International Journal of Current Engineering and Technology
ISSN 2277 - 4106


Research Article

# Behavior of Zipper Braced Frame (ZBF) compared with other Concentrically Braced Frame (CBF)

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Accepted 05 September 2013, Available online 01 October 2013, **Vol.3, No.4 (October 2013)**

***Abstract***

*In this study the Behavior of Zipper Braced Frame (ZBF) is investigated and compared with Concentrically Braced Frame (CBF). In order to ensure the systems behavior in a stable manner, different concentrically braced configuration has been studied. The frame has the same geometry as the conventional Chevron braced frame except a vertical structural element, the Zipper column, is added at the beam mid-span point from the second to the top story of the frame. To evaluate this new system Opensees software are used to model different two dimensional frames with Zipper brace. These frames are analyzed under pushover and cyclic conditions and their ductility, drift and internal forces of the members are compared with each other. Analyses show the formation of plastic hinges in higher stories, and the participation of all braces in dissipation of seismic forces. The analyses verify the reduction of mid-point deflections of beams in the braced system as well as improvement of ductility and response modification factor in comparison to the other concentric braces.*

***Keywords:*** *Chevron bracing system, Zipper bracing system, Zipper strut, CBF*

## 1. Introduction

Over viewing the damage of structures in past earthquake shows that ductility and energy absorption of steel structures are more economical and have better performance compare to other structures. In general, designing of common steel structures is not economical to remain in elastic zone in the area of severe earthquakes. Seismic design of structures based on an element shows non-elastic behavior and absorbs seismic energy under severe earthquake.

Despite the fact that Concentrically Braced Frames (CBF) are known as one of the lateral load resistance in the past severe earthquakes, it is also possible not to have suitable functions under lateral loads. Since the weaknesses of Concentrically Braced Frames and poor failure mechanisms with a negligible structural ductility are important, for this regard, zipper bracing system is introduced to overcome some of the weaknesses.

As Chevron bracing system can resist lateral loads for steel structures, on this subject matter various studies have been done in order to overcome the problems caused by beam failure. For this reason, Khatib et al. 1988, Remennikov and Walpole 1998, Sabelli 2001, Tremblay and Robert 2001 have illustrated that chevron bracing systems under strong seismic loads cause mechanism to be formed in the frame of the structure. And cause drifts and bracing ductility to be happened over the height of the building. When the beam are not designed to unbalanced vertical forces caused by bracing system which will be occurred when the bracing system buckled and lose the compressive strength. As a result, plastic hinge will be formed in beams where they are connected to the buckled braces, and then it will reduce storey shear resistance and result lateral deformation. Further on, Khatib proposed to add a new vertical brace, named Zipper, to attach the brace-to-beam intersection points between adjacent floors. In this way, Zipper bracing system reacts under compressive and tension loads which stimulate Zipper mechanism to operate and braces at stories to buckle simultaneously

To investigate new bracing system 2-Dimensinal bracing frame of two different kind of bracing systems are modeled using Opensees program. The models are analyzed using the push over and cyclic method, and ductility, displacements and internal force members are compared.

### 1.1 V and Chevron bracing system

If the cross bracing system is used in the building, it will be impossible to have an opening in the braced frame.

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Therefore, designed concentrically braced system should provide structural and architectural requirements. These braces were introduced in two models as V and Chevron braces. There are similarities in terms of form but quite different when comparing with cross bracing system. Fig (1)

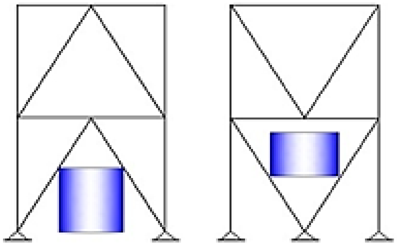


**Fig 1** V and Chevron bracing

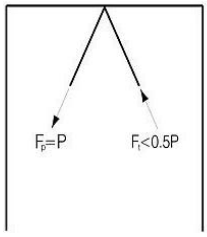



**Fig 2** Unbalanced force on the beam

The frameset of both tensile and compressive element and beams are affected by lateral loads. When force is applied to the frame system both diagonal members will be under pressure and tension, but compressive member never yield stresses and consequently it buckles and loses the stability. Experiments show that if P is considered as a tensile force to the member, the compressive force members would be less than 0.5P. In other words, unlike the results of elastic analysis of these bracing systems where the compressive and tensile forces are equals, the forces will not be the same and the beams, where the diagonal members are connected, will be affected by huge loads and it should be designed for these kinds of loads. Fig (2)

