ingegneria sismica
International Journal of Earthquake Engineering

Evaluation of the seismic performance of steel frames with semi-rigid connections with zipper bracing system under near-fault earthquakes using Opensees

Amir lamei javan[1]*, Maryam Parvaresh*[2]

[1] Department of Civil Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

[2]Department of Civil Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

SUMMARY: *The presented study investigated the improvement of the seismic performance in steel buildings with semi-rigid connections with the Chevron bracing system. The seismic performance of such frames should be improved to prevent possible damages and failures. Accordingly, modelling Chevron bracing system was first done using openness software by adding zipper columns in the semi-rigid steel frames in three 5-, 8- ,and 12-story structures as representatives of low-rise, medium-rise, and high-rise buildings, respectively. 84 semi-rigid frames were analyzed under seven near-fault records using dynamic non-linear time history analysis. The analysis of frames was done for both pinned and ductile connections and the case of removing and adding the zipper column. The results showed that the use of zipper columns in Chevron braces in the steel frames with pinned and semi-rigid connections controls both relative story displacement and maximum lateral story displacement. This effect is significant in frames with ductile connections.*

KEYWORDS: *Semi-rigid frames, Chevron bracing, Zipper column, Near-fault area*

1 Introduction

Steel structures with rigid connections were significantly damaged in the Northridge Earthquake (1994). In a study, Khatib et al., in 1988, investigated the behavior of Chevron and Zipper bracing frames in rigid and pinned frames and concluded that a vertical zipper column in a Chevron bracing caused a uniform distribution of damage over the height of the building. In addition, it could provide more flexibility in the design of the link beam in the zipper brace. Trica and Tremblay, in 2004, evaluated the impact of building height and type of ground motion on the seismic performance of conventional 4-, 8- and 12-story Zipper concentrically braced frames. After the occurrence of this earthquake and studying the damage to buildings, the researchers suggested that using semi-rigid connections as they have high ductility and ability to enter into the inelastic region. These connections had a high rotation capacity, and they were more efficient in providing ductility and dissipating the seismic energy in the steel frames [Hosseinzadeh *et al.*, 2008]. In another research, Kim et al., in 2008, modeled a 15-story frame and used dynamic and static analysis. The results showed that the seismic performance of the frame was better in the presence of a vertical zipper member in a Chevron brace than in the state without such a column. In particular, their studies showed that relative displacements of the 1st and 14th stories were significantly decreased. Longo et al (2008) studied the concentrically braced steel frames that could stand seismic horizontal forces and a collapse mechanism of the global type that was according to the capacity design. This method of

---

Corresponding author: Maryam Parvaresh, Department of Civil Engineering, University of Mohaghegh Ardabili, Iran.
Email: maryam_parvaresh@yahoo.com

designing needs the non-dissipative zones that are designed to withstand the internal actions coming from the seismic design horizontal forces and the vertical loads acting in the seismic load combination. 1n 2009, Longo et al., scrutinized several design tactics. Eurocode 8 was utilized for the first tactic to correlate the requirements that were used for structures' design for earthquake resistance. While, the second tactic was according to a capacity design criteria's rigorous application for the control of the failure mode. Additionally, Longo et al., (2009) in line with their research, studied a novel model of bracing members that was established. They investigated the V-braced frames' seismic performance that was calculated based on the Eurocode8 requirements and the suggested methodology. Finally, a probabilistic tactic according to the combination of probabilistic seismic demand analysis (PSDA), probabilistic seismic capacity analysis (PSCA), and probabilistic seismic hazard analysis (PSHA) was taken to scrutinize the designed structures' seismic performance. They reached the result that the suggested design method was a great method for enhancing the seismic performances of the structure while the cost of construction of structures increases a little. The reasons included stress concentration in the connections, low ductility, and low capacity of rigid connections under the effects of dynamic loads caused by the earthquake [Karimi, 2010]. In 2010, Yang et al. considered a modified zipper-braced frame with larger braces. For this purpose, the roof story needed to behave elastically to prevent the formation of a complete story mechanism. This modification in the form of frames was known as suspended Zipper-braced framing. The unbalanced vertical force will be directed to the ground through an elastic truss cap on the roof story, and plastic hinges will be formed in the columns and tensile braces, resulting in more ductile behavior for this type of frame. In another study, Chen (2012) used an outrigger truss to decrease the influences of large deformations in high-rise structures with zipper-braced frames. They used two 12- and 16-story structures with zipper braces in the high-risk seismic regions in two states, including with and without trigger truss. The results showed that the trigger truss decreased the relative displacement of the upper stories. In 2013, Razavi and Sheidaei studied the behavior of Zipper-braced frames and Chevron-braced systems. They performed a non-linear dynamic time history analysis on a variety of structural models having Chevron and Zipper bracing systems. Finally, they showed that the ductility and behavior factors were better for Zipper-braced frames than Chevron-braced frames. Zahrai et al., (2013) investigated the hysteretic behavior of eccentric-braced frames with a zipper member. Using the finite element method, they evaluated the link beam and zipper member behavior under cyclic loads. Amiri et al., (2014) investigated adding of a Zipper member into eccentric-braced steel frames. They concluded that increasing the length of the link beam in eccentric Chevron-braced spans decreased the bearing capacity of frames, and the damages were concentrated on connections. The addition of a zipper column in these frames changed the location of the plastic hinge formation and increased the stiffness and bearing capacity of the frame considerably. In 2015, Farahani and Mirzagol Tabar studied the seismic rehabilitation of zipper-braced frames, examined their performance in regular and irregular frames, and determined their behavior factors. In 2016, Costanzo et al., studied the steel chevron concentrically braced frames that eradicate the seismic energy by yielding of brace under tension; while, the beam and columns act elastically. Ozelik et al., (2016) modeled 3- and 9-story frames. They used pushover analysis to compare the seismic performance of steel frames with Chevron and suspended zipper-braced systems. They found that the behavior of a 9- story suspended Zipper-braced frame was better in comparison to the behavior of a steel frame with pinned Chevron-braced system, and similar results were shown in 3-story steel-braced frames, while pinned Chevron-braced frames had a better performance in medium-rise structures. In 2018, Costanzo et al. investigated that the impact of the secondary frame influence that was provided by moment-resisting beam-to-column connections are property to the braced bays in the chevron concentrically braced frames (C-CBFs). This method was used for enhancing the chevron bracings' ductility and energy dissipation capacity. Additionally, low, medium and high-rise multi-story buildings were designed based on the non-linear analyses. The results show that fully connections could affect significantly on providing an additional reserve of ductility, strength, and stiffness. Ghorbani and Karimi (2018) studied several three-span 15-story steel frames as high-rise frames with rigid and semi-rigid connections combined in different modes under three near-fault accelerograms. In another study, Zandi et al., in 2021, studied the seismic performance of dual steel moment-resisting frames having concentric braces with and without a zipper column against near-fault earthquakes by modeling several structures in SAP2000 software and defining plastic hinges. They concluded that the presence of a zipper member causes fewer plastic hinges to form at the beams, and they have been transferred to the braces, which is ideal for dual steel systems. In 2022, Narayan and Pathak studied a novel approach to renewing conventionally constructed concentric and eccentric chevron braced in the steel frames. This tactic would be so cost-effective, easy to use, least disruptive, and cause minimal structural intervention. It considerably developed the ductility and strength in the chevron-braced frames. In 2022, Comeau et al. investigated the possibility of utilizing the chevron bracing outline for multi-tiered concentrically braced frames exposed to seismic excitations. Inelastic response with restricted residual deformations was suitable for frames as a result of the re-center capacity that was equipped by the strut acting in flexure. In 2023, li et al., scrutinized the braces in chevron braced frames that were damaged by big cyclic deformation in the earthquakes. In a chevron braced frame, a brace buckling and additional brace yielding would persuade the unbalanced resultant force to braced beams. In their study, the influence of concentrically braced frames with different beam stiffness and strengths on the seismic act, and several numerical analyses containing hysteresis analysis, pushover analysis, and incremental dynamic analysis were utilized. In 2023, Zheng did research for diminishing the vertical deformation and unbalanced force at the brace connection. This research offered a polyline chevron-braced frame (ZXC), and lateral rod chevron-braced frames (ZCG) and an arc-shaped chevron-braced frame (HZC). Concurrently, the monotonic loading act, hysteresis act, bearing capacity degradation, failure mode, vertical displacement at the brace point connection, energy dissipation capacity, and fracture trend of the ZXC, ZCG, and HZC were compared with those of the chevron braced frames.

