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COMPARISON OF LOW-RISE STEEL CHEVRON AND SUSPENDED ZIPPER BRACED FRAMES

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Abstract. *This study compares the nonlinear behaviors of low-rise steel chevron and suspended zipper braced frames. A suspended zipper braced frame has the same configuration with a chevron braced frame except for the zipper struts attached between the story beams and a heavy truss system between the top two stories. These zipper struts redistribute the unbalanced vertical force resulting from the buckling of the compression braces; as a result, they eliminate the use of stiff beams. Three-story frames for both configurations are analyzed under static and dynamic loads. For each analysis, member deformations, member forces, story drifts and base shears are collected. The beams, columns and braces are modeled by using nonlinear force-formulation frame elements, and the section response is obtained by fiber discretization. The nonlinear geometric effects are included by adopting corotational transformation. The results appear to indicate that both configurations provide similar lateral stiffness and base shear capacity. In addition, the suspended zipper braced frame demonstrates more uniform inter-story drifts along the building height.*

1 INTRODUCTION

The chevron, or inverted-v [Figure 1(a)], is one of the most popular concentrically braced frame (CBF) configurations used in engineering practice. Acting as a cantilevered vertical truss under a lateral load, in each story one brace resists the lateral load in tension; in contrast, the counter one develops compression. Up to the buckling of the compression brace, the resultant force acting on the mid-span of the intersecting beam has a horizontal component only. After the buckling of the compression brace, the axial load capacity of the compression brace reduces significantly while the axial load capacity of the tension brace is retained, which results in a resultant force on the beam with components in both vertical and horizontal directions. The vertical component of the resultant force causes large bending moment demands in the beam, which will lead to plastic hinging in the beam, soft story formation and potential collapse unless a deep and heavy beam is used and designed in accordance with capacity design requirements as prescribed in AISC Seismic Provisions [1].

Khatib et al. [2] proposed adding zipper columns between the beams from the first story to the roof to transfer the vertical component of the resultant force of the story braces to the adjacent stories to eliminate the use of heavy story beams. In this configuration, the inelastic action is expected to be distributed more uniformly along the building height. The main drawback of this configuration is that there will be hinging in the beams when all the compression braces buckle and no further redistribution of the vertical forces is possible [3].

Leon and Yang [4] enhanced the configuration by adding a suspension system between the top two stories called hat truss. The hat truss system is to be designed to remain elastic when the system reaches its ultimate capacity, so that instability and collapse is eliminated. This CBF configuration is called suspended zipper braced frame (SZBF) [Figure 1(b)].

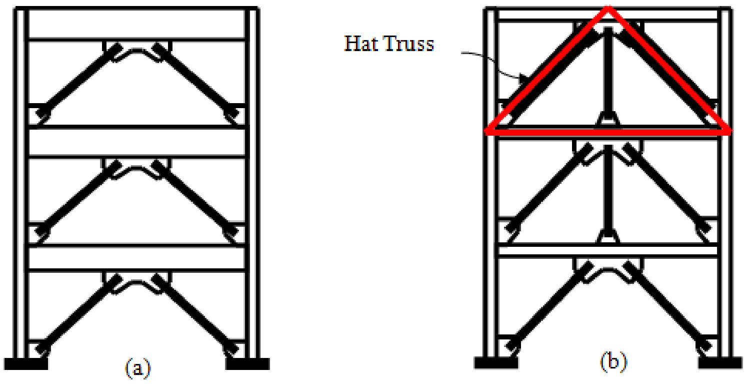

Figure 1: Chevron (a) and suspended zipper (b) braced frames

Although the behavior of SZBFs has been investigated by other researchers [3,4,7], a detailed comparison of an inverted-v braced frame (IVBF) and a SZBF designed for the same lateral load demand is not available. In this study, the performances of a three-story building designed as IVBF and SZBF under static and dynamic loads are compared.

2 METHODOLOGY

To compare the performances of the low-rise IVBF and SZBF, a two-dimensional three-story building designed for both brace configurations are analyzed under static and dynamic loads using OpenSEES[5].

