



Paper Type: Original Article

Interaction between Architectural Design and Seismic Performance of High-Rise Steel Buildings with Truss Belt Systems under Near-and Far-Fault Earthquakes

Faezeh Nejati¹ , Atefeh Ashoori^{1,*} 

¹ Research Institute of Earthquake Engineering, Faculty of Civil Engineering, Isfahan, Iran; civilinj1998@gmail.com; ati.ashoori1372@gmail.com.

Citation:

Received: 21 April 2025
Revised: 03 June 2025
Accepted: 13 August 2025

Nejati, F., & Ashoori, A. (2025). Interaction between architectural design and seismic performance of high-rise steel buildings with truss belt systems under near-and far-fault earthquakes. *Architectural dimensions and beyond*, 2(4), 277-290.

Abstract

With the increasing cost of land, limited horizontal space, and the demand for optimal vertical utilization in urban areas, the construction of high-rise buildings has grown significantly in recent decades. Integrating efficient architectural design and structural engineering is a major challenge in high-rise building development. The truss belt and outrigger system is recognized as an effective mechanism to enhance seismic performance, control lateral displacement, and improve architectural stability. In this study, nonlinear time-history analyses were conducted on a high-rise steel building subjected to near-fault and far-fault earthquakes to investigate the impact of truss belt configuration on seismic behavior. Results show that the inclusion of truss belt and outrigger systems increases the base shear by about 10% and 17% while reducing floor accelerations by approximately 14% and 23% under near- and far-fault earthquakes, respectively. Moreover, roof displacement and acceleration decreased by 3% and 6% for near-fault and 9% and 8% for far-fault ground motions. The torsional response analysis indicated a 26% reduction in floor plan twisting. The findings emphasize the importance of integrating architectural form and structural systems to achieve optimal seismic performance and architectural stability in high-rise steel buildings.

Keywords: High-rise building, Truss belt system, Outrigger, Seismic performance, Architectural design, Near-fault earthquake, Far-fault earthquake.

1 | Introduction

Located on the Alpine–Himalayan seismic belt, Iran has experienced more than 130 earthquakes with magnitudes of 7.5 or greater over the past centuries. Seismic hazard zoning maps indicate that over two-thirds

 Corresponding Author: ati.ashoori1372@gmail.com

 <https://doi.org/10.48314/ad.b.v2i4.44>



Licensee System Analytics. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0>).

of the country's area lies within high-risk seismic regions, where most of the densely populated cities are also located.

During the past century, approximately 3,500 earthquakes have occurred in Iran, among which 535 events had magnitudes greater than 4. On average, one major earthquake with a magnitude of 7 or higher occurs every ten years, and around two hundred smaller and larger earthquakes are recorded annually. Moreover, while earthquake-related fatalities worldwide have accounted for about 1% of the global population during the last century, this figure in Iran has reached approximately 6%, emphasizing the country's high seismic vulnerability.

These statistics highlight the importance of improving the seismic performance of structures and the urgent need for structural strengthening and retrofitting.

Seismic loads act on buildings in two perpendicular directions; therefore, a building must be designed to resist earthquake-induced forces in both orthogonal axes (X and Y). Earthquake forces are applied alternately and repeatedly in these two directions, making the bidirectional seismic design of structures essential for ensuring their safety and stability.

An earthquake is a natural phenomenon that can lead to the destruction of buildings, loss of life, economic damage, and disruption of vital lifelines. On average, Iran experiences a major earthquake approximately every ten years, a fact that underscores the necessity for increased awareness and preparedness among the engineering community [1], [2].

An earthquake is a natural phenomenon that can lead to the destruction of buildings, loss of life, economic damages, and disruption of vital lifelines. On average, Iran experiences a major earthquake approximately every ten years, a fact that underscores the necessity for increased awareness and preparedness among the engineering community [1], [2].

In a study by Shah and Gore [2], titled "Review on Behavior of Tall Buildings Equipped with Outrigger Systems", published in the International Journal of Engineering and Technology, a new concept of outrigger systems was introduced. The authors conducted this study to investigate the use of truss belt systems alone for improving the performance of high-rise buildings under dynamic loads.

Their research concluded that the implementation of outrigger systems in tall buildings reduces overall lateral displacement, base shear, and inter-story drift. Furthermore, the use of multiple outrigger systems enhances the structural performance compared to a single-outrigger configuration. It was also demonstrated that the combined use of outrigger and truss belt systems significantly increases the stiffness and stability of the building, while simultaneously reducing the maximum deformation of the structure [3].

In a study by Rahgozar et al. [4], titled "A simple mathematical model for approximate analysis of tall buildings", a mathematical model was presented to facilitate the approximate analysis of high-rise buildings. The authors demonstrated the simplicity and practicality of the proposed model through several numerical examples, showing that it can be effectively used in preliminary design due to its accuracy, efficiency, and logical formulation.

Their findings indicated that the optimal placement of the truss belt system can minimize lateral displacements, stresses, and strains induced by lateral loads, thereby enhancing the overall structural performance [5]. In a study by Abdi Moghadam and Meshkat-Dini [3], titled "Effect of truss belt level on the performance of tall buildings under Near-Fault earthquakes", published in Amirkabir Journal of Engineering, nonlinear time-history dynamic analyses were conducted for three far-fault and three near-fault earthquakes. A detailed evaluation of the analysis results revealed that the presence of a truss belt system significantly increases structural stiffness while reducing inter-story drift and base shear. Moreover, it was found that in structures where the truss belt is positioned at 0.5 of the building height, the maximum drift occurs at approximately 0.83 to 0.9 of the normalized building height [6].

In a study by Tavakoli et al. [5], titled "Optimal truss belt position in tall buildings using multiple criteria under blast loads," published in the journal of civil engineering, the authors investigated the optimal

placement of truss belts for various types of loads. Their findings indicated that the base shear during blast loading differs significantly when the truss belt is located on the first floor compared to its placement on other floors [7].

In a study by Daril John and Srinidhilakshmish [6], titled “Comparison of seismic performance of outrigger and belt truss system in a RCC building with vertical irregularity”, published in the International Journal of Engineering and Technology Research, a 30-story building was modeled using ETABS software. The study compared base shear, ultimate displacement, and inter-story drift. Based on the results of base shear and ultimate load, it was concluded that tall buildings equipped solely with a truss belt system exhibit better seismic performance compared to buildings with only an outrigger system or those with both outrigger and truss belt systems [8].

In a study by Alhaddad et al. [7], titled “A comprehensive introduction to outrigger and truss belt systems in High-Rise buildings”, published in 2020, the authors examined the advantages and disadvantages of outrigger and truss belt systems. Their research highlighted that these systems are among the most effective methods for reducing ultimate loads in tall and super-tall buildings. However, they also emphasized that the implementation of these systems requires careful consideration of numerous aspects and detailed analyses to ensure reliable structural behavior. This study serves as an initial reference point for further research in this field.