Based on the past research on structures connections it can be seen that past research that is done on structures with rigid or pinned connections with Chevron and Zipper bracing systems. Therefore, in line with the development of research in this study, it is focused on structures with semi-rigid connections, which are specially built in buildings. Accordingly, the required improvements have been addressed in this study. In the present research, seven accelerograms are selected by reviewing the studies on steel frames with Chevron and Zipper bracing systems which have pinned and rigid connections and the studies conducted on tall steel frames with semi-rigid connections, as well as the results obtained from previous research. Two pinned and semi-rigid steel frames with Chevron braces with and without zipper columns were modeled in Opensees software. The seismic performance is investigated under near-fault area records. The non-linear dynamic time history analysis was used. Improvement of frame seismic behavior and feasibility of using ductile connections have been evaluated. Adding a zipper column to the Chevron bracing system in the frames with pinned and semi-rigid connections in near-fault areas has been studied in terms of the distribution of forces over the height of the structure and the control of the relative and maximum displacement of the stories. The results show that a desirable performance could be achieved to control relative displacement and dissipate seismic energy in the near-fault area by using ductile (semi-rigid) connections in combination with the Chevron column having a zipper column in tall steel buildings. At the same time, the ductility of the whole structure is met.

2 Semi-rigid steel frames, Chevron, and zipper braces

Improving the seismic performance of structures is an essential issue to resist the dynamic forces of an earthquake so that the structural systems used in the design can dissipate energy effectively and resist seismic excitations without damaging the building. The structure should be capable of dissipating seismic energy by providing appropriate ductility and allowing the structure to enter within the inelastic behavior region, and controlling displacements within the allowable limits. Therefore, structures with ductile connections having sufficient stiffness to control structural displacements are suitable systems to meet this function.

2.1 Chevron -braced frames

Chevron (or reverse V) concentrically braced system is used as a lateral resisting system in steel structures. This system creates a vertical truss to resist lateral forces. It has high stiffness and strength, while its post-buckling behaviour is not good. The Chevron system cannot redistribute induced large vertical unbalanced forces uniformly [Khatib et al., 1988]. In this system, one of the bracing members is under tension while the other is compressed. As the lateral forces increase, the compressed member buckles, and plastic hinges are formed.

2.2 Zipper- braced frames

Improper distribution of forces in the Chevron bracing system and the transfer of unbalanced vertical force to the location of braces and upper beam intersection cause massive displacement and result in large and non-cost-effective beams than other structural members. Therefore, when a zipper column is added to the intersection of the diagonal members with the upper beam, the upward forces created by the buckling of the braces are directed to the upper stories through this column. This bracing system, called Zipper bracing system, decreases the damage over the height of the structure and improves the seismic behaviour of steel frames with the Chevron bracing system [Zandi et al, 2021].

2.3 Ductile beam-to-column connection

European codes classify beam-to-column connections of steel structures into three types, including pinned, semi-rigid, and rigid connections. The behaviour of connections is dependent on the type of structure and its lateral resisting system, too. The ductility of the connections can be determined by defining the moment and dimensionless rotation according to the following equations and the diagrams presented in Figure 1 [Ghorbani Asl and Karimi 2018].

$$\bar{M} = \frac{M}{M_p} \bar{M} = \frac{M}{M_p} \tag{1}$$

$$\bar{\varphi} = \frac{\varphi}{\varphi_P} \tag{2}$$

In Equation 1, M is the moment of connection and M_p is the plastic moment of beam attached to it equalled to $M_p = \frac{E_b I_b}{L_b}\bar{\varphi}_b$. In Equation 2, φ is the rotation of connection and φ_P is the plastic rotation of the beam attached to it. The beam-to-column connections used in this research included a pinned connection with 10% rigidity and a C0808-type semi-rigid connection selected from different semi-rigid connections presented in Table 1. According to European Code, the relations to calculate connection stiffness are as follows:

$$\theta_p = \frac{M_{pb}}{(\frac{E_b I_b}{5d_{be}})} \tag{3}$$

$$K_{\sup} = \frac{25EI_b}{L_b} \tag{4}$$

where θ_p refers to the rotation corresponding to the plastic moment of a beam by the length of $5d_{be}$ [Ghorbani Asl and Karimi 2018].

