Study of the Behavior of Zipper Braced Frames

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SUMMARY:
Due to the buckling of compressive brace in inverted-chevron braced frames, an unbalanced vertical force has to be applied on the intersection of braces and above beam, which will make an oversized displacement at the beam mid-span. This disparate force results in a strong beam design which is not proportionate to other members. Also, buckling of the compressive brace, results in a localization of the failure and loss of the lateral resistance. One of the ways to overcome this problem is to use a vertical structural element at the beam mid-span from the second to the stories above, called *zipper strut*. In order to evaluate the behavior of this new system, known as the zipper braced frame, some in-plane frames with zipper struts was modeled in OpenSees, along with chevron frame system. These models were analyzed under pushover conditions and their ductility, drift and internal forces of the members were compared with each other.

Keywords: inverted-v- braced frames, zipper braced frames, pushover analysis

1. INTRODUCTION

Investigation of damaged structures in past earthquakes shows that due to ductility of materials, steel structures have better performance under seismic loads than other structures (Akhlaghi, 2001). Under lateral earthquake loads, simple steel frames undergo large lateral displacements that may damage structural and non-structural members. One of the practical ways to prevent steel frames undergoing large lateral displacements is to use diagonal members, called *brace*. These members increase lateral stiffness of the frame and enhance the capacity of the energy dissipation by plastic deformations.

Common brace members are single-profile elements which are designed to carry out both tensile and compressive forces and buckling of these members is controlled by slenderness ratio. Since the single-profile braces are designed to tolerate compression forces, usually, an extensive cross-section is required to prevent member from buckling. Concentrically braced frames, in general, have a limited energy dissipation capacity, unsymmetrical hysteresis behavior and significant strength deterioration under compressive loading (Shokrgozar, 2006).

A typical brace frame configuration, is the well-known inverted-v-braced frame. In this system, with the increase of lateral loads the compressive members buckle and plastic hinges will form in the brace elements. But because of the fact that plastic hinges share no distribution; buckling just occurs in the lower stories, and only these members dissipate seismic forces and, therefore, braces of the higher stories remain elastic. Due to buckling of the compressive brace, also, the shear capacity of the frame decreases. To overcome to these shortcomings of chevron system, *zipper braced frames* have been proposed. The main idea of this paper is to investigate nonlinear response of zipper braced frames to lateral seismic loads and to make a comparison between the seismic behavior of chevron braced frames and that of zipper braced frames. In order to reach this aim, several chevron and zipper braced frames have been modeled in OpenSees, and verified using existent experimental data. In the following sections, first, inelastic cyclic behavior of concentric braces will be discussed and then, simulated frames, their properties, analysis and loading condition will be defined. Finally, the results of the numerical simulations of various frames will be discussed.

2. HYSTERITIC BEHAVIOR OF CONCENTRIC BRACES

In Fig. 2.1 a typical inelastic cyclic response of a pin connected brace member is illustrated. When the first cycle is compressive, as the force in the member reaches Cu in point B, the brace buckles and a plastic hinge forms in the mid-span. Due to the formation of the plastic hinge, compressive strength of the member reduces. The equation of moment equilibrium in the plastic hinge section results in the following expression:

$$P.\delta_m = M = EIy'' \tag{2.1}$$

Where P is the axial force, M is the bending moment in the mid-span, δ_m is the lateral displacement in the mid-span, EI is the bending rigidity of the brace and y is the lateral displacement curve function. When a plastic hinge in the mid-span forms, resistant bending moment (M) of that section reaches plastic moment (M_p) and remains constant. Thus, if the lateral displacement of the mid-span (δ_m) at the left side of the above Equation increases, the axial force (P) must be reduced. Therefore, when the member buckles at the point B, axial force starts to reduce. This reduction continues until point C where an elastic load reversal occurs. In this region, by rotation of the plastic hinge, the member comes close to its initial straight form (point D in Fig. 2.1a). Internal force in the brace, finally, reaches the yield strength (A_gF_y) and by increase of the axial force, more plastic deformations occur in the member. In the next cycles due to Bauschinger effect, residual out-of-plane deformations of previous cycles and local buckling in the plastic regions, the yield strength of the member reduces significantly (point F). In Fig. 2.1b it is illustrated that overall behavior of the brace when the first cycle is tensile is similar to the state that the first cycle is compressive.

