low values are used, i.e. from 1% to 3%. As this value increases, the P-Δ effect is not considered and its effect on the response becomes less important. For higher values, i.e. 7% and 10%, this effect is almost negligible, and the response is almost strain hardening independent. A strain hardening factor of 3% is demonstrated to be adequate to overcome the effects of the P-Δ action.

2- Behavior and response of conventional bracing systems highly depends on the selection of the slenderness ratio. Although any chosen value, smaller than the maximum permitted (Ymax=120 for A36 steel), will satisfy the design requirements, the different values of Y will produce different cross sectional areas and stiffness, and very different responses. It is notable that stocky members, with low slenderness ratios, tend to provide more uniform responses along height. On the contrary, the response with slender members varies significantly along the height of the frame.

3- As the slenderness ratio increases, the appearance of concentration of inter story drift in some stories is more vivid.

4- The obtained deformation of BRBFs is generally a midpoint between the different options (in terms of the slenderness ratio) of normal buckling braces and it does not have the smallest deformations on the frame.

5- Normal buckling braces with low slenderness ratio behave similar to the BRBFs. However, these members require large cross sectional areas and may not be suitable for real applications due to architectural and economical limitations.

6- Comparing the behavior of all possible configurations of normal buckling braces and BRBFs, the response of retrofitted frame with BRBs is very uniform along its height, without any sudden changes in the deformation pattern in respect of the level of deformation, and without concentration of deformation in one story, particularly in seven-story frame.

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