

## Response Evaluation of Braced Frames with Suspended Zipper Struts and Chevron Braced Frames in Near-Fault Earthquake Ground Motions

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### Abstract

This paper presents the results from Analytical models of a special inverted-V-braced steel frame with zipper struts. Zipper elements are vertical elements added at the intersections of the braces above the first floor and designed to carry upward the unbalanced loads resulting from buckling of the braces. In this study, this system, referred to as Suspended Zipper Braced Frame, is compared with Chevron bracing system in terms of ductility and drift ratios. For this purpose, three zipper-braced models were designed on the basis of the proposed design procedure to carry the same masses as the 4-, 8-, 12-story buildings are analyzed using nonlinear dynamic analysis in Seismostruct. IDA analyses of the models were performed to estimate the overstrength, inelastic strength and deformation capacities for the entire structures, and assess the sequence of yielding and buckling in the members. The analyses indicate that the design procedure produces safe designs, with the design becoming more conservative as the number of stories increases. The distribution of interstory drifts demonstrates the efficiency of the zipper struts in achieving uniform damage over the height of the structure, and generally satisfies allowable interstory drift ratio limits.

**Keywords:** Steel frames; Seismic design; Steel; Struts; Nonlinear analysis

### INTRODUCTION

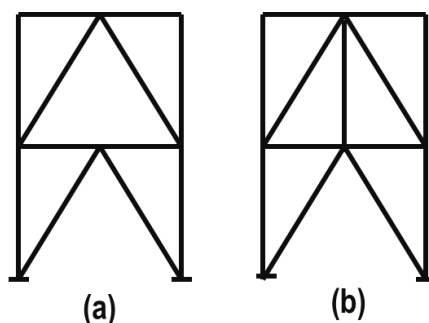
Steel is one of the most widely used materials for building construction in Iran. The inherent strength and toughness of steel are characteristics that are well suited to a variety of applications, and its high ductility is ideal for seismic design. To utilize these advantages for seismic applications, the design engineer has to be familiar with the relevant steel design provisions and their intent and must ensure that the construction is properly executed. This is especially important when welding is involved. Concentrically braced frames are frequently used to provide lateral strength and stiffness to low- and mid-rise buildings to resist wind and earthquake forces. Although some architects favor the less intrusive moment frames, others have found architectural expression in exposing braced frames which the public intuitively associates with seismic safety

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in some earthquake-prone regions. Past earthquakes have demonstrated that this idealized behavior may not be realized if the braced frame and its connections are not properly designed. Numerous examples of poor seismic performance have been reported.

The unexpected failure of welded steel connections during the 1994 Northridge and 1995 Kobe earthquakes led to a reexamination of the robustness and economy of moment frame systems through the SAC (Structural Engineers Association of California, Applied Technology Council, California Universities for Research in Earthquake Engineering) program (Kunnath and Malley 2002) [1]. The results of the SAC research indicate that reliable moment frame performance requires expensive detailing and quality control/assurance. This conclusion, in turn, has resulted in a fresh look at braced systems for resisting seismic forces. Braced systems are perceived by designers to be very efficient, economical, and easy to adapt to architectural needs. However, past performance of braced systems subjected to large earthquake forces has not been satisfactory due primarily to the buckling and elongation of the braces, which result both in large losses of stiffness and strength and the concentration of deformations generally in a single low story [2]. This is particularly true for the inverted V-braced frame configuration [Fig. 1(a)].



**Fig.1** Sidesway mechanisms for: (a) conventional IVBF; (b) conventional zipper

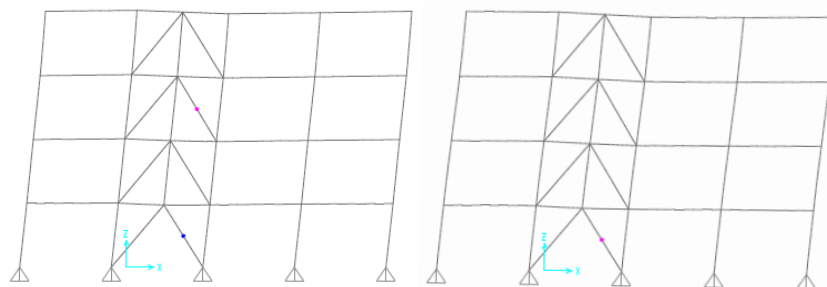
Improved strength and stiffness performance of bracing elements can be achieved by decreasing width/thickness ratios, closer spacing of stitches, and special design and detailing of end connections (Tang and Goel 1987, 1989; Hassan and Goel 1991; Astaneh-Asl et al. 1986) [3,4,5]. At the global level, however, the localization of deformations in the lower stories of conventional inverted V-braced frames is more difficult if not impossible to prevent. This can be demonstrated by a recent cyclic test on a conventional two-story special inverted- V-braced frame (SIVBF) designed in compliance with the 1997 American Institute of Steel Construction (AISC) seismic provisions, where the beam design accounted for the unbalance tension and compression loads in the braces (Uriz and Mahin 2004) [6]. The test specimen, with nominally the same lateral capacity in both stories, was loaded only at the top story; i.e., the same shear was applied to both stories. Nonetheless, once buckling in the lower level braces was initiated, the interstory drifts were concentrated. Nonetheless, once buckling in the lower level braces was initiated, the interstory drifts were concentrated in the first story. In addition, this behavior was followed by fractures in the first-story column flanges and webs due to pounding between the deep beams and