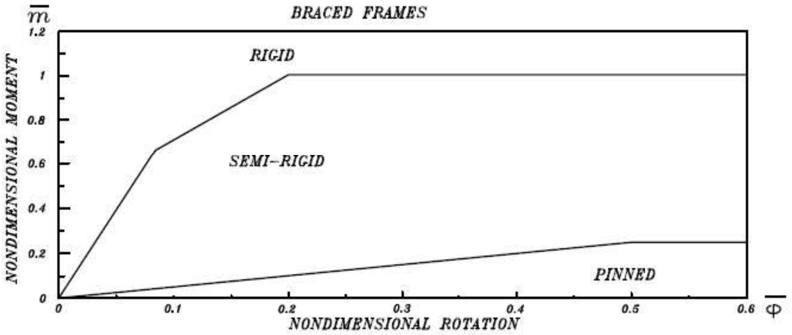


Figure 1 - *Diagram of connection categories*

Table 1 - *Properties of semi-rigid connections*

Type of Connection	Connection strength	Connection stiffness
Rigid	$1.2M_{pb}$	∞
C0808	$0.8M_{pb}$	$0.8K_{\sup}$
C0608	$0.6M_{pb}$	$0.8K_{\sup}$
C0606	$0.6M_{pb}$	$0.6K_{\sup}$

To provide ductility, the plastic rotational capacity of the beams was calculated and defined according to the following equations [Gioncu and Petcu 1997].

$$\theta_u = (1 + R_{av})\theta_p \tag{5}$$

$$R_{av} = 0.6 \times 3 \times 10^4 \frac{b}{b - 0.5t_w - 0.8r} \frac{t_f}{bL_{sb}} \frac{235}{f_{yw}} (0.8 + 0.2\frac{f_{yw}}{f_{yf}}) \tag{6}$$

where: r, b, t_w and t_f are the radius of the flange to web joint in the section, half of the flange width, web thickness, and flange thickness, respectively. f_{yw} and f_{yf} are yield limits of web and flange, respectively. L_{sb} is the member's standard length. Furthermore, due to the amount of stiffness and period of the connections, a semi-rigid connection has to be selected since a semi-rigid connection has suitable plasticity for the structure and simultaneously, it absorbs more earthquake energy. In fact, the selected semi-rigid connection is the middle of a rigid and pinned connection, which in reality semi-rigid connections are more used due to implementation problems when a rigid and pinned connection is performed.

3 Geometric specifications of frames and modelling considerations

Three 5-, 8- and 12-story structures as representatives of low-rise, medium-rise, and high-rise buildings, respectively were first designed in ETABS software, and the sections of beams, columns, and braces were achieved. Then, two-dimensional frames were modeled and analyzed in OPNSEES software for each structure in four states as follows: 1- Frame with pinned connections with Chevron bracing system 2- Frame with pinned connections with zipper bracing system 3- Frame with semi-rigid connections with Chevron bracing system 4- Frame with semi- pinned connections with zipper bracing system. In this research, the number of frames was 12, and the number of analyses was 84, according to the number of selected near-fault area records. The frames had three 5–meter spans with the same height of 3 meters in all stories. There was a Chevron bracing system in the middle span. The columns had BOX-type sections, and beams were IPE-type sections. Diagonal members of braces and Zipper columns were CIRC-type sections. The specifications of sections of 5-, 8- and 12-story frames have been presented in Table 2:

Table 2 - *Sections of 5-, 8- and 12-story members*

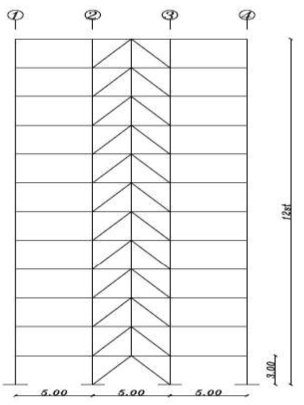
Frame	Braces and zipper columns	Columns	Beams of non-braced spans	Beams of braced spans
1st to 3rd stories	CIRC 250-12	BOX350*350-20	IPE300	IPE400
4th to 7th stories	CIRC 200-12	BOX300*300-20	IPE300	IPE400
8th to 10th stories	CIRC 200-12	BOX250*250-15	IPE270	IPE300
11th to 12th stories	CIRC 150-10	BOX200*200-12	IPE240	IPE270

Steel02Material was used for beams, columns, and braces in non-hardening and hardening modes, respectively [Menegotto and Pinto1973]. The segments of beams, columns, and braces as Fiber segments were defined to the software. This segment had a symmetrical figure that contains smaller regular figures, namely squares, and circles that are called Patch. Beams, columns, and braces were defined by disBeamColumnBrace, also, pinned and semi-rigid

connections were identified by the zeroLength portion. Moreover, proper materials were identified for connections and rotational directions and their rigidity level in transitional in the software. For semi-rigid and pinned connections, two multilinear materials were utilized. For one material, M_y , θ_y , $M_u and\ \theta_u$ were used in the software, and for another, elastic material was consumed. Precisely, elasticity's initial modulus, strain hardening ratio, yield stress, parameters, and other standards were defined in the software. Masses were defined in Opensees by the model that was created in Sap2000. Gravitational loads were applied by the Pattern Plain command while the lateral loadings are defined by accelerometers with 5% damping that was applied in SeismoSignal software.
A sample model for a 12-story frame having Chevron and Zipper bracing system has been illustrated in Figures. 2 and 3, respectively. Similarly, the 5-, 8- and 12-story frames having pinned and semi-rigid connections were modeled and analyzed. The results have been provided in the current paper.