Buckling of compressive members and bending behavior of beams, where the diagonal members are connected, will cause to reduce plasticity of bracing systems.

*1.2 Zipper-Braced Frame (ZBF)*

Engineers found Chevron braced frames difficult to design, since they are not able to distribute unbalanced large forces because of buckling at bracing system.

In order to achieve the advantages like the effectiveness of stiffness and resistance to limit the displacement ratio and also ensure the behavior of the stability of the structure, concentrically zipper-braced frame is shaped. Fig3

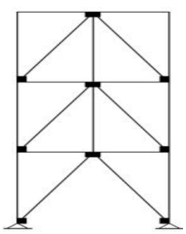


**Fig 3** Zipper frame

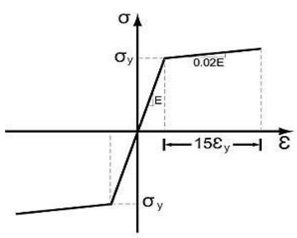



**Fig 4** Steel 01 material

ZBF theory was first proposed in 1988 by Khatib . This system is similar to Chevron system, but only just one additional element, which was a vertical structural member, connected at the top and down to the beams at the mid-span point. Compressive bracing at the first floor will be buckled in the event of an earthquake shake which will cause unbalanced vertical force at the middle of the beam. When the force is applied to the floor, compressive and tensile forces are distributed to the bracing members. According to the statics relations, the two distributed forces are equal and so the result in intersection of the vertical beam floor is zero. Since the force level of the floor is increasing, the force of the compressive member goes further and causes the member to buckle. In this case, internal force of the tensile bracing member increases, while the force of the compressive bracing member remains constant, finally unexpected deformation will be caused to the beam due to unbalanced vertical forces. Zipper columns distribute unbalanced vertical forces to the top floor and will cause compressive force of bracing member to increase and buckle. Buckling of the bracing member spreads towards the top, until all the compressive bracing members buckled and plastic hinges are being created. This function will distribute forces desirably. Simultaneously buckling of all braces at the height of the building will cause failure uniform distribution, which is the main objective of this design.

*1.3 Modeling the structure in Opensees*

Computational model of the structures was developed using the modeling capabilities of the software framework of Opensees . This is the finite element software which has been specifically designed in performance systems of soil and structure under earthquake. For modeling of the members in nonlinear range of deformation, following assumptions were assumed.

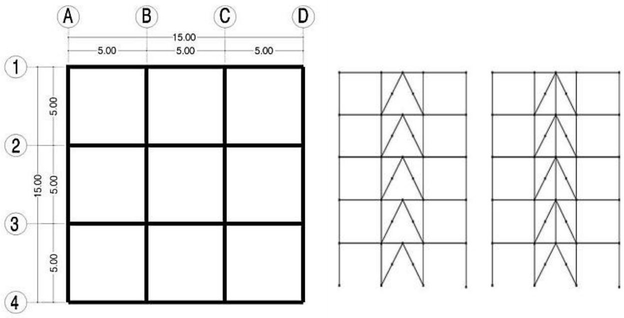
All frame members, i.e., beams, columns and braces, are considered as pin-ended. In this way, the earthquake lateral forces are carried only by the vertical; however the gravity loads are sustained mainly by the columns. For the dynamic analysis, story masses were placed in the story levels considering rigid diaphragms action.

