USE OF ASYMMETRIC BUCKLING-RESTRAINED BRACES IN ZIPPER FRAMESFOR IMPROVEMENT OF PEAK AND RESIDUAL RESPONSE

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ABSTRACT

Buckling-restrained braces (BRBs) are known to improve the energy dissipation properties of structures by preventing the bracing elements from buckling in compression. As a result, structures equipped with BRBs exhibit better performance mainly in terms of maximum responses. On the other hand, the bilinear behaviour and usually low post-yield stiffness of these devices may lead to undesirable permanent drifts. An asymmetrical configuration of BRBs along with zipper elements is considered in this study to reduce the residual drifts without increasing the peak response values. This way, the advantages of zipper frames, namely the more uniform distribution of drifts along the elevation and the reduced demands on beams are combined with the enhanced energy dissipation properties of the BRBs to improve the overall seismic response of structures. Nonlinear time-history analyses have been carried out for low- and mid-rise buildings to investigate the effects of the proposed configuration on the response characteristics of the structure. It is shown that the asymmetrical configuration of BRBs together with zipper elements proposed herein is an effective approach for reduction of residual response parameters while keeping the peak demands as low as those of ordinary frames equipped with symmetrical BRBs.

INTRODUCTION

Among the failure modes that are identified for inverted-V (concentric chevron) braced frames, formation of soft story mechanisms is thought to be the most prominent. This usually occurs due to the compression buckling of one of the braces in a story, leading to large amounts of unbalanced forces on beams. Due to their architectural appeals, considerable research has been dedicated to the improvement of these configurations (Uriz and Mahin, 2008). The improved configurations include (i) the addition of zipper struts designed to transfer the unbalanced loads to the upper stories proposed by Khatib et al. (1988) and studied by many others (Yang et al., 2008; Chen and Tirca, 2012, Tirca and Chen, 2012), and (ii) the use of special energy dissipation devices in place of braces such as friction and viscous dampers and buckling-restrained braces (BRBs) (Uang and Nakashima, 2003), designed to show identical behaviors in tension and compression. Particularly, the BRBs are relatively low-cost elements that achieve this goal by encasing the bracing elements in a filled hollow steel pipe that provide an almost continuous lateral bracing to inhibit the lateral buckling in compression.

While the use of BRBs in frames is known to improve the overall energy dissipation capacity of the structure and reduce the peak seismic responses, such frames usually suffer from significant amounts of residual deformations following earthquake events. Sabelli et al. (2003) reported that residual inter-story drifts may reach up to 40% of the maximum inter-story drift. In this study, the mean peak and residual drift values for a 6-story buckling-restrained braced frame (BRBF) subjected to a suite of ground motions corresponding to 2% probability of exceedance in 50 years from the SAC database (Sumerville, 1997) were recorded to be 4.5 and 2.2%, respectively. These large residual drifts usually make the structure unusable after a major earthquake and are associated with large retrofit costs. Hence, considerable research has been dedicated to improving the residual drift problem of BRBFs. Among them, Uang and Kiggins (2006) used BRBs in moment frames to create dual systems that showed significant improvements of residual and maximum drifts. Such design, however, was shown to create concerns over the adequacy of connections. Chao et al. (2013) proposed the usage of BRBs in a few lower levels of the concentrically braced frames, whereby the overall performance was shown to improve, but the residual response was not studied. Vaezzadeh (2013) proposed a novel structural configuration consisting of BRBs of varying yield strengths within each story of a building, showing that this can improve the residual response of BRBFs without severely affecting the peak demands. Such configuration, however, will require the use of the different BRBs in an X-braced span, or when dictated by architectural requirements, as multiple symmetric chevron-braced ones to avoid the exertion of large unbalanced force to the beams or formation of soft stories.

Alternatively, as explored herein, asymmetrical BRBs can be installed in an inverted-V configuration within a single span of a story, provided that the unbalanced forces at the chevron vertex are handled properly. This can be achieved using zipper elements that transfer the unbalanced forces to the braces in the upper stories. In addition to substantially reducing the unbalanced force demands on beams and preventing the concentration of damages in a single story, the zipper elements have been known to help better distribute the lateral force demands throughout the elevation (Yang et al., 2008). In this study, it is shown that, in addition to the architectural advantages of single-span chevron bracing, the use of asymmetric BRBs in zipper frames is very effective in the reduction of the usually-significant residual drift response, while keeping the peak demands near their minimum.

