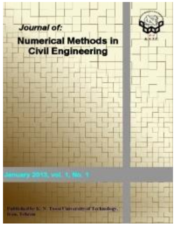
Numerical Methods in Civil Engineering, 8-1 (2023) 35-44



Numerical Methods in Civil Engineering

Journal Homepage: https://nmce.kntu.ac.ir/

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

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ARTICLE INFO

RESEARCH PAPER

Article history:
Received:
September 2022.
Revised:
May 2023.
Accepted:
August 2023.

Keywords:
Semi-frames,
Chevron braces,
Zipper columns,
Near-fault areas,
Tall buildings

Abstract:

In this article, the enhancement of the seismic function in tall buildings with semi-rigid connections accompanied by the Chevron bracing system was studied. Therefore, it is better to improve the seismic performance of such frames to prevent possible damages and failures. For this purpose, modeling Chevron bracing system was first done using Opensees software by adding zipper columns in tall semi-rigid steel frames in two 12-story and 15-story structures as representatives of tall buildings. 56 semi-rigid frames were analyzed under seven near-fault records using dynamic non-linear time history analysis. The analysis of modeled 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, and this effect is more significant in frames with ductile connections. In other words, more ductility capacity and better dissipation of seismic forces in the near-fault areas for semi-rigid frames could lead to desirable seismic performance. The presence of zipper columns in Chevron braces has made an integrated frame performance in the entire height of the structure due to the transmission of unbalanced vertical forces induced in the braced spans while decreasing story displacements. In addition, it has improved the seismic behavior of semi-rigid steel frames.

1. Introduction

The Northridge Earthquake (1994) caused remarkable damage to steel structures having rigid connections. 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 [1]. After the occurrence of this earthquake and after studying the damage to buildings, the researchers suggested using semi-rigid connections as they have high ductility and the 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 [2].

Tall buildings with semi-rigid and pinned connections experience large displacements under near-fault area records. The bracing systems are common for controlling the displacement of the stories because of their high stiffness. One of these bracing systems is Chevron bracing with and or without zipper columns. In a study, Khatib et al. investigated the behavior of Chevron and Zipper bracing frames in both rigid and pinned configurations 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 [3]. In another research, Kim et al. 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 without the vertical zipper member. In particular, their studies showed that relative displacements of the 1st and 14th stories were significantly decreased [4]. Razavi and Sheidaei

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https://doi.org/10.52547/NMCE.10.799.1

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 Chevron and Zipper bracing systems. Finally, they showed that the ductility and behavior factors were better for Zipper-braced frames than Chevron-braced frames. This better performance of Zipper bracing results from the presence of a vertical member (called the zipper column) is effective in the uniform distribution of deformation over the height of the building, and it significantly decreases the relative displacement of the stories [5].

In another study, Zhi Chen 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 an outrigger truss. The results showed that the trigger truss decreased the relative displacement of the upper stories [6]. Amiri et al. investigated adding 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 substantially [7]. Ozelik et al. 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 systems, and similar results were shown in 3-story steel-braced frames, while pinned Chevron-braced frames had a better performance in medium-rise structures [8]. Zahrai et al. investigated the hysteretic behavior of eccentric-braced frames with a zipper member. Using the finite element method, they evaluated the behavior of the link beam and zipper member under cyclic loads [9]. 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 [10]. Ghorbani et al. 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 [11].

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. The elastic truss prevents the overall collapse of the structure [12]. Trica and Tremblay evaluated the effect of building height and type of ground motion on the seismic performance of conventional 4-, 8- and 12-story Zipper concentrically braced frames [13]. In another study, Zandi and Lamei Javan 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. Their studies also showed that the presence of a zipper member in a frame with rigid connections could effectively control the story displacements and decrease the damage index [14]. Costanzo et al. investigated chevron concentrically braced frames (C-CBFs) that enhanced architectural functionality and decreased the price of construction and installation like X bracings. low, medium, and high-rise multi-story structures are analyzed based on non-linear analyses. Restrained joints could influence significantly creating an extra strength reserve, ductility, and stiffness [15]. Narayan & Pathak presented an improved approach to the promotion of conventionally made chevron braces (eccentric and concentric). The chevron brace’s promoted shape was named an MLEC (multilevel eccentric chevron). This approach was cost-effective, easy of building, minimally disorderly, makes minimal structural interposition, and enhanced the ductility and strength of the conventionally built chevron-braced frames [16]. Comeau et al. discussed the probability of utilizing the chevron bracing shape for multi-tiered concentrically braced frames exposed to seismic excitations. The re-centering capacity of the brace acting in flexure had a significant effect on the frames that demonstrated a steady inelastic response with restricted remaining deformations [17].