columns, resulting in a worse first story response. The limitations of braced systems subjected to seismic loads led Khatib et al. (1988) to investigate concentrically braced frames with a variety of bracing configurations, including V, X, inverted-V, and split-X configurations. Some new configurations were also proposed, including one referred to as the zipper frame. In this configuration, small zipper columns (zipper struts) are added between floor beams to link the brace-to-beam intersection points, as shown in Fig. 1(b). As the lower stories begin to buckle, the zipper struts redirect the unbalanced brace forces upward, distributing yielding throughout the height of the structure and achieving stable hysteretic behavior without having to use overly stiff beams. This system has been described in the commentary to the structural steel seismic specification (AISC 2005) since 1992, but experimental tests, design studies, and design recommendations have not been proposed. Developments and improvements to this system are the primary focus of this paper. Chevron bracing system is prone to buckling of the first story compression brace while the tension one is still at its linear stage of axial behavior. This phenomenon produces an unbalanced vertical force imposed to the top beam leading to concentration of story drifts in one story. Zipper is a vertical member that is added to brace to beam connections in all stories except the 1st one resulting in contribution of the bracing elements at upper stories to lateral force resistance of the structure. Also, this system leads to more economical section for the 1st story compression brace member and uniform distribution of drifts over the height of the structure. Brittle response is considered as one of the main problems of this system, to avoid which the last story members are strengthened. Even in a zipper frame, however, instability and collapse is triggered by the formation of the full-height zipper mechanism in a braced bay. This occurs when all compression braces buckle, some tension braces yield, and plastic hinges occur at the column bases and the middle length of the beams [Fig. 1(b)]. In the only other analytical research available for this type of frame, Tremblay and Tirca (2003) performed studies on the response of four-, eight-, and 12-story zipper frames (regular and non-regular) under three different seismic ground motions (near-field and far-field). When subjected to near-field and subduction earthquake motions, the 12-story structures collapsed because of dynamic instability. In addition to the potentially unstable nature of the full-height zipper mechanism, the design of zipper struts to transmit the unbalanced vertical forces upward or downward automatically was found to be complex.

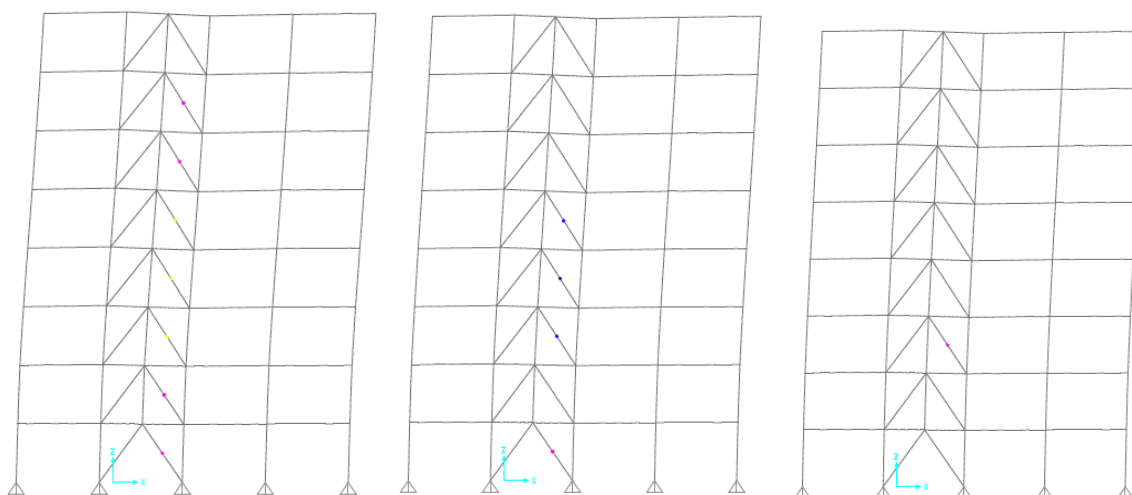
### Design procedure

The design procedure is based on LRFD Specification (1999) and AISC Seismic Provisions (2005). The loads and load combinations are determined with respect to ASCE 7-05 and static equivalent lateral load procedure is utilized to determine the design earthquake loads. The frames are assumed to be in high seismic area, the local site class is chosen as D. Base shear is obtained with respect to first hinge in structure and the effect of the accidental torsion is added. Steel types, those are convenient with the sections are chosen; ST37, steel is used for the beams, brace and the columns. The entire Euro wide-flange section database is assumed available for beams. Column and brace sections are chosen from IPB series and from rectangular hollow sections with

equal depth and width values, respectively (Fig2 and Fig3). Parametric studies require many number of designed Chevron and zipper for the purpose of generalization, in fact, optimization of design is also necessary for the conservatism of results. Therefore, a computer program is coded for the design of braced chevron frames and zipper braced frames.



**Fig.2** Plastic hinges in 4story zipper frame (regular)



**Fig.3** Plastic hinges in 8story zipper frame (regular)

### Inelastic analyses and Accelerograms

Incremental dynamic inelastic analyses have been carried out with reference to three accelerograms. Data pertinent to the ground motions considered in this investigation are presented in Table 1 and Table2. The single non-linear dynamic analysis, referring to a particular accelerogram and peak ground acceleration, has been carried out by means of the SeismoStruct program by taking into account the P-Delta effect. The SeismoStruct program, which includes Menegotto-Pinto's model in its finite element library, has been adopted for performing the inelastic dynamic analyses of this study. The analytical models were centreline representations of the frames for which inelasticity has been restricted to the diagonals while the elements of the backup frame were modelled as elastic beam-columns. Diaphragm action was assumed at every

floor due to the presence of the slab, while Rayleigh damping corresponding to 5% of critical damping at the first two modes was adopted.

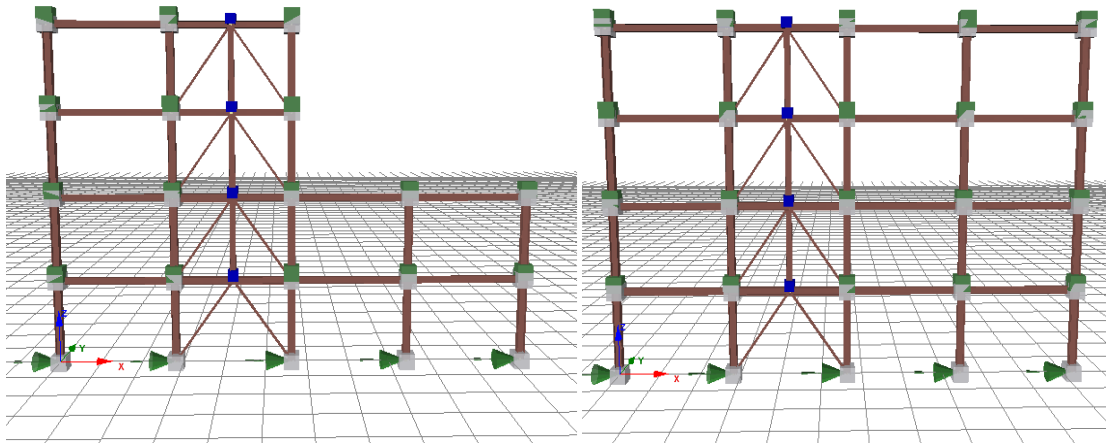
**Table1.** Far-Field Earthquake Records Used for 4-8 and 12-Story Buildings Analyses