4 Selecting and scaling the near-fault area accelerograms

Seven near-fault accelerograms, including #5 El Centro Array-Imperial Valley, Kobe, Japan-KJMA, Kobe, Japan-Takarazuka, Northridge, Rinaldi Receiving Sta, Kobe, Japan –Takatori, Park field - Fault Zone 1 and Chi-Chi, Taiwan - TCU065 records have been used to analyze the frames. The specifications of the records have been presented in Table 3 Specifications of the Table 3 include maximum acceleration (g), maximum velocity (cm/sec), maximum displacement (cm), ratio of maximum velocity to maximum displacement (V_{max} / A_{max} (sec)) and distance from the fault (km). The intensity of chosen records influences the results of the time history analysis. Therefore, the selected accelerograms have to be scaled in order to being comparable. The selected records were scaled based on the Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No.2800, 4th edition). Therefore, the mean value of Standard No.2800 was divided by the mean value of each accelerogram, and then some factors (less than 1) were attained, called the scale factor. The scaled accelerograms were obtained by multiplying scale factors by the initial accelerograms, and the results were applied to the structure. The scaled accelerograms should be from 0.2T to 1.5T and be 1.4 times higher than the standard design spectrum.



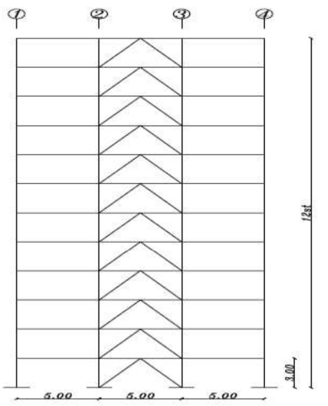


Figure 2 - *Sample of a 12-story modeled frame with a zipper bracing system*

Figure 3 - *Sample of a 12-story modeled frame with Chevron bracing system*

Table 3 - *Specifications of near-fault records*

Near-Fault Ground Motion	Maximum Acceleration (g)	Maximum Velocity (cm/sec)	Maximum Displacement (cm)	V_{max} / A_{max} (sec)	Rrup (km)
#5 El Centro Array-Imperial Valley	0.529	48.911	48.882	0.094	3.95
Kobe, Japan-KJMA	0.834	91.105	21.110	0.111	0.96
Kobe, Japan-Takarazuka	0.697	68.406	26.673	0.100	0.27
Northridge , Rinaldi Receiving Sta	0.874	147.998	41.882	0.173	6.5
Kobe, Japan –Takatori	0.671	122.964	29.621	0.187	1.47
Park field - Fault Zone 1	0.833	81.392	10.805	0.1	2.51
Chi-Chi, Taiwan - TCU065	0.79	125.346	108.727	0.162	0.57

5 Analysis of structural models in OPENSEES software

Dynamic time history analysis gives good results in both elastic and inelastic regions. The structure can enter the inelastic region due to the nature of near-fault earthquakes, so the use of dynamic time history analysis is appropriate to evaluate the behaviour of structures. In this paper, the same method was used in the Opensees software, and the frames have been analysed by applying seven near-fault records. An incremental method was applied to start from 0.1g acceleration to 1g acceleration with a 0.1g acceleration increment in each step [Ghorbani Asl and Karimi 2018]. The relative story displacement should be limited to a maximum value to prevent damage to the structures. The allowable relative story displacement limit was 0.025h, where h refers to the height of the story from the bottom of the considered story to the bottom of the upper story [Standard No.2800, 2015].

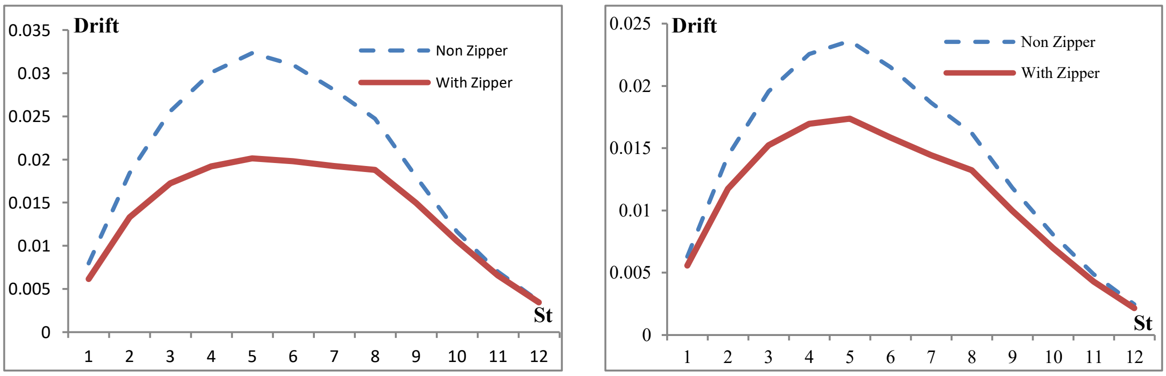
6 Review of the analyzed samples and results

6.1 Relative story displacement

The analysis results for all 5-, 8- and 12-story steel frames have been reviewed and compared in four states under the effect of seven near-fault records. The relative displacement of the stories was compared in pairs in the case of a pinned frame with a Chevron bracing system in comparison with a pinned frame with a zipper bracing system. Then, it was compared in the case of a semi-rigid frame with a Chevron bracing system concerning a semi-rigid frame with the zipper bracing system. Relevant diagrams were analyzed under seven near-fault records, and the results were obtained. Examples of the results have been presented in the present paper.