BUILDING MODELS AND ASSUMPTIONS

Two steel buildings with 3- and 6-story steel braced frames previously studied by Sabelli et al. (2003) are re-designed in this study according to the ASCE (2010) provisions. As shown in Fig. 1, only one of the braced peripheral spans (circled) in the north-south direction of each building is modeled. This is carried out by considering the rigidity of floor diaphragms and symmetry of the structures in plan. The dotted closed areas in Fig. 1 indicate the location of the penthouses.

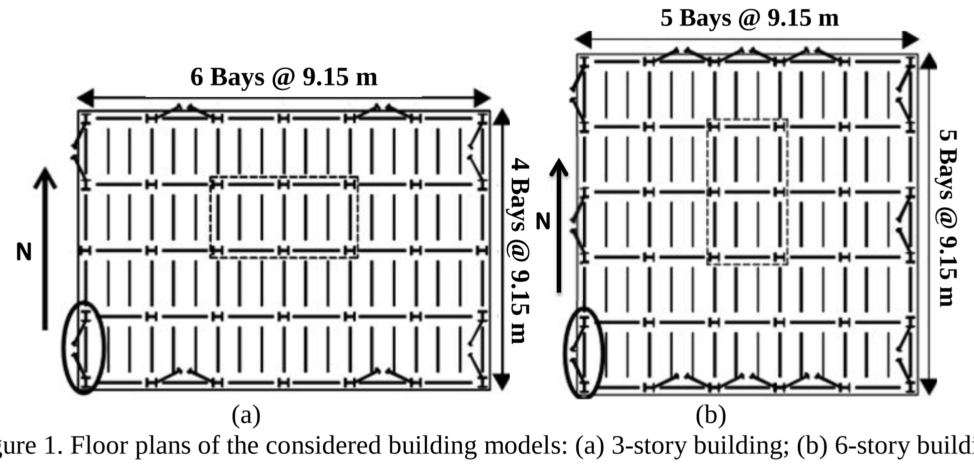


Figure 1. Floor plans of the considered building models: (a) 3-story building; (b) 6-story building

The buildings are assumed to be located at downtown Los Angeles on soil type S_D. The loadings used for the analysis of the frames include floor dead (4.6 kPa and 4.12 kPa for calculation of weight and mass, respectively), roof dead load (3.97 kPa plus 5.55 kPa for the penthouses), and reduced live load (9.58 kPa). The seismic mass for the 3-story structure is then 1035 kN.s^2/m for the roof and 956 kN.s^2/m for the other floors. These values for the 6-story structure are 1067 and 990 kN.s^2/m, respectively.

The factor of the material over-strength (R_y), compression strength adjustment (β), and strain-hardening adjustment (ω) are taken to be 1.3, 1.1, 1.4, respectively, in the design of BRBs per AISC recommendations. Two parallel designs are carried out using two response reduction factor (R) values of 6 and 8 based on ASCE (2010). These values are selected based on general variations of the fundamental periods of the low- and mid-rise braced frames. More details on these selections will be presented in the next section. The steel grade is assumed to be A992 Gr.50 (nominal Fy = 345 MPa) for all beams and columns with the material over-strength factor (R_y) of 1.1. The nominal yield strength, F_y, for the BRBs is 248 MPa. Detailed design parameters are summarized in Table 1. An elevation of the structure showing member sections and brace cross-sectional areas (mm^2) for R values of 6 and 8 is illustrated in Fig. 2.