2.1 Analytical Model

The three-story prototype building described in the SAC steel project [6] located in downtown Los Angeles was designed using SZBFs by Yang et al. [7] following the procedure outlined by Yang et al [4,7]. The building was assumed to have six SZBFs in north-south direction of the building. The equivalent lateral load method of IBC2000 [8] was implemented for the mapped spectral accelerations of 2.16 g and 0.72 g for the short period and the 1 s period, respectively. The building was assumed to stand on a stiff soil profile which is classified as class D in ASCE7-05 [9] and to be a critical structure which yields an importance factor of 1.5 as per ASCE 7-05 [9]. A response modification factor of 6 was assumed for the SZBF, which is equal to the response modification factor of a special steel concentrically braced frame.

The authors of this study removed the hat truss and zipper columns to turn the frame into an IVBF. The story beams are redesigned as per AISC Seismic Provisions [1] to carry the gravity loads and resist the vertical component of the resultant of the story braces after the buckling of the compression brace. The total seismic weight is calculated as 4821 kN and the design base shear is 1736 kN for both frames. The fundamental periods of the IVBF and the SZBF as determined by numerical models, are 0.34 s and 0.35 s, respectively.

All connections are assumed to be simple connections. The gravity load on the braced frame is neglected and the gravity load at each story level is applied to an axially rigid leaner column connected to the braced frame to account for P-Δ effects. ASTM A500 Grade B steel with the nominal yield strength of 317 MPa is used for braces and zipper columns and ASTM

A572 Grade 50 steel with the nominal yield strength of 345 MPa is used for columns and beams. The member sizes for the IVBF and the SZBF are tabulated in Table 1.

Table 1: Member sizes for the IVBF and the SZBF

Story	Beam-SZBF	Beam-IVBF	Column	Brace	Zipper C.
1	W10x88	W44x290	W12x96	HSS 8x8x5/8	-
2	W10x88	W44x262	W12x96	HSS 8x8x1/2	W 12x45
3	W8x58	W44x262	W12x96	W 14x132 (SZBF) HSS 8x8x1/2(IVBF)	W 12x96

2.2 Brace Model

The modeling of brace cyclic behavior is crucial in the analytical model to obtain realistic results. In this study, the brace model proposed by Uriz et al. [10] is adopted to achieve a proper buckling behavior. The model requires the brace to be divided into two distributed-plasticity forced-based nonlinear frame elements with an initial imperfection defined at the mid-length of the brace. The imperfection value of L/500 (where L is member length) given in the AISC LRFD Manual [11] is selected for this study. Corotational transformation is to be used to capture the effects of transverse displacements at the mid-length of the brace, as a result, to capture the brace buckling behavior. The interaction between the axial load and the bending moment in each section is achieved by the integration of the uniaxial stress-strain relation of the fibers over the cross-section. The effect of the shear stress is neglected. The inelastic response is monitored at several sections along the brace axis. The Menegetto-Pinto steel model is used which accounts for the strain hardening and the Bauschinger effect. Although the Menegetto-Pinto steel model does not account for low-cycle fatigue, the built-in low-cycle fatigue function in OpenSEES [5] is used. The model does not simulate steel rupture.

3 RESULTS

To compare the performances of the IVBF and SZBF, two-dimensional three-story buildings designed for both configurations are analyzed under static and dynamic loads using OpenSEES [5]. The results are presented as follow:

3.1 Nonlinear Static Analysis

A set of nonlinear static analyses is performed in OpenSEES [5] to compare the earthquake performance of the IVBF and SZBF. Each frame is pushed monotonically until reaching a roof drift ratio (RDR) of 3%. Since the fundamental periods of the frames are approximately 0.3 s, each story is assumed to carry the same seismic weight, and the story heights are the same; a triangular lateral load pattern is used for analyses.

The pushover curves for both the IVBF and SZBF are given in Figure 2. Both CBFs show similar responses. In the elastic range, the IVBF has a slightly higher lateral stiffness resulting from stiffer story beams. The maximum lateral load capacity for both systems is about 70% of the total seismic weight (3425 kN for the IVBF and 3300 kN for the SZBF). After the buckling of the first story compression braces both systems undergo lateral strength drops approximately 12% of their maximum lateral strengths (420 kN for the IVBF and 350 kN for the SZBF). For RDRs higher than 0.5%, both CBFs demonstrate a stable response with a gradual decrease in the base shear capacity with the increasing RDR due to the P-Δ effects. In general, the IVBF and SZBF show similar responses in terms of the pushover curve.