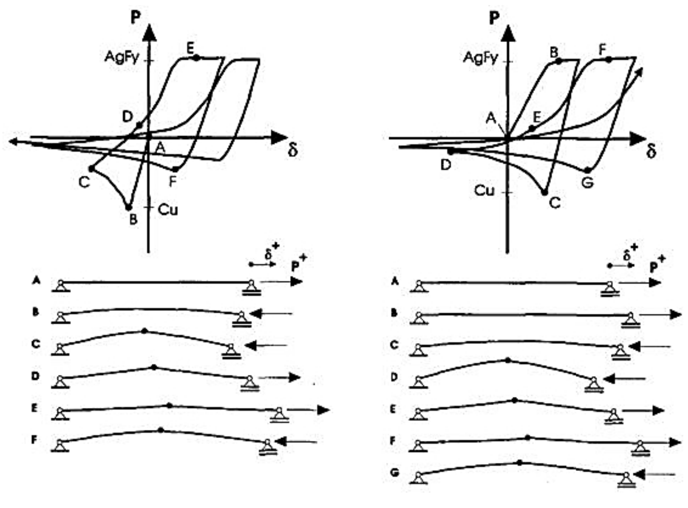

Figure 2.1 Typical inelastic cyclic behavior of a pin connected brace (Tremblay, 2001)

Other descriptions of the inelastic cyclic behavior of concentric braces also exist. Ikeda and Mahin, 1986, divided a cycle of the hysteretic behavior of a brace member to four parts: *elastic*, *plastic*, *elastic buckling* and *yielding* regions. This model consists of two beam elements which yield under tensile load and an elasto-plastic hinge. Elastic and plastic states are related to the plastic hinge and tensile yielding is related to the beam elements. Elastic region, in turn, is subdivided to two parts: *elastic length reduction* and *elastic elongation* region. Both tensile and compressive regions of a cycle have these four parts; therefore a full cycle includes eight regions. In Fig. 2.2 and Fig. 2.3 axial force is illustrated versus axial deformation and plastic hinge rotation, respectively. In these figures, ES1 is the elastic length reduction in compression, EL1 is the elongation under compression, P1 is the plastic region under compression, BU is buckling in compression, ES2 is the elastic length reduction in tension, EL2 is the elongation in tension; P2 plastic region in tension and PY is tensile yielding.

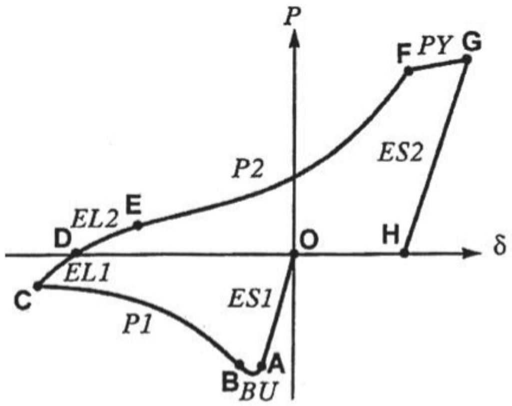

Figure 2.2 Axial force versus axial displacement in a pin connected brace (Ikeda & Mahin, 1986)

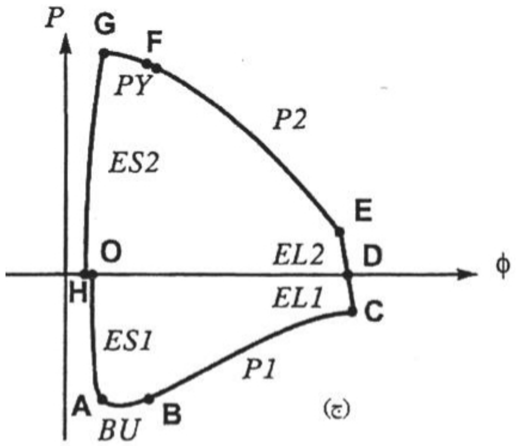

Figure 2.3 Axial force versus plastic hinge rotation in a pin connected brace (Ikeda & Mahin, 1986)

In each cycle, a brace member experiences inelastic out-of-plane buckling and tensile yielding and permanent elongation occurs in the member. After several cycles, under compression, local buckling occurs in the plastic hinge regions and in the next cycle, the member fails under tension. This failure load is usually less than ultimate tensile strength of the member. This is because of the *ultra-low cycle fatigue* phenomenon which can be simulated by new computational models (Davaran & Easazadehfar, 2005).