Li et al. studied the effect of concentrically braced frames on seismic performance with different beam strengths and stiffness. Also, several numerical analyses, namely hysteresis analysis, incremental dynamic analysis, and pushover analysis were discussed in this work [18]. In their last study, a polyline chevron-braced frame (ZXC), a lateral rod chevron-braced frame (ZCG), an arc-shaped chevron-braced frame (HZC), and Chevron-braced frames were designed to decrease the unbalanced force and vertical deformation at the brace junction by Zheng et al. Simultaneously, bearing capacity decay, hysteresis accomplishment, monotonic loading accomplishment, failure mode, fracture trend, energy dissipation volume, and vertical displacement at the brace point junction of the ZCG, ZXC, and HZC were investigated. These were then contrasted with the chevron braced frames [19]. In the present research, seven accelerograms were selected by reviewing the studies done on steel frames with Chevron and Zipper bracing systems having pinned and rigid connections and 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, and the seismic performance was investigated under near-fault area records. The non-linear dynamic time history analysis was used. The improvement of seismic frame behavior and feasibility of using ductile connections have been evaluated. The addition of 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 showed 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. This also ensures the ductility of the whole structure.

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 will be able to dissipate energy effectively and resist seismic excitations without imposing damage to 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 behavior is not good. The Chevron system cannot redistribute induced large vertical unbalanced forces uniformly [3]. 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. In this condition, the braces in lower stories attract more seismic energy and experience plastic behavior due to improper redistribution of forces, while the braces in upper stories behave in their elastic domain. The base shear capacity in the braced frame is decreased because of the buckling of braces in lower stories, and therefore, the system does not show proper seismic behavior.

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 the Zipper bracing system, decreases the damage over the height of the structure and improves the seismic behavior of steel frames with the Chevron bracing system [14].

2.3. Ductile beam-to-column connection

European codes classify beam-to-column connections of steel structures into three types, i: pinned, semi-rigid, and rigid. The behavior of connections is dependent on the type of structure and its lateral resisting system, too [20]. 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 Figure1 [11]:

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

$$\bar{\varphi} = \frac{\varphi}{\varphi_P} \quad M_p = \frac{E_b I_b}{L_b}\bar{\varphi}_b \tag{2}$$

In Equation 1, M is the moment of connection and M_p is the plastic moment of beam attached to it equally. 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:

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

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

ere θ_p refers to the rotation corresponding to the plastic moment of a beam by the length of $5d_{be}$ [11].

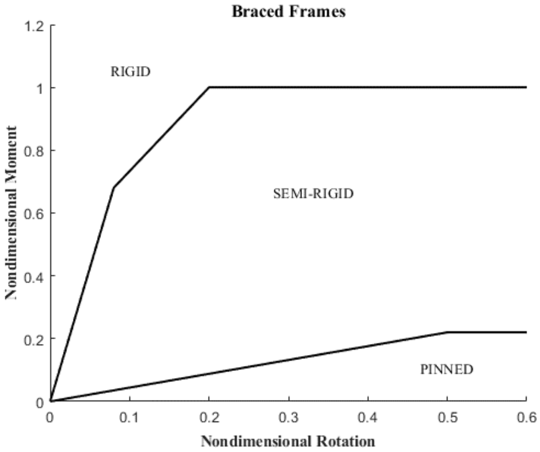


Fig. 1: Diagram of connection categories [11]

Table 1: Properties of semi-rigid connections [11]

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 [21].