Table 1. Parameter values used in design

Design parameters	**3-story braced frame**	**6-story braced frame**
5%-damped design spectral accelerations at short and 1 second periods, S_{DS}, S_{D1} (g)	1.393, 0.77	1.393, 0.77
Design period, T (sec)	$T = T_a = C_t h_n^{\,x} = 0.02\times(11.9\times0.3048^{-1})^{0.75} = 0.31$	$T = 0.02\times(25.3\times0.3048^{-1})^{0.75} = 0.55$
Response reduction factors, R	R = 6, R = 8	R = 6, R = 8
Base shear coefficients, C_s (corresponding to R = 6, 8, respectively)	$C_s = \frac{S_{DS}}{R/I} = \frac{1.393}{R} = 0.232, 0.174\ (\le \frac{S_{D1}}{(R/I)\times T})$	$C_s = 0.232, 0.174$

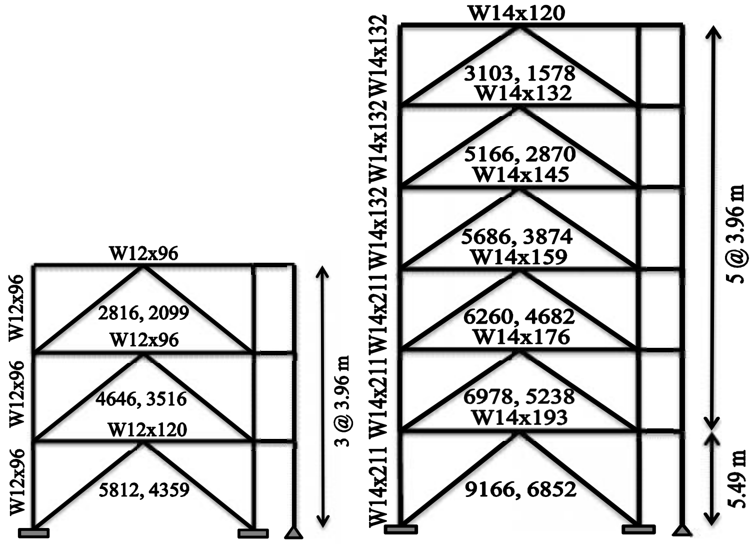


Figure 2. Elevations, member sections and BRBs' area for the 3- and 6-story frames

OpenSees software was used for modelling and analysis of the frames (Mazzoni et al., 2006). As shown in Fig. 2, the $P-\Delta$ effects for the gravity frames were considered by adding a set of pinned gravity columns constrained to the main frame at each floor. Numerical modelling of the BRBs was carried out using uniaxial corotTruss elements with Menegotto material model whose initial elastic stiffness and secondary stiffness were calibrated to previous uniaxial tests of the BRBs (Black et al., 2004).

STUDY FRAMES AND OPTIMIZATION RESULTS

Each braced frame introduced previously is studied in three cases of brace configurations and horizontal and vertical distribution of brace cross-sectional areas, as listed in Table 2. As shown, the first configuration corresponds to an ordinary design of inverted-V braced frame, while others represent structures in which brace cross-sectional areas are distributed vertically and horizontally. For performance comparisons, two dimensionless relative performance indices (RPIs) are defined, one of which considers the acceleration and drift responses and the other considers the residual drift, both normalized by the corresponding values from the originally designed frame, designated as 3(6)IVB-R=6:

$$\mathrm{RPI\ 1} = 0.5\frac{D}{D_0} + 0.5\frac{A}{A_0},\ \ \mathrm{RPI\ 2} = 0.5\frac{RD}{RD_0} \qquad (1)$$

where D and A are the maximum values of the inter-story drift and absolute acceleration, respectively. Also

RD is the largest absolute value of the residual inter-story drift recorded at the end of the earthquake simulation. These maximum values can occur anywhere along the elevation of the buildings. The values of D_0, A_0 and RD_0 corresponding to the base frames are obtained to be 1.9%, 8.84 m/s^2 and 0.24%, respectively for 3IVB-R=6 and 1.4%, 11.24 m/s^2 and 0.24% for 6IVB-R=6.

