International Journal of Researches on Civil Engineering with Artificial Intelligence

www.ceai.reapress.com

REA Research Expansion Alliance

Int. J. Res. Civ. Eng. AI. Vol. 3, No. 4 (2026) 264–282.

Paper Type: Original Article

Comparison of Single-Brace and Knee-Brace Configurations in Regular and Plan-Irregular Reinforced Concrete Buildings Using Nonlinear Static (Pushover) Analysis

Masoud Ghasemi[1,*], Shahab Zinali[2]

[1] Department of Civil Engineering, Faculty of Engineering, Universiti Malaya, 50603 Kuala Lumpur, Malaysia; ghasemi@um.edu.my.
[2] Department of Civil Engineering, Ayandegan University, Tonekabon, Iran; shahabzeinali@outlook.com.

Citation:

Received: 22 March 2026 *Revised: 05 July 2026* *Accepted: 17 September 2026*	Ghasemi, M., & Zinali, Sh. (2026). Comparison of single-brace and knee-brace configurations in regular and plan-irregular reinforced concrete buildings using nonlinear static (pushover) analysis. *International journal of researches on civil engineering with artificial intelligence,* 3(4), 264-282.

Abstract

Iran is located in one of the seismically active regions of the world. Experience from recent earthquakes has demonstrated that the importance of designing structures resistant to earthquake loads is no less than that of designing structures to withstand gravity loads. Therefore, in recent years, increasing attention has been paid to providing appropriate measures for constructing earthquake-resistant buildings. In the design of earthquake-resistant structures, two different parameters should be considered separately. First, under weak or moderate earthquakes, the structure should possess sufficient stiffness to minimize lateral displacement and prevent damage to nonstructural members. Eccentrically Braced Frames (EBFs) are one of the lateral load-resisting systems used for the seismic retrofitting of reinforced concrete buildings. These systems provide high stiffness in the elastic range, together with good ductility and energy dissipation capacity in the plastic range. Depending on the number and configuration of vertical link elements, two types of eccentrically braced systems are considered in this study: EBFs with a single vertical link and Knee-Braced Frames (KBFs). The present study investigates the effect of the configuration of EBFs with a single vertical link and knee-braced systems on the seismic behavior of plan-irregular reinforced concrete buildings. To obtain the required results, three plan-irregular reinforced concrete building frames with 4, 8, and 12 stories were considered. The buildings were first designed using a single-link eccentric bracing system and subsequently using a knee-bracing system with four different configurations. The buildings were designed in accordance with the fourth edition of Iranian Standard No. 2800. In addition, the designed building frames equipped with the two aforementioned systems were evaluated using nonlinear static (pushover) analysis. Finally, based on the comparison and evaluation of the results, it was observed that the buildings retrofitted with the KBF system exhibited greater energy dissipation and a greater reduction in the stress ratio of columns. However, from a constructional perspective, the connection of the KBF system to the beams and columns of the frame at five points may increase the possibility of cracking and weakening of the primary structural members. Furthermore, among the four bracing configurations investigated, the second configuration exhibited better overall performance.

Keywords: Bracing configuration, Nonlinear static analysis, Single vertical link, Knee-bracing system, Reinforced concrete building, Plan irregularity, Pushover analysis.

1 | Introduction

Buildings with plan or vertical irregularities may exhibit more complex behavior during earthquakes than regular buildings because of the uneven distribution of mass, stiffness, and strength. Such irregularities may

Corresponding Author: Ghasemi@um.edu.my
https://doi.org/10.48314/ijrceai.v3i4.72

lead to concentration of displacement and seismic demand in certain stories and structural members and, consequently, increase the likelihood of undesirable mechanisms and localized damage. Therefore, selecting appropriate methods for the seismic retrofitting of existing structures, particularly irregular reinforced concrete buildings, is of considerable importance.

One effective method for increasing the seismic capacity of structures is the use of Eccentrically Braced Frames (EBFs). In this system, a specific portion of a structural member, known as the "link," acts as the primary region for yielding and seismic energy dissipation. Accordingly, through capacity-based design, nonlinear deformations can be concentrated as much as possible within the link, while the remaining primary structural members can be maintained within or close to the elastic range. Previous studies have shown that the performance of EBFs depends on parameters such as link length, shear capacity, overstrength, and the distribution of links along the height of the structure [1–4].

In conventional EBFs, the link is generally incorporated into the main beam. Consequently, after a severe earthquake, considerable damage may occur in the primary beams, making structural repair difficult and costly. For this reason, the use of replaceable links, particularly vertical links, has received increasing attention in recent years. A vertical link makes it possible to concentrate nonlinear deformation and energy dissipation to a greater extent within a member separated from the main beam, thereby facilitating the replacement of the damaged member after an earthquake [5–7]. Experimental studies on replaceable links have also demonstrated that these members can provide adequate nonlinear rotation capacity and stable hysteretic behavior [5], [6].

The use of vertical links in EBFs has also been investigated through experimental and numerical studies. Lian and Su [8] investigated a steel EBF with a vertical shear link and demonstrated that the vertical link can accommodate a major portion of the nonlinear deformations and energy dissipation, while the primary members of the frame remain largely within the elastic range. Their study also investigated the behavior of the system through static tests, cyclic loading tests, and shake-table testing.

In 2023, Ince [9] experimentally investigated the effect of link length on the behavior of reinforced concrete frames retrofitted using a Y-EBF system. In this study, five single-story, single-bay reinforced concrete frame specimens were tested under cyclic loading, and four different lengths were considered for the vertical link. The results showed that the use of Y-EBFs can increase the lateral load-carrying capacity and energy dissipation of reinforced concrete frames, while link length plays an important role in the ductility and seismic performance of the system.

In 2024, Elgammal et al. [10] directly investigated the seismic retrofitting of existing reinforced concrete buildings using shear links and eccentric steel braces. In their study, two existing reinforced concrete buildings were retrofitted using aluminum shear links and steel bracing systems, and the structural responses were evaluated through pushover analysis, nonlinear time-history analysis, incremental dynamic analysis, and fragility analysis. The results showed that the proposed system can reduce lateral displacement and interstory drift while dissipating a substantial portion of the seismic energy through the links.

More recent research has also moved toward the development of repairable and earthquake-resilient structural systems. In 2024, Xiong et al. [11] investigated a self-centering Y-EBF system in which shear links act as ductile fuses, with the primary objective of reducing residual displacement and damage to the main structural members after an earthquake. In addition, studies conducted in 2024 [12] on the geometric and topological optimization of vertical links have shown that the structural resistance and energy dissipation capacity of links can be improved while reducing the amount of material used.

In 2025, Louzai and Abed [13] proposed a simplified design procedure for the seismic retrofitting of reinforced concrete frames with vertical irregularities caused by setbacks using eccentric steel braces and vertical shear links. In their study, the distribution of vertical links along the height of the frame was determined using a procedure based on pushover analysis and the capacity spectrum method, and the performance of the frame before and after retrofitting was compared using nonlinear time-history analysis.

The results showed that the proposed system can reduce both global and local seismic demands and prevent the formation of an undesirable mechanism at the setback story. In terms of subject matter, this study is one of the most closely related recent studies to the present research.