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

$$R_{av} = 0.6\times3\times10^4 \frac{b}{b-0.5t_w-0.8r}\frac{t_f}{bL_{sb}}\frac{235}{f_{yw}}(0.8+0.2\frac{f_{yw}}{f_{yf}}) \tag{6}$$

where: t_w, t_f, b and r are web thickness, flange thickness, half of the flange width, and radius of the flange to web joint in the section, respectively. f_{yf} and f_{yw} are yield limits of flange and web, respectively. L_{sb} is the standard length of the member.

3. Geometric specifications of frames and modeling considerations

Two 12- and 15 story steel structures as representatives of high-rise buildings 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 eight, and the number of analyses was 56 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 12- and 15- story frames have been presented in Table 2:

Table 2: Sections of 12- and 15- story frame 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 15th stories	CIRC 150-10	BOX200*200-12	IPE240	IPE270

The sections of beams, columns, and braces, were defined to the program as Fiber sections. This section has a general geometric shape that consists of smaller regular shapes such as circles and squares called Patch. disBeamColumnBrace was used to define beams, columns, and braces, and the zeroLength element was used to identify pinned and semi-rigid connections. Suitable materials were defined for connections, and their rigidity degree in transitional and rotational directions in the software. For semi-rigid and pinned connections, two multilinear materials were used where M_y, θ_y, M_u and θ_u were applied in the software for one material, and Elastic material was used for the other one. Steel02Material was used for beams, columns, and braces in non-hardening and hardening modes [22].

In this material model, yield stress, initial modulus of elasticity, strain hardening ratio (ratio between modulus of elasticity after yielding, and initial modulus of elasticity), parameters, and other values were defined in the software. In the case without isotropic hardening, the area of hysteresis rings remains almost constant, but in the case of isotropic hardening, the area of hysteresis rings in each ring was increasing in pressure and tension.

Masses were used to apply in Opensees software through the model created in Sap2000 software, and the data were extracted and assigned to each node in two dimensions. Gravitational loads were applied through the Pattern Plain command and lateral loading by defining the characteristics of accelerometers, and 5% damping was applied in SeismoSignal software.

A sample model for a 15-story frame having Chevron and Zipper bracing system has been illustrated in Figures 2 and 3, respectively. Similarly, the 15-story and 12-story frames having pinned and semi-rigid connections were modeled and analyzed. The results have been provided in the current paper.

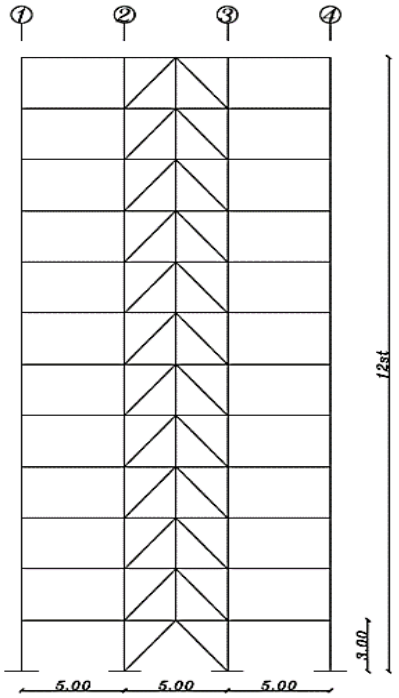


Fig. 2: Sample of a 12-story modeled frame with a zipper bracing system

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 Table 3 include max acceleration (g), maximum velocity (cm/sec), maximum displacement (cm), the 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 to be comparable. The selected records were scaled based on the Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No.2800, 4th edition) [23].