Name	Date	Station	PGA(g)	PGV(cm/s)	PGD(cm)
NORTHRIDGE	1/17/94	BEVERLY HILLS	0.617	40.8	8.57
KOBE	01/16/95	SHIN-OSAKA	0.243	37.8	8.54
CHI-CHI	09/20/99	CHY101	0.44	115	68.75

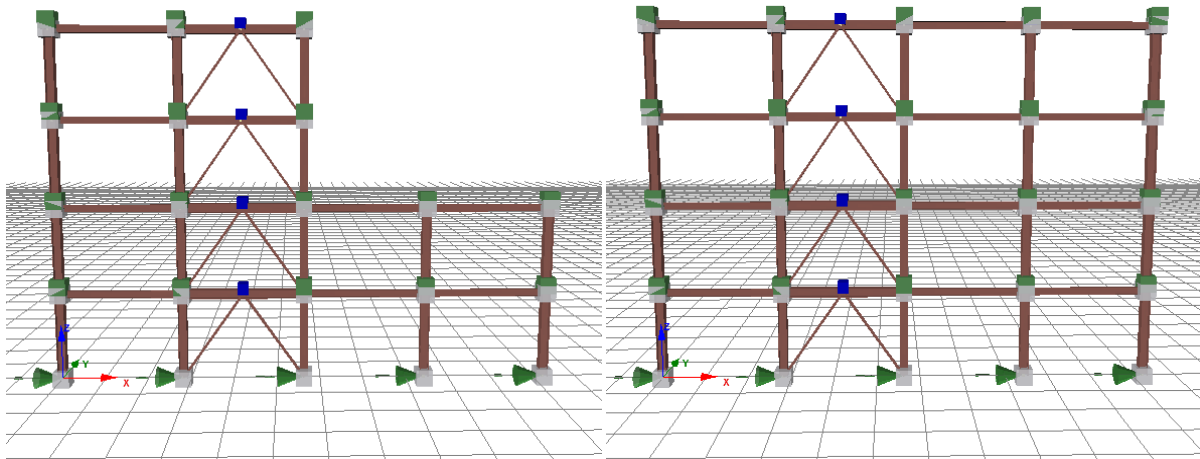
**Table1.** Near-Field Earthquake Records Used for 4-8 and 12-Story Buildings Analyses

Name	Date	Station	PGA(g)	PGV(cm/s)	PGD(cm)
NORTHRIDGE	1/17/94	RINALDI RECEIVING	0.852	50.7	11.65
ERZINCAN	03/13/92	ERZIKAN	0.515	83.9	27.35
SUPERSTITN HILLS	11/24/87	Hill	0.455	112	52.8

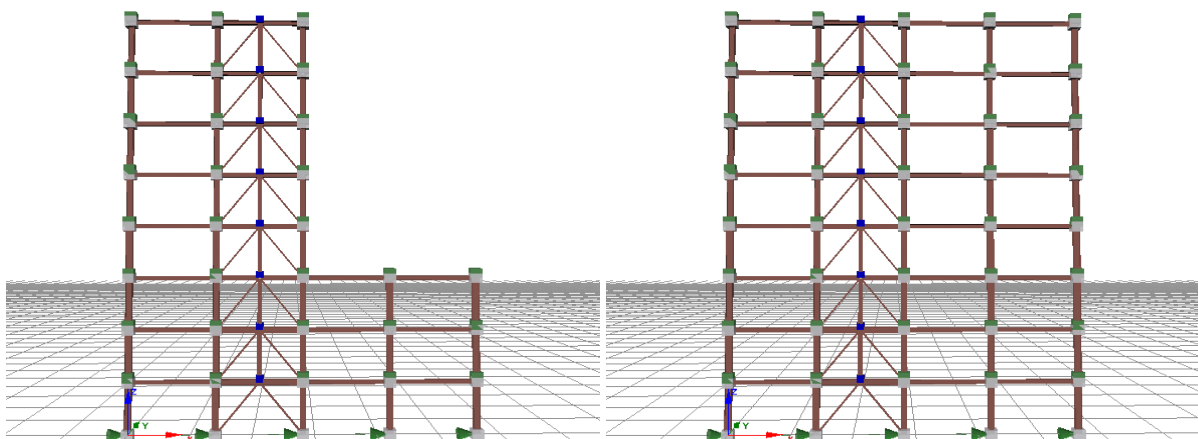
The study is based on frames which are plane, regular and non-regular with storey heights and bay widths equal to 3 and 4 m, respectively. The columns are pinned at their base but capable of carrying moments along the whole height of the building, while beams are shear connected to the columns. This assumption of pin connections between the framing members is widely accepted, although the presence of gusset plates increases the stiffness and hence decreases the inelastic deformation demands. Gravity load on the beams is assumed equal to 27.5 kN/m (dead and live loads of floors), while the yield stress of the material is set equal to 235MPa. Since the structural elements of the backup frame are designed according to the capacity design philosophy which protects them from yielding and buckling, all the seismic input energy is dissipated through cyclic deformations of the diagonals.