On the other hand, Tonyali [14] investigated the behavior of EBFs with short links under pulse-like ground motions in 2025 and demonstrated that the distribution of link capacities along the height of the structure can influence damage concentration in the lower stories. The use of the concept of Uniform Damage Distribution can lead to a more appropriate distribution of dissipated energy throughout the height of the structure. This issue is particularly important for multi-story structures because an increase in the number of stories may alter the distribution of seismic demand and lead to concentration of deformation in specific stories.

In 2026, new research was also published on vertical links and repairable EBF systems. Yu et al. [15] proposed a replaceable truss-type link for EBFs that, in addition to maintaining load-carrying capacity, improves the repairability and replaceability of the system after an earthquake. Furthermore, Saleh et al. [16] investigated topologically optimized shear links in EBFs in 2026 and demonstrated that the use of appropriate stiffeners in optimized links can increase shear capacity and energy dissipation compared with conventional links.

Moreover, a very recent study in 2026 [17] directly investigated the seismic performance of reinforced concrete frames equipped with vertical links. In that study, reinforced concrete frames braced with an EBF system and vertical links were subjected to cyclic loading, and parameters such as strength, ductility, stiffness, and crack patterns were investigated.

Despite considerable progress in this field, a large proportion of existing studies still focuses on steel frames or single-story experimental specimens. Recent studies on reinforced concrete frames have mainly focused on existing buildings, vertical irregularities caused by setbacks, or the effects of parameters such as link length. Therefore, simultaneous investigation of the effects of plan irregularity, number of stories, and vertical-link configuration in reinforced concrete buildings can contribute to filling the existing research gap. In particular, comparison of the performance of single vertical links with configurations incorporating multiple or knee-type links in irregular reinforced concrete buildings, together with evaluation of changes in strength, stiffness, ductility, interstory drift, and plastic hinge formation mechanisms, still requires further investigation.

Accordingly, the present study investigates the seismic behavior of plan-irregular reinforced concrete frames with different numbers of stories, including 4-, 8-, and 12-story buildings. The performance of the frames before and after retrofitting with an eccentric bracing system and different vertical-link configurations is evaluated and compared using nonlinear static (pushover) analysis. The primary objective is to investigate the effect of vertical-link configuration on the lateral load-carrying capacity, stiffness, ductility, interstory drift, and distribution of seismic demand along the height of the frame.

2 | Literature Review

EBFs are among the important lateral load-resisting systems that provide seismic energy absorption and dissipation by combining the appropriate stiffness of the braces with the ductility capacity of the link. In this system, the link is designed as the primary energy-dissipating component, while the remaining structural members must have sufficient strength to resist the forces generated by the link in accordance with capacity-design principles. Previous studies on the behavior of EBFs have shown that link length and the associated yielding mechanism are among the most important factors affecting system response [1], [2].

Ghobarah and Elfath [3] conducted one of the early important studies on the use of eccentric steel bracing for the seismic retrofitting of reinforced concrete frames. In their study, the seismic performance of a three-story non-ductile reinforced concrete building retrofitted with eccentric steel bracing was investigated. The results demonstrated that the use of eccentric bracing can increase the seismic capacity of reinforced concrete frames and improve their response to ground motions.

Subsequently, researchers focused on the use of replaceable links. Mansour et al. [4] experimentally investigated replaceable shear links in EBFs. The experimental results showed that replaceable links can provide stable cyclic behavior and adequate deformation capacity while concentrating damage in a replaceable structural component.

Bozkurt and Topkaya [5] investigated replaceable links with direct brace attachments in 2017. Eight nearly full-scale specimens were tested under cyclic loading, and the results showed that the proposed links provided adequate nonlinear rotation capacity and satisfied the relevant code requirements. The considerable overstrength of the links also demonstrated the importance of designing the non-yielding members based on the actual capacity of the links.

In 2018, Bozkurt and Topkaya [6] proposed new details for replaceable links with gusseted brace connections. The results of nine nearly full-scale tests demonstrated that the proposed links were capable of achieving nonlinear rotations greater than the code-specified limits while maintaining satisfactory performance of the replaceable connections.

Bozkurt et al. [7] subsequently developed a detachable replaceable-link system in 2019 in which the connection was located at the middle of the link length. An important advantage of this system is the possibility of replacing the link even in the presence of residual drift in the frame. The results of six nearly full-scale tests showed that the proposed links possessed adequate nonlinear rotation capacity and could be used to improve the repairability of EBF systems.

In 2017, Lian and Su [8] investigated the seismic behavior of a steel EBF with a vertical shear link through a series of static, cyclic, and shake-table tests. The results demonstrated that the vertical link plays the primary role in seismic energy absorption and dissipation. The use of high-strength steel in the beams and columns can also reduce structural weight while maintaining satisfactory performance of the primary structural members.

One of the important parameters affecting the performance of vertical links is link length. In 2023, Ince [9] experimentally investigated the effect of different link lengths on Y-EBF systems used to retrofit reinforced concrete frames. Five single-story, single-bay reinforced concrete specimens were tested under cyclic loading. Four specimens were retrofitted using vertical links with different lengths, while one specimen was maintained as the reference bare frame. The results showed that the Y-EBF system increased the lateral load-carrying capacity and energy dissipation of the frame, while link length had a significant influence on ductility and energy dissipation capacity.

In 2024, Elgammal et al. [10] investigated the seismic retrofitting of existing reinforced concrete buildings using aluminum shear links and eccentric steel braces. Pushover analysis, nonlinear time-history analysis, incremental dynamic analysis, and fragility analysis were performed. The results showed that the use of shear links can increase the lateral capacity of the buildings, reduce interstory drift, and dissipate a substantial portion of the input seismic energy through the links. However, the study also emphasized the need to investigate the influence of the links on the local behavior of beams and adjacent structural members.

In the same year, Xiong et al. [11] investigated a self-centering Y-EBF system. In this system, shear links act as ductile fuses, while the main objective is to reduce damage to the primary structural members and residual displacements after earthquakes. The cyclic tests and numerical analyses demonstrated the capability of the system to improve energy dissipation capacity and seismic resilience.

In the same year, Saleh et al. [12] investigated the topology optimization of vertical shear links. The results showed that reducing the volume of material can improve the shear resistance and energy dissipation capacity of the link. In the optimized models, the reduction in material volume was achieved while maintaining or improving mechanical performance, which can be considered in the development of lightweight and efficient next-generation links.

In 2025, Louzai and Abed [13] conducted a study directly related to irregular reinforced concrete frames. The objective of their research was to propose a simplified procedure for determining the required dimensions and distribution of vertical shear links and eccentric steel braces in reinforced concrete frames with setbacks. A six-story reinforced concrete frame with vertical irregularity was investigated, and its performance before and after retrofitting was compared using pushover and nonlinear time-history analyses. The results showed that the proposed procedure can reduce global and local seismic demands and prevent the formation of an undesirable mechanism at the setback story.

Tonyali [14] also investigated the behavior of EBFs with short links under pulse-like ground motions in 2025. In this study, a six-story frame with different link sections along its height was analyzed, and the concept of Uniform Damage Distribution was proposed to reduce damage concentration in the lower stories. The results indicate that the distribution of link capacity along the height of the frame can significantly influence the distribution of energy and damage throughout the structure.

