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Comparison of Chevron and Suspended Zipper Braced Steel Frames

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Abstract

Chevron braced steel frames require large beams to redistribute the unbalanced vertical forces exerted on the beams after brace buckling. A new frame configuration similar to chevron brace was proposed in literature, where zipper columns were attached between mid-spans of the beams from second to top story. During severe ground motion, the unbalanced vertical forces caused by buckling of lower story braces are in this case redistributed to the upper story braces by these zipper columns. Consequently, all story braces buckle successively from first to top story brace instead of concentration of inelastic action in few stories. This system has been improved recently by adding an elastic hat truss between the top two stories to prevent formation of a full height zipper mechanism and collapse.

A numerical study is undertaken in this study to evaluate and compare the response of chevron and suspended zipper braced frames. For this purpose, three, nine and twenty-story buildings are designed for both brace configurations. The designed buildings are analyzed under static and dynamic loadings. Member deformations, member forces, inter-story drifts, top story drifts, base shears are collected for each analysis. The beams, columns and braces are modeled by using nonlinear force formulation frame elements, and the section response is obtained through fiber discretization. Nonlinear geometric effects are considered through corotational transformation. Rotational springs are added at the ends of the braces to represent the effects of gusset plates. An initial imperfection is assigned to the mid-length of the braces to achieve proper buckling behavior.

Keywords: *Steel frames; steel; chevron brace; zipper brace; nonlinear analysis*

1 Introduction

Inverted-V braced (chevron braced) frames shown in Figure 1(a) are one of the most popular concentrically braced frame configurations. During ground excitations, one of the story braces develops axial tension; on the other hand, the counterpart of it develops axial compression. Increasing lateral deformation leads to the compression brace to buckle and lose the lateral strength of the brace while the lateral strength of the tension brace remains, which results in an unbalanced vertical force exerted at the mid-length of the intersecting beam. This unbalanced vertical force emerging in the post-buckling range causes to soft story formation and potential collapse unless deep and stiff beams are used which are designed in accordance with the AISC Seismic provisions, requiring the intersecting beam to resist the potential unbalanced vertical load with gravity loads.

Khatib et al. (1988) proposed to add zipper columns between apexes of the braces along the height of the structure but not extending to ground. Thus, the unbalanced force developing in the post-buckling range was transferred to the upper story braces by zipper columns so that simultaneous buckling of the compression braces and distribution of energy dissipation along building height could be achieved and the localization of the deformation could be prevented. This configuration was named as zipper braced frame. The disadvantage of the zipper brace is that the full height zipper mechanism formation reduces the lateral strength of the system leading to instability and collapse (Tremblay and Tirca, 2003).

Leon et al. (2003) enhanced the zipper braced frame that suspension system was introduced to the zipper brace system. The top story braces and the beam of the story below the top story were designed to remain elastic when all compression braces buckled and the zipper columns yielded so that the partial height zipper mechanism formed instead of the full height zipper mechanism, leading to ductile behavior without instability problem. This configuration is called suspended zipper braced frame shown in Figure 1(b). Since the zipper struts transfer the unbalanced forces on the beams to the upper story braces, the flexible beams can be used, resulting in material savings. Another advantage of this system is to have a clear force path that makes the capacity design more straightforward.

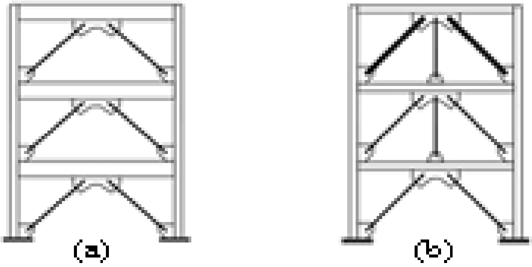

Figure 1. (a) Chevron brace; (b) suspended zipper brace configuration

2 Analytical Models

3-, 9- and 20-story SAC (joint venture of Structural Engineers Association in California, Applied Technology Council and California Universities for Research in Earthquake Engineering) moment resisting frames redesigned by Yang et al. (2008) as suspended zipper braced frames (SZBF) to carry same masses form a benchmark for this study. Yang et al. (2008) used ASCE 7-05, AISC LFRD 2005 and IBC 2000 as design codes for minimum design loads, member design and lateral equivalent earthquake force, respectively. In the current study, these frames are modified so that the zipper struts and elastic hat are taken out, the beams are redesigned in accordance with the AISC Seismic provisions to redistribute the potential unbalanced vertical force in post-buckling; in other words, the SZBFs are turned into inverted-V braced frames (IVBF) using the braces and columns of SZBFs. The sizes of the beams for 3-, 9- and 20-story IVBFs are given in Table 1, Table 2 and Table 3, respectively.