For the modeling of braces, nonlinear beam and columns element with the materials behavior of Steel01 was used. Considering idealized elasto-plastic behavior of steel material compressive and tensional yield stresses were considered equal to steel yield stress. The used section for each member is the fiber section. The strain hardening of 2% and maximum ductility of 15 were considered for the member behavior in inelastic range of deformation (Fig4).

For prediction of linear or nonlinear buckling of columns, both element usual stiffness matrix and element geometric stiffness matrix were considered. An initial mid span imperfection of 1/1000 for all columns was considered and a fiber cross section element was considered for plastification of element over the member length and cross section for linear and nonlinear buckling prediction. For considering geometric nonlinearities the simplified P-Δ stiffness matrix is considered.

1.3.1 Design of model structures

In order to evaluate the over strength, ductility, and the response modification factors of buckling restrained braced frames 5 story building with the bay length of 5 m and two different bracing types(chevron-Inverted v and Zipper) were designed as per the requirement of Iranian Earthquake Resistance Design Code and Iranian National Building Code, part 10, steel structure design. Fig5a, b show the typical configuration of the models used. The story height of the models was considered as 3.2 m. For member design subjected to earthquake, equivalent lateral static forces were applied on all the story levels. These forces were calculated following the provisions stated in Iranian Earthquake code (standard No. 2800).The dead and live loads of 6 and 2 KN/m² were used for gravity load, respectively.




(a) Plane (b) Brace configuration

**Fig 5** Configuration of model structures

The design base shear was computed as follows,

$$V = CW \longrightarrow C = \frac{ABI}{R} \quad (1)$$

In which V is base shear of structure, C is seismic coefficient and W is the equivalent weight of the structure. A x B is the design spectral acceleration, expressed as the ratio of gravitational acceleration, for the fundamental period of structure T and soil type (Fig6), I is the importance factor and R is the response modification factor.

The importance factor of I=1, preliminary response modification factors of R=6 and seismic zone factor of A=0.35 were considered for frame design.

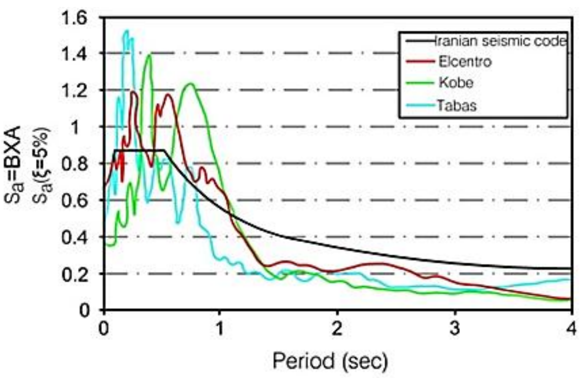



**Fig 6** Variation of spectral acceleration with period of structure

Braces were designed to sustain 100 percent of the lateral load and the beam-column joints were assumed to be pinned at both ends. Allowable stress design method was used to design frame members in accordance to part 10 of Iranian national code. To ensure that vertical bracing columns have enough strength to resist the force transferred from bracing elements; Iranian Standard No. 2800 has instruction to design vertical bracing columns for the following load combinations:

(a)Axial compressive according to:

$$P_{DL}+0.85P_{LL} + 2.8P_E<P_{SC}=1.7F_aA \quad (2)$$

(b)Axial tension according to:

$$0.85\ P_{DL}+2.8P_E<P_{ST}=F_yA. \quad (3)$$

In which Fa is allowable compressive stress, Fy is the yield stress, A is the area section of column. PDL , PLL , PE , are axial load from dead, live and earthquake load, respectively, and PSC , PST are design tensile and compressive strength of column, respectively.

*1.4 Push over analysis*

In order to investigate the structural behavior, firstly, pushover analysis is used. Systems that have been modeled are V shaped, Chevron and zipper bracing system. Buckling of bracing system under the structural deformation using pushover analysis is demonstrated in Fig7.