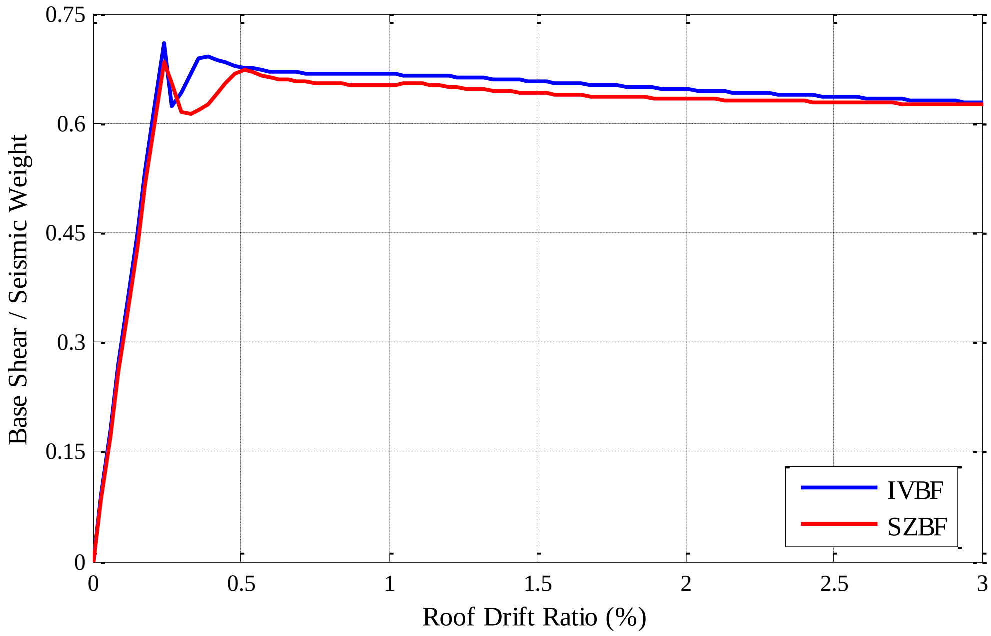

Figure 2: Normalized base shear vs. roof drift ratio

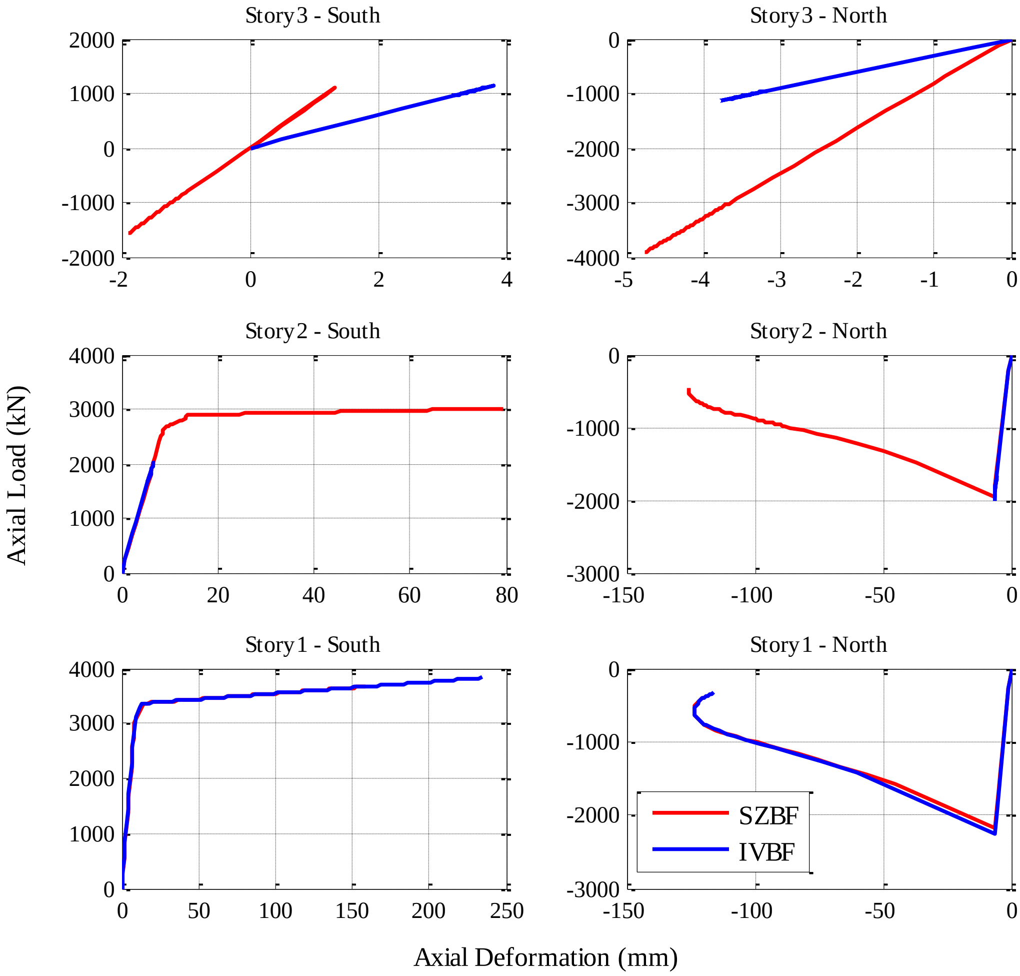

Figure 3: Brace axial forces vs. axial deformations

Figure 3 shows the brace axial forces vs. axial deformations for both CBFs. The lateral load is applied from south to north; therefore, north braces are in compression and south braces are in tension in the elastic range. The first story braces for both CBFs show very similar responses. For the IVBF and SZBF, the first story tension braces yield, the first story compression braces buckle, and the brace axial load capacities are almost identical. However, the second and third story braces have different responses. When the first story north brace of the SZBF buckles, an unbalanced vertical force emerges at the mid-span of the first story beam to be redistributed to the second story braced by the zipper strut placed between the first and second story. This redistributed unbalanced vertical force is resisted by the second story braces and the zipper strut placed between the second and third story. Further increase in the lateral deformation and, thus, increase in the unbalanced force due to the decrease in the axial load capacity of the first story compression brace cause the second story north brace to buckle. At this stage, another unbalanced vertical force emerges at the mid-span of the second story beam. The unbalanced vertical forces at the mid-spans of the first and second stories are transferred to the top story braces by the zipper struts and these forces increase the compression in the top story braces. As can be seen from Figure 3 (Story 3 - South), the third story tension brace develops compression after the buckling