Table 2. Description of the considered cases of bracing configurations

Designation	Description
3(6)IVB-R=6,8	The original frames designed according to the ASCE (2010) with the response reduction factors of 6 or 8
3(6)IVB	A 3- or 6-story inverted-V BRBF obtained by distributing the brace cross-sectional areas along the elevation
3(6)ASZ	A 3- or 6-story zipper braced frame with asymmetrical chevron BRBs obtained by distributing the cross-sectional areas of the individual braces within each story

The distribution of cross-sectional areas of the BRBs over the height of the structure can be defined by an $N \times 1$ vector (where N = 3 or 6) as **A**= $\{A_i\}$ in which $1 \le i \le N$. There are several ways to determine constraints on the values of bracing cross-sectional areas, such as considering the maximum acceptable inter-story drift. The approach used in this study consists of using two response reduction factor (R) values of 6 and 8, each providing a bounding value of bracing cross-sectional areas, while the gravity load carrying elements remain the same. The selected R values are in agreement with a number of pioneering research publications in this field (Sabelli et al., 2003; Chao et al., 2013). Based on these assumptions, the constraint inequalities governing the brace cross-sectional areas (in cm^2) are given by:

$$\text{3IVBs: } 40 \le A_1 \le 60, 30 \le A_2 \le 50, 20 \le A_3 \le 40 \quad (2)$$

$$\text{6IVBs: } 70 \le A_1 \le 90, 50 \le A_2 \le 70, 45 \le A_3 \le 60, 40 \le A_4 \le 55, 30 \le A_5 \le 50, 15 \le A_6 \le 30 \quad (3)$$

The base excitation records are taken from the SAC/FEMA joint venture project on steel moment-resisting frames and representative of ground motions for downtown Los Angeles soil type S_D for the hazard level corresponding to 10% probability of exceedance in 50 years. While all 10 pairs of ground motions (Sumerville, 1997) were used in performance comparisons, only the record numbers LA01 (Imperial Valley, 1940, El Centro), LA12 (Loma Prieta, 1989, Gilroy) and LA16 (Northridge, 1994, Newhall) were considered in design. The optimization problem for the symmetric configuration of braces would then be finding the optimum distribution of brace cross-sectional areas $\{A_i\}$, constrained by Eq. (2) or Eq. (3) to minimize either of the relative performance indices introduced in Eq. (1). This optimization procedure is carried out by developing a program written in the MATLAB environment, linking OpenSees and MATLAB software for building and analyzing all the frames that are in the constrained domain.

Fig. 3 shows RPI values for building models with symmetrical configuration of braces (labelled 3(6)IVBs in Table 2) during the optimization. Each graph represents an attempt to minimize one of the performance indices while merely showing the value of the other index. This will then result in two design alternatives, one optimizing RPI 1 (labelled 3(6)IVB$_{opt,\ RPI\ 1}$) and the other optimizing RPI 2 (labelled 3(6)IVB$_{opt,\ RPI\ 2}$). As shown in Fig. 3 (a) and (c), it can be observed that RPI 1 can be reduced by 6 and 11% in the 3- and 6-story frames, respectively, without constraining the value of RPI 2. In the same order, the amounts of reduction in RPI 2 are observed to be 26% and 28% as illustrated in Fig. 3 (b) and (d). These reductions in individual performance indices, however, are usually associated with an increase in the other performance index. In other words, it can be observed that keeping both peak and residual response near their minimum is impossible in the symmetrically-configured frames by only modifying the distribution of cross-sectional areas through the elevation.

Next, it is attempted to improve the response by asymmetrically distributing the brace cross-sectional areas in the same frames with addition of zipper elements to help carry the unbalance forces. For this purpose, the 3(6)IVB$_{opt,\ RPI\ 1}$ model that was optimized for RPI 1 by finding a proper distribution of brace cross-sectional areas through the elevation is redesigned with asymmetric brace cross-sectional areas in each story. This is carried out by finding the optimum values of the brace area ratios within each story (defined as {i,j,k} or {i,j,k,r,t,w} for 3- and 6-story frames, respectively), leading to another group of models designated as 3(6)ASZs in Table 2. An area ratio equal to 0.5 indicates that the cross-sectional areas of each BRBs placed in the corresponding story are the same. On the other hand, an area ratio of 0.9 is considered to be the maximum practical value, indicating the cross-sectional area in one brace is 9 times greater than that of the other. It should be noted that the sum of the cross-sectional areas of the BRBs in each story is kept equal to those when the braces were configured symmetrically.