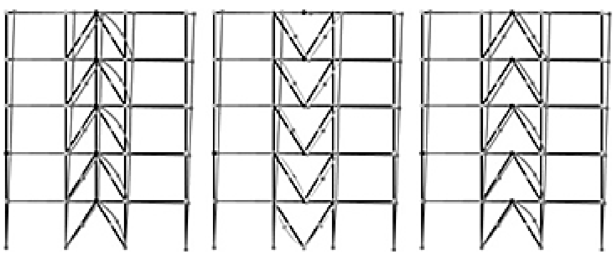


**Fig 7** Deformation of Braced Frames ( V, Chevron and zipper)

The proposed of using new bracing system (zipper) is because of weakness in V and Chevron bracing system. As it is clear, plastic hinge are created up to the top floor in compressive bracing member. But in other bracing system only just the first floor bracing system is buckled and also plastic hinge is created. As it is clear, under no circumstances no other members will participate in non-linear behavior of structures. Apparently, the reason is because of connecting the bracing system of the first floor to the foundation of the structure and also no effect of buckling of first floor bracing system to the higher floors. Due to the considering of difference behavior of V bracing system, investigation is focused on other system. And we will carefully compare the behavior of the members.

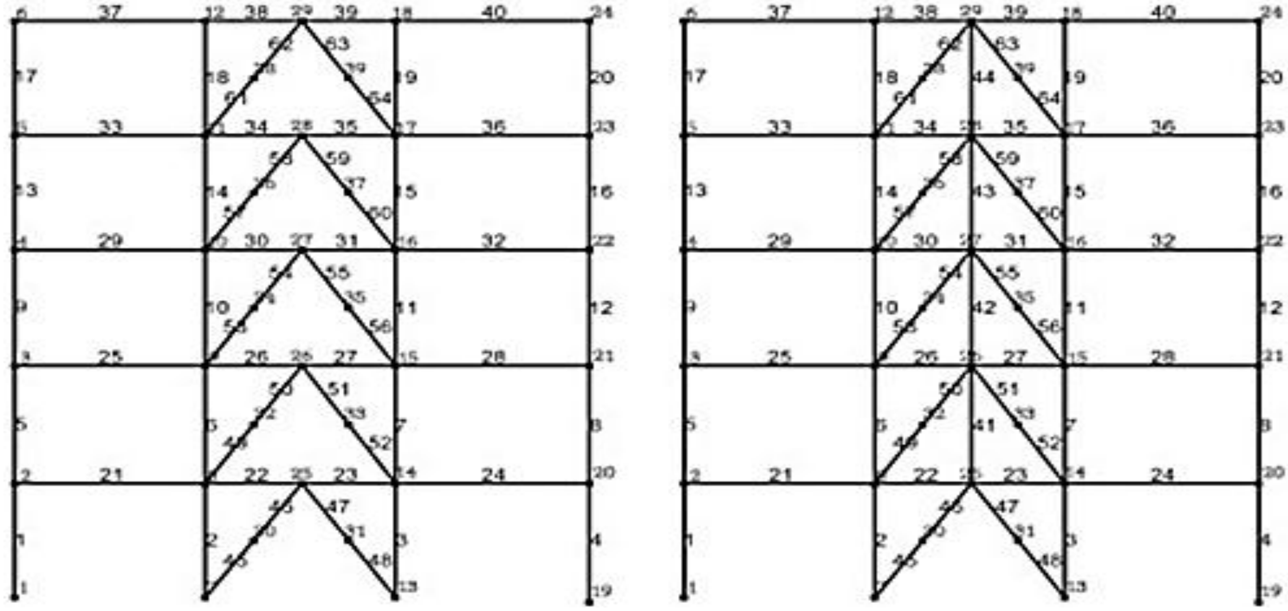


**Fig 8** Display the number of nodes and elements of braced frame with Chevron and Zipper

1.4.1 Investigating the axial force of bracing members

Since the bracing member's behavior is like truss, as a result, the axial force members will have a decisive role in the frame. As regards to the importance of increasing the lateral forces the behavior and energy absorption of each member are being determined at each floor. Therefore, the axial-shear force diagram and also axial force-drifts of floors are drawn.