In 2026, Yu et al. [15] proposed a replaceable truss-type link for EBFs. Quasi-static and component-replacement tests demonstrated that the proposed system can maintain load-carrying capacity and energy dissipation while providing satisfactory replaceability after seismic damage. This study reflects the recent transition in seismic engineering from merely increasing structural strength toward improving repairability and structural resilience.

Saleh et al. [16] also investigated the behavior of topologically optimized and stiffened shear links in EBFs in 2026. The numerical results showed that some optimized geometries can provide greater shear capacity and energy dissipation than reference links. The study also considered the influence of stiffeners on stress distribution and link ductility.

In the most recent studies published in 2026, Wiranatha et al. [17] experimentally investigated the seismic performance of reinforced concrete frames equipped with vertical links. The study directly focused on the behavior of reinforced concrete EBFs with vertical links and evaluated parameters such as strength, ductility, stiffness, and crack patterns under cyclic loading. This study is particularly relevant to the present research because it demonstrates that the use of vertical links in reinforced concrete frames remains an active and up-to-date research topic.

A review of the aforementioned studies indicates that, although the behavior of vertical links, replaceable links, and EBF systems has been extensively investigated in recent years, significant gaps remain in the study of multi-story and plan-irregular reinforced concrete frames. A considerable proportion of the available experimental studies has focused on single-story, single-bay specimens, whereas multi-story studies have mainly considered steel frames or vertical irregularities. Furthermore, direct comparison of single vertical-link configurations with multiple-link or knee-bracing configurations in irregular reinforced concrete buildings, particularly for structures with different numbers of stories, remains insufficiently investigated.

Therefore, the present study focuses on plan-irregular reinforced concrete frames with 4, 8, and 12 stories and investigates the effects of the eccentric bracing system and different vertical-link configurations on seismic structural behavior. The structural responses are evaluated using nonlinear static (pushover) analysis, and parameters including lateral capacity, stiffness, ductility, interstory drift, roof displacement, and plastic hinge formation are considered to compare the performance of the investigated systems.

3 | Research Methodology

3.1 | Model Geometry

The buildings are analyzed and designed using three-dimensional structural models. The buildings are geometrically irregular in plan. Each building consists of three bays in the X direction and three bays in the Y direction, with a bay spacing of 5 m. In the buildings retrofitted with steel bracing, the braces are located in the middle bay in both the X and Y directions. The story height is assumed to be 3.2 m.

The structural system of the buildings is a medium-ductility moment-resisting frame. The gravity-load-resisting system consists of composite floor slabs, and a 25-cm-thick joist-block floor system is considered.

The structures are assumed to be located in Mazandaran Province, which is classified within a relatively high seismic hazard zone. The site soil is assumed to correspond to Soil Type II, and the buildings are considered to have residential occupancy.

For the buildings retrofitted with EBFs incorporating vertical links, the vertical link length is assumed to be 50 cm. For the buildings retrofitted with knee-bracing systems, the link length is assumed to be 100 cm.

The plans and elevations of the structural models are presented in *Figs. 1-9*.

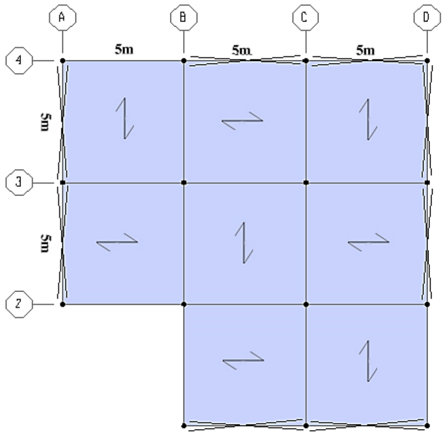

Fig. 1. Plan view of the selected models.

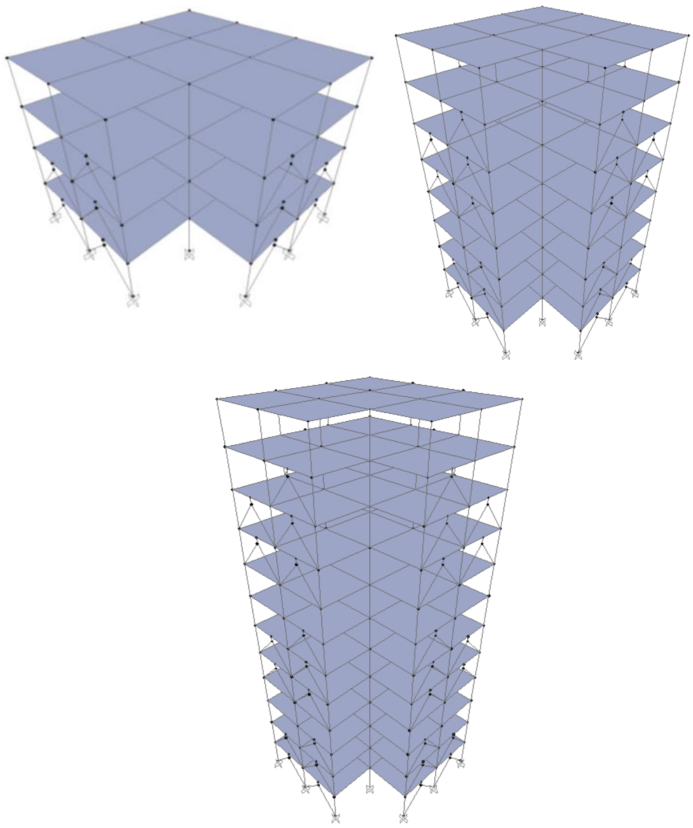

Fig. 2. Elevation view of the first bracing configuration of V-EBF with a single vertical link in the four-, eight-, and twelve-story buildings.

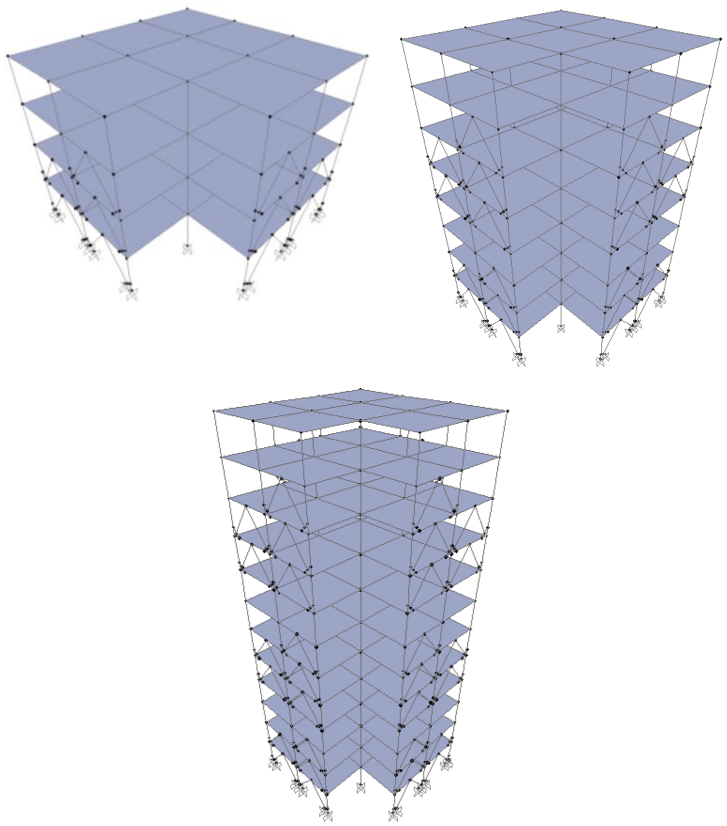

Fig. 3. Elevation view of the first knee-bracing configuration in the four-, eight-, and twelve-story buildings.