of the first and second story braces. The second and third story braces of the IVBF do not buckle; therefore, the tension and compression braces share the lateral load equally and there is no unbalanced vertical force at the mid-spans of the second and third story beams. In brief, the braces of the SZBF connected by the zipper struts help each other to resist the unbalanced force emerging after the buckling of the braces; however, the braces of IVBF transfer the unbalanced force to the story beams.

Table 2: Maximum compressive column axial loads

	IVBF		SZBF	
Story	South Column (kN)	North Column (kN)	South Column (kN)	North Column (kN)
1	No compression	2997	No compression	2930
2	No compression	751	1040	2588
3	0	0	0	0

As explained earlier, the unbalanced vertical forces emerging in the SZBF are transferred to the top story braces. The top story braces transfer these forces to the columns and the columns transfer them to the ground; therefore, the columns of the SZBF are expected to resist higher axial demands compared to those of the IVBF. Maximum compressive column loads of both CBFs are tabulated in Table 2. The first story axial load demands on columns are very similar; however, the second story columns of the SZBF have to carry higher axial loads compared to those of the IVBF. Another interesting observation is that both south and north second story columns of the SZBF develop axial compression since both top story braces resist the unbalanced vertical force in compression; however, in the IVBF while the north column develops compression and the south column develops tension. As a result, the SZBF requires stiffer columns to resist higher axial loads and the SZBF is more prone to stability problems.