3. ZIPPER BRACED FRAMES

Inverted-v-braced frame is one of the common systems which are used to carry out earthquake loads. Seismic response of this system is usually controlled by buckling of the compressive brace members. To resist seismic loads, a building should have a large capacity of energy dissipation, but in the concentrically braced frames which there is no other member such as link beam in eccentrically braced frames to dissipate earthquake energy, the alternating buckling and tensile yielding leads to poor hysteretic behavior, the formation of a soft-story mechanism and final collapse of the structure. In fact, by the increase of the lateral displacement, the compressive brace buckles and its axil load carrying capacity reduces when tensile brace reaches yielding. Thus, after buckling of the compressive member, an unbalanced force will be imposed to the intersection point of the beam and braces. Since this unbalanced force is relatively large, the beam should be a massive member to prevent the structure from overall collapse. To reach this aim, a design code must consider this force in combination with common gravity loads (Yang *et al*, 2008). The unbalanced force according to *allowable stress design* method and *ultimate limit state design* method is illustrated in the Figs. 3.1 and 3.2, respectively.

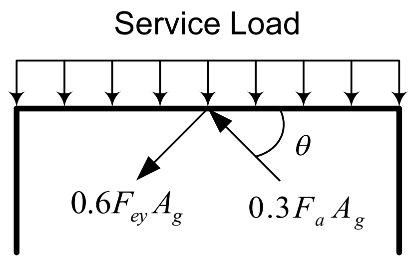

Figure 3.1 Unbalanced forces in allowable stress design method

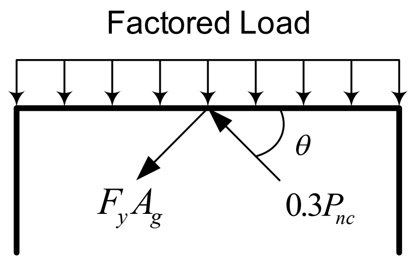

Figure 3.2 Unbalanced forces in ultimate limit state design method

In the above figures, A_g is the cross-section of the brace member, F_{ey} is the expected yield stress, F_a is the compressive allowable stress, P_{nc} is the nominal compressive strength and F_y is the yield stress of steel. Writing force equilibrium equation in the y-direction in allowable stress design method yields:

$$T_z = \left(0.6F_{ye}A_g - 0.3F_aA_g\right)\sin\theta \tag{3.1}$$

and for ultimate limit state design method:

$$T_z = \left(F_{ye}A_g - 0.3P_{nc}\right)\sin\theta \tag{3.2}$$

where T_z is the unbalanced force. In this paper allowable stress design method has been used. In any case, buckling of the brace and bending behavior of the beam reduces ductility of the whole structure. To prevent chevron braced frames from soft story formation in the first story, Khatib *et al*, 1988, proposed to add a vertical member, called *zipper strut*, in the intersection of the braces and floor beam in all stories except first story. In Figs. 3.3 and 3.4 typical behavior of the inverted-v-braced frame and that of the zipper braced frame is illustrated, respectively.

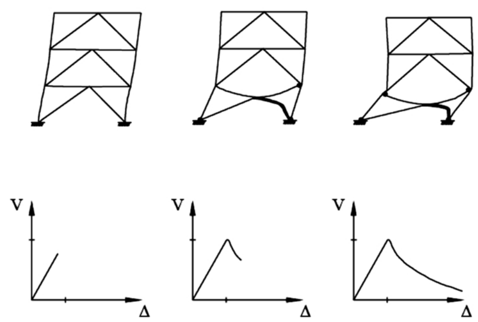

Figure 3.3 Typical response of an inverted-v-braced frame to lateral displacement

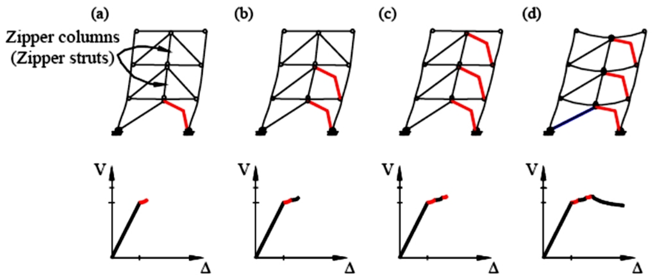

Figure 3.4 Typical response of a zipper braced frame to lateral displacement

As it can be understood from the Figs. 3.3 and 3.4, the aim of using zipper struts is to enforce all compressive braces to buckle. The benefit of this behavior is that all stories have contribution in the energy dissipation. For instance, if the compressive brace of the first story buckles, an unbalanced force will be imposed to the mid-span of the first floor beam (Fig. 3.4a). This unbalanced force is transferred to the intersection of the second story beam and braces and increases the compressive force in the brace. This leads to buckling of the compressive brace of the second story (Fig. 3.4c). This process continues until buckling of the compressive brace. Although buckling of the all compressive braces results in a uniform distribution of the energy dissipation in the height of the structure, but it is not always a good result. Due to the formation of the complete zipper mechanism in the height of the structure, overall instability and failure can occur in the system (Fig. 3.4d). This shortcoming limits the use of this system (Yang *et al*, 2008).