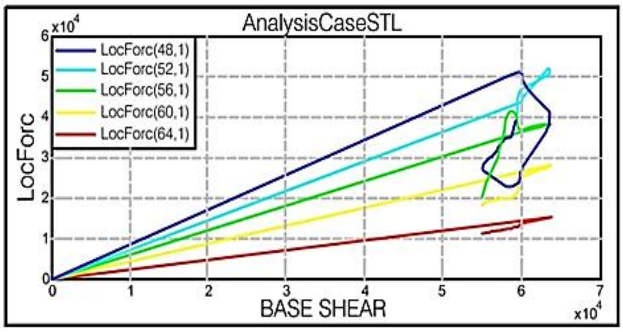



**Fig 9** Tensile force of Chevron bracing system

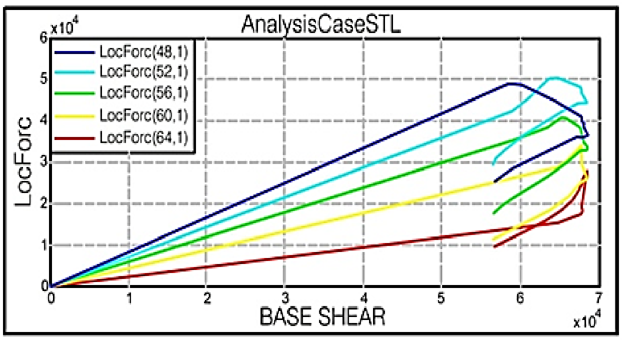



**Fig10** Tensile force of Zipper bracing system

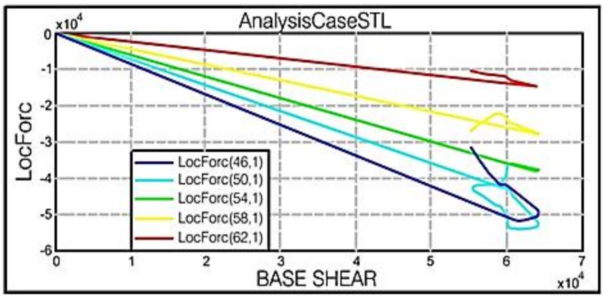



**Fig11** Pressing force of Chevron bracing system

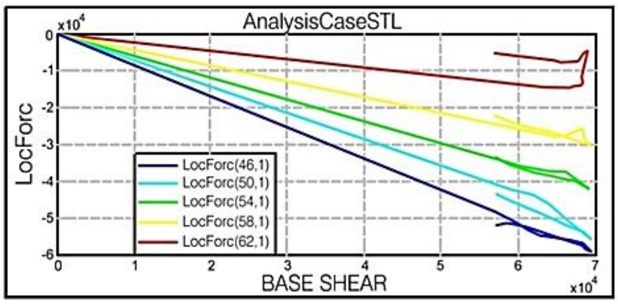



**Fig12** pressing force of Zipper bracing system

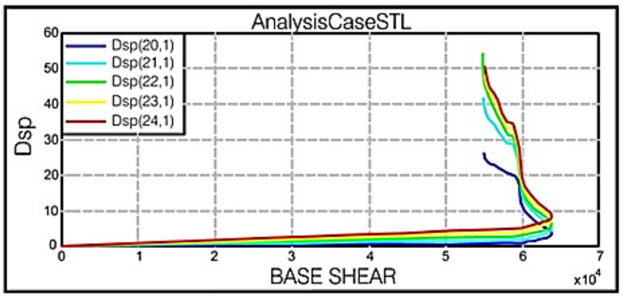


**Fig13** Lateral displacement of Chevron braced frame

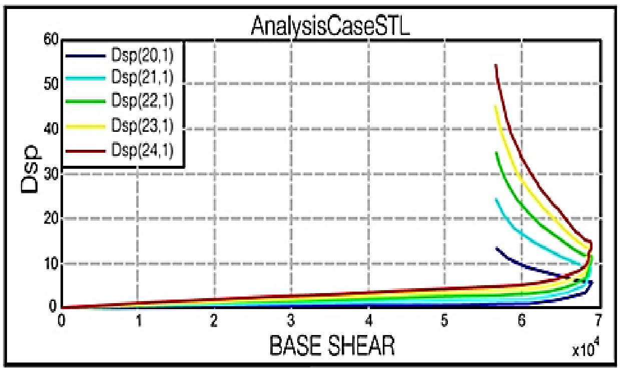



**Fig14** Lateral displacement of Zipper braced frame

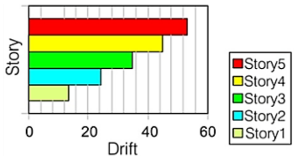



**Fig15** The amount of lateral displacement of Chevron braced frame

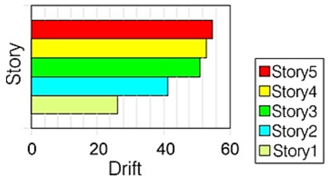



**Fig16** The amount of Lateral displacement of Zipper braced frame

According to the diagrams, the advantages of the system of Chevron braced frame to Zipper frame are named as follows:

1. High lateral load resistance with the same section
2. Participating of top floor members under loading and the amount of forces is identical in the elements
3. with no sudden loss of bracing forces which demonstrate the behavior of ductility
4. Appropriate displacement of the floors at the height of the building caused overall suitable displacement

It should be noted that the advantages of Zipper bracing system to Chevron are sensible in compressive members and less difference is considerable in tensile members. It is clear that the proposed model is based on the behavior of compressive members. Details will be investigated for the buckling of this system.

1.4.2 Buckling of compressive members

If axial deformation of the member is drawn to the axial force of the member in a diagram, it will be appropriate criteria for that buckling member. Buckling in compressive members is due to increasing of axial force which shows non-linear behavior and creating of plastic hinges. According to the figure 17, In Chevron bracing system, buckling is occurred in compressive members at first, second and partially at third floor. It is demonstrating that only three first floors bracing members will be into non-linear region and are important in absorbing earthquake energy. But as it is illustrated in figure 18, buckling of compressive members of Zipper bracing system shows an appropriate function of all bracing system under lateral loading.