The results in all cases show that the presence of a vertical zipper member reduced the relative story displacements in both pinned and semi-rigid frames. The average amount of such reduction is ranged from 0.1 to 8% in the 5-story steel frame with pinned connections, while it is between 0.1 and 9% for a steel frame with semi-rigid connections in different stories. For the 8-story steel frame, the amounts ranged from 0.1 to 6% and 5 to 28% for pinned and semi-rigid connections, respectively. In addition, in the 12-story steel frame, the amounts ranged from 2 to 26% and 2 to 36% for the 12-story steel frame with pinned and semi-rigid connections, respectively.

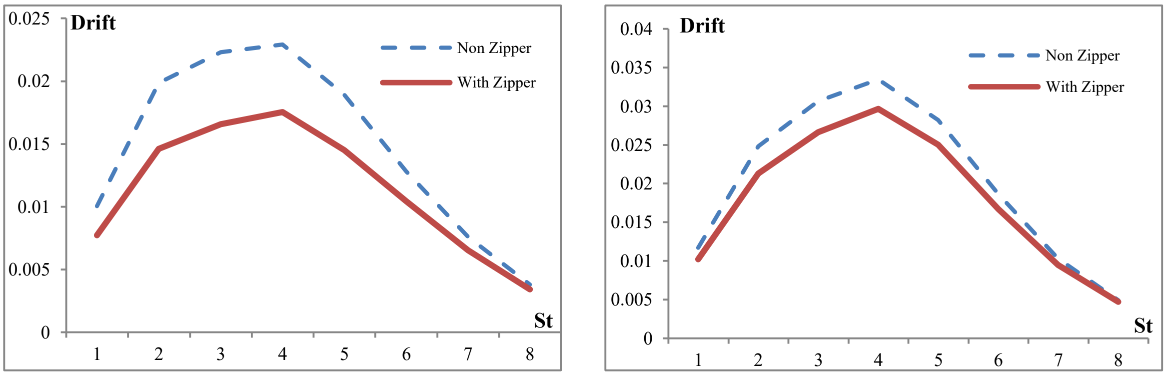
As the results shown in the Figure 4, 5, 6, the reduction in the relative displacement of the stories was evident after adding a zipper column to the Chevron bracing system, and in some cases, it had a significant value depending on the frequency content of the earthquake, its intensity, and period of the analyzed building. The control of relative story displacement in all 5-, 8- and 12-story steel frames was greater for ductile connections than pinned connections. In addition, the most significant effect of the zipper column was in the middle and lower stories up to the second story. Due to massive displacements in these stories, the zipper column in the Chevron braces could help the integrated performance of the structure and control of displacement. Comparing the impact of the zipper column in the three buildings modeled as representatives of low-rise, medium-rise, and high-rise buildings show that the influence of the zipper column in tall buildings is significant due to more displacement of the structure. In contrast, such effects in low-rise short buildings with pinned and semi-rigid beam-to-column connections are low. In medium-rise buildings, the effect of the zipper column is significantly increased in control of the relative story displacement by converting pinned beam-to-column connection to a semi-rigid one. In addition, due to the low height of the 5-story building modeled as a symbol of the low-rise building, the relative story displacement is almost the same after adding the zipper control column led to more integration of the structure.



(a): With semi - rigid connection with a zipper bracing system relative to a Chevron bracing system under Takarazuka record

(b): With pinned connection with a zipper bracing system relative to a Chevron bracing system under KJMA record

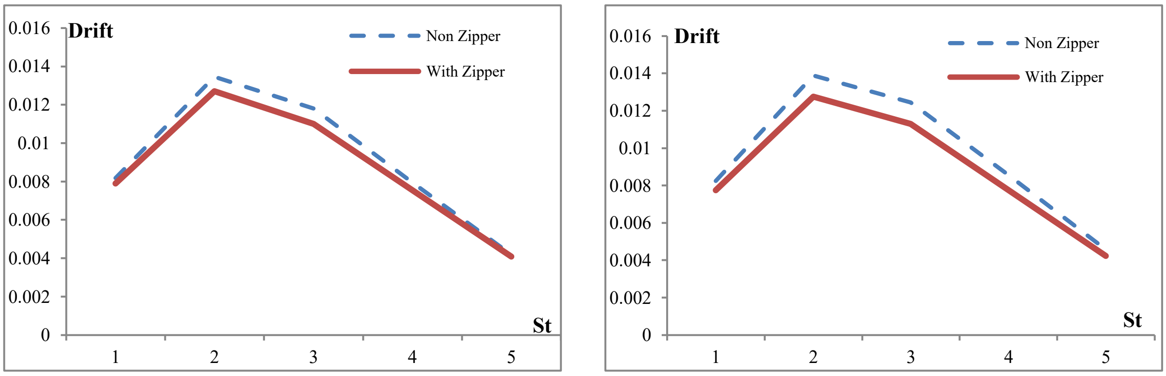
Figure 4 - *Diagram of reduction in the relative displacement of 12- story frame*



(a): With semi - rigid connection with a zipper bracing system relative to a Chevron bracing system under Rinaldi record

(b): With semi - rigid connection with a zipper bracing system relative to a Chevron bracing system under Takatori record

Figure 5 - *Diagram of reduction in the relative displacement of 8- story frame*

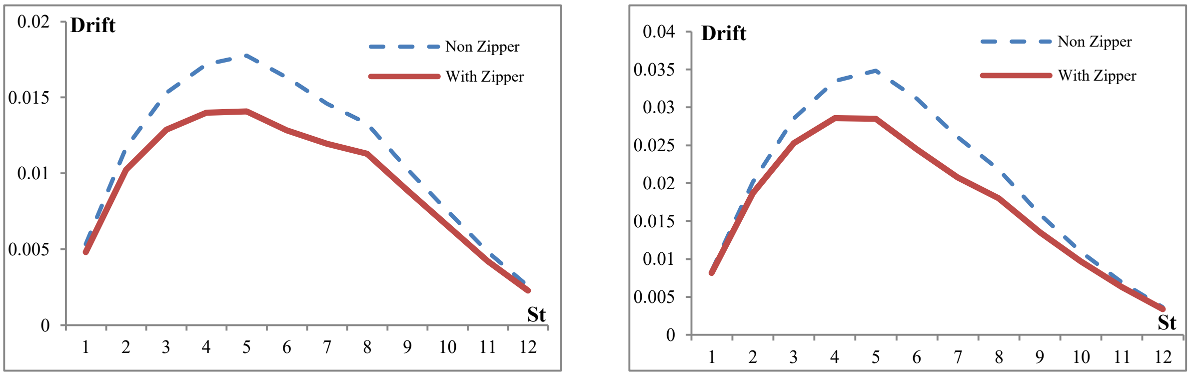


(a): With semi - rigid connection with a zipper bracing system relative to a Chevron bracing system under El Centro record