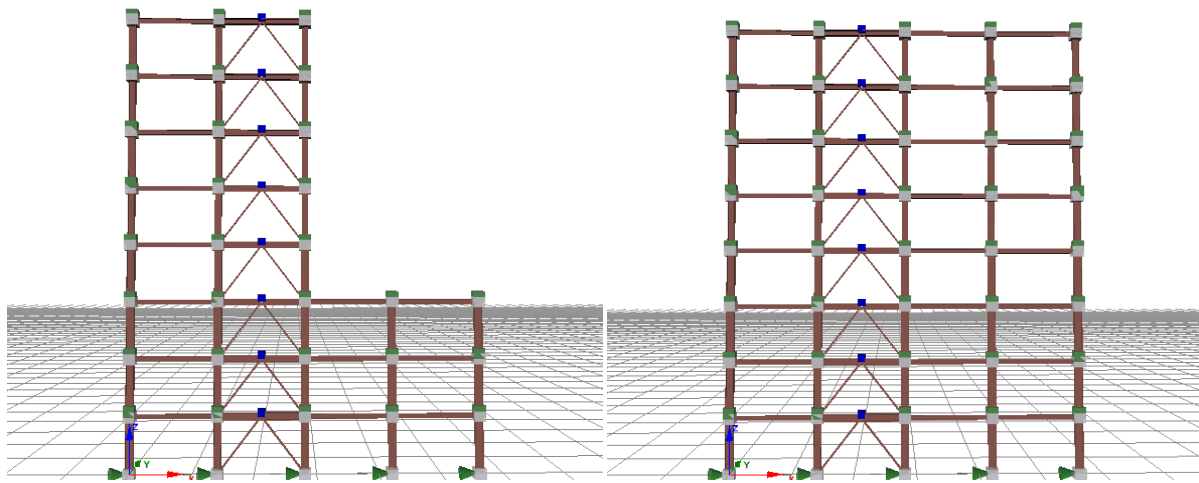
**Fig.4** Elevation for the 4-story zipper frames



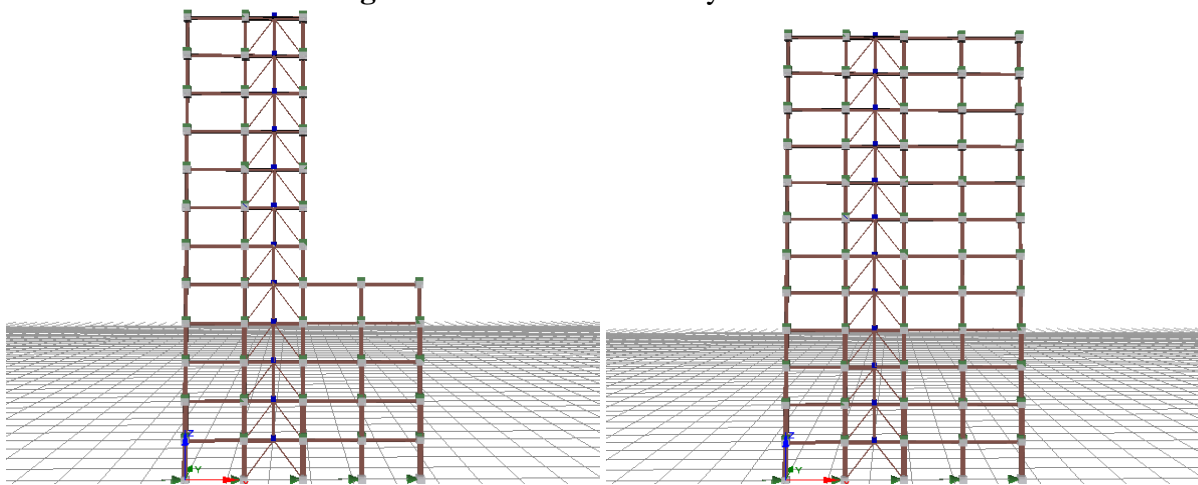
**Fig.5** Elevation for the 4-story chevron frames



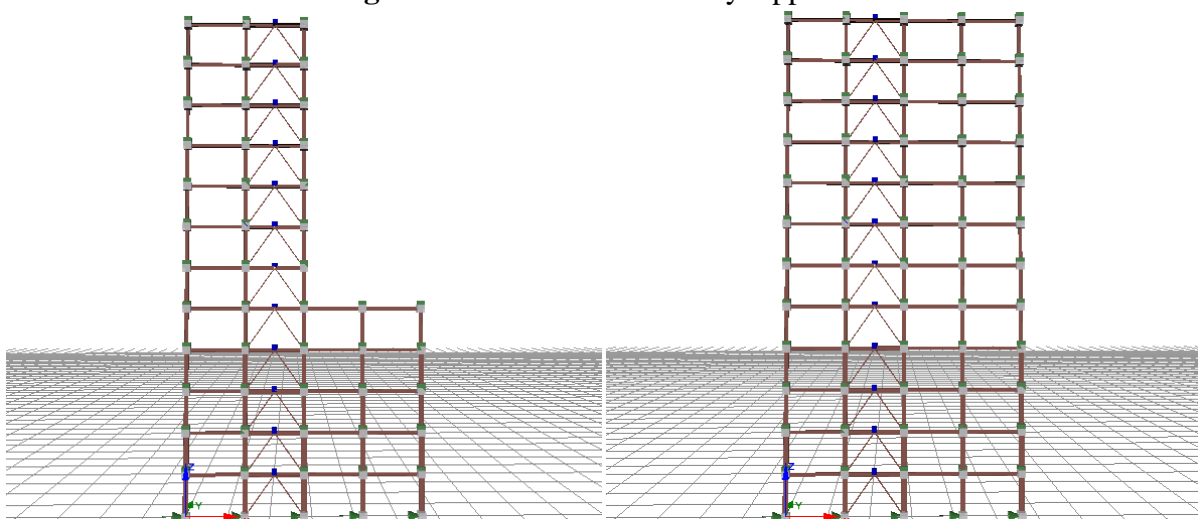
**Fig.6** Elevation for the 8-story zipper frames