Table 3: Buckling loads and corresponding drift ratios of braces

	IVBF			SZBF		
Story	BL (kN)	RDR at BL (%)	ISDR at BL (%)	BL (kN)	RDR at BL (%)	ISDR at BL (%)
1	2269	0.24	0.24	2190	0.24	0.27
2	-	-	-	1949	0.27	0.29
3	-	-	-	-	-	-

Table 3 tabulates the buckling load (BL) of the braces and corresponding RDRs and interstory drift ratios (ISDR). As given in Figure 3, the first and second story compression braces of the SZBF buckle and the third story compression brace remains elastic; on the other hand, the first story brace of the IVBF buckles, and the second and third story compression braces do not buckle. The BL for the first story compression brace of the IVBF is slightly higher than that of the SZBF. At the BL of the first story brace of IVBF, the RDR and ISDR are identical that means the distribution of the lateral deformation along the building height is very uniform up to the corresponding RDR. However, higher ISDRs compared to RDRs for the first and second story compression braces of the SZBF prove a more localized lateral deformation at the first and second story, as can be seen from Figure 4. This result for the SZBF can be attributed to the very stiff hat truss at the third story. In conclusion, the IVBF show a more uniform lateral deformation distribution along the building height prior to the inelastic action.

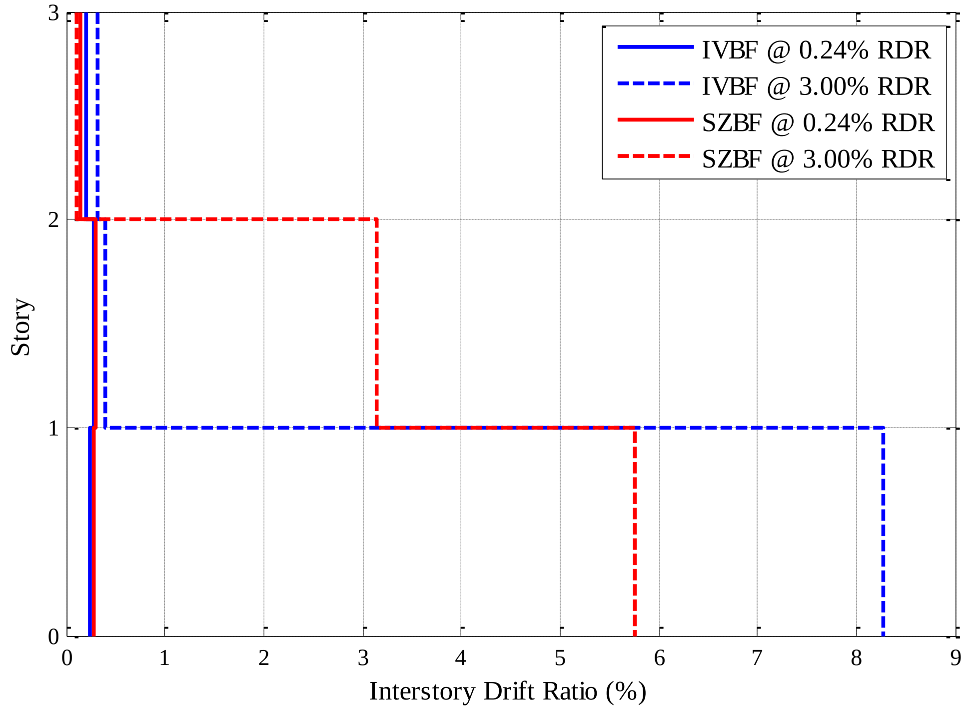

Figure 4:Interstory drift ratios at 0.24% and 3.00% roof drifts

Figure 4 shows the ISDRs at 0.24% and 3.00% for both CBFs. Prior to reaching a RDR of 0.24%, both the IVBF and SZBF are in elastic range, and their response is very similar. The IVBF demonstrates slightly more uniform ISDR distribution. However, for a RDR of 3.00%, the responses differ significantly. In the IVBF, the inelastic action is only limited to the first story; on the other hand, the SZBF is capable of distributing the inelastic action among the first and second stories. In brief, the SZBF demonstrates a superior performance compared to the IVBF in terms of the distribution of inelastic action.