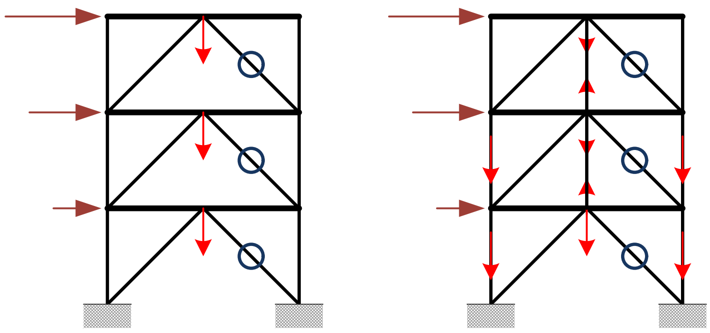

Figure 3.5 Transformation of vertical unbalanced force by the zipper strut

4. DEFINITION OF THE MODELS

In this paper two 4- and 8-story buildings with inverted-v-braced system and zipper-braced system has been modeled. Each frame has three bays and the problem is two-dimensional. Height of the stories is 3 meters and all bays have 4 meters length. In all models the middle bay is braced. Nonlinear static analysis (pushover) is performed on each model using OpenSees software and the results have been discussed in the following sections.

5. COMPARISON OF ZIPPER- AND INVERTED-V-BRACED FRAMES

5.1. Axial force of the braces

Axial force of the brace members plays an important role in the overall performance of the system. In fact, axial force of the brace element shows the story capacity of force absorption. Thus, diagram of axial force of the braces versus base shear can be one of the helpful diagrams to understand behavior of the braced frames. In Figs. 5.1and 5.2 node and element numbers of zipper- and inverted-v-braced frame has been shown. In Figs. 5.3 and 5.4, also, axial force of the brace elements has been plotted against base shear of the building.

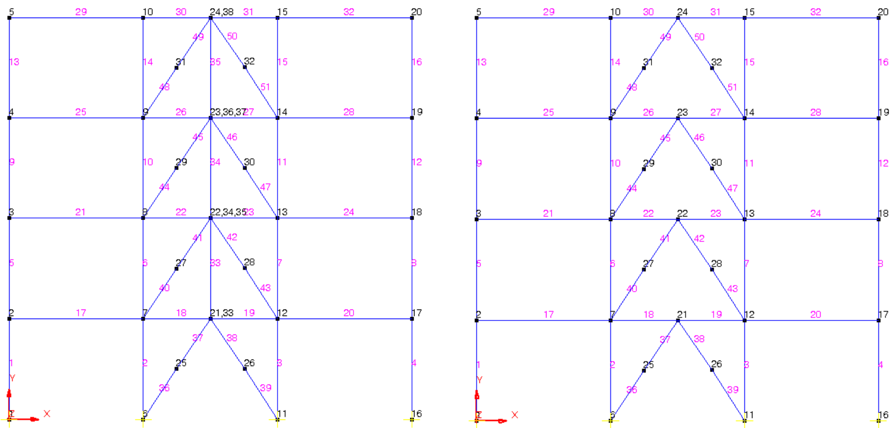

Figure 5.1 Node and element numbers for the 4-story zipper- and the inverted-v-braced frames