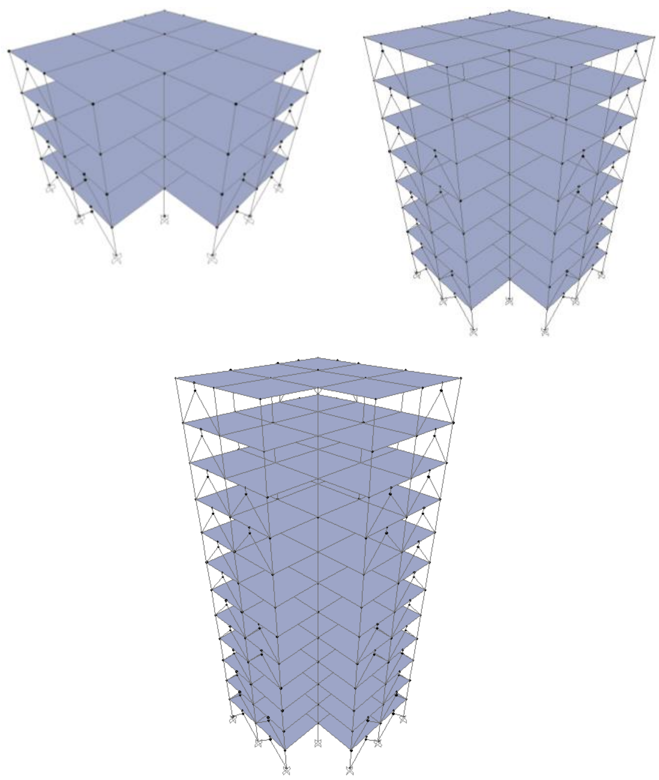

Fig. 4. Elevation view of the second bracing configuration of V-EBF with a single vertical link in the four-, eight-, and twelve-story buildings.

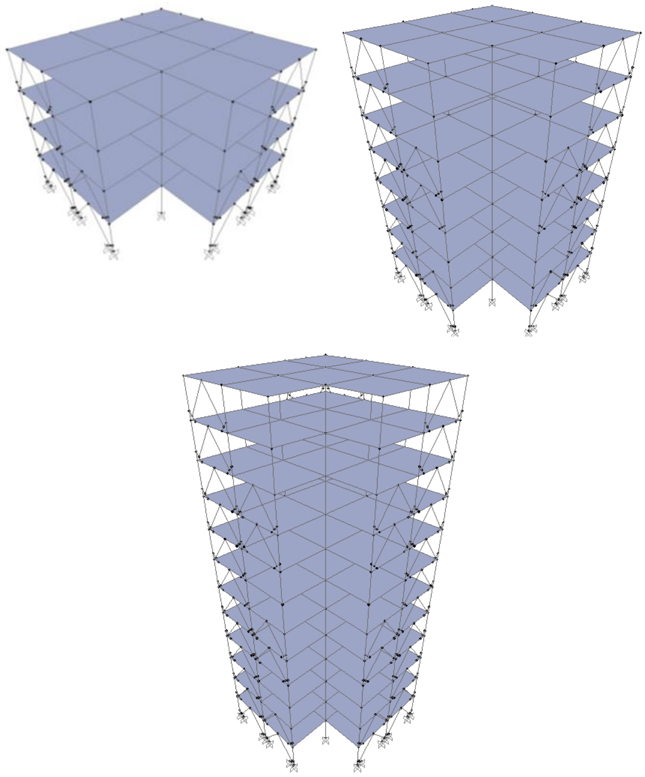

Fig. 5. Elevation view of the second knee-bracing configuration in the four-, eight-, and twelve-story buildings.

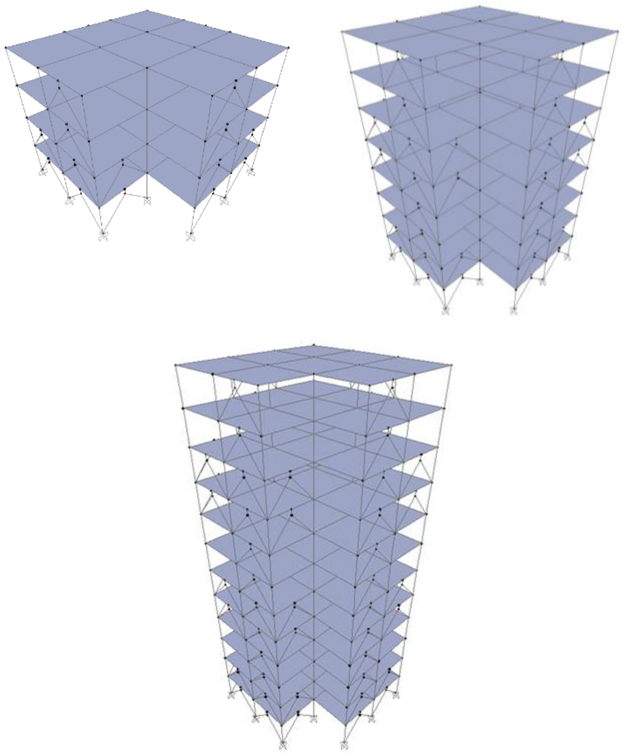

Fig. 6. Elevation view of the second bracing configuration of V-EBF with a single vertical link in the four-, eight-, and twelve-story buildings.

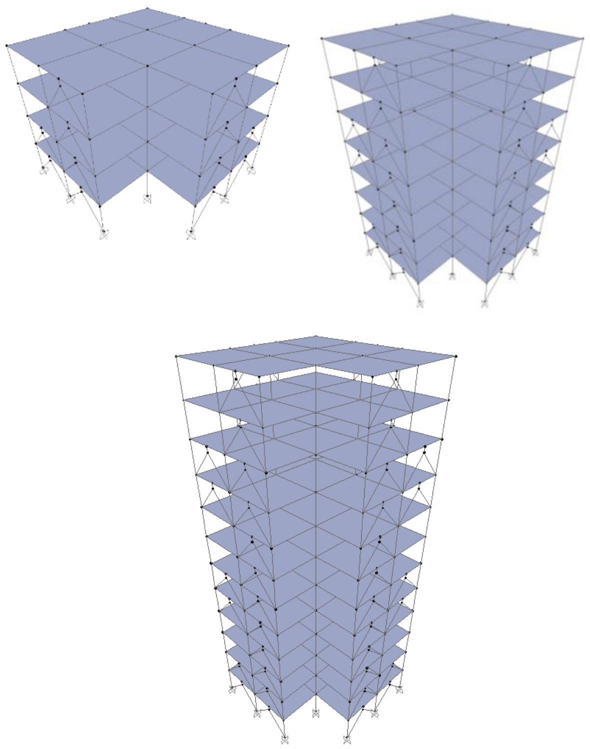

Fig. 7. Elevation view of the third knee-bracing configuration in the four-, eight-, and twelve-story buildings.