(b): With pinned connection with a zipper bracing system relative to a Chevron bracing system under El Centro record

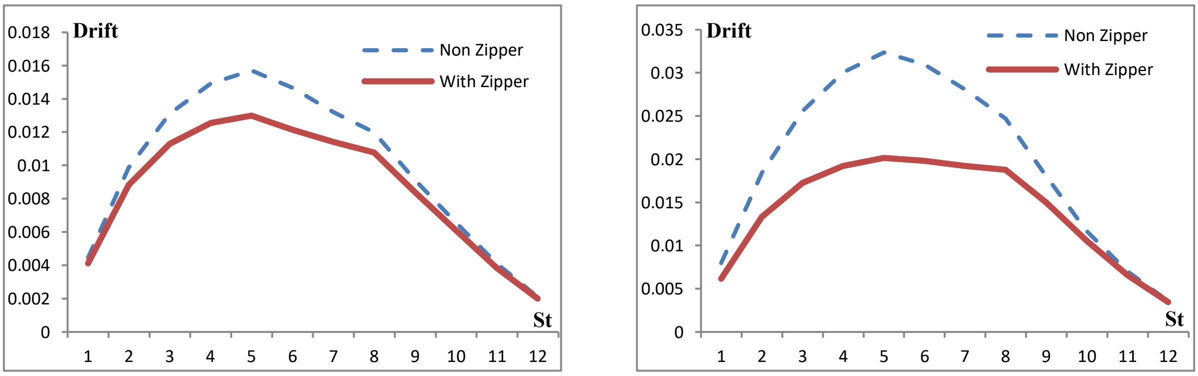
Figure 6 - *Diagram of reduction in the relative displacement of 5- story frame*

Figures 7and 8 present some diagrams related to the control of relative story displacement in the 12-story steel frames with pinned and ductile connections braced by a Chevron concentric bracing system with and without a zipper column under Parkfield and Takarazuka records, respectively. The diagrams are linear to show the amount of reduction in the relative displacement in the stories as well as the effect of a zipper column in different stories. Figure 9 shows similar diagrams for an 8-story frame. In addition, Figures 10 and 11 represent diagrams related to a 5-story structure.



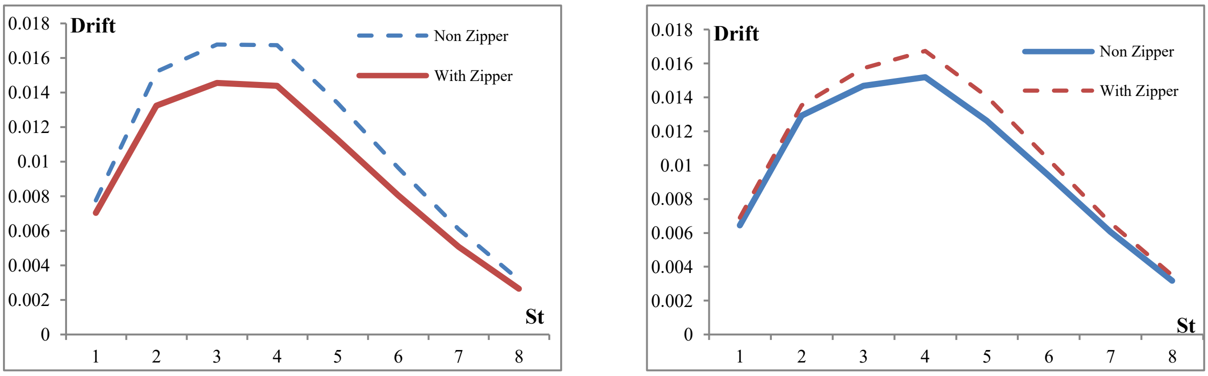
(a): Pinned connections *(b): Semi-rigid connections*

Figure 7- Diagram of reduction in the relative story displacement of the 12- story frame with a zipper bracing system relative to a Chevron bracing system under Parkfield record



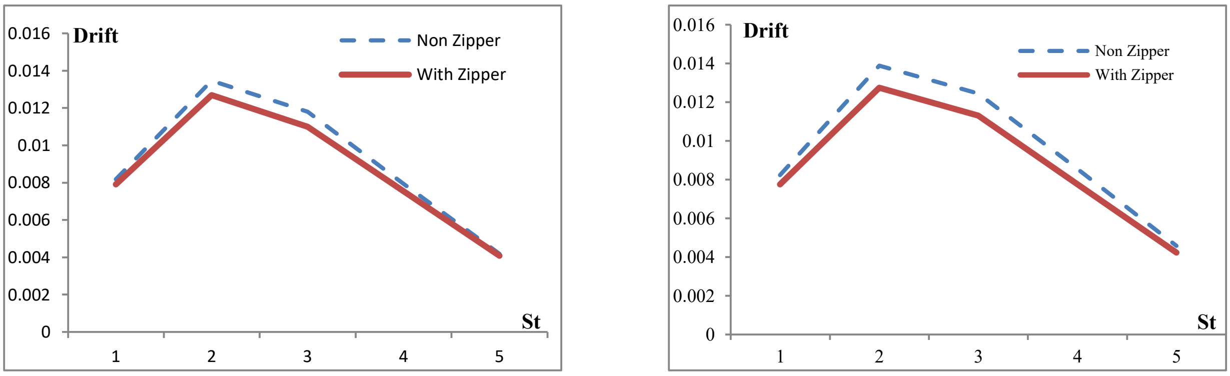
(a): Pinned connections *(b): Semi-rigid connections*