**Fig.7** Elevation for the 8-story chevron frames



**Fig.8** Elevation for the 12-story zipper frames

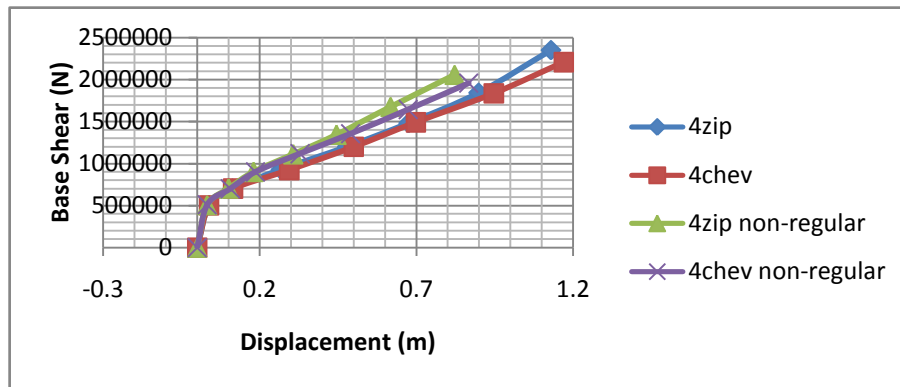


**Fig.9** Elevation for the 12-story chevron frames

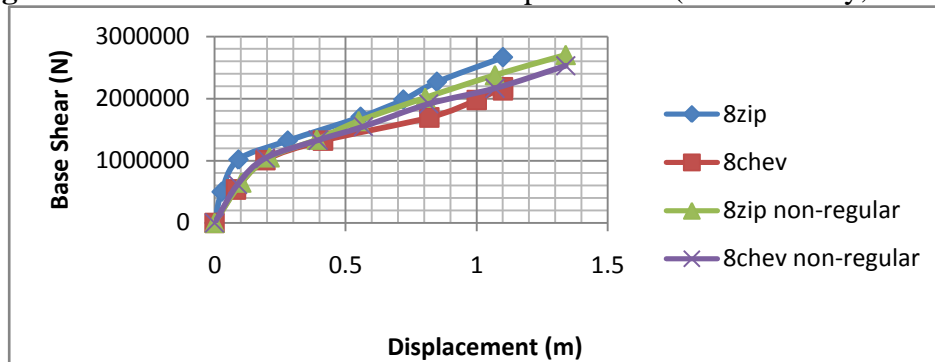


## Dynamic Analysis Results and Discussion

The probabilistic analysis of structural response has been obtained by performing a set of nonlinear dynamic analyses using 6 natural seismic motions provided by PEER database. The SeismoStruct computer program has been used for incremental dynamic nonlinear analyses (IDA). Incremental dynamic analysis (IDA) is a parametric analysis method that has recently emerged in several different forms to estimate more thoroughly structural performance under seismic loads. It involves subjecting a structural model to one (or more) ground motion record(s), each scaled to multiple levels of intensity, thus producing one (or more) curve(s) of response parameterized versus intensity level. The maximum inter-storey drift was used as an index to assess the seismic performance of the analysed frames. Fig.10 to Fig.27 shows the distribution of maximum inelastic displacement versus shear base.