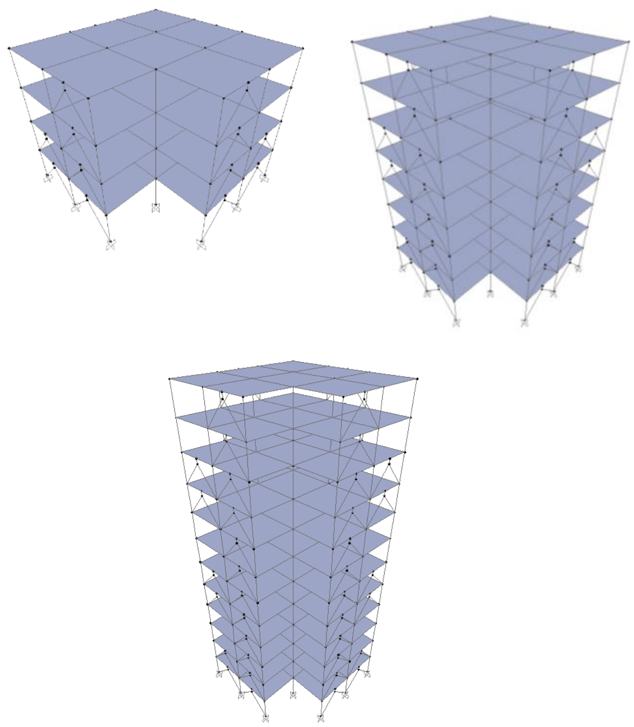

Fig. 8. Elevation view of the fourth bracing configuration of V-EBF with a single vertical link in the four-, eight-, and twelve-story buildings.

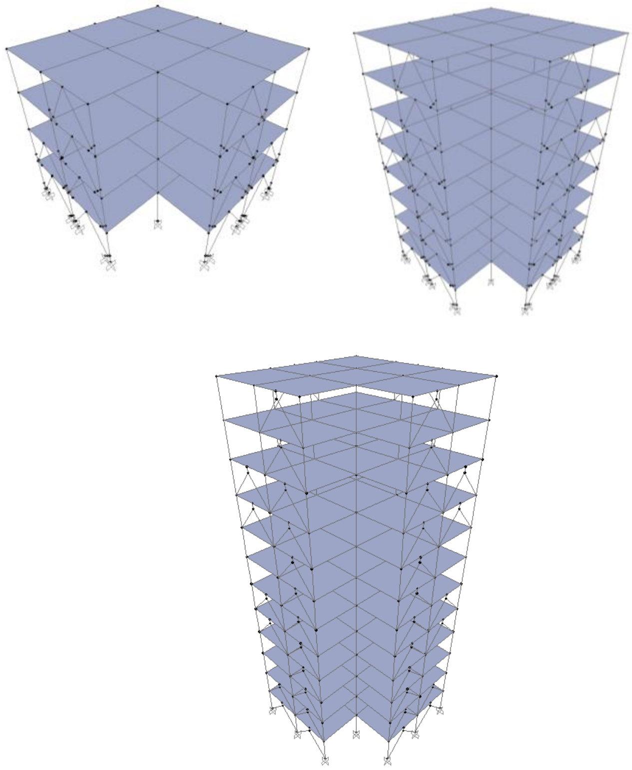

Fig. 9. Elevation view of the fourth knee-bracing configuration in the four-, eight-, and twelve-story buildings.

3.2 | Material Properties

Structural design requires the mechanical properties of the materials and the properties of the structural sections. In these buildings, an effort was made to select material properties that are representative of those commonly used in construction projects in the country. The material properties are presented in *Tables 1-3*.

Table 1. Concrete material properties.

Property	Symbol	Value
Unit weight	W	2450 kg/m³
Modulus of elasticity	E_s	2.3×10^5 kg/cm²
Poisson's ratio	ν	0.20
Compressive strength	f_c'	250 kg/cm²

Table 2. Mild steel material properties.

Property	Symbol	Value
Unit weight	W	7850 kg/m³
Modulus of elasticity	E_s	2.1×10^6 kg/cm²
Poisson's ratio	ν	0.30
Yield stress	F_y	2400 kg/cm²
Ultimate stress	F_u	3700 kg/cm²

Table 3. Soil properties.

Property	Symbol	Value
Subgrade modulus	k_s	1.8 kg/cm³
Allowable bearing stress	q_a	1.5 kg/cm²
Soil type according to the code	—	Type II

3.3 | Gravity Loading

The loads applied to the buildings were determined in accordance with Chapter 6 of the Iranian National Building Regulations and are presented in *Table 4*.

Table 4. Gravity loads on floor levels.

Load Type	Loading Description	Load Intensity	Loading Unit	Total Load
Dead load	Floor finishing	400	kg/m²	600 kg/m²
Dead load	Equivalent partition load	200	kg/m²	—
Dead load	Roof	500	kg/m²	500 kg/m²
Dead load	Exterior walls	840	kg/m	840 kg/m
Live load	Floor levels	200	kg/m²	200 kg/m²
Live load	Roof	150	kg/m²	150 kg/m²

4 | Modeling

SAP2000 software was used for the modeling, analysis, and design of the considered structural models. The software is capable of analyzing and designing structures in accordance with internationally recognized design codes and standards.

The structural models were developed and designed in accordance with Standard 2800 and Chapters 9 and 10 of the Iranian National Building Regulations, and the required design checks were performed.

Following the analysis and design of the structures using ACI 318-99 through the software, the necessary checks were carried out in accordance with the seismic design provisions of Chapter 9 of the Iranian National Building Regulations. Where necessary, the cross-sections of certain structural members, such as beams and columns, were modified.

In the next stage, Standard 2800 was changed from its Second Edition to its Fourth Edition. The Second Edition was initially used to provide a more detailed assessment and clearer illustration of the changes resulting from the transition between different editions of the standard, since this edition was applicable during the years 1997–2005, when seismic considerations were less prominent in building design. Following the change to the Fourth Edition, inadequacy was observed in a number of column sections. Therefore, to eliminate the deficiencies resulting from the change in Standard 2800, eccentrically braced steel frames with single vertical links and knee-bracing systems were employed. The steel bracing members were analyzed using the LRFD method in accordance with the UBC97 provisions.

Subsequently, after performing linear static analysis in SAP2000, nonlinear static analysis was conducted to evaluate the performance and response of the modeled structures in accordance with the provisions of FEMA 356. It should be noted that the Guideline for Seismic Rehabilitation of Existing Buildings, Publication No. 360 of the Management and Planning Organization of the country [39], was derived from the FEMA 356 provisions. In the subsequent stage, the modeled buildings were subjected to nonlinear dynamic time-history analysis. Finally, the structural responses obtained from the time-history analyses, which were conducted using the horizontal components of earthquake response spectra, were used to evaluate and compare the structural performance.

The fundamental difference between static and dynamic analysis lies in the distribution of seismic forces over the height of the structure. The force distribution is related to the deformation pattern of the structure. The outcome of dynamic analysis is a more representative distribution of seismic forces over the height. Although the total seismic force considered in both approaches is comparable, its distribution over the height differs. In summary, the main advantage of dynamic analysis is that it provides a more realistic distribution of seismic forces, resulting in a more reliable and accurate assessment. Another advantage is its potential economic benefit, as it may lead to a lighter structural system. This is because, in many cases, the fundamental period obtained from dynamic analysis is greater than that obtained from static analysis. Therefore, considering the general shape of the building response spectrum, expressed as the relationship between the building response coefficient and the fundamental period, a longer fundamental period corresponds to a lower building response coefficient, thereby reducing the base shear and seismic forces to a considerable extent.