Figure 8- Diagram of reduction in the relative story displacement of the 12- story frame with a zipper bracing system relative to a Chevron bracing system under Takarazuka record



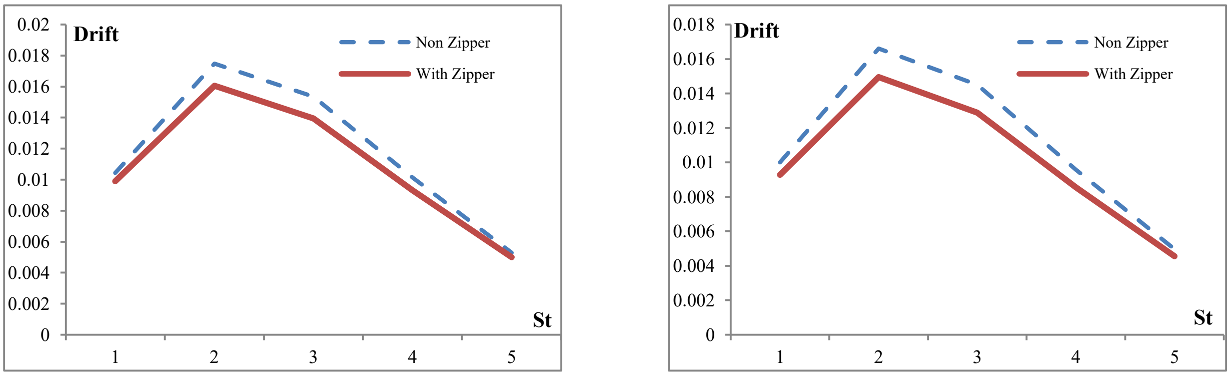
(a): Parkfield record *(b): Chi chi record*

Figure 9- Diagram of reduction in the relative story displacement of the 8- story semi-rigid frame with a zipper bracing system relative to a Chevron bracing system



(a): Pinned connections *(b): Semi-rigid connections*

Figure 10- Diagram of reduction in the relative story displacement of the 5- story frame with a zipper bracing system relative to a Chevron bracing system under El Centro record



(a): Pinned connections *(b): Semi-rigid connections*

Figure 11- Diagram of reduction in the relative story displacement of the 5- story frame with a zipper bracing system relative to a Chevron bracing system under Takatori record

6.2 Maximum displacement of the roof story

Table 4 illustrates the results of reduction in the roof story's maximum displacement for all three states of the 5-, 8- and 12-story steel model frames under seven near-fault records.

Table 4 - *Reduction in the roof story's maximum displacement for the 5-, 8- and 12-story steel frames under seven near-fault records (%)*

Near fault area record	5-story frame with pinned connections due to the zipper column (%)	5-story frame with semi-rigid connections due to the zipper column (%)	8-story frame with pinned connections due to the zipper column (%)	8-story frame with semi-rigid connections due to the zipper column (%)	12-story frame with pinned connections due to the zipper column (%)	12-story frame with semi-rigid connections due to the zipper column (%)
Chi-Chi	3	9	3	9	12	29
El Centro	2	8	8	6	4	6

KJMA	3	17	3	2	21	10
Parkfield	3	13	4	6	17	14
Rinaldi	3	16	6	8	16	29
Takarazuka	5	13	5	3	13	31
Takatori	4	12	8	10	11	12

The results show that the maximum lateral displacements of the roof story in the steel frame with pinned connections with the Chevron bracing system were decreased up to 5%, 8%, and 21% as a result of using the zipper column in the 5-, 8- and 12- story building, respectively. These values were about 17%, 10%, and 31% for the frame with ductile connections, respectively. Therefore, it can be said that adding the zipper column was better in the semi-rigid frames than the pinned frames in controlling the maximum displacement. The influence of adding the zipper column was more evident in the high-rise building than in the medium-rise and low-rise structures. The values obtained for the reduction in the maximum displacement of the roof story were more obvious in the low-rise building than in the medium-rise one. The reduction of the maximum displacement of different stories has been presented in Table 5 for the 5-story frame with semi-rigid connections under 7 near-fault records.

Table 5 - *Reduction in the maximum displacement of different stories for the 5-story frame with semi-rigid connections after adding the zipper column (%) under 7 near-fault records*

	Chi-Chi	Elcentro	KJMA	Parkfield	Rinaldi	Takarazuka	Takatori
ST1	6.8	6.8	6.8	3.4	6.8	2.5	7.3
ST2	8.1	8.1	8.1	4.8	8.2	1	9
ST3	8.8	8.8	8.8	5.5	9	1	9.7
ST4	9.2	9.2	9.2	5.8	8.1	2	9.9
ST5	9.3	9.3	9.3	5.8	7.4	2	9.8

The results show that the effect of the zipper column is noticeable in decreeing the maximum story displacement of high-rise structures like in medium-rise and high-rise structures but its value depends on the height of the structure, and the nature of the earthquake record and its pulses. The most significant reduction in the maximum story displacement was in the middle stories. The influence of the zipper column was incremental and uniform in the low-rise building due to the low height of the structures. The zipper column led to an integrated performance of the steel structure in terms of displacement, distribution, and direction of the forces to the upper stories and vice versa.

7 Conclusion

In the present research paper, the behaviorr of low-rise, medium-rise, and high-rise steel frames by concentrically Chevron bracing with a zipper bracing system was investigated in both pinned- and ductile- connection modes through modeling and analyzing in Opensees software. The research aimed to study the behavior of structures located in the near-fault area, so seven near-fault records were used for analysis, and finally, 84 samples were analyzed, the results are as follows:

The presence of a zipper column in all three low-rise, medium-rise, and high-rise steel frames with pinned and semi-rigid connections was effective in controlling and decreasing relative displacement in stories. The average amount of such reduction ranged from 2 to 26% in the 12-story steel frame with pinned connections, while it was between 2 and 36% for the steel frame with semi-rigid connections in different stories. The average amount of such reduction ranged from 0.2 to 6% and 5 to 28% in the 8-story steel frame with pinned and semi-rigid connections, respectively. The average reduction value was between 0.1 to 8% in the 5-story steel frame with pinned connections, while it ranged from 0.1 to 9% for the steel frame with semi-rigid connections in different stories. It can be concluded that, in all ductile frames, the zipper column was effective in decreasing relative story displacement and such influence was more evident in the high-rise building than the medium-rise and low-rise structures.