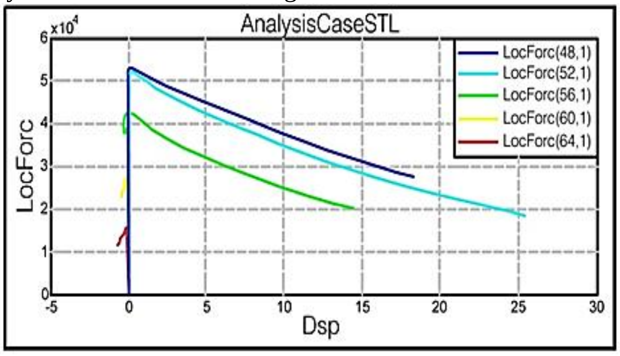



**Fig17**. Buckling of compressive members of Chevron bracing system

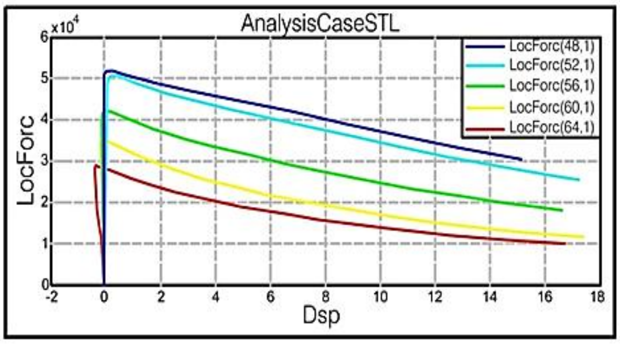



**Fig18**. Buckling of compressive members of Zipper bracing system

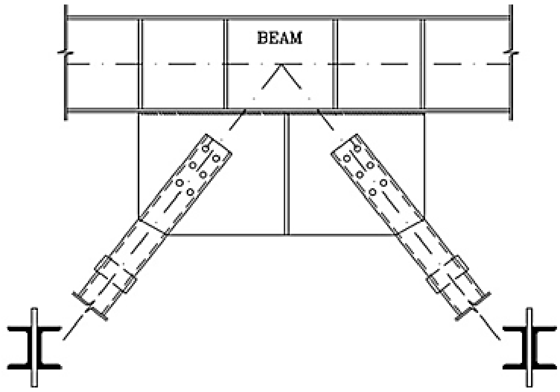



**Fig19** Connection of bracing system to the upper beam

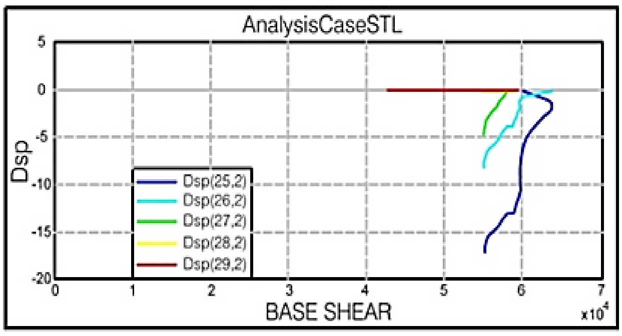


**Fig 20** Vertical displacement of the beam where Chevron bracing system is connected

One of the major problems of Chevron bracing system is the displacement of the beam at the intersection of the bracing systems. This displacement is because of compressive bracing member and it is considerable only at low levels.

Furthermore, the mid-span point displacements of the beams ratio to the base shear are drawn. As it can be observed in figures 20 and 21, the mid-span point displacement of the beam using Zipper bracing system is less when compared with Chevron bracing system, and it is identical at higher floors.

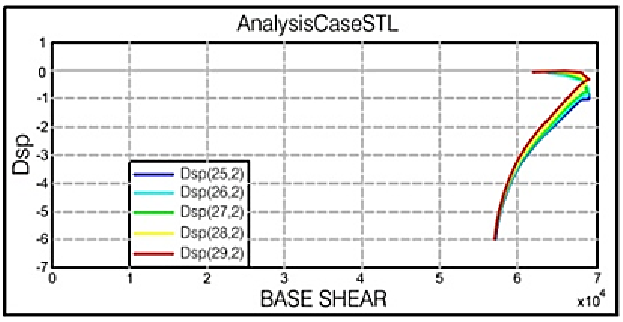



**Fig 21** Vertical displacement of the beam where Zipper bracing system is connected

1.4.3 Performance of Zipper column

Where the changes are considered in the behavior of the Zipper bracing members to Chevron is because of Zipper column had been added to the frame. According to the excessive displacement at the intersection of the braces at the top floor beam, which is the most important weakness of the Chevron bracing system, it can be concluded that the element, which connect the entire nodes together, perform as a tensile member.

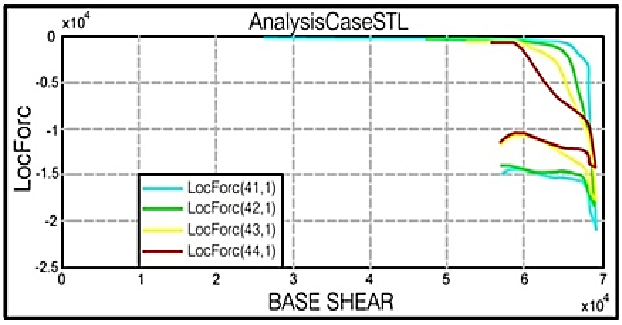



**Fig 22** Internal force of Zipper column

According to the figure 22, while the structure is not in non-linear region and also compressive members are not buckled, then internal force of Zipper column is zero. The figure shows that columns are not involved in bearing and performance of the frame. But after buckling of compressive bracing members, their tensile force increases.