5 | Diagrams and Results Analysis

Following the description of the modeling, loading, and analysis procedures for the investigated buildings, the results obtained from the analyses are evaluated in this section. For each case, the stresses in the columns are first examined following the static analysis. Subsequently, following the nonlinear static analysis, the capacity curves, base shear, displacement, transient and residual drift of the structures, bending and shear forces in the link beams, and, finally, the pattern of plastic hinge formation are presented. The structural responses at the aforementioned stages are then examined, and the structural behavior is evaluated based on the obtained results.

5.1 | Structural Capacity Curve

As shown in *Figs. 10-15*, for the 4-, 8-, and 12-story buildings, the Knee-Braced Frame (KBF) configurations exhibit greater energy absorption than the buildings retrofitted with a single Eccentrically Braced Frame (VEBF), as indicated by the larger area under the capacity curve. Among the different building configurations, the first type has the smallest area under the capacity curve and consequently the lowest energy absorption. For all buildings, Types 2 and 3 exhibit the highest energy absorption compared with the other configurations. In addition, except for Type 3 of the single Vertical-link Eccentrically Braced Frames (VEBFs) configuration, the greatest displacement is observed in Type 3. The buildings equipped with KBF systems also exhibit greater displacement than those with VEBF systems. Although the KBF configurations provide higher energy absorption, their greater displacement may result in increased damage to structural and, particularly, nonstructural components.

The base shear of the 4-story building retrofitted with KBF configurations Types 1 to 4 increases by 57%, 57%, 59%, and 31%, respectively, compared with the single VEBF configuration. For the 8-story building, the corresponding increases are 10%, 29%, 30%, and 28%, respectively. Similarly, for the 12-story building, the base shear of KBF configurations Types 1 to 4 increases by 41%, 33%, 54%, and 48%, respectively, compared with the single VEBF configuration.

As expected, the structural weight of the KBF buildings is greater than that of the VEBF buildings. Furthermore, the structural weight increases with increasing building height. In the 12-story building, however, the base shear is observed to be lower than that of the 8-story building. As is well known, the base shear is a function of the structural weight and the seismic coefficient. Since the structural weight does not decrease with increasing building height, the significant reduction in base shear observed for the 12-story building can be attributed primarily to the reduction in the seismic coefficient.

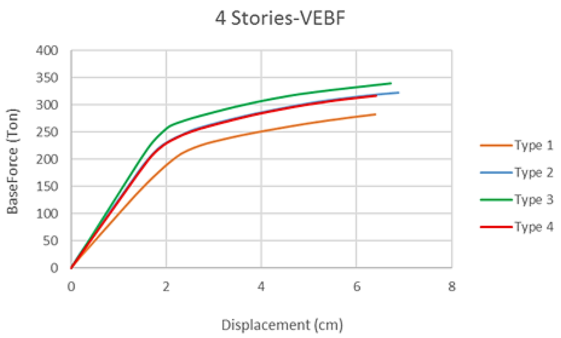

Fig. 10. Pushover curves of the four-story buildings retrofitted with V-EBF using different bracing configurations.

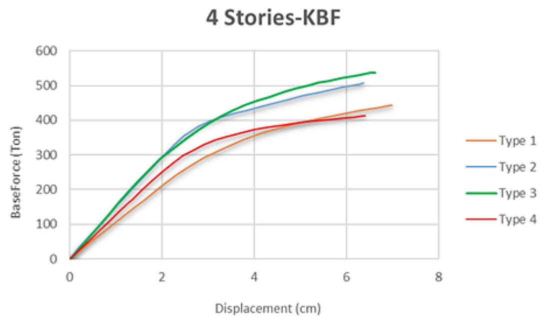

Fig. 11. Pushover curves of the four-story buildings retrofitted with KBF Using different bracing configurations.

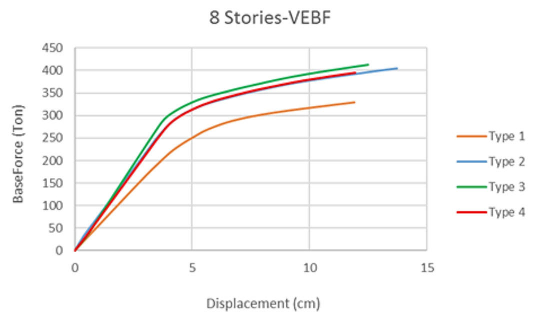

Fig. 12. Pushover curves of the eight-story buildings retrofitted with V-EBF using different bracing configurations.

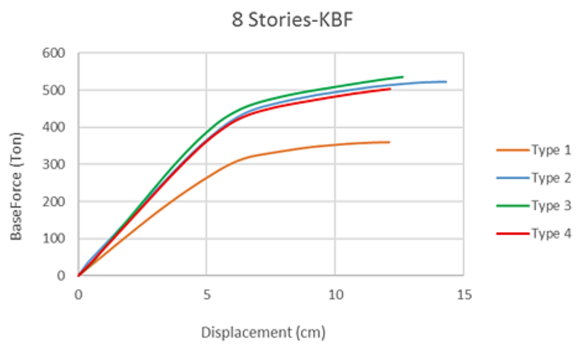

Fig. 13. Pushover curves of the eight-story buildings retrofitted with KBF using different bracing configurations.

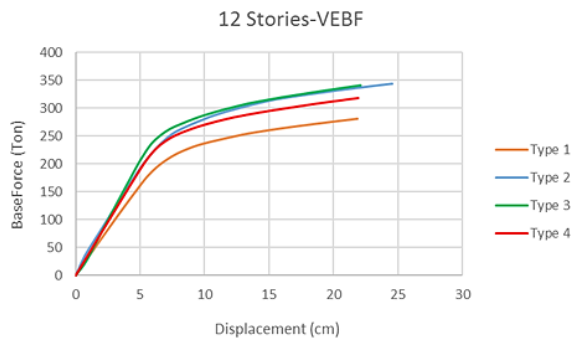

Fig. 14. Pushover curves of the twelve-story buildings retrofitted with V-EBF using different bracing configurations.

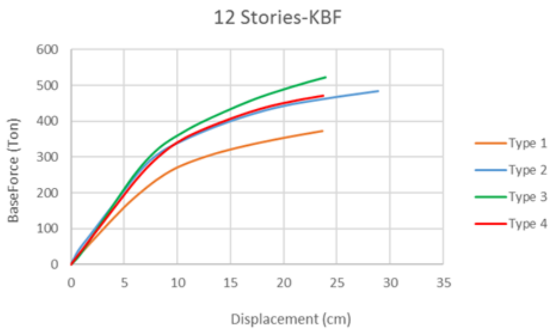

Fig. 15. Pushover curves of the twelve-story buildings retrofitted with KBF using different bracing configurations.

5.2 | Lateral Displacement Corresponding to the Formation of the First Plastic Hinge in the Building

As shown in *Figs. 16-21*, the maximum story displacement at the time of formation of the first plastic hinge in the 4-, 8-, and 12-story buildings retrofitted with both single EBFs and KBFs occurs in Type 1 configuration.