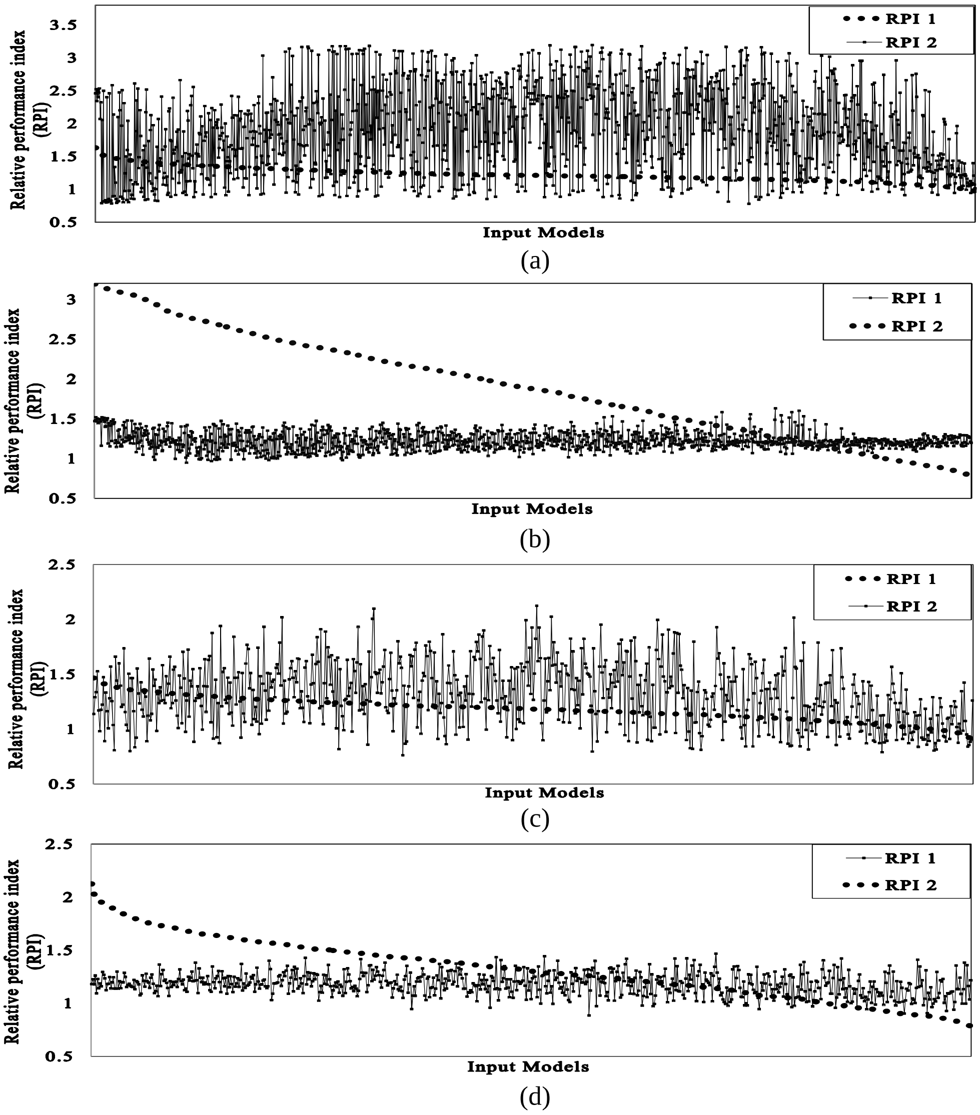


Figure 3. RPI values during optimization: (a) RPI 1 for 3IVBs; (b) RPI 2 for 3IVBs; (c) RPI 1 for 6IVBs; (d) RPI 2 for 6IVBs

Due to the asymmetry of cross-sectional areas, vertical unbalanced forces will be produced at the vertex of chevron BRBs. In zipper frames, these forces are transferred to the BRBs in the upper stories. The zipper struts should then be designed elastically to ensure their proper functioning, as proposed by Tirca and Chen (2012). Hence, these elements at each story are simply designed as a compressive element for a square root of the sum of the squares (SRSS) of the unbalanced vertical forces that can be transmitted from the stories below and the story under consideration. As an example, Fig. 4 shows the elevation view of 3ASZ models along with the selected sections for zipper elements.