3.2 Nonlinear Dynamic Analysis

Time-history analyses are conducted to compare the performances of the IVBF and SZBF. Both CBFs are subjected to a suite of ground motions (GM) given in Table 4. All ground motions whose normalized 5% damped response spectra given in Figure 5 are scaled to match the 2% exceedance in 50 years hazard level [6] at the fundamental period of the frame. Table

5 tabulates the peak ground acceleration (PGA) values used for scaling the response accelerations (S_a). A Rayleigh damping of 5% is assigned to the first and last modes.

Table 4: Details of selected ground motion records

GM #	Earthquake	Country	Date	Station	M_w	PGA (g)
1	Northridge	USA	17.01.1994	Castaic - Old Ridge	6.69	0.490
2	Imperial Valley	USA	15.10.1979	Cerro Prieto	6.53	0.176
3	Kocaeli	Turkey	17.08.1999	Duzce	7.51	0.326
4	Tabas	Iran	16.09.1978	Tabas	7.35	0.813
5	Kobe	Japan	16.01.1995	KSMA	6.90	0.711
6	Kocaeli	Turkey	17.08.1999	Yarimca	7.51	0.306

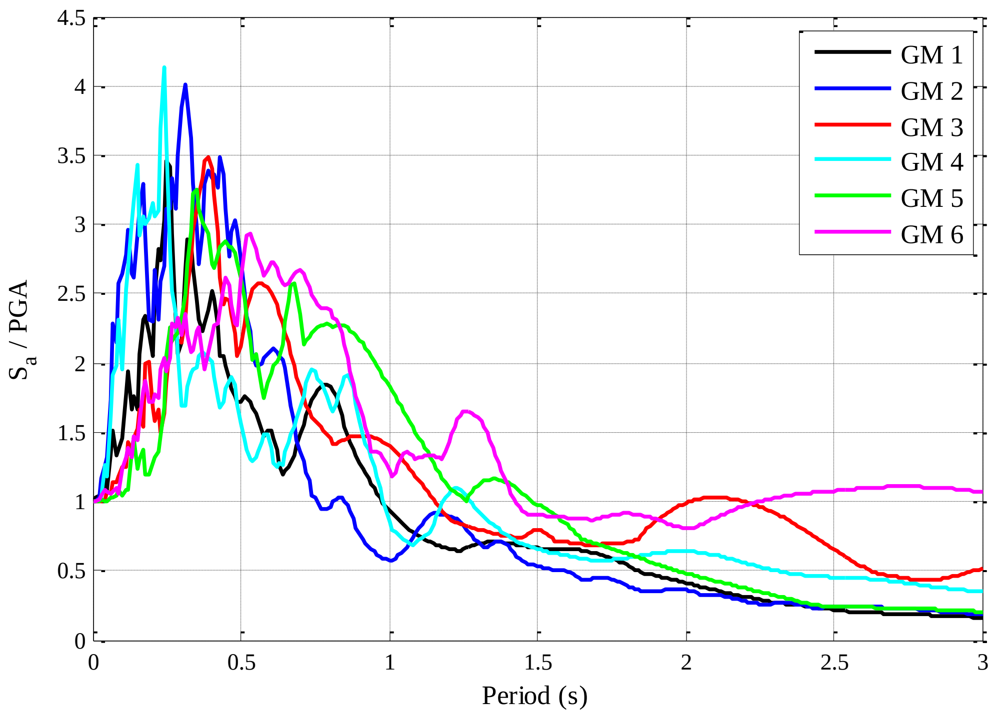

Figure 5:Normalized response spectra for selected ground motion records

Table 5: PGAs to scale the response spectra

GM	IVBF (g)	SZBF (g)
1	0.757	0.836
2	0.599	0.682
3	0.782	0.715
4	1.122	1.103
5	0.732	0.668
6	1.041	1.007

Figure 6 shows the maximum ISDRs for both CBFs under dynamic loads. Similar to the nonlinear static analysis, the SZBF exhibits a more uniform distribution of inelastic action along the building height. For the IVBF, the inelastic deformation is mainly concentrated on the first story; however, the inelastic action for the SZBF takes place in both the first and second stories. The top stories of both systems do not show significant lateral deformation. Especially, the lateral deformation at the top story of the SZBF is very limited thanks to the stiff hat truss.