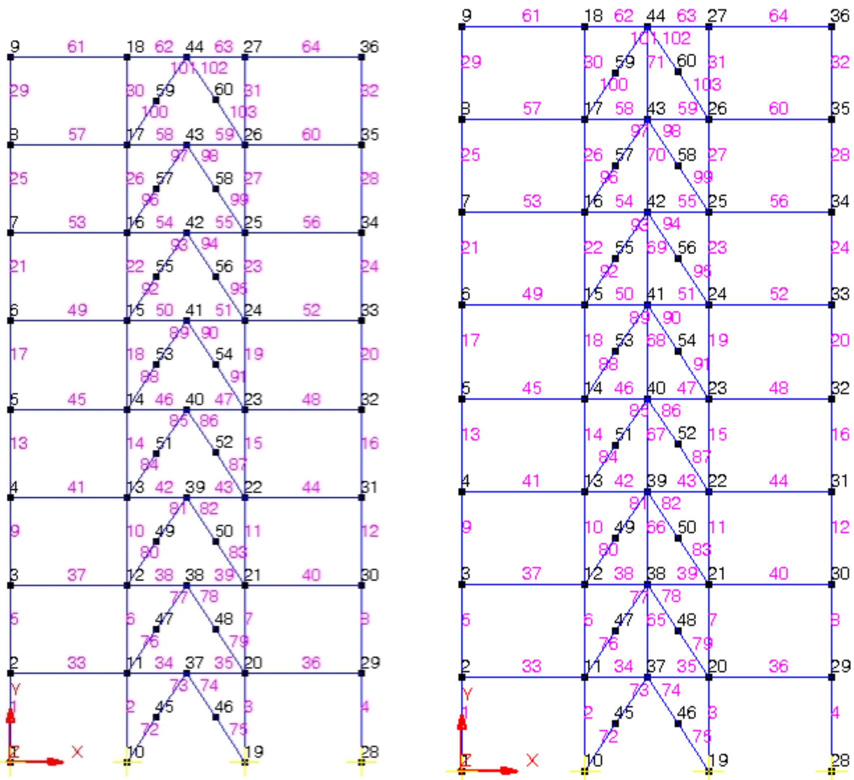

Figure 5.2 Node and element numbers for the 8-story zipper- and inverted-v-braced frames

Each diagram of Figs. 5.3 to 5.6 can be subdivided into three parts. First part is linear. In the second part by the increase of base shear, axial force of the brace decreases. This is due to the buckling of the compressive brace which cannot sustain further load. In the third part, base shear of the building starts to decrease which is also due to buckling of the braces.

As it can be seen it Fig. 5.3, reduction of axial force of the brace in first story is clear, but in second story it is poor. In third and fourth stories, by the decrease of axial force of the braces, base shear of the buildings, also, decreases. In Fig. 5.4, however, reduction of axial force of the brace in all stories is relative soft. In other words, before the reduction of the shear base, axial force of the braces steps down. This implies that buckling has also occurred in the stories above. It will be discussed later that the buckling has really occurred in the stories above or not.

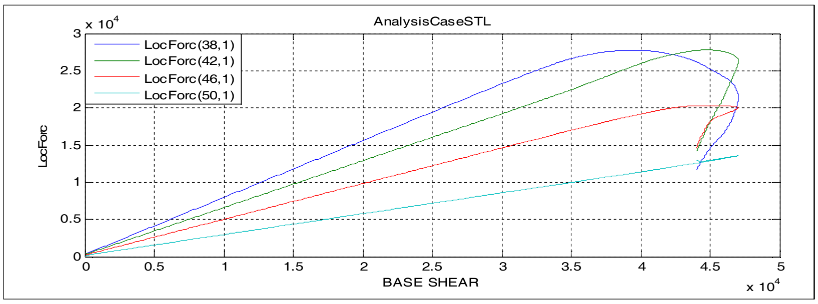

Figure 5.3 Axial force of the compressive braces vs. base shear, 4-story inverted-v-braced frame

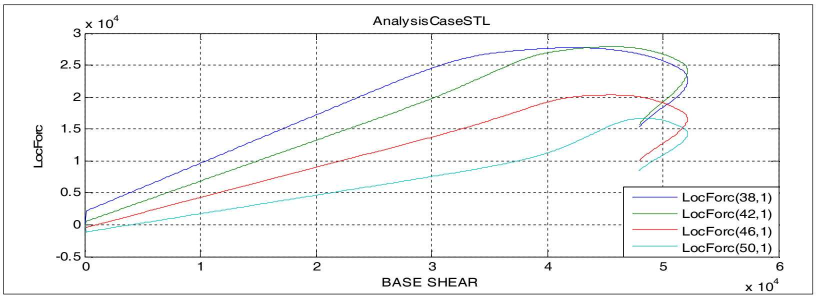

Figure 5.4 Axial force of the compressive braces vs. base shear, 4-story zipper braced frame