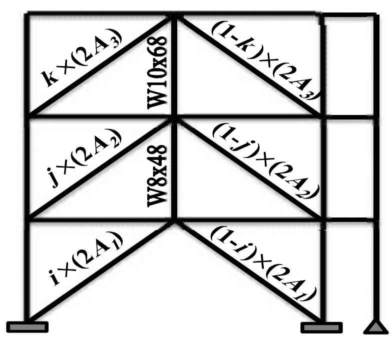
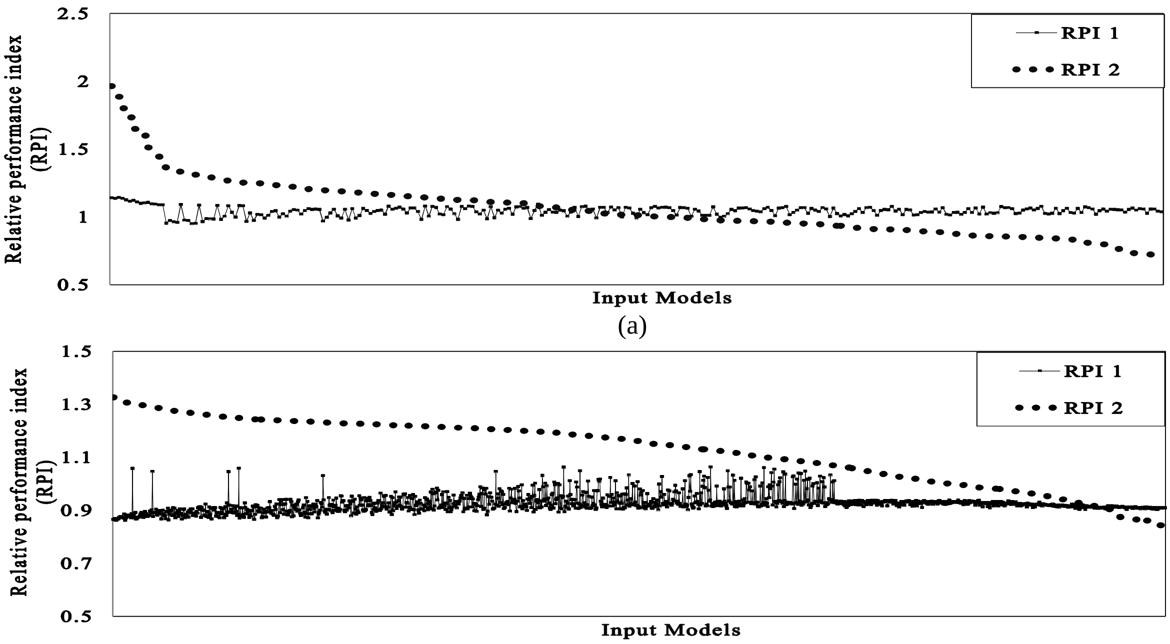


Figure 4. Schematic elevation of 3ASZ models

The optimization progress for minimization of RPI 2 for 3(6)ASZ models (previously optimized to minimize RPI 1) is shown in Fig. 5. As indicated, the values of RPI 1 for 3(6)ASZ frames remain almost unchanged while RPI 2 can still be reduced.



(a)

(b)

Figure 5. RPI 2 values during optimization for the asymmetric inverted-V bracing configuration with zipper columns: (a) 3ASZs; (b) 6ASZs

The properties of the optimized models and the amounts of response reductions are summarized in Table 3. As indicated, for the considered excitations, the maximum residual inter-story drift (*RD*) for the optimized 3ASZ (3ASZ$_{opt}$) is 0.17%. This is about 30% smaller than that obtained in the corresponding symmetrical BRBF with BRB cross-sectional areas optimized for RPI 1 (3IVB$_{opt,\ RPI\ 1}$), while the peak demands (*A* and *D*) of both configurations are close together. For the 6ASZ$_{opt}$ model, the *RD* value is 0.2%, which is about 9% smaller than that in the 6IVB$_{opt,\ RPI\ 2}$, both having about the same amounts of the maximum demands (*A* and *D*). It should be noted that the fundamental periods of the frames remains almost constant in the considered design alternatives. This implies that the performance improvement resulting from the proposed configuration is not a mere result of a change in lateral stiffness or a shift in natural period of vibration. Rather, this phenomenon is attributed to the better distribution of plastic energy dissipation through the elevation of the structure, which is achieved by utilizing zipper struts.