Table 1. Beam sizes for 3-story IVBF

Story	Beam	Story	Beam	Story	Beam
1	W44x290	2	W44x262	3	W44x262

Table 2. Beam sizes for 9-story IVBF

Story	Beam	Story	Beam	Story	Beam
1	W44x290	4	W40x211	7	W 40x183
2	W40x211	5	W40x211	8	W 40x183
3	W40x211	6	W40x211	9	W36x210

Table 3. Beam sizes for 20-story IVBF

Story	Beam	Story	Beam	Story	Beam	Story	Beam
1	W44x290	6	W40x211	11	W 40x183	16	W40x167
2	W40x211	7	W40x211	12	W 40x183	17	W33x141
3	W40x211	8	W40x211	13	W36x210	18	W30x124
4	W40x211	9	W 40x183	14	W36x210	19	W30x116
5	W40x211	10	W 40x183	15	W40x167	20	W30x116

In design stage, ASTM A500 Grade B steel (nominal yield strength of 317 MPa) is used for braces and zipper struts and ASTM A572 Grade 50 steel is used for columns and beams in all frames. The dead load of 21.0 kN/m and live load of 4.4 kN/m are applied on the beams. The total seismic weights of 3-, 9- and 20-story models are 4821 kN, 14712 kN and 10648 kN and the design base shears are 1746 kN, 2942 kN, 1491 kN, respectively. All connections in all of the frames are assumed to be simple connections.

3 Analytical Study

Two dimensional 3-, 9- and 20-story SZBFs designed by Yang et al. (2008) and IVBFs designed by the authors are analyzed in Open System for Earthquake Simulation (OpenSEES) under static and dynamic loadings to evaluate and compare the performances of SZBFs and IVBFs.

3.1 Brace Model

The brace model proposed by Uriz et al. (2008) is implemented in this study to achieve proper buckling behavior of a brace in compression. The model requires the brace to be divided into at least two sub distributed plasticity force-based nonlinear frame elements and assigned a small initial imperfection at the common node of two sub elements. Corotational transformation is needed to be used to represent the moderate to large deformations resulting from inelastic buckling of braces. The interaction between axial load and bending moment is achieved by the integration of the uniaxial stress-strain relation of fibers over the cross section. Menegotto-Pinto hysteretic model is used as steel material, accounting for isotropic hardening and the Bauschinger effect. The inelastic response is monitored at several sections along the axis of the element. Two linear rotational springs are added at the end nodes of the braces to represent the end restraints.

The initial imperfection and the rotational spring stiffness values are two ambiguous parameters to be determined. Due to lack of experimental data to calibrate the axial load vs. axial deformation curves of the braces in compression, the values recommended by AISC are implemented here. The axial load values are normalized by nominal compression strengths given by AISC LFRD manual and the axial displacements are normalized by yielding displacements. For the initial imperfection value of L/150 (where L is the length of the brace) and rotational spring stiffness value of 475 kNm/rad, the peak strength ratio is close 1 and the post-buckling strength ratio is close 0.3 at 10 to 20 times yield displacement, which is the specified criteria for minimum post-buckling strength ratio in AISC Seismic provisions.

3.2 Nonlinear Static Analysis

A set of 2D pushover analyses are performed in OpenSEES to compare the capacity curves of the IVBFs and SZBFs with different heights. Triangular lateral load distribution is applied to all six frames until reaching a roof drift ratio of 3%.

The gravity load is ignored during all analyses. Besides, the braces are assumed to be safe against low-cycle fatigue and local buckling since the brace model proposed by Uriz et al. (2008) does not account for them.

The plots of normalized base shear vs. roof drift ratio for all frames are given in Figure 2. In figure, V_{base} and W stand for base shear and total seismic weight of the frame, respectively.