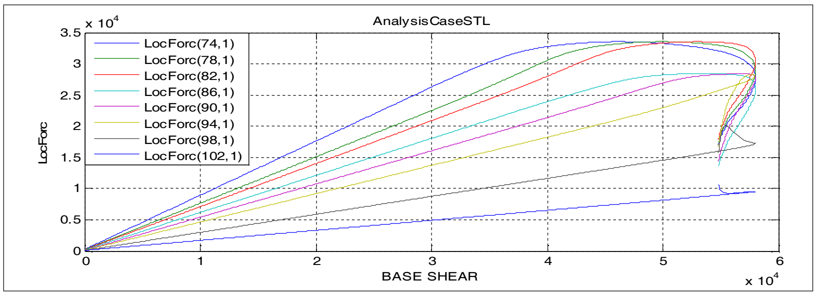

Figure 5.5 Axial force of the compressive braces vs. base shear, 8-story inverted-v-braced frame

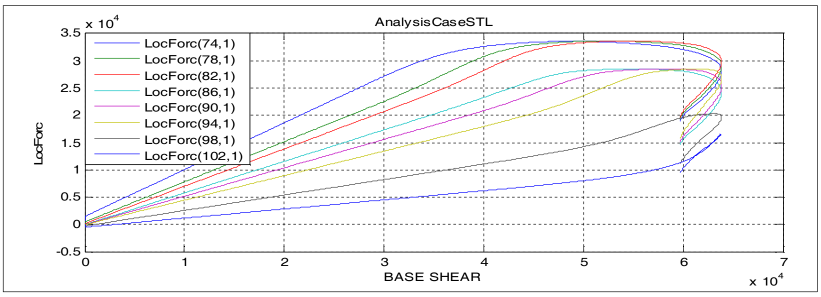

Figure 5.6 Axial force of the compressive braces vs. base shear, 8-story zipper braced frame

All of the above discussions is, also, correct about 8-story zipper- and inverted-v-braced frame and is illustrated in Figs. 5.5 and 5.6. Distribution of the brace buckling, however, is not as well as 4-story frames.

5.2 Relative lateral displacements

In Figs. 5.7 and 5.8 relative lateral displacements (drift) of the stories have been illustrated. As it is clear from Figs. 5.7 and 5.8, drift of the first story is significantly greater than that of other stories in the inverted-v-braced frame, but in the zipper braced frame the difference between story drifts is not considerable.

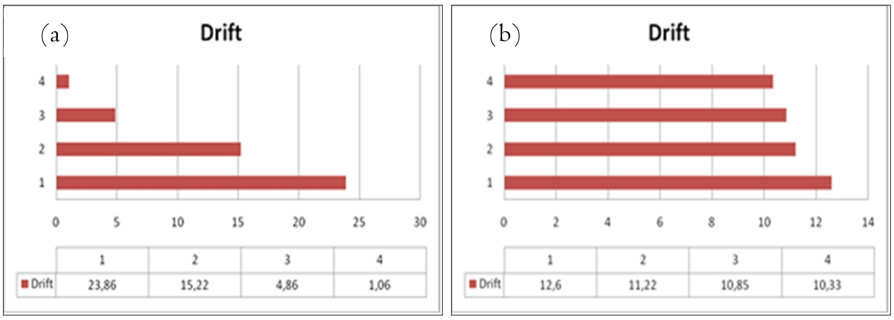

Figure 5.7 Drift of the stories for the 4-story building, (a) inverted-v-braced frame, (b) zipper braced frame

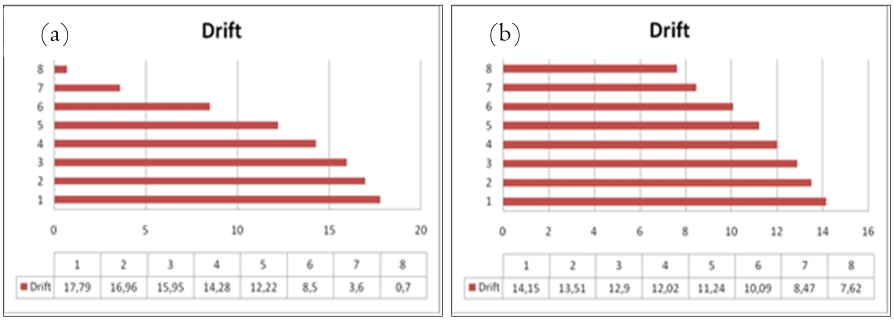

Figure 5.8 Drift of the stories for the 8-story building, (a) inverted-v-braced frame, (b) zipper braced frame

5.3 Buckling of the compressive members

In Fig. 5.9a axial force of the compressive braces against its axial displacement has been drawn for the 4-story inverted-v-braced frame. As it can be seen, just the braces of the first and second story have buckled and gotten into the nonlinear stage. By using the zipper strut in this frame, unbalanced force is transferred to above braces and enforces them to buckle. This is clear from Fig. 5.9b where the axial force of the compressive braces of the zipper braced frame has been illustrated versus axial displacement. Fig. 5.10 shows the same result about an 8-story building.