According to *Fig. 13*, the average story displacement at the time of formation of the first plastic hinge in the 4-story building retrofitted with KBF configurations Types 1 to 4 decreases by 26%, 21%, 2%, and 23%, respectively, compared with the single VEBF configuration. In the 8-story buildings retrofitted with KBF, the corresponding values increase by 44%, 24%, 12%, and 12%, respectively. For the 12-story buildings, decreases of 25%, 14%, 20%, and 20%, respectively, are observed.

The results indicate that plastic hinges form earlier in buildings retrofitted with VEBF than in those retrofitted with KBF. It is noteworthy that buildings retrofitted with single EBFs enter the plastic range earlier than those retrofitted with KBFs.

Since structural members can be designed such that, during an earthquake, certain members are permitted to enter the plastic range, this behavior allows the structure to dissipate the imposed seismic energy and subsequently return toward its normal response state. Based on the results obtained, the single VEBF system enters the plastic range earlier and thereby delays the yielding of other structural members.

According to the results, in the 4-story buildings, Types 2 and 4 configurations enter the plastic range earlier; in the 8-story buildings, Types 3 and 4 exhibit earlier entry into the plastic range; and in the 12-story buildings, Types 2 and 3 enter the plastic range earlier.

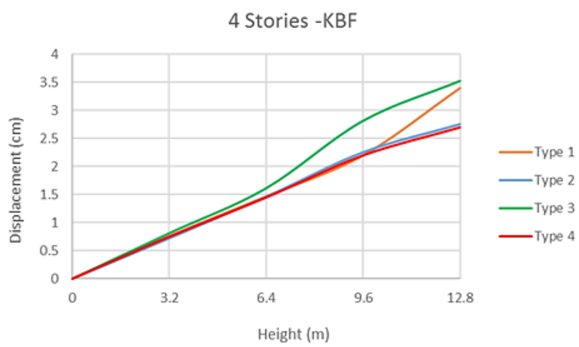

Fig. 16. Displacement at the formation of the first plastic hinge in the four-story building with KBF.

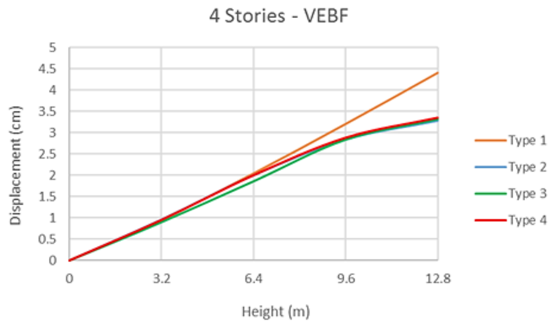

Fig. 17. Displacement at the formation of the first plastic hinge in the four-story building with V-EBF.

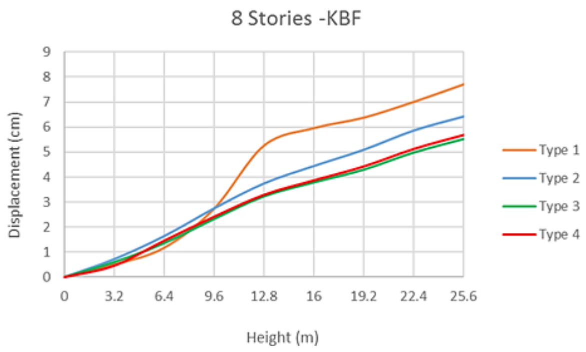

Fig. 18. Displacement at the formation of the first plastic hinge in the eight-story building with KBF.

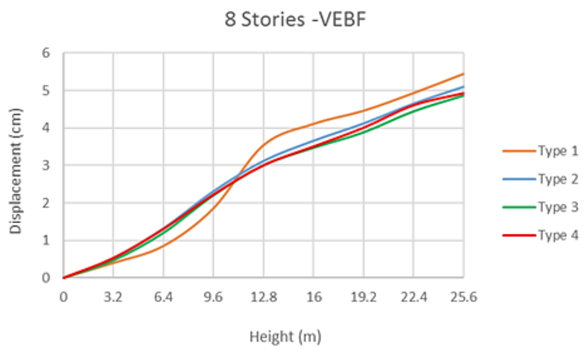

Fig. 19. Displacement at the formation of the first plastic hinge in the eight-story building with V-EBF.

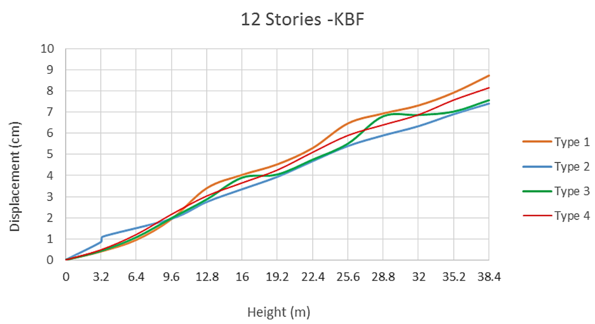

Fig. 20. Displacement at the formation of the first plastic hinge in the twelve-story building with KBF.

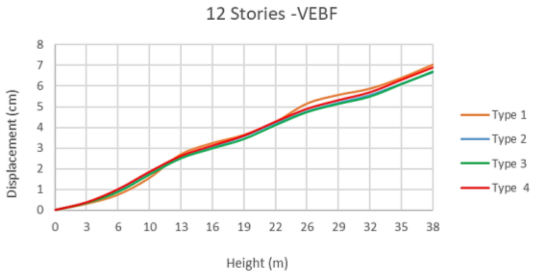

Fig. 21. Displacement at the formation of the first plastic hinge in the twelve-story building with V-EBF.

The results of the nonlinear static analyses demonstrate that both single VEBFs and KBFs can effectively improve the seismic performance of reinforced concrete buildings. In general, the introduction of steel bracing reduced the stress ratios of the columns compared with the unretrofitted buildings designed according to the Fourth Edition of Standard 2800. The reduction in column stress ratios was observed for all three building heights and for all investigated bracing configurations. The greatest overall reduction was generally obtained with Configuration 2, indicating that the arrangement of the bracing system has a significant influence on the distribution of seismic demands among the primary structural members.

For the 4-story building, the VEBF configurations reduced the column stress ratios by 44%, 57%, 52%, and 48% for Configurations 1 to 4, respectively, while the corresponding reductions for KBF were 51%, 59%, 57%, and 52%. For the 8-story building, the reductions were 58%, 59%, 58%, and 57% for VEBF and 60%, 61%, 60%, and 60% for KBF. For the 12-story building, the corresponding reductions were 28%, 36%, 32%, and 32% for VEBF and 29%, 35%, 33%, and 33% for KBF. These results indicate that KBF generally provides a slightly greater reduction in column stress ratios than VEBF, although the difference between the two systems becomes relatively small in some configurations.

The capacity curves further demonstrate the importance of bracing configuration in the seismic response of the buildings. KBF systems generally exhibited a larger area under the capacity curve and, consequently, greater energy absorption than VEBF systems. Configuration 1 showed the lowest energy absorption, whereas Configuration 2 generally provided the most favorable overall response. This behavior can be attributed to the ability of the KBF system to provide additional load paths and to distribute the lateral seismic demand through the link and bracing members. Similar research has emphasized the important role of the link as the primary energy-dissipating component of an EBF system.