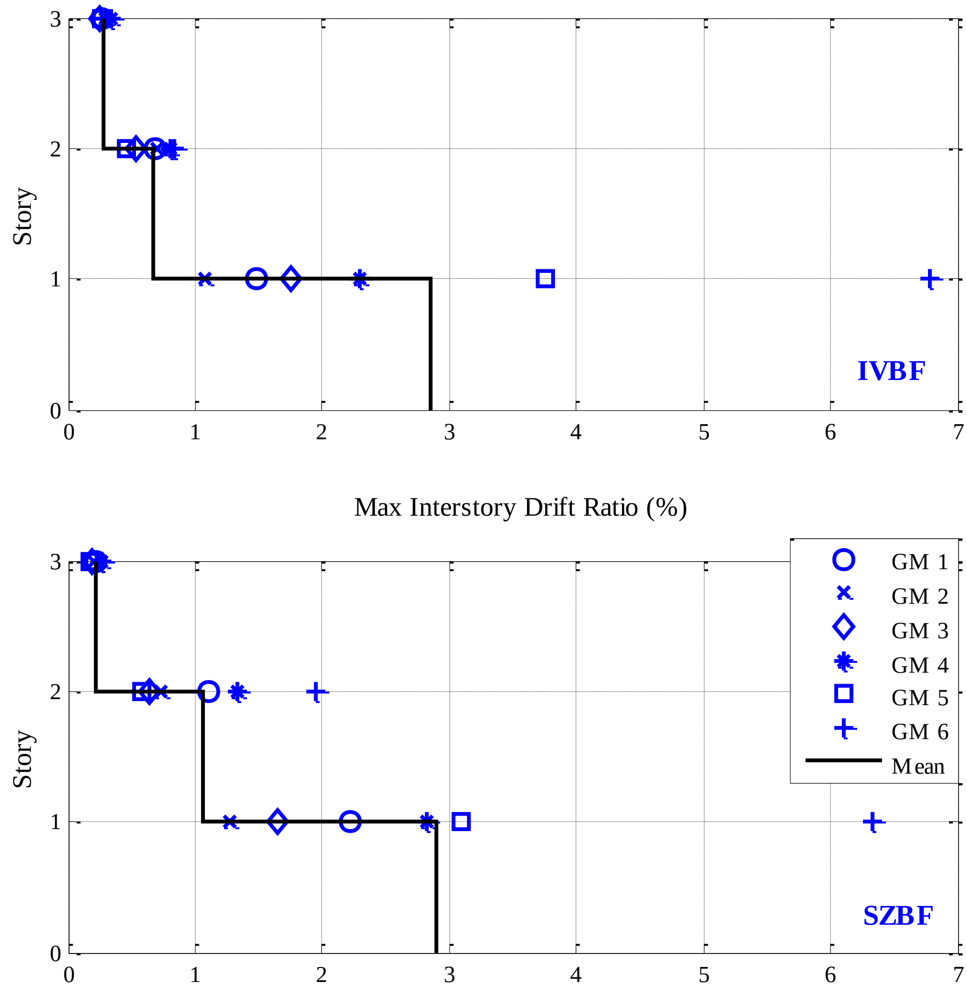

Figure 6: Max inter-story drift ratios for time-history analyses

4 CONCLUSIONS

Two-dimensional three-story IVBF and SZBF are analyzed under static and dynamic loads to compare their earthquake performances. The conclusions drawn from the results of this study are as follow:

- In terms of the base shear capacities, both CBFs show very similar response. The IVBF has a slightly higher maximum base shear capacity and higher lateral stiffness prior to the buckling of the braces.
- The lateral deformation demands in the SZBF are more uniformly distributed compared to the IVBF. The IVBF appears to be more likely to develop a soft story.
- It is verified that the zipper struts are capable of transferring the unbalanced vertical forces emerging at the midspans of the story beams after brace buckling, thus eliminating the need for stiff beams to resist the unbalanced vertical force.
- The axial compressive load demands on the columns of the SZBF are higher than those of the IVBF due to the redistribution of the unbalanced vertical forces from the top story braces to the columns, which suggests that the columns of the SZBF are more prone to stability problems.

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