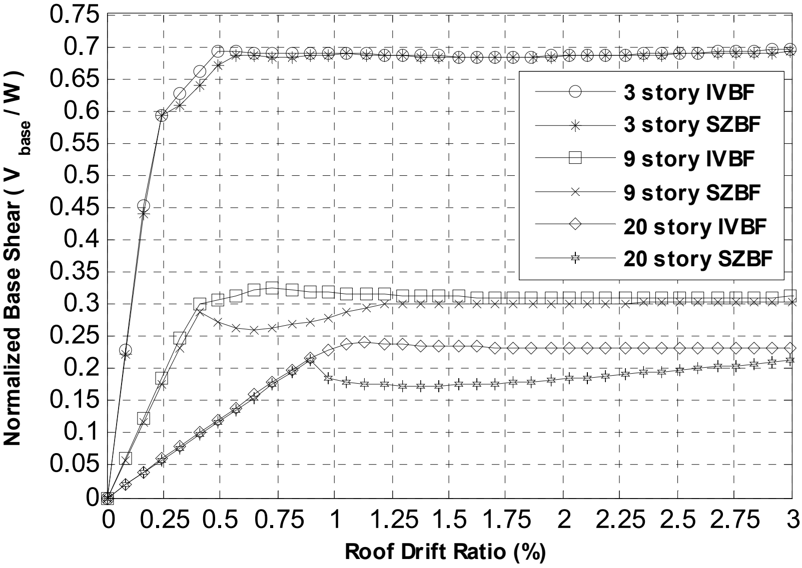

Figure 2. Pushover curves for IVBFs and SZBFs

The pushover response of 3-story SZBF is very similar to that of IVBF. Both configurations display the trilinear pushover curves, which is a design goal. In elastic range and in the range with roof drift ratios greater than 0.5%, the responses are exactly same; however, the slope of the pushover curve of SZBF between first buckling and yielding point is slightly lower than that of IVBF. The total material weight of the structural parts (beams, columns, braces and zipper struts) of SVBF is 28% lighter than that of IVBF.

In elastic range, the responses of 9-story IVBF and SZBF are almost same; however, after the first buckling point, the pushover curve of SZBF experiences a strength drop of 9%, while this is not the case for IVBF. The base shear capacities of both frame configurations are very close for roof drift ratios greater than 1.2 %. The total material weight of the structural parts of SVBF is 10% lighter than that of IVBF.

In elastic range, 20-story IVBFs and SZBFs yield same results; however, after the first buckling point of the pushover curve, there exists a 20% strength drop for SZBF, whereas IVBF preserves its base shear capacity. Besides, first buckling point of SZBF is lower than those for IVBF. Although, the base shear capacity of SZBF increases with increasing roof drift ratio after the first buckling point, its capacity is still lower than that of IVBF. Besides, there is no saving for 20-story SZBF in the amount of material used for structural members compared to IVBF.

3.3 Nonlinear Dynamic Analysis

A set of nonlinear dynamic analyses is performed to assess the deformation demands of the IVBFs and SZBFs.