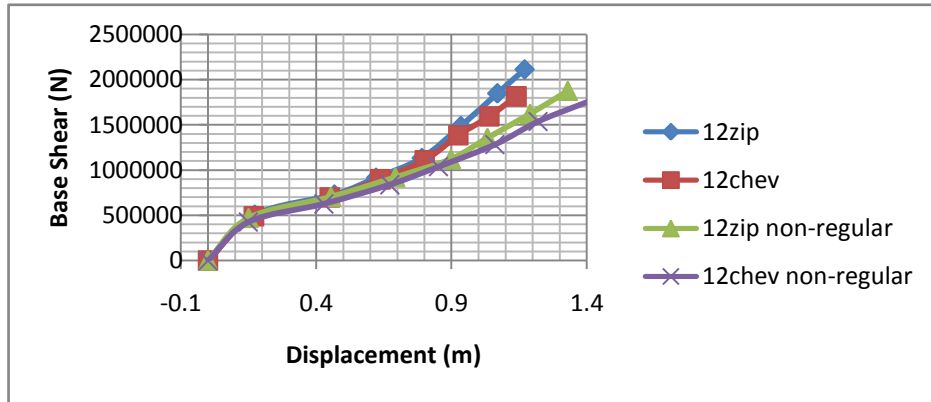


**Fig.10** IDA results for the considered drift parameters (Kobe-4-Story; far-fault)

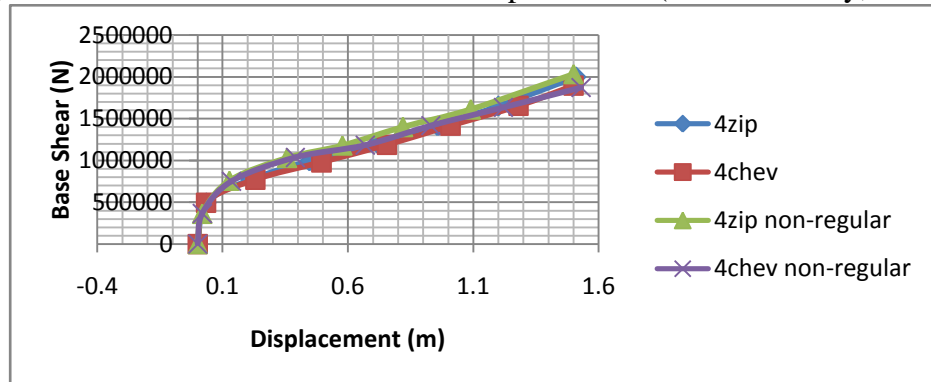


**Fig.11** IDA results for the considered drift parameters (Kobe-8-Story; far-fault)

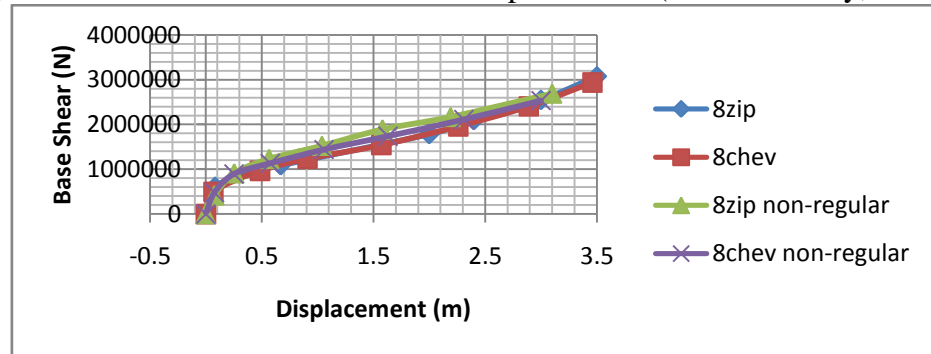




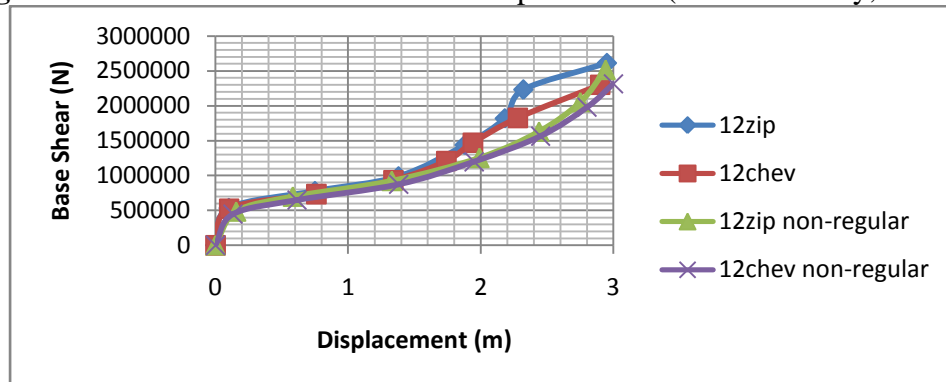
**Fig.12** IDA results for the considered drift parameters (Kobe-12-Story; far-fault)



**Fig.13** IDA results for the considered drift parameters (Chichi-4-Story; far-fault)



**Fig.14** IDA results for the considered drift parameters (Chichi-8-Story; far-fault)



**Fig.15** IDA results for the considered drift parameters (Chichi-12-Story; far-fault)

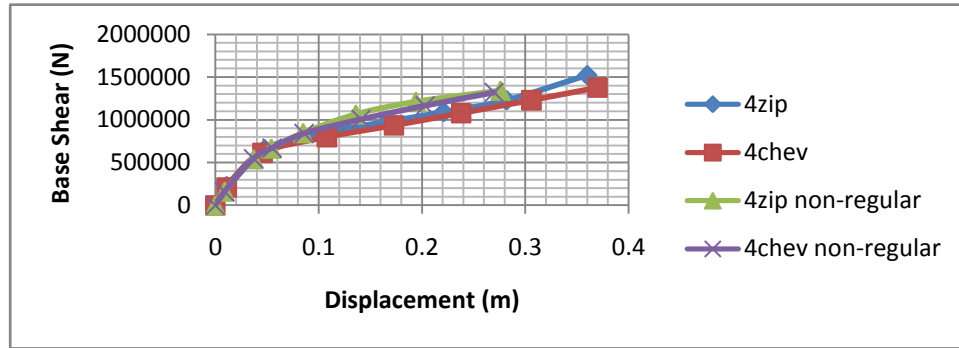


Fig.16 IDA results for the considered drift parameters (NORTHTRIDGE-4-Story; far-fault)

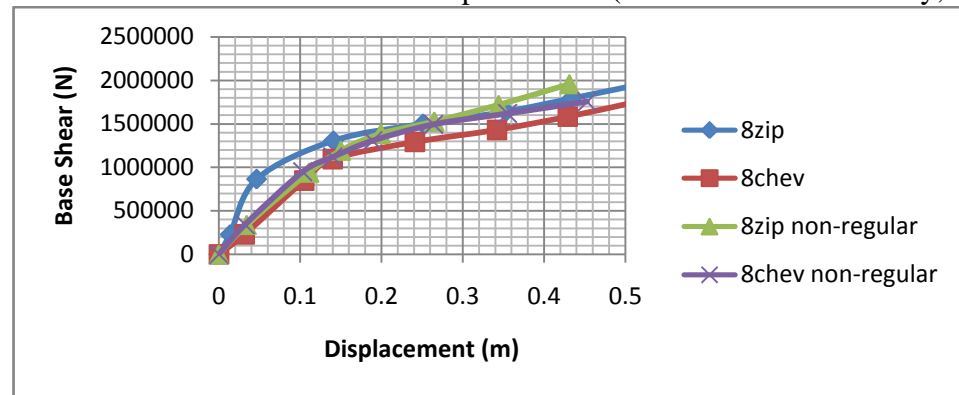


Fig.17 IDA results for the considered drift parameters (NORTHTRIDGE-8-Story; far-fault)

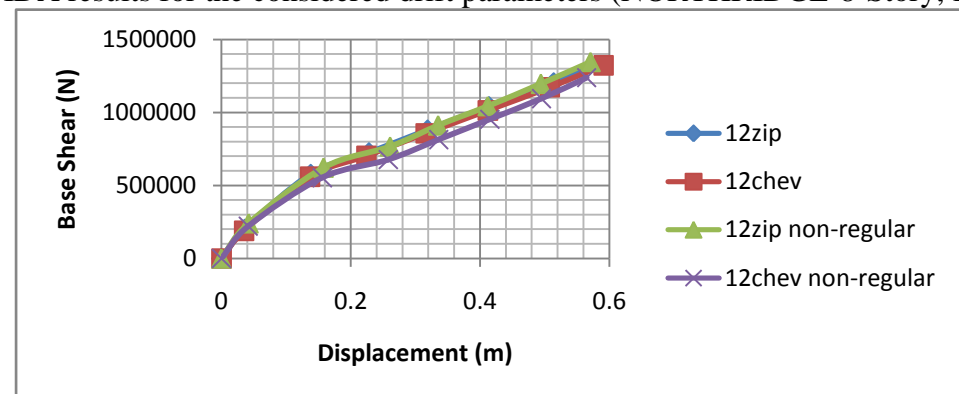


Fig.18 IDA results for the considered drift parameters (NORTHTRIDGE-12-Story; far-fault)