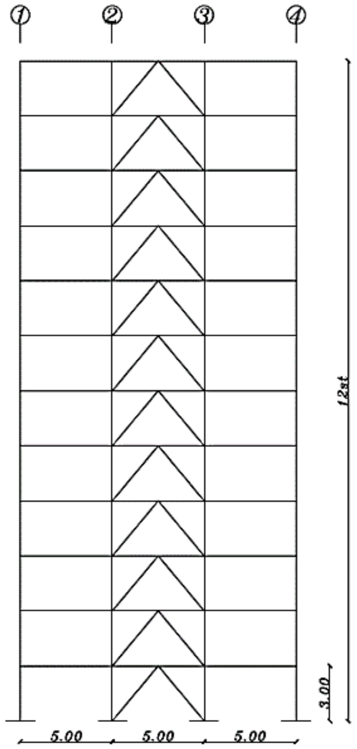


Fig. 3: Sample of a 12-story modeled frame with Chevron bracing system

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

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.

5. Analysis of structural models in Opensees software

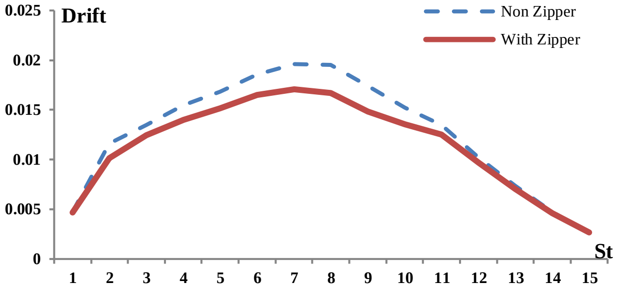
Dynamic time history analysis gives good results in both elastic and inelastic regions. The structure can enter the inelastic region due to the nature of near-fault earthquakes, so the use of dynamic time history analysis is appropriate to evaluate the behavior of structures [11]. In this paper, the same method was used in the OpenSees software, and the frames have been analyzed by applying seven near-fault records. An incremental method was applied to start from 0.1g acceleration to 1g acceleration with 0.1g acceleration increment in each step [11]. 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 [23].

6. Review of the analyzed samples and results

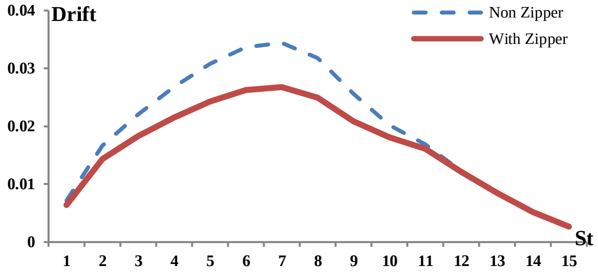
6.1. Relative story displacement

The analysis results for both 12- and 15-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 as a pinned frame with a Chevron bracing system and a pinned frame with a zipper bracing system. Then, it was compared as a semi-rigid frame with a Chevron bracing system and a semi-rigid frame with a 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 ranged from 1% to 22% in the 15-story pinned steel frame, while it becomes between 2% and 35% for the semi-rigid structure in different stories. 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. Figures 4 and 5 show more information about the 15- story structure having pinned and semi-rigid connections, respectively.

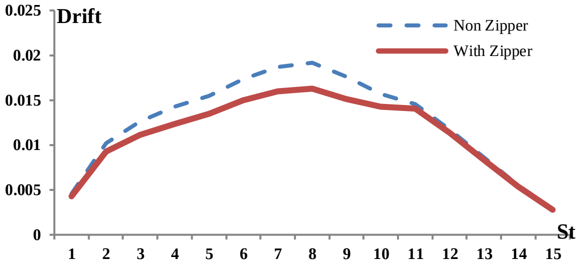
As the results show, the reduction in the relative displacement of the stories was evident after adding a zipper column to the Chevron bracing system, and in some cases, it had a significant value depending on the frequency content of the earthquake, its intensity, and period of the analyzed building. The control of relative story displacement in both 12- and 15-story 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. In fact, in large deformations and ductile connections, the zipper column started to act and control the behavior of the structure.