In a study by Patil and Sangle [8], titled “seismic behavior of tall steel buildings equipped with truss belt systems”, published in 2016, high-rise steel buildings with 20, 25, 30, and 35 stories were analyzed using nonlinear pushover analysis. The study compared various truss belt locations, base shear, inter-story drift, and increases in stiffness. The authors concluded that the optimal position of the truss belt may vary depending on different loading patterns.

In a study by Zhou et al. [9], titled “A decision framework for optimal installation of truss belt systems in tall buildings,” published in 2018, the proposed framework was applied to a 600-meter-tall building. Their research indicated that the truss belt system is expected to ensure structural safety and stability in high-rise construction.

In a study by Bayati et al. [10], titled “Optimal use of multiple outrigger systems in stiff high-rise buildings”, presented at the world conference on earthquake engineering, the authors reported the results of a study on reducing inter-story drift in buildings equipped with stiff outrigger systems. The findings indicated that the optimal use of multiple outrigger systems can significantly improve the seismic response of high-rise buildings.

In a study by Kamgar and Rahgozar [11], titled “Determination of optimal flexible truss belt system location in irregular tall buildings using the energy method”, published in the international journal of civil engineering optimization, a tall building was modeled with a combined system of truss belt, outrigger, central core, and braced frame. The study investigated the optimal truss belt location under three types of lateral loads: uniform, triangular, and concentrated. The results indicated that for different central core stiffnesses and truss belt systems, multiple optimal configurations were identified, which can be used to determine the best placement of truss belt and outrigger systems [12].

In a study by Khandelwal and Singh [13], titled “Optimal configuration and location of truss belt systems for tall buildings under seismic loads”, published in the international journal of innovative technology and exploring engineering, a 30-story building with one truss belt, a 45-story building with two truss belts, and a 60-story building with three truss belts were analyzed. The results indicated that the optimal truss belt locations were on the 10th, 15th, and upper floors, respectively [14].

2 | Structural Description, Earthquakes, and Modeling in Software

At the beginning of this chapter, the structural specifications, geometric dimensions, and the locations of the truss belt along the building height are defined. It should be noted that the building under study was designed

in accordance with the seismic design provisions of the Iranian code for seismic resistant design of buildings [5]. Next, the characteristics of the applied earthquakes and the method of scaling them are described. The building was modeled in SAP2000, version 20, and plastic hinges were assigned to the structural members using the ASCE 41-13 provisions available within the software.

1.2| Geometric Specifications of the Building

The building considered in this study is a 30-story braced steel structure with concentric cross-bracing, in which truss belts are installed at two configurations: every 15 floors and every 10 floors. The building is assumed to be located in a very high seismic hazard zone on soil type II, according to Iranian Standard 2800, 4th Edition. The structural plan is regular, with bay lengths of 5 meters in both X and Y directions, and all floor heights are 3 meters. The dead and live loads applied on the floors are 750 kg/m^2 and 200 kg/m^2 , respectively.

Fig. 1 illustrates the structural plan and 3D view of the building. *Table 1* presents the cross-sectional dimensions of beams, columns, and braces used in the structure.

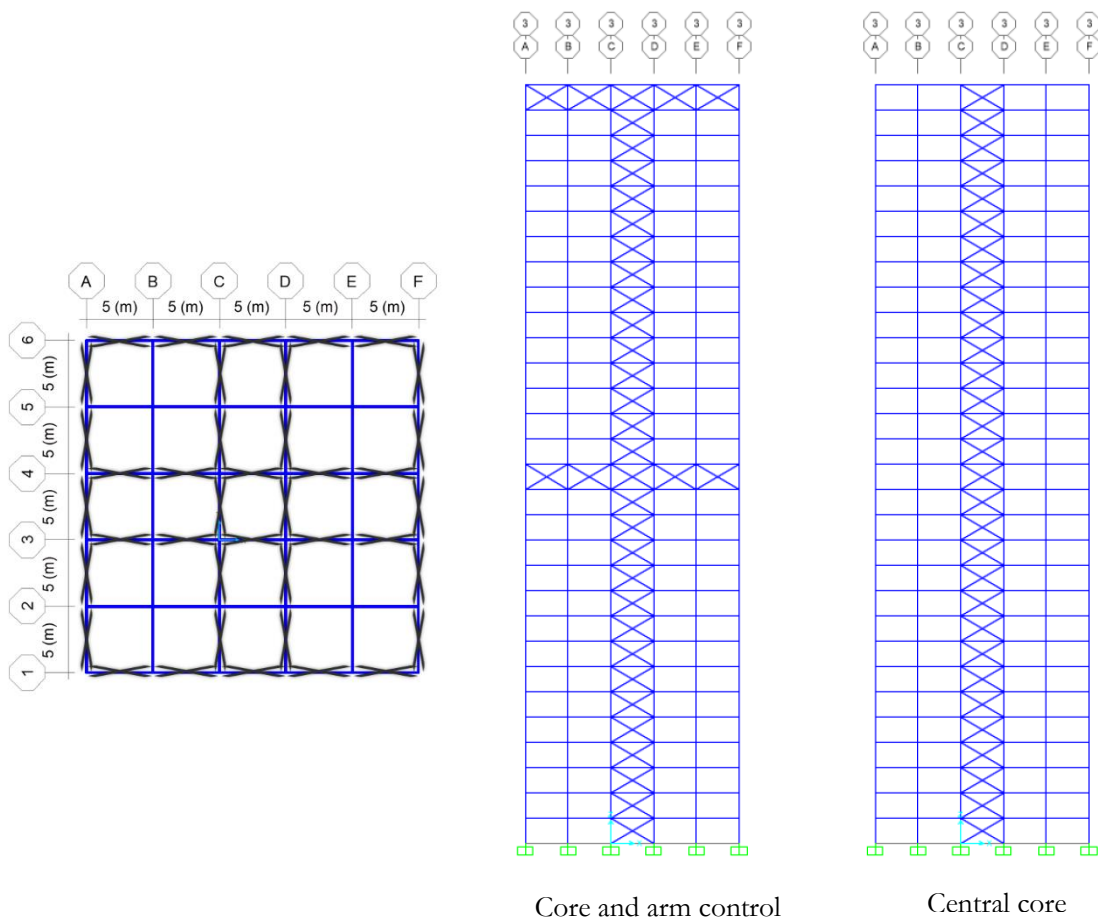


Fig. 1. Plan and 3D view of the building under study.

Table 1. Cross-sectional dimensions of structural members used in the building under study.

Beam Section	Brace Section	Column Section at Brace Bay (Central Core)	Exterior Column Section (Dimensions in cm)	Floor Number
IPE 400	2UNP200	BOX 50X50	BOX 60X60	1-6
IPE 400	2UNP200	BOX 45X45	BOX 50X50	7-11
IPE 400	2UNP160	BOX 45X45	BOX 45X45	12-15
IPE 400	2UNP180	BOX 45X45	BOX 45X45	16-18
IPE 400	2UNP160	BOX 45X45	BOX 45X45	19-20
IPE 400	2UNP160	BOX 40X40	BOX 40X40	21
IPE 400	2UNP140	BOX 40X40	BOX 40X40	22-23
IPE 300	2UNP140	BOX 40X40	BOX 40X40	24-25
IPE 300	2UNP140	BOX 35X35	BOX 35X35	25-30

The center of stiffness of a building is the point at which the structure resists applied lateral forces. Since the cross-sectional properties of the structural members do not change during the building’s service life, the location of the stiffness center remains constant. On the other hand, the center of mass is the point where lateral forces act. This point can change over time due to factors such as modifications in building usage, uneven redistribution of mass in the plan, or other alterations during the building’s service life.