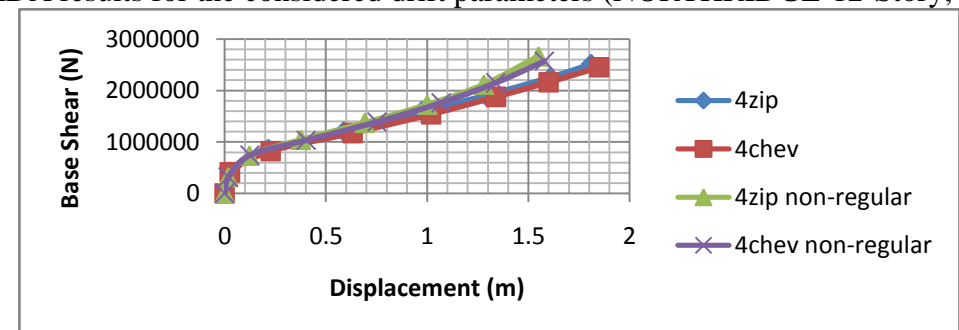
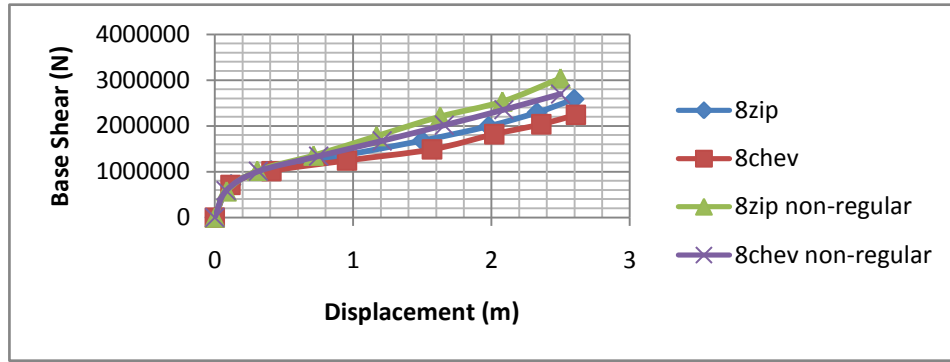
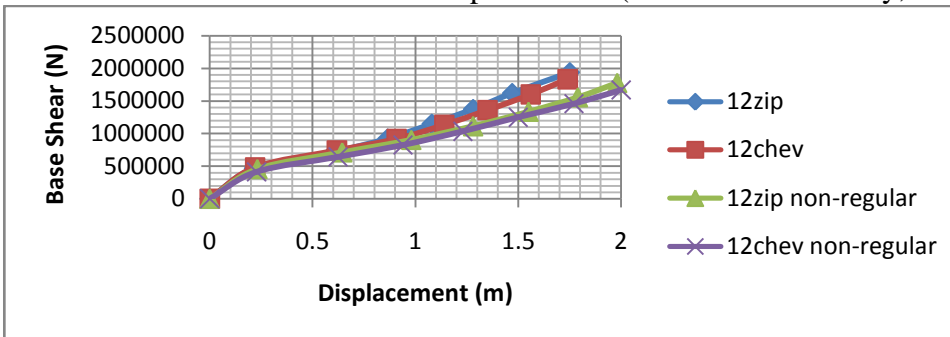


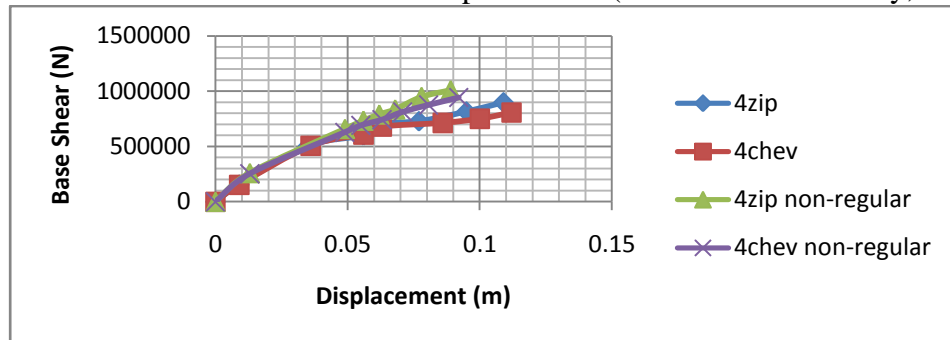
Fig.19 IDA results for the considered drift parameters (ERZINCAN-4-Story; near-fault)



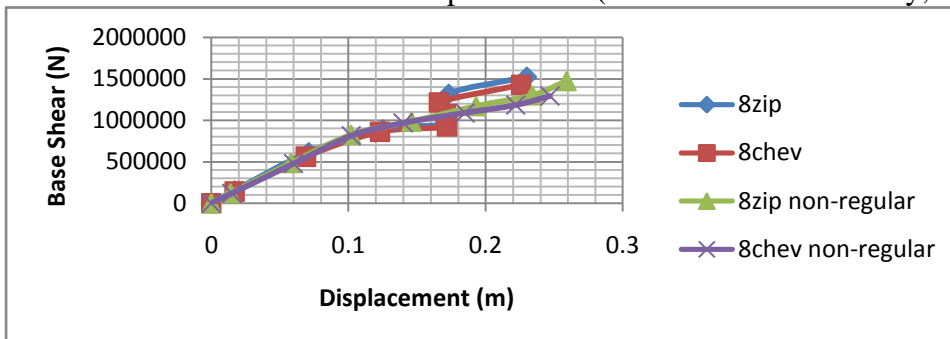
**Fig.20** IDA results for the considered drift parameters (ERZINCAN-8-Story; near-fault)