When the displacement increases in the stories, the zipper column plays a more critical role, and the amount of reduction in both relative and maximum displacements of the stories becomes more noticeable. Maximum lateral displacements in the steel frame with pinned connections with Chevron bracing system were decreased up to 5%, 8%, and 21% as a result of using zipper columns in the 5-, 8-, and 12-story buildings, respectively. These values were about 17%, 10%, and 31% for the frame with ductile connections, respectively. Therefore, it can be said that adding a zipper column was better about two times in the semi-rigid frames than in pinned frames in controlling maximum displacement. Furthermore, it should be said that the limitations of the zipper column are more related to the architectural issue and the presence of the zipper column inside the chevron brace in some openings will cause an obstacle to easy access in that opening.

Last but not least, the existence of a zipper column in combination with a chevron brace is not a factor in increasing the structure’s ductility, but in structures with ductility connections, which are semi-rigid connections of the same type of connections, it will control large deformations and consume more energy. The zipper column in combination with the convergent Chevron brace provides simultaneously a ductility structure with the ability to consume more energy in the connections and a stable structure that has a maximum controlled displacement within the acceptable range for every single structure. Also, the existence of the zipper column causes the transfer of unbalanced vertical forces created to the higher floors and integrates the function of the structure. It can prevent the total collapse of the building and prevent the creation of failure mechanisms in structural members due to unbalanced forces and more displacement.

References

Chen, Z. (2012). Seismic response of high-rise zipper braced frame structures with outrigger trusses, Ph.D. diss., Concordia University, Montreal, Quebec, Canada.

Costanzo, S., D’Aniello, M., & Landolfo, R. (2016). Critical review of seismic design criteria for chevron concentrically braced frames: the role of the brace-intercepted beam. Ingegneria Sismica, 33(1-2), 72-89.

Costanzo, S., D’Aniello, M., & Landolfo, R. (2018). The influence of moment resisting beam-to-column connections on seismic behavior of chevron concentrically braced frames. Soil Dynamics and Earthquake Engineering, 113, 136-147.

Comeau, C., Cano, P., Imanpour, A., & Tremblay, R. (2022, May). Seismic Behaviour and Design of Chevron Multi-tiered Concentrically Braced Frames. In Proceedings of the 10th International Conference on Behaviour of Steel Structures in Seismic Areas: STESSA 2022 (pp. 379-387). Cham: Springer International Publishing.

Dubina, D., Stratan, A., & Dinu, F. (1998). Suitability of Semi-Rigid Joint Steel Building Frames in Seismic Areas, in Proceedings of European Conference on Earthquake Engineering, Balkema, Rotterdam, Netherlands.

Ghorbani Asl, A., & Karimi, F. (2018). Seismic performance of tall steel frames with semi-rigid connections under the effects of near-fault accelerogram records, National Conference on Basic Research in Civil Engineering, Architecture and Urban Planning, Tehran, Iran.

Gioncu, V., & Petcu, D. (1997). Available rotation capacity of wide-flange beams and beam-columns Part 1. Theoretical approaches, Journal of Constructional Steel Research, Vol. 43, pp. 161-217.

Hosseinzadeh, Y., Gholipur feizi, M., & Behravesh, A. (2008). Seismic performance of steel moment–resisting frames with mixed use of rigid and semi-rigid connections, Journal of Tabriz University, Faculty of Engineering, Tabriz, Iran, Vol. 35, No. 3 (Civil Engineering), pp. 38-48.

Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No.2800), (2015). Building and Housing Research Center (BHRC) Press, 4th Edition.

Karimi, F. (2010). Seismic behavior of tall frames with semi-rigid connections, International Conference on Light Weight Construction and Earthquake, Kerman Jahad Daneshgahi, Kerman, Iran, pp. 1-9.

Khatib, I. F., Mahin, S. A., & Pister, K. S. (1988). Seismic behavior of concentrically braced steel frames. Berkeley, CA, USA, Report No.UCB/EERC-88/01: Earthquake Engineering Research Center, University of California.

Kim, J., Cho, C., Lee, K., & Lee, C. (2008). Design of zipper column in inverted V braced steel frames. Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China.

Li, H., Zhang, W., & Zeng, L. (2023, March). Seismic assessment of chevron braced frames with differently designed beams. In Structures (Vol. 49, pp. 1028-1043). Elsevier.

Longo, A., Montuori, R., & Piluso, V. (2008). Failure mode control of X-braced frames under seismic actions. Journal of Earthquake Engineering, 12(5), 728-759.

Longo, A., Montuori, R., & Piluso, V. (2009). Seismic reliability of chevron braced frames with innovative concept of bracing members. Advanced Steel Construction, 5(4), 367-389.

Longo, A., Montuori, R., & Piluso, V. (2009). Seismic reliability of V-braced frames: Influence of design methodologies. Earthquake engineering & structural dynamics, 38(14), 1587-1608.

Menegotto, M., Pinto, P.E. (1973). Method of analysis for cyclically loaded R.C. plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending. Proc. of IABSE Symposium on Resistance and Ultimate Deformability of structures Acted on by Well Defined Repeated Loads, Vol.13, pp. 75-101.

Narayan, & Pathak, K. K. (2022). Numerical Analysis of Multilevel Eccentric Chevron Braced Frame for Improved Inelastic Behavior. *Practice Periodical on Structural Design and Construction*, *27*(1), 04021066.

Nodeh Farahani, R., & Mirzagol Tabar, A.R. (2015). Study of reinforcement details of steel frame braced with zipper brace, The International Conference on Human, Architecture, Civil Engineering and City (ICOHACC 2015), Tabriz, Iran.