The distinction of this study from previous research is that it assumes the floor mass centers of the studied buildings have shifted due to changes in building use by occupants. Consequently, the force couple generated between the center of mass and the center of stiffness leads to increased torsion in the structure, which was not considered in the initial design by the engineer. Most seismic design codes assume an accidental eccentricity of 5% of the building dimension at each floor in the direction perpendicular to the applied lateral force.

Fig. 2 illustrates the considered locations of the centers of mass for the studied buildings. It is assumed that, in these buildings, the center of mass at each floor is located at 7.5% of the building dimension perpendicular to the lateral force.

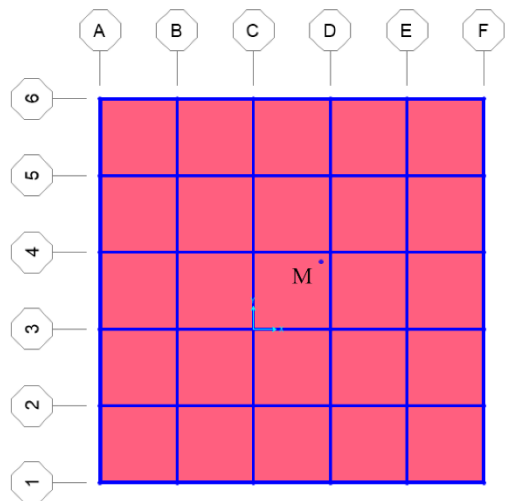


Fig. 2. Location of the floor mass centers in the building.

According to Clause 1-7 of Iranian Standard 2800, 4th Edition, buildings are considered irregular if they exhibit any of the following characteristics in terms of geometric shape, mass distribution, or stiffness distribution in plan and elevation; otherwise, they are classified as regular.

The building selected for this study, although having a regular geometric plan, is classified as irregular in terms of structural configuration due to the significant distance between the center of mass and the center of stiffness, taking into account accidental torsion [5], [15].

3| Data Analysis

The building was initially designed in ETABS software and then analyzed in SAP2000. In this study, three 30-story steel buildings were modeled:

- I. A building with a central core only, without any truss belts or outrigger systems.
- II. A building with a central core, two truss belts, and outrigger systems.
- III. A building with a central core, three truss belts, and outrigger systems.

All models were subjected to nonlinear time-history dynamic analysis to investigate the effects of the central core and truss belt systems. The truss belts were connected to the central core via outrigger systems.

In this chapter, the responses of the building with two truss belts located on the 15th and 30th floors are compared first. Then, based on the nonlinear analysis results, the building with three truss belts located on the 10th, 20th, and 30th floors is analyzed and compared.

3.1| Comparison of Inter-Story Drift in the X and Y Directions

In this section, the inter-story displacements of the two considered structures under near-fault and far-fault earthquakes are compared, as illustrated in Fig. 5.

3.1.1| Inter-story drift under seismic ground motions

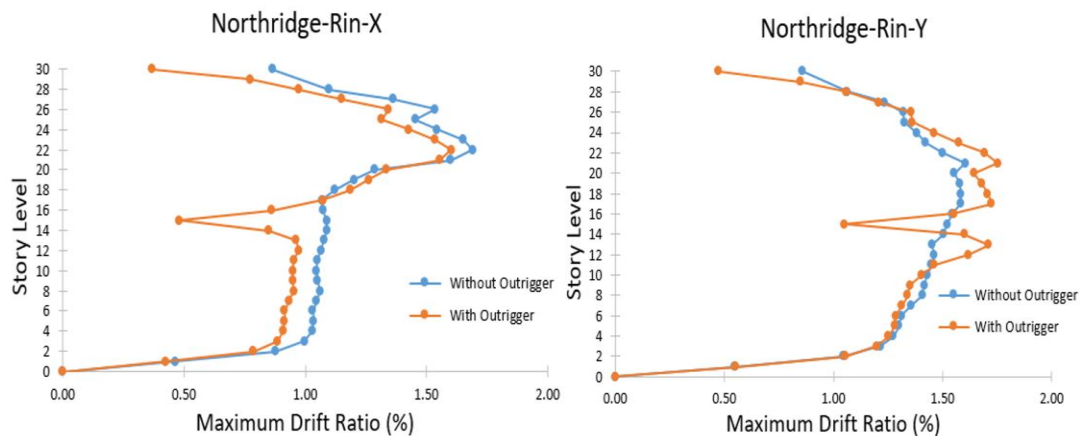


Fig. 3. Inter-story drift under the Northridge-Rinaldi earthquake.

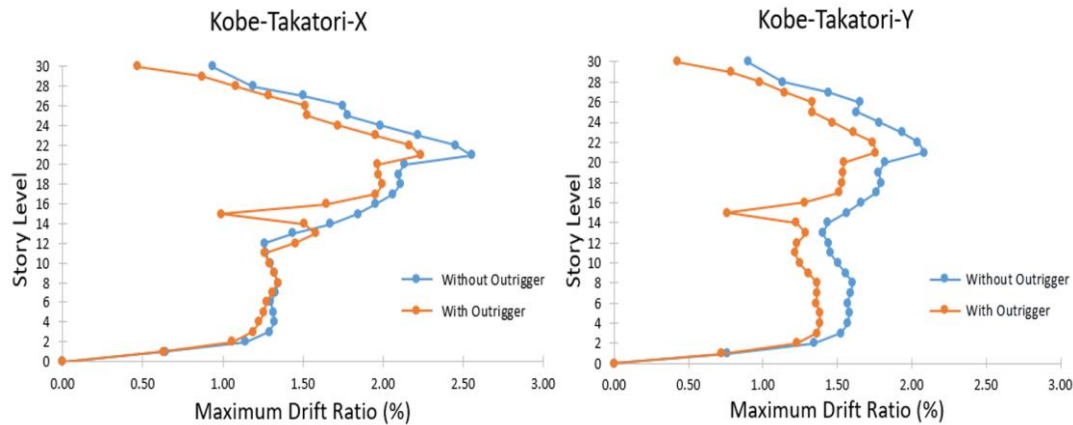


Fig. 4. Inter-story drift under the Kobe-Takatori earthquake.