(a): Parkfield record

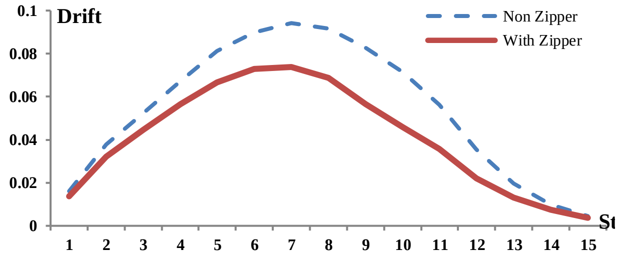


(b): Rinaldi record

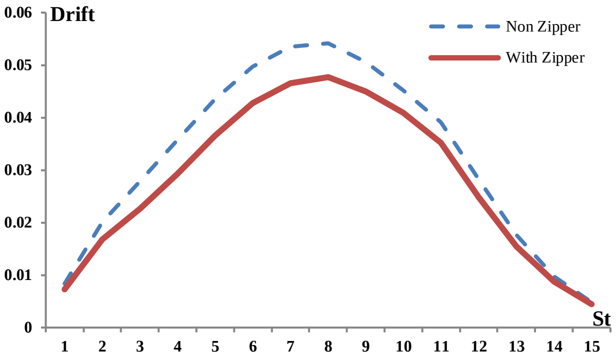


(c): Takarazuka record

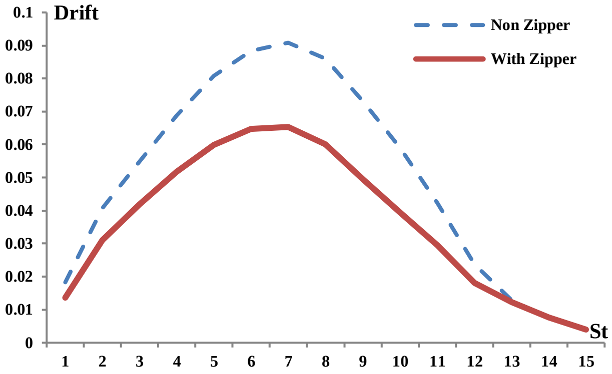
Fig.4: Diagram of reduction in the relative displacement of a pinned 15- story frame with a zipper bracing system relative to a Chevron bracing system under various records.



(a): KJMA record



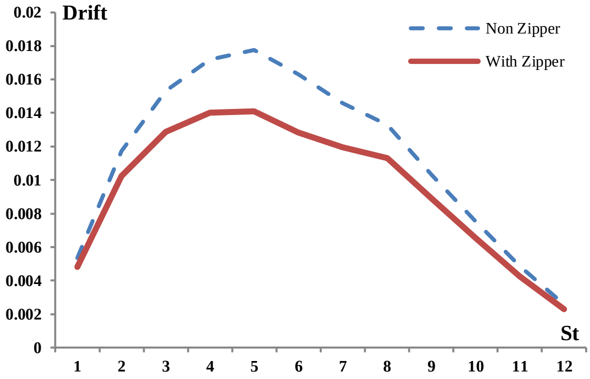
(b): Takatori record



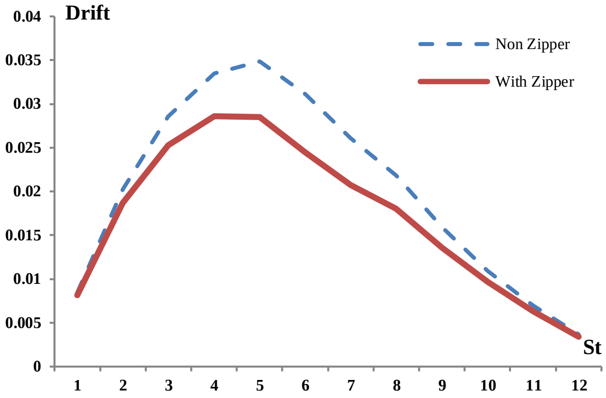
(c): Rinaldi record

Fig. 5: Diagram of reduction in the relative displacement of a semi-rigid 15- story frame with a zipper bracing system relative to a Chevron bracing system under various records.

Figures 6 and 7 present some diagrams related to the control of relative story displacement in the 12-story steel frames with pinned and ductile connections brace 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 relative displacement in the story and the effect of a zipper column in different stories.