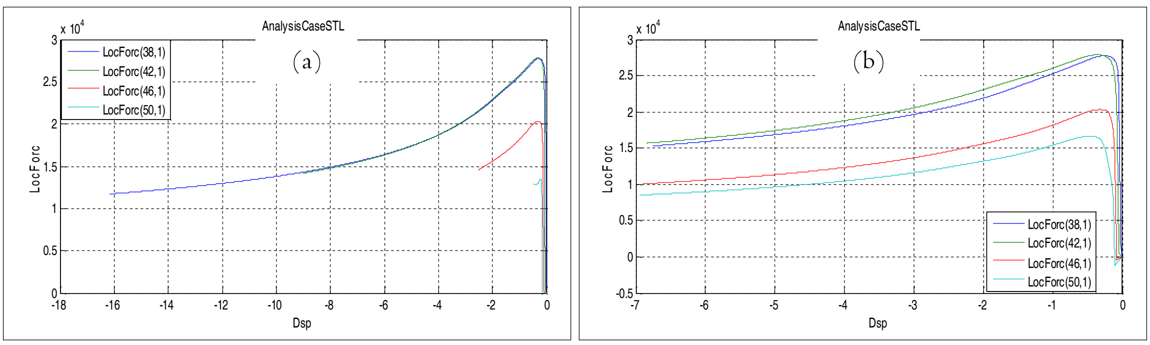

Figure 5.9 Axial forces of the compressive braces vs. axial displacement for 4-story building, (a) inverted-v-braced frame, (b) zipper-braced frame

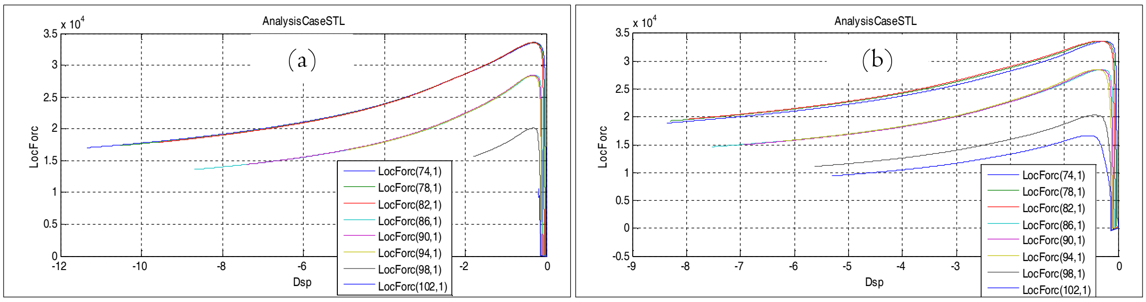

Figure 5.10 Axial forces of the compressive braces vs. axial displacement for 8-story building, (a) inverted-v-braced frame, (b) zipper-braced frame

5.4 Displacement of the mid-span point of beams

As mentioned before, one of the main shortcomings of the inverted-v-braced frames is the relative large displacement of the mid-span point of the braced bay beams. This large displacement is due to the unbalanced force. In Figs. 5.11 and 5.12 this large displacement for all stories has been drawn versus the base shear. It is clear that in inverted-v-braced frames, displacement of the mid-span point of the beam in the first story is large, but is small in the stories above. However, in the zipper-braced frame displacements of the mid-span point of the braced bay beams is close which demonstrates better force distribution in the zipper-braced frames.

5.5 Base shear vs. lateral displacement

Diagram of base shear versus lateral displacement is used to determine ductility factor and response modification factor of structures. This diagram has been illustrated in Fig. 5.12 for both 4- and 8-story buildings.

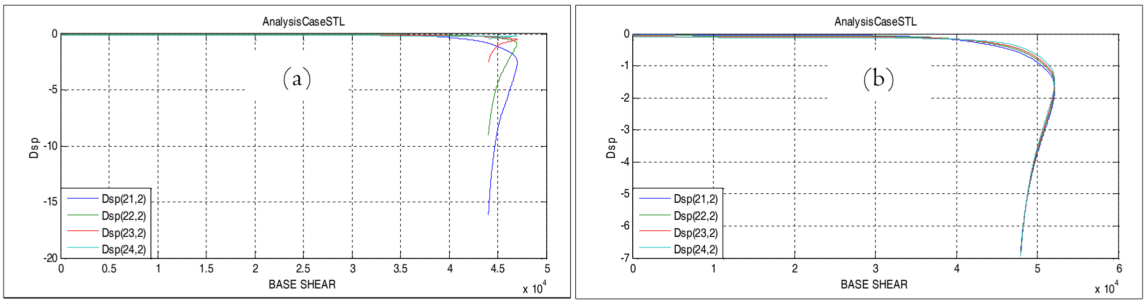

Figure 5.11 displacement of the mid-span pint of the braced bay beam vs. base shear for 4-story building, (a) inverted-v-braced frame, (b) zipper-braced frame