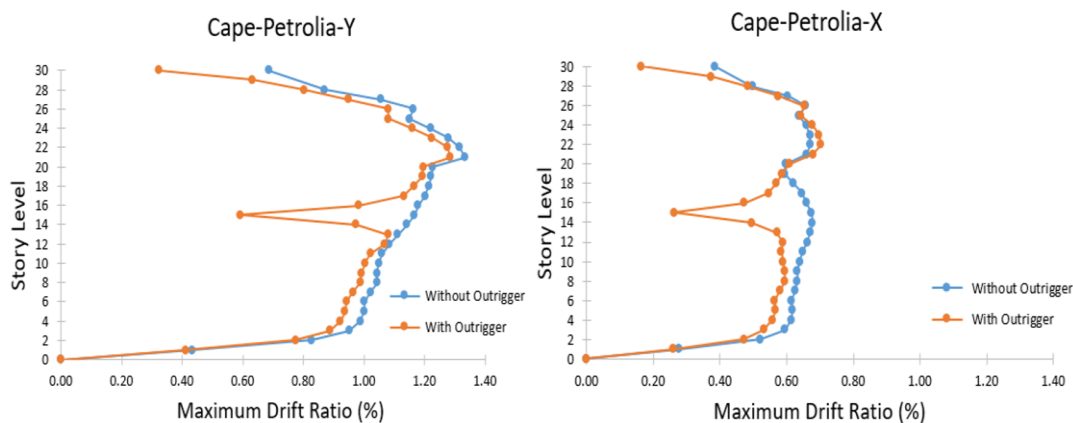


Fig. 5. Inter-story drift under the Cape-Petrolia earthquake.

As observed in Fig. 5, the inter-story drift in the building with truss belts shows a significant reduction in the floors equipped with truss belts and outrigger systems. Moreover, in the remaining floors and across all directions, the building also exhibits a reduction in drift compared to the structure without truss belts.

2.1.3 | Inter-story drift under far-fault earthquakes

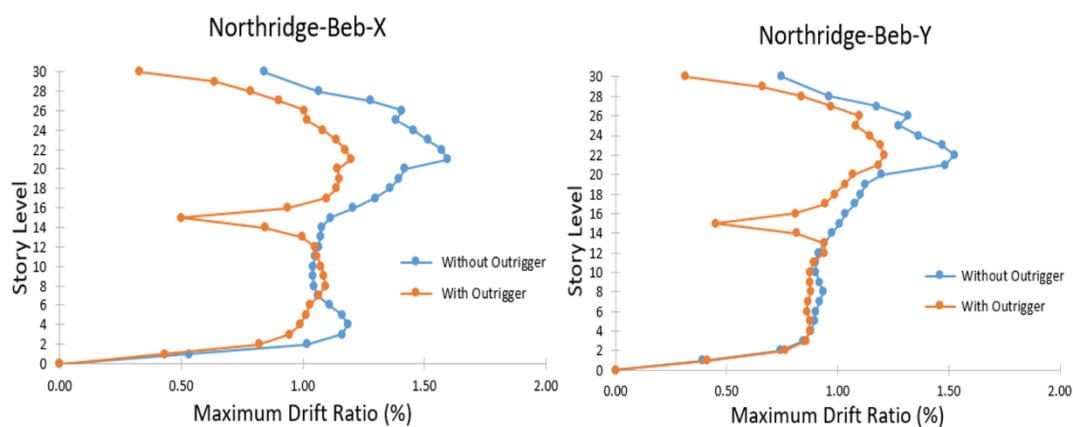


Fig. 6. Inter-story drift under the Northridge-Beverly earthquake.

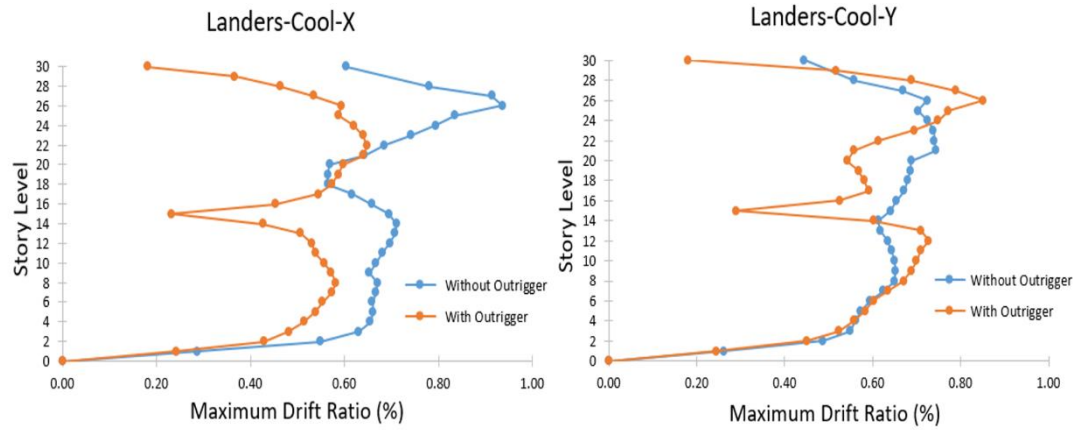


Fig. 7. Inter-story drift under the Landers-CoolWater earthquake.

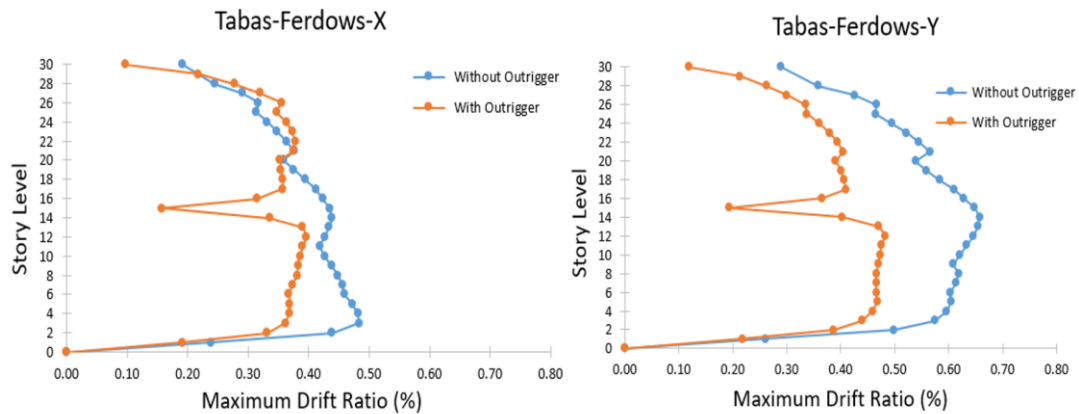


Fig. 8. Inter-story drift under the Tabas-Ferdows earthquake.

As observed in *Figs. 8*, the inter-story drift of the building with truss belts and outrigger systems under far-fault earthquakes shows a decreasing trend compared to the building without truss belts and outriggers, with the most significant reduction occurring in the floors equipped with truss belts. Moreover, the drift reduction under far-fault earthquakes is more significant than that observed under near-fault earthquakes.

2.3 | Comparison of Floor Accelerations

In this section, the floor accelerations of buildings with and without truss belt systems are compared, as illustrated in *Fig. 11*.