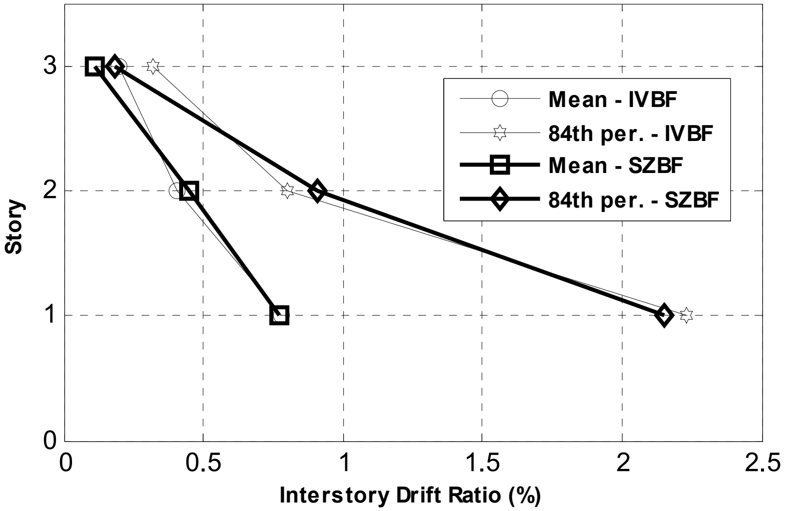

Figure 3. Peak interstory drift ratios for 3-story IVBF and SZBF

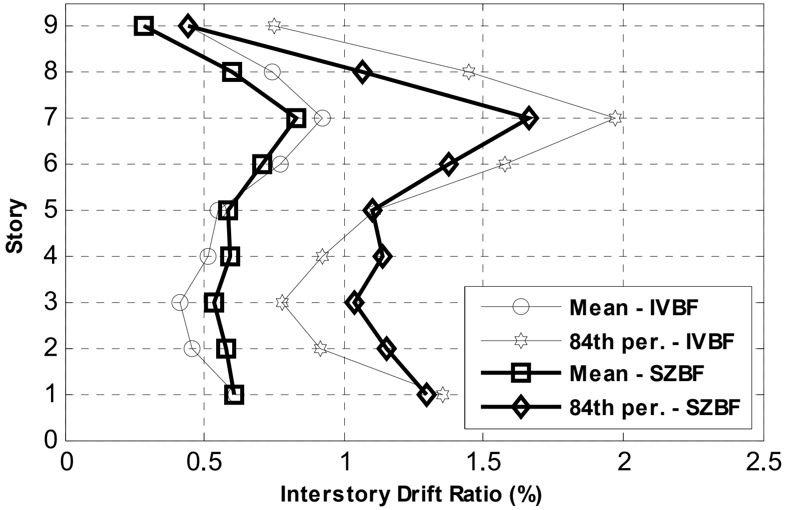

Figure 4. Peak interstory drift ratios for 9-story IVBF and SZBF

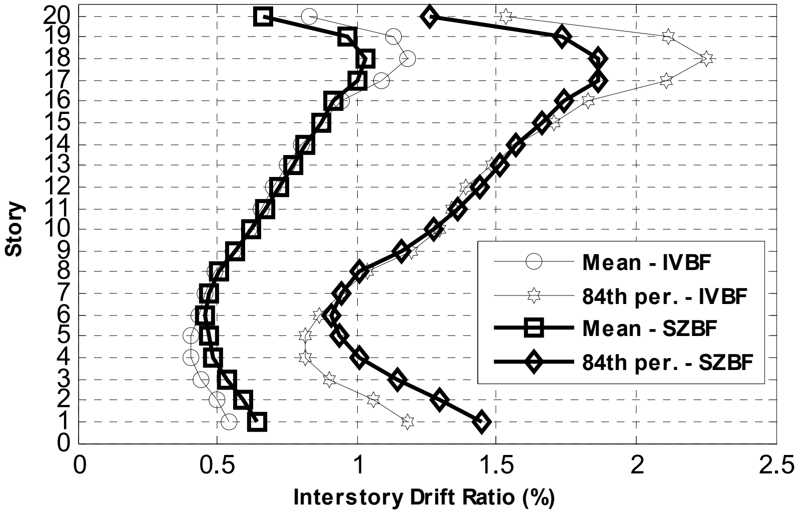

Figure 5. Peak interstory drift ratios for 20-story IVBF and SZBF

Each frame is subjected to twenty ground motions data. The floor masses are assumed to be same over the frame height. 5% Rayleigh damping is assigned to first and last modes of vibration.

The plots of mean and 84th percentile peak interstory drift ratios of 3-, 9- and 20-story frames for both configurations are given in Figure 3, Figure 4 and Figure 5, respectively.

Figure 4, Figure 5 and Figure 6 reveal that the interstory drift demands for both configurations yield similar results. For higher stories, the interstory demands of IVBFs are higher than that of SZBFs; on the other hand, for lower stories, the interstory demands for SZBFs are higher than that of IVBFs. In brief, although both configurations result in similar trends, the SZBFs lead to more uniform interstory drift demands along the building height for both mean and 84th percentile series.

4 Summary and Conclusion

Two different concentrically braced frame configurations with different heights are analyzed under static and dynamic loadings to evaluate and compare their performance.

The followings are the conclusions to be drawn from the results of this study:

1. Regardless of the building height, the use of zipper struts between the midlengths of the beams from second to top story leads to more uniform

interstory drift demands along building height compared to the interstory drift demands of IVBFs.

2. For low rise buildings, the SZBFs demonstrates almost same behavior as IVBFs designed according to AISC Specifications and Seismic Provisions in terms of base shear capacity and interstory drift demands without requiring overly stiff beams.

3. For moderate rise buildings, the suspended zipper braced frames demonstrates similar behavior as chevron braced frames except for a slight strength drop after first buckling point.

4. For high rise buildings, the suspended zipper braced frames demonstrates rather poor performance in terms of base shear capacity compared to chevron braced frame.

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