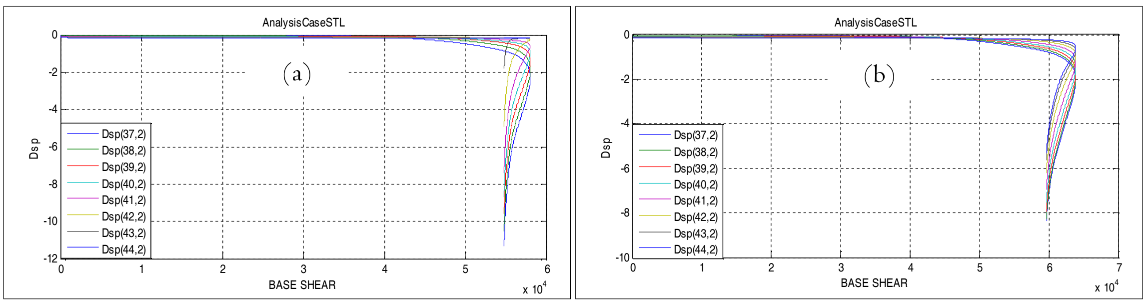

Figure 5.11 displacement of the mid-span pint of the braced bay beam vs. base shear for 8-story building, (a) inverted-v-braced frame, (b) zipper-braced frame

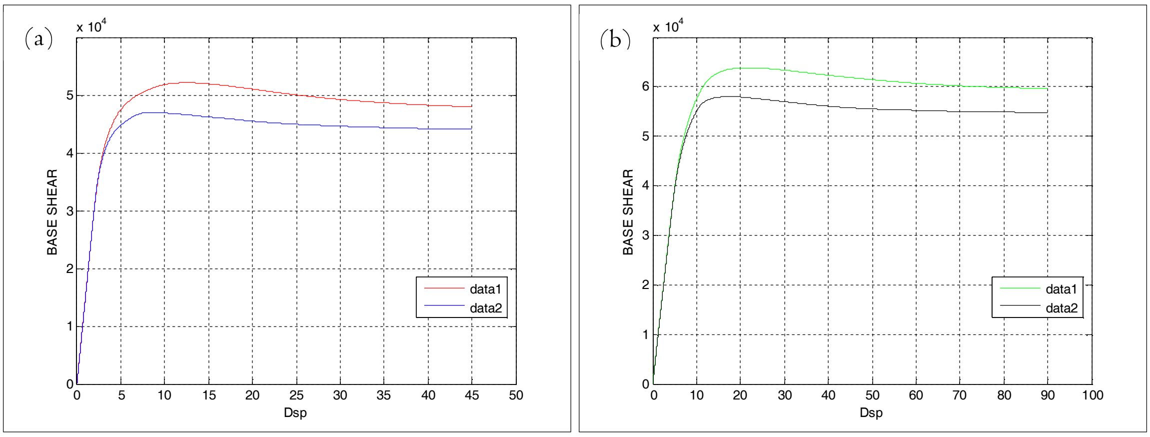

Figure 5.12 Base shear vs. lateral displacement, (a) 4-story building, (b) 8-story building, data1: inverted-v-braced frame, data 2: zipper-braced frame

6. CONCLUSIONS

Considering all results and performed investigations, following conclusions can be obtained. The zipper strut has a desirable effect on overall behavior of structures. It transforms unbalanced tensile load from lower stories to top stories and, thus, enforces compressive braces to buckle. As a result, in the all compressive braces a plastic hinge forms. By making use of the zipper strut, also, vertical displacement of the mid-span point of the braced bay beam is considerably reduced. In zipper-braced frame this displacement is almost equal for all stories. It has been shown that in zipper-braced frames, lateral displacement distributes uniformly in all stories and do not concentrate in the lower stories. All of the above effects, finally, results in an enhanced base shear-lateral displacement behavior and increase energy absorption capacity of the structure.

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