1.2.3 | Floor accelerations under near-fault earthquakes

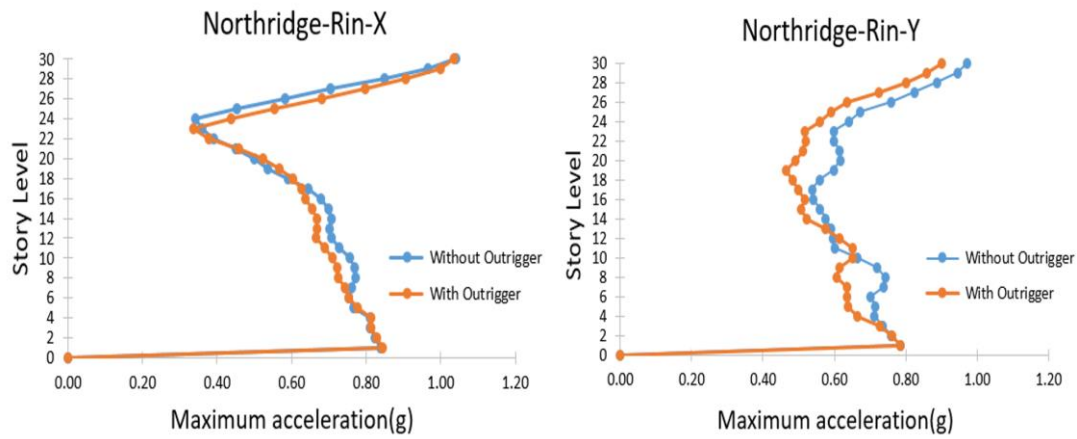


Fig. 9. Floor accelerations under the Northridge-Rinaldi earthquake.

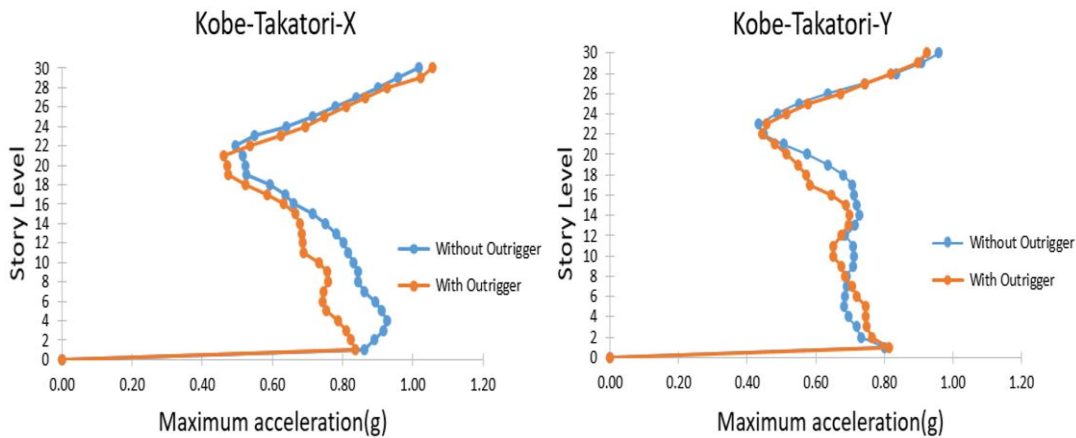


Fig. 10. Floor accelerations under the Kobe-Takatori earthquake.

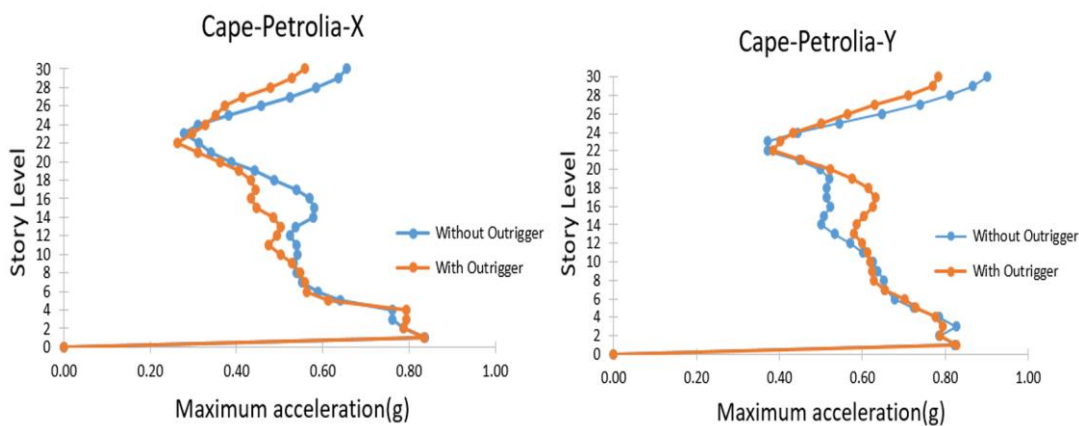


Fig. 11. Floor accelerations under the Cape-Petrolia earthquake.

As observed in Fig. 11, the floor accelerations in the building equipped with truss belts and outrigger systems are reduced by approximately 90% of the structure compared to the building without truss belts and outriggers under near-fault earthquakes.

2.2.3 | Floor accelerations under far-fault earthquakes

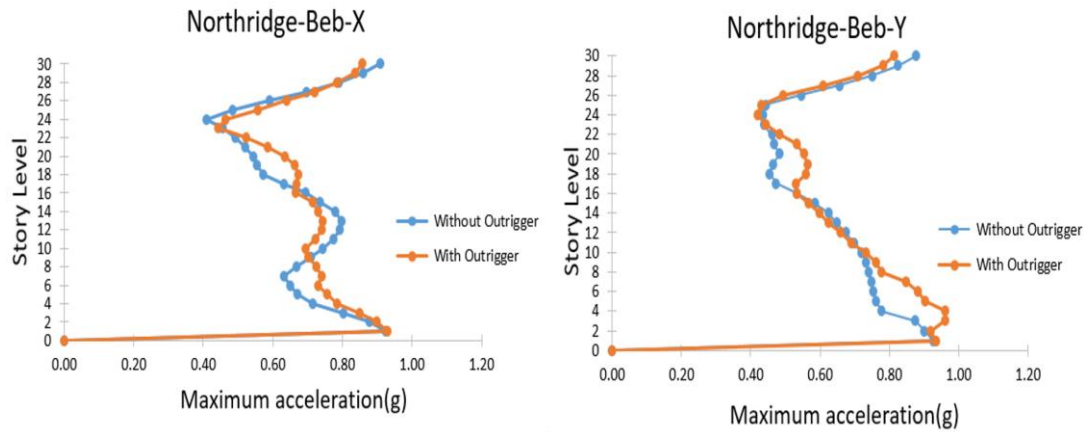


Fig. 12. Floor accelerations under the Northridge-Beverly earthquake.