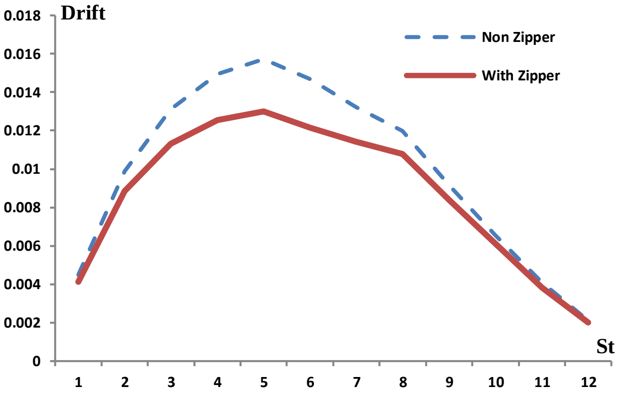


(a): Pinned connections

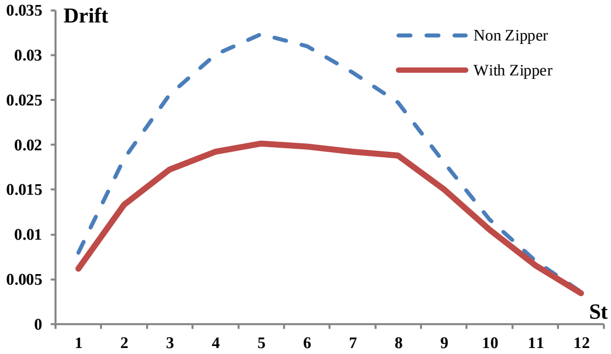


(b): Semi-rigid connections

Fig. 6: Diagram of reduction in the relative story displacement in a 12- story frame with a zipper bracing system relative to a Chevron bracing system under Parkfield record.



(a): Pinned connections



(b): Semi-rigid connections

Fig. 7: Diagram of reduction in the relative story displacement in a 12- story frame with a zipper bracing system relative to a Chevron bracing system under Takarazuka record.

6.2. Maximum displacement of the roof story

Table 4 presents the results of the maximum displacement of the roof story for all four states of the modeled 12-story steel frames under two records of seven near-fault.

Table 4: Maximum displacement of the roof story for the 12-story steel frame

Type of connection	Pinned connections			Semi-rigid connections		
Record	with Chevron braces (cm)	with zipper braces (cm)	Reduction due to zipper column (%)	with Chevron braces (cm)	with zipper braces (cm)	Reduction due to zipper column (%)
Takarazuka	35.95	31.25	13.1	69.10	47.59	31.2
Chi-Chi	31.59	27.68	12.4	61.5	43.2	29.8

The results show that the maximum lateral displacement in the steel frame with pinned connections with Chevron bracing systems decreased up to 13% due to the addition of a zipper column. This value is about 30 % for the frame with ductile connections. Therefore, adding a zipper column is about 17% better in a semi-rigid frame than a pinned frame in control of maximum displacement. The reduction of the maximum displacement in the roof and eighth story of the 15-story frame under near-fault records has been presented in Table 5 for both pinned and semi-rigid connections.

Table 5: Reduction in the displacement in the roof and eighth stories for the 15-story frame

	Chi-Chi	Elcentro	Kjma	Parkfield	Rinaldi	Takarazuka	Takatori
The amount of reduction in the displacement of the roof story for the 15-story frame with pinned connections after adding a zipper column (%)	10.09	2.35	0.46	10.92	15.3	10.66	4.22
The amount of reduction in the displacement of the roof story for the 15-story frame with semi-rigid connections after adding a zipper column (%)	10.02	1.54	23.38	24.13	25.85	25.96	13.19
The amount of reduction in the displacement of the eighth story for the 15-story frame with pinned connections after adding a zipper column (%)	9.35	12.43	1.75	10.42	19.59	12.74	4.81
The amount of reduction in the displacement of the eighth story for the 15-story frame with semi-rigid connections after adding a zipper column (%)	19.69	5.89	18.69	24.02	26.05	27.3	14.81