In total, internal force of Zipper column system is less when compared with other elements forces; so weaker section will be used. In addition, the type of connection of these columns to the top and down floor beams is hinged.

1.4.4 Base shear-Displacement graph

One of the criteria for behavior of structures is the Base shear-displacement graph which is used for calculating the coefficient of vulnerability and behavior factor of the structure. It is determined that the amount of absorbing energy in Zipper bracing members is more than Chevron when two curves are compared. (Fig23)

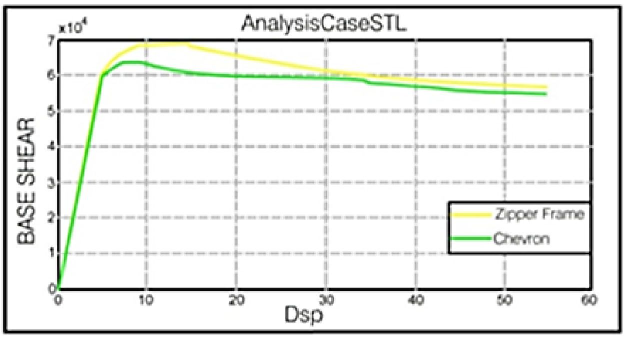



**Fig 23** Base shear-Displacement graph

1.4.5 Investigating the hysteresis cycle

In order to study the cyclic behavior of the frame, displacement of the highest point of the floor to base shear is drawn under cyclic loading.

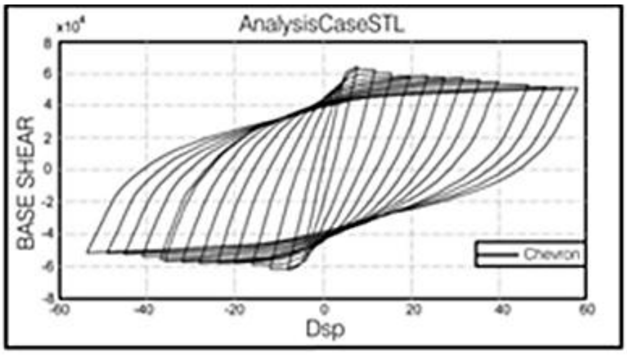



**Fig 24** Hysteresis curve for Chevron braced frame

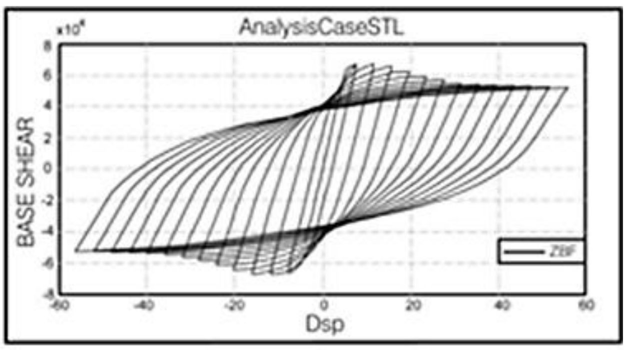


**Fig 25** Hysteresis curve for Zipper braced frame

Regards to the diagrams above it can also be determined that the amount of absorbing energy in Zipper bracing members is more than Chevron.

*1.5 Conclusion*

According to the study, it can be seen that adding vertical Zipper member had good effects on the behavior of the frames. Thus, as it was seen, while the compressive braced frame members at the first floor was not buckling (at the beginning of lateral loading), internal force in Zipper braced member was zero. Then suddenly, tensile force was created in all of the members through to the top floor. This performance causes to distribute unbalanced forces at the height of the frame suitably and also causes plastic hinges to be created in compressive members. Vertical displacement of the mid-span point of the beam at the first floor, which shows the weakness of the Chevron bracing member, is modified and remains constant for all floors at the height of the frame. Also, lateral displacement focusing at the first floor was eliminated and then distributed at the height of the frame.

Finally, considering two final diagrams of base shear-displacement and the hysteresis cycle, it is also clear that amount of absorbing energy in Zipper bracing members is more than Chevron.

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