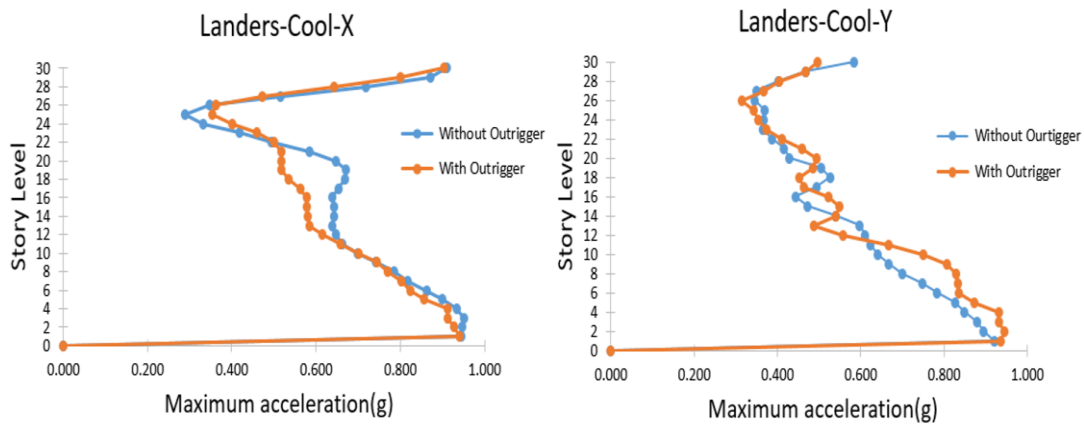


Fig. 13. Floor accelerations under the Landers-CoolWater earthquake.

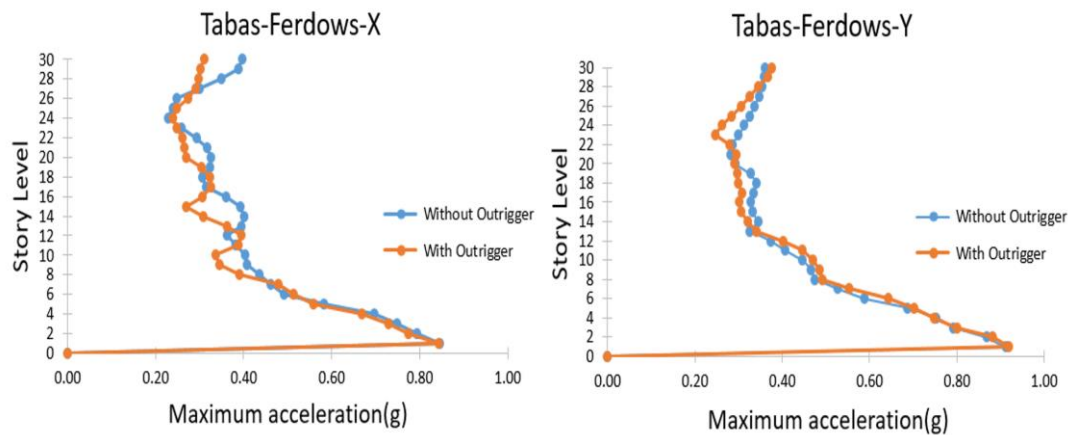


Fig. 14. Floor accelerations under the Tabas-Ferdows earthquake.

As observed in Fig. 14, the floor accelerations in the building equipped with truss belts and outrigger systems are reduced in most floors compared to the building without truss belts and outriggers under far-fault earthquakes.

3.3 | Comparison of Floor Displacements

1.3.3 | Floor displacements under near-fault earthquakes

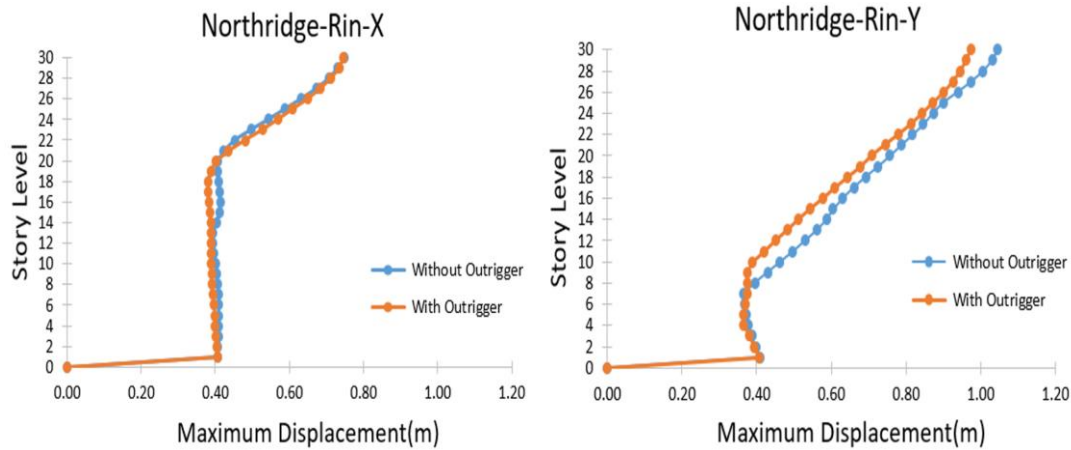


Fig. 15. Floor displacements under the Northridge-Rinaldi earthquake.

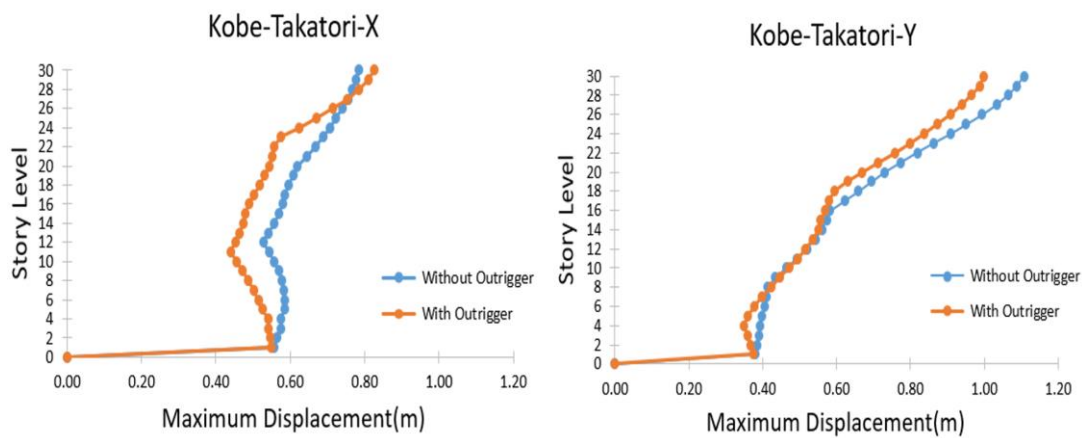


Fig. 16. Floor displacements under the Kobe-Takatori earthquake.