The results show that the effect of the zipper column is noticeable in decreasing the maximum story displacement in tall structures, but its value depends on the height of the structure, the nature of the earthquake record, and its pulses. The most significant reduction in the maximum story displacement was in the seventh and eighth stories, in which the zipper column leading 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 study, the behavior of tall steel frames with concentrically Chevron bracing with a zipper bracing system was investigated in both pinned- and ductile-connection modes through an analysis 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, 56 samples were analyzed, whose results are as follows:

The presence of a zipper column in tall steel frames with pinned and semi-rigid connections was effective in controlling and decrease the relative displacement of the stories. The average amount of such reduction ranged from 1% to 22% in the 15-story steel frame with pinned connections, while it was between 2% and 35% for semi-rigid steel frames in different stories. The average amounts ranged from 2% to 26% and 2% to 36% in the 12-story steel frame with pinned and semi-rigid connections, respectively. In tall steel frames with ductile connections, it is possible to dissipate the seismic energy in the near-fault area by adding a zipper column while decreasethe relative displacement.

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 displacement in the steel frame with pinned connections with Chevron bracing system decreased up to 13% as a result of use of zipper column. This value was about 30 percent for the frame with ductile connections. Therefore, adding a zipper column was about 17% better in the semi-rigid frame than a pinned frame in controlling maximum displacement.

The most significant effect of adding a zipper column in tall steel frames was in the middle and lower stories up until the second story. It is due to more deformation of these stories in the near-fault earthquakes. The zipper column can help the integrated performance of the structure in the overall height of the frame through the transmission of induced vertical forces to the upper stories.

For seismic rehabilitation of tall steel frames through pinned connections and Chevron bracing systems, one of the valuable and low-cost solutions with easy implementation is to use semi-rigid connections instead of pinned connections and then add a zipper column into the concentric Chevron bracing system.

References

[1] 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.

[2] 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.

[3] 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.

[4] 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.

[5] Razavi, M., & Sheidaei, M. R. (2013). Comparative study of seismic behavior of frames braced with Zipper and special Chevron bracing systems, Ferdowsi Civil Engineering Quarterly Journal, Mashhad, Iran, Vol. 25, No. 1, pp. 72-59.

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

[7] Vaseghi Amiri, J., Abdollahzadeh, G. R., & Panahi, S. (2014). Evaluating the use of vertical Zipper members in the eccentrically braced frames using ABAQUS software, 1st National Conference on Development of Civil Engineering, Architecture, Electricity and Mechanical in Iran. Gorgan, Iran.

[8] Ozcelik, Y., Saritas, A., Clayton, PM. (2016). Comparison of chevron and suspended-zipper braced steel frames, Journal of Constructional Steel Research. No. 119, pp. 75-169.

[9] Zahrai, S.M., Pirdavari, M., Farahani, H.M.(2013). Evaluation of hysteretic behavior of eccentrically braced frames with the zipper-strut upgrade. Journal of Constructional Steel Research. No. 83, pp.10-20.

[10] 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.

[11] 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.

[12] Yang, C.-S., Leon, R.T., & DesRoches, R. (2010). Cyclic behavior of zipper-braced frames, Journal of Earthquake Spectra, Vol 27, Issue 2, pp.561-582.

[13] Tirca, L., & Tremblay, R. (2004). Influence of building height and ground motion type on the seismic behavior of zipper concentrically braced steel frames. 13th World Conference on Earthquake Engineering, Paper No. 2894, Vancouver, Canada,

[14] Zandi, N., Adlparvar, M.R., & Lamei Javan, A. (2021). Evaluation on Seismic Performance of Dual Steel Moment-resisting Frame with Zipper Bracing System Compared to Chevron Bracing System against Near-Fault Earthquakes, Journal of Rehabilitation in Civil Engineering, pp. 3-9.

[15] 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.

[16] 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.

[17] 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.

[18] 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.

[19] Zheng, L., Dou, S., Zhang, C., Wang, W., Ge, H., Ma, L., & Gao, Y. (2023). Seismic performance of different chevron braced frames. Journal of Constructional Steel Research, 200, 107680.

[20] 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.

[21] 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.

[22] 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.

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