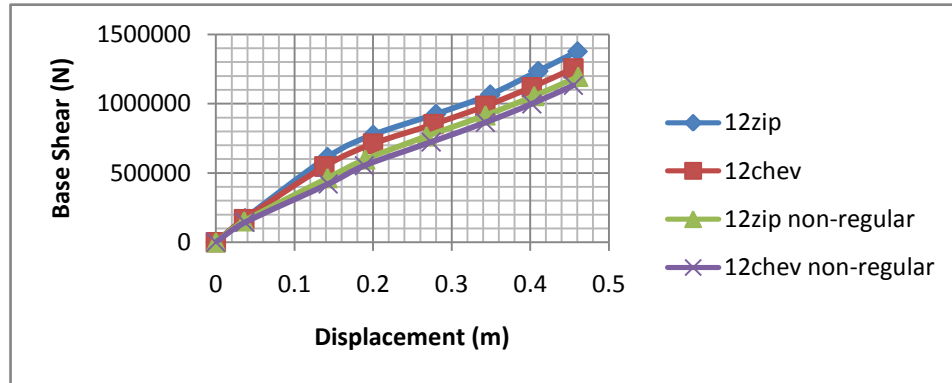
**Fig.21** IDA results for the considered drift parameters (ERZINCAN-12-Story; near-fault)



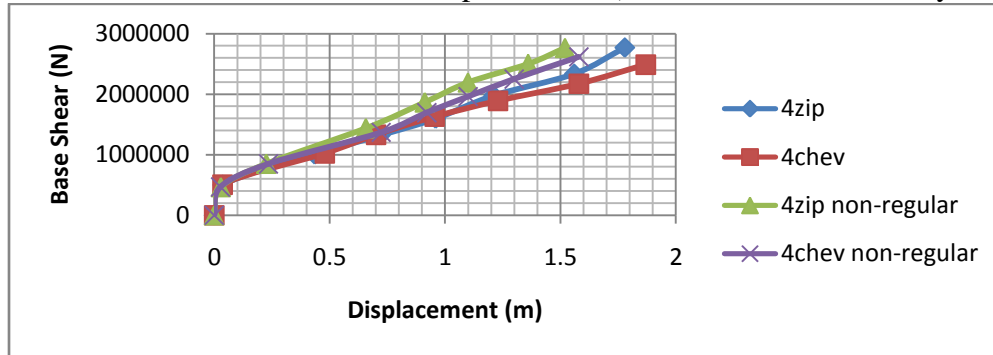
**Fig.22** IDA results for the considered drift parameters (NORTHRIDGE-4-Story; near-fault)



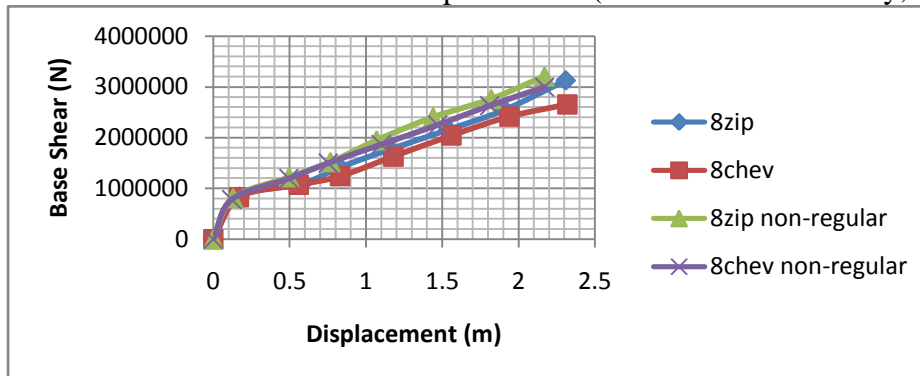
**Fig.23** IDA results for the considered drift parameters (NORTHRIDGE-8-Story; near-fault)



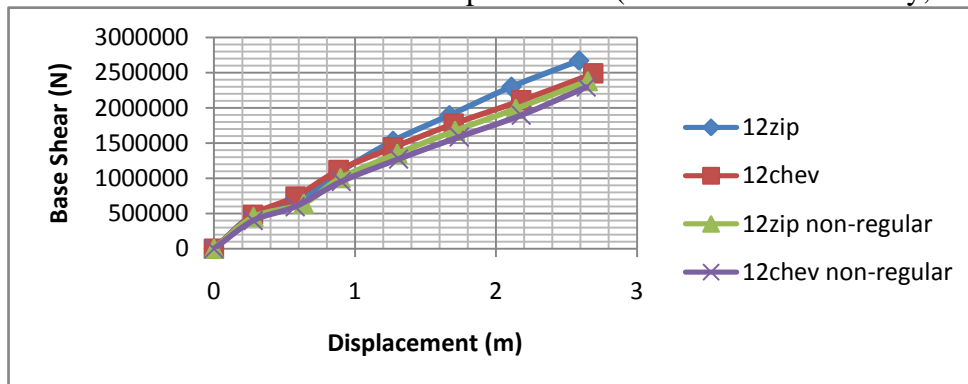
**Fig.24** IDA results for the considered drift parameters (NORTHRIDGE-12-Story; near-fault)



**Fig.25** IDA results for the considered drift parameters (SUPERSTITN-4-Story; near-fault)



**Fig.26** IDA results for the considered drift parameters (SUPERSTITN-8-Story; near-fault)



**Fig.27** IDA results for the considered drift parameters (SUPERSTITN-12-Story; near-fault)

## CONCLUSIONS

A procedure in terms of simple formulae for estimating global and local seismic drift and ductility demands in regular and non-regular multi-story zipper and chevron steel buildings subjected to ordinary (i.e. with near-fault and far-fault effects) ground motions has been presented. In almost all the structures investigated here the collapse mechanism is characterized by yielding of brace at all floors. The result is logical because design internal forces of members have been obtained starting from the ultimate design internal forces of brace and by means of mathematical expressions which well interpret statics of zipper. The main advantage of Suspended Zipper Braced Frame is uniform distribution of drifts over the height. Braced frames can control drifts but exhibit brittle response. Zipper is a ductile braced frame which reaches the ductility with distributing drifts over the height. Chevron-braced frames are prone to develop a story collapse mechanism, and the P-Delta instability implies the drift concentrations in particular stories. The design procedure results in zipper struts and top-story braces with reasonable strengths in low-and moderate-rise buildings, and with conservative strengths in high-rise buildings. The effects of higher modes, which become more important as the number of stories increases, appear to account for the increased conservatism of the procedure as the number of stories increases.

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