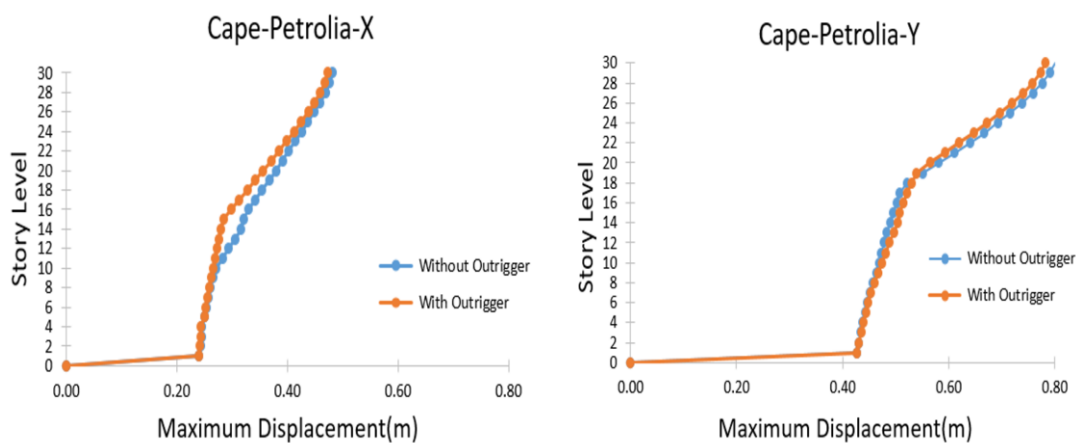


Fig. 17. Floor displacements under the Cape-Petrolia earthquake.

As observed in *Fig. 17*, the floor displacements under near-fault earthquakes are reduced in the building equipped with truss belts and outrigger systems compared to the building without truss belts and outriggers.

2.3.3 | Floor displacements under Far-Fault earthquakes

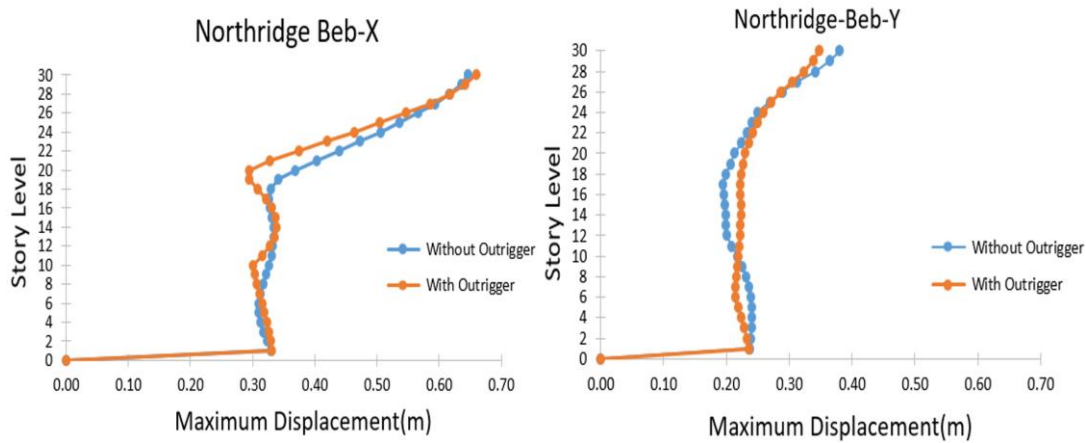


Fig. 18. Floor displacements under the Northridge-Beverly earthquake.

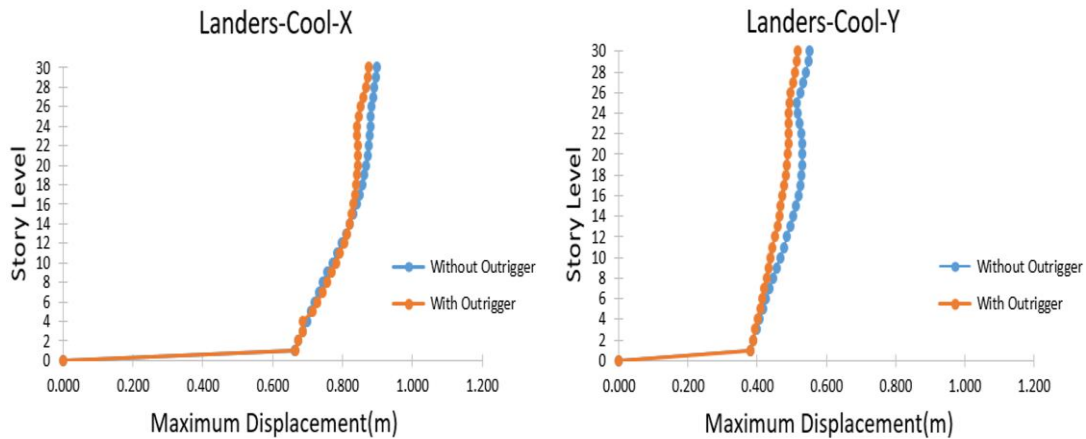


Fig. 19. Floor displacements under the Landers-CoolWater earthquake.

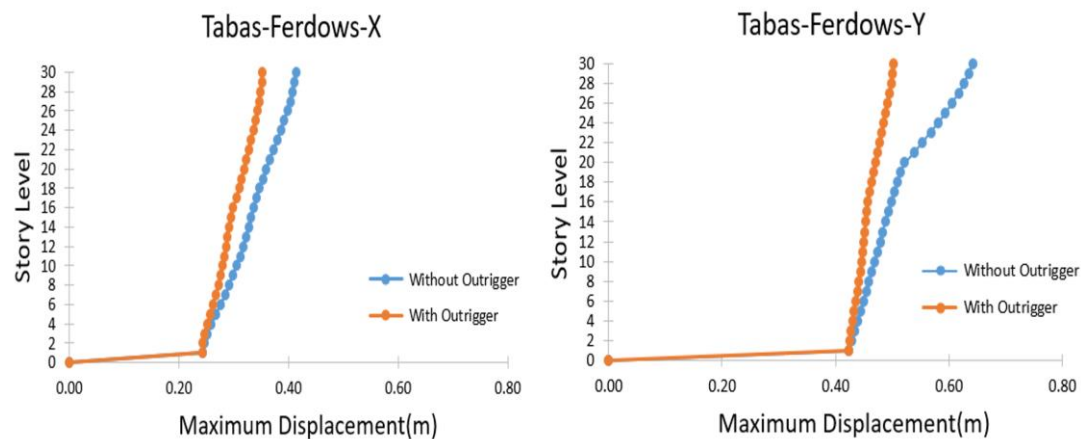


Fig. 20. Floor displacements under the Tabas-Ferdows earthquake.

Under far-fault earthquakes, similar to near-fault earthquakes, the truss belts and outrigger systems contribute to a reduction in floor displacements compared to the structure without truss belts and outriggers.