Table 3. Summary of the optimization results

Properties	**3IVB$_{opt,\ RPI\ 1}$**	**3IVB$_{opt,\ RPI\ 2}$**	**3ASZ$_{opt}$**	**6IVB$_{opt,\ RPI\ 1}$**	**6IVB$_{opt,\ RPI\ 2}$**	**6ASZ$_{opt}$**
T (sec)	0.447	0.489	0.509	0.744	0.724	0.746
A ($\frac{m}{sec^2}$)	8.35	13.30	7.91	9.92	12.91	10.10
D (%)	1.84	2.73	2.03	1.32	1.83	1.31
RD (%)	0.24	0.18	0.17	0.22	0.19	0.20
BRB areas (cm^2)	{60,50,30}	{56,30,36}	{60,50,30}	{70,70,60,55,30,30}	{90,70,45,55,50,30}	{70,70,60 ,55,30,30}
Area ratios	-	-	{0.9,0.65,0.5}	-	-	{0.5,0.5,0.65 ,0.5,0.5,0.5}
RPI 1	0.946	1.47	1.037	0.903	1.216	0.910
RPI 2	1.014	0.74	0.678	0.902	0.763	0.837

Finally, the maximum and residual inter-story drifts are studied over the elevation of the considered structures. Fig. 6 shows the drift ratio profiles obtained for the considered excitations in the different bracing configurations of 3-story frames considered in this study. While the previous research has shown the concentration of drifts in only one story or a few stories of concentrically braced frames and BRBF systems (Sabelli et al., 2003; Chao et al., 2013), it can be observed that the drift ratios are more uniformly distributed when the proposed asymmetrical configuration of BRBs is used with zipper elements, particularly in low-rise frames. The damage concentration in ordinary frames is usually attributed to the small post-yield stiffness of BRBs. However, the zipper elements are shown here to provide some additional lateral support for the stories with yielded braces by transferring the unbalanced forces to upper stories, thus helping distribute the drifts more uniformly along the structural elevation.

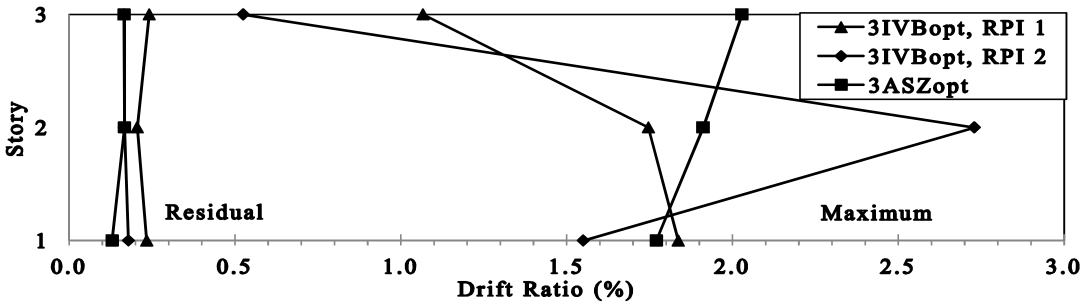


Figure 6. Maximum and residual inter-story drift ratio profile for 3-story frame

CONCLUSIONS

This paper presents a novel structural configuration using asymmetrical BRBs in zipper frames to improve the performance of BRBF systems by reducing the maximum and residual response simultaneously. For comparison purposes, various braced frames with different configurations of BRB elements and zipper struts were studied using nonlinear time-history analyses. Particularly, the ordinary BRBFs are known to be prone to significant residual drifts, and any attempt to reduce the residual response is usually associated with an increase of peak demands. The proposed bracing configuration, however, makes it possible to combine the benefits of BRBs with those of zipper elements in a cost-effective manner, allowing for the concurrent participation of braces along the structural elevation to improve the seismic response. This is achieved by the aid of zipper elements that transfer the unbalanced forces (produced by unequal brace cross-sectional areas) to upper stories, providing some additional support for lower stories, which otherwise would show very small post-yield stiffness. It is shown that in this manner, the amount of reduction in residual drifts may reach up to 30% compared to symmetrical configurations, while keeping the peak demands near their minimum.

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