4 | Conclusion

The analyses conducted in this study aimed to compare the seismic performance of steel buildings equipped with truss belt and outrigger systems. The main findings are summarized as follows:

- I. Plastic hinge formation in buildings equipped with truss belt systems provides a better performance level compared to structures without truss belts.
- II. Equipping the structure with truss belts and outrigger systems leads to an increase in base shear, as adding outriggers increases the structural weight. Under near-fault earthquakes, the minimum base shear increase occurs in the X-direction of the Kobe earthquake with 1.38%, while the maximum increase is in the X-direction of the Petrolia earthquake with 17.02%. For far-fault earthquakes, the minimum base shear increase occurs in the X-direction of the Tabas earthquake (4.58%) and the maximum in the Y-direction of the Northridge-Beverly earthquake (25.75%). On average, the base shear of the structure increased by 10% and 17% under near-fault and far-fault earthquakes, respectively.
- III. Examination of inter-story displacement diagrams reveals that equipping the structure with truss belts and outrigger systems yields the best performance in reducing inter-story displacements on the 15th floor. Under near-fault and far-fault earthquakes, the maximum reduction in this floor is 51% (Kobe) and 70% (Tabas), respectively. On average, inter-story displacements decreased by 14% and 23% under near-fault and far-fault earthquakes. Overall, floors equipped with truss belts and outriggers exhibit superior drift reduction compared to other floors.
- IV. Analysis of floor acceleration diagrams indicates that the 15th floor also shows the best performance in reducing floor accelerations when the structure is equipped with truss belts and outriggers. Under near-fault earthquakes, the maximum acceleration reduction in this floor occurs in the Petrolia earthquake (23%), and under far-fault earthquakes, the Tabas earthquake shows a maximum reduction of 31%. On average, floor accelerations decreased by 8% and 6% under near-fault and far-fault earthquakes, respectively.
- V. Evaluation of maximum floor displacements shows that the 11th floor demonstrates the best performance under near-fault earthquakes, with the Kobe earthquake showing a 19% reduction. Under far-fault earthquakes, the 30th floor shows the best performance in the Tabas earthquake with a 21% reduction. On average, the maximum floor displacements decreased by 5% under both near-fault and far-fault earthquakes.
- VI. Considering the importance of roof acceleration in tall buildings, the results indicate that the truss belt and outrigger system is effective in reducing roof acceleration. Under near-fault earthquakes, the minimum reduction occurs in the X-direction of the Rinaldi earthquake (0.58%), and the maximum reduction occurs in the X-direction of the Petrolia earthquake (13.09%). For far-fault earthquakes, the minimum and maximum reductions occur in the X-direction of the Landers (0.80%) and Tabas (21.85%) earthquakes, respectively. On average, the system reduces roof acceleration by 6% and 8% under near-fault and far-fault earthquakes.

Acknowledgments

The authors would like to express their sincere gratitude to all individuals who contributed to the completion of this research through their valuable insights, technical support, and constructive feedback. Their assistance and encouragement were essential to the successful preparation of this study.

Funding

This research did not receive any specific grant or financial support from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Certain parts of the dataset may not be publicly accessible due to confidentiality considerations.

References

- [1] Virde, V., Singh, D. R., & Rathore, A. (2020). Analysis of High-Rise Building With Outrigger Using Non-Dimensional Parameter. *International journal of advanced research in engineering and technology (IJARET)*, 11(3), 360-370. <https://ssrn.com/abstract=3567698>
- [2] Shah, N. K., & Gore, N. G. (2016). Review on behavior of outrigger system in high rise building. *International research journal of engineering and technology (IRJET)*, 3(6), 56-2395. <https://www.academia.edu/download/54548546/IRJET-V3I6520.pdf>
- [3] Moghadam, M. A., & Meshkat-Dini, A. (2018). The effect of belt truss level on the performance of steel high-rise buildings subjected to near-field earthquakes. *Amirkabir journal of civil engineering*, 49(4), 209-212. <https://doi.org/10.22060/ceej.2017.10553.4905>
- [4] Rahgozar, R., Ahmadi, A. R., & Sharifi, Y. (2010). A simple mathematical model for approximate analysis of tall buildings. *Applied mathematical modelling*, 34(9), 2437-2451. <https://doi.org/10.1016/j.apm.2009.11.009>
- [5] Tavakoli, R., Kamgar, R., & Rahgozar, R. (2018). The best location of belt truss system in tall buildings using multiple criteria subjected to blast loading. *Civil engineering journal*, 4(6), 1338-1353. <http://dx.doi.org/10.28991/cej-0309177>
- [6] Prasad, D. J., & Kumar, S. (2016). Comparison of seismic performance of outrigger and belt truss system in a RCC building with vertical irregularity. *International journal of research in engineering and technology*, 5(20), 125-132. https://www.academia.edu/download/54922427/OUTRIGGER_BY_IS.pdf
- [7] Alhaddad, W., Halabi, Y., Xu, H., & Lei, H. (2020). A comprehensive introduction to outrigger and belt-truss system in skyscrapers. *Structures* (Vol. 27, pp. 989-998). Elsevier. <https://doi.org/10.1016/j.istruc.2020.06.028>
- [8] Patil, D. M., & Sangle, K. K. (2016). Seismic behaviour of outrigger braced systems in high rise 2-D steel buildings. *Structures* (Vol. 8, pp. 1-16). Elsevier. <https://doi.org/10.1016/j.istruc.2016.07.005>
- [9] Zhou, K., Luo, X. W., & Li, Q. S. (2018). Decision framework for optimal installation of outriggers in tall buildings. *Automation in construction*, 93, 200-213. <https://doi.org/10.1016/j.autcon.2018.05.017>
- [10] Bayati, Z., Mahdikhani, M., & Rahaei, A. (2008). Optimized use of multi-outriggers system to stiffen tall buildings. *The 14th world conference on earthquake engineering* (Vol. 64, No. 02, pp. 183-194). <https://www.researchgate.net>
- [11] Kamgar, R., & Rahgozar, R. (2015). Determination of optimum location for flexible outrigger systems in non-uniform tall buildings using energy method. *International journal of optimization in civil engineering*, 5(4), 433-444. <https://www.academia.edu/download/75659555/article-1-226-fa.pdf>
- [12] Edalatpanah, S. A., Nejati, F., Zhian, M., & Safar, M. F. (2020). Computational modeling of yielding octagonal connection for concentrically braced frames. *Magazine of civil engineering*, 2(94), 31-53. <https://cyberleninka.ru/article/n/computational-modeling-of-yielding-octagonal-connection-for-concentrically-braced-frames>
- [13] Khandelwal, R., & Singh, S. (2020). Optimum shape and position of outrigger system for high rise building under earthquake loading. *Regular issue*, 9(3), 3268-3275. <https://doi.org/10.35940/ijitee.C8961.019320>
- [14] Haukaas, T., & Der Kiureghian, A. (2004). *Pacific earthquake engineering research center*. University of California, Berkeley. https://peer.berkeley.edu/sites/default/files/0314_t_haukaas_a_der_kiureghian.pdf
- [15] Tavakoli, R., Kamgar, R., & Rahgozar, R. (2019). Seismic performance of outrigger-belt truss system considering soil-structure interaction. *International journal of advanced structural engineering*, 11(1), 45-54. <https://doi.org/10.1007/s40091-019-0215-7>