Despite their higher energy-dissipation capacity, KBF systems generally produced larger lateral displacements than VEBF systems. For the 4-story building, the lateral displacement increased by 2%, 3%, and 7% in KBF Configurations 1, 3, and 4, respectively, while Configuration 2 resulted in an 8% reduction. For the 8-story building, increases of 2%, 5%, 1%, and 2% were obtained for Configurations 1 to 4, respectively. For the 12-story building, the corresponding increases were 8.5%, 18%, 7%, and 8%. Therefore, except for Configuration 2 of the 4-story building, VEBF generally provided lower lateral displacement. This finding is important because excessive lateral deformation can increase damage to nonstructural components and adversely affect post-earthquake functionality.

The increase in base shear observed in the KBF buildings is another important aspect of their seismic response. Compared with the corresponding VEBF systems, the base shear increased by 57%, 57%, 59%, and 31% for the four configurations of the 4-story building; by 10%, 29%, 30%, and 28% for the 8-story building; and by 41%, 33%, 54%, and 48% for the 12-story building. The higher base shear is partly associated with the greater structural weight of the KBF configurations. Among the investigated arrangements, Configuration 3 generally produced the highest base shear, which is consistent with its relatively greater structural weight.

The development of plastic hinges indicates that the link members successfully participated in the intended inelastic response of the bracing systems. In the VEBF buildings, the vertical links generally yielded before the main structural members and helped prevent the formation of plastic hinges in the columns at the Life Safety performance level. This behavior is desirable because it promotes concentration of inelastic deformation in designated energy-dissipating components rather than in the primary load-carrying members. Recent studies on vertical-link EBF systems similarly emphasize the importance of concentrating nonlinear deformation and energy dissipation in the link region.

The comparison of the column bending moments reveals an important trade-off between energy dissipation and demand on the primary members. The KBF systems generated considerably higher bending moments in the investigated column C1 than the corresponding VEBF systems. The maximum values were observed in Configuration 1 for the 4- and 8-story buildings and in Configuration 3 for the 12-story building. Therefore, although KBF can provide higher energy absorption and base shear capacity, its effect on the force demands of the main structural members should be carefully considered in design.

The results also show that the use of vertical links can substantially reduce the rotation of the main beams, with the reduction being more pronounced in KBF systems. Limiting beam rotation is particularly important in structures where sensitive equipment or nonstructural components are connected to the floor beams. In this regard, the ability of EBF systems to concentrate inelastic behavior in dedicated link elements provides an important advantage for seismic damage control.

Overall, the numerical results indicate that the seismic response of the investigated RC buildings is strongly influenced by both the type and arrangement of the bracing system. KBF generally provides greater energy absorption and higher lateral resistance, whereas VEBF tends to provide lower lateral displacement and lower bending demands in the primary columns. Consequently, the selection between VEBF and KBF should not be based solely on strength or energy absorption; rather, column demand, lateral displacement, structural weight, and the desired location of inelastic deformation should be considered simultaneously.

6 | Conclusion

Based on the results obtained from the linear and nonlinear static analyses, both single vertical-link eccentric bracing and knee-bracing systems can be considered effective seismic retrofit solutions for reinforced concrete buildings. The introduction of these systems substantially reduced the stress ratios of the columns compared with the unretrofitted buildings designed according to the Fourth Edition of Standard 2800.

Among the investigated configurations, Configuration 2 generally demonstrated the most favorable overall performance, particularly in terms of reducing column stress ratios and providing a relatively high energy-dissipation capacity. KBF systems generally exhibited greater energy absorption than VEBF systems, as reflected by the larger area under the capacity curves. However, this advantage was accompanied by greater lateral displacement, higher structural weight, higher base shear, and, in several cases, greater bending demands in the primary columns.

The results further indicate that VEBF systems generally provide lower lateral displacement and lower demands on the main structural members, while effectively concentrating inelastic deformation in the vertical links. This behavior contributes to preventing premature formation of plastic hinges in the columns and can help limit damage to both structural and nonstructural components.

The nonlinear static analyses also confirmed the importance of designing the link members to exhibit shear-dominated behavior. When the link acts as the primary energy-dissipating component, the seismic demand can be concentrated in a controlled region, thereby reducing the likelihood of undesirable plastic mechanisms in the main structural members.

Considering the combined effects of energy absorption, column stress ratios, base shear, lateral displacement, plastic hinge formation, and column bending moments, both VEBF and KBF systems demonstrated satisfactory seismic performance. However, the results suggest that KBF is more advantageous when higher energy dissipation and lateral resistance are the primary objectives, whereas VEBF may be preferable when limiting lateral displacement and demands on the primary structural members is prioritized. Among the investigated KBF arrangements, Configuration 2 can be considered the most favorable overall configuration.

Future studies should investigate these systems under nonlinear dynamic time-history analyses using a broader set of ground motions, particularly near-fault and pulse-like records. Experimental validation of the proposed KBF configurations, investigation of different vertical link lengths and section properties, and assessment of the effect of plan and vertical irregularities would also provide a more comprehensive understanding of their seismic behavior. In addition, the development of replaceable link elements could improve post-earthquake repairability and enhance the resilience of retrofitted reinforced concrete buildings.

References

[1] Aied Qissab Al-Janabi, M., & Topkaya, C. (2021). Seismic performance of eccentrically braced frames designed to AISC341 and EC8 specifications. *Structures*, *29*, 339–359. https://doi.org/10.1016/j.istruc.2020.11.031

[2] Kazemzadeh Azad, S., & Topkaya, C. (2017). A review of research on steel eccentrically braced frames. *Journal of constructional steel research*, *128*, 53–73. https://doi.org/10.1016/j.jcsr.2016.07.032

[3] Ghobarah, A., & Abou Elfath, H. (2001). Rehabilitation of a reinforced concrete frame using eccentric steel bracing. *Engineering structures*, *23*(7), 745–755. https://doi.org/10.1016/S0141-0296(00)00100-0

[4] Mansour, N., Christopoulos, C., & Tremblay, R. (2011). Experimental validation of replaceable shear links for eccentrically braced steel frames. *Journal of structural engineering*, *137*(10), 1141–1152. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000350

[5] Bozkurt, M. B., & Topkaya, C. (2017). Replaceable links with direct brace attachments for eccentrically braced frames. *Earthquake engineering & structural dynamics*, *46*(13), 2121–2139. https://doi.org/10.1002/eqe.2896

[6] Bozkurt, M. B., & Topkaya, C. (2018). Replaceable links with gusseted brace joints for eccentrically braced frames. *Soil dynamics and earthquake engineering*, *115*, 305–318. https://doi.org/10.1016/j.soildyn.2018.08.035

[7] Bozkurt, M. B., Kazemzadeh Azad, S., & Topkaya, C. (2019). Development of detachable replaceable links for eccentrically braced frames. *Earthquake engineering & structural dynamics*, *48*(10), 1134–1155. https://doi.org/10.1002/eqe.3181

[8] Lian, M., & Su, M. (2017). Seismic performance of high-strength steel fabricated eccentrically braced frame with vertical shear link. *Journal of constructional steel research*, *137*, 262–285. https://doi.org/10.1016/j.jcsr.2017.06.022

[9] INCE, G. (2022). Effect of link length in retrofitted RC frames with Y eccentrically braced frame. *Steel and composite structures*, *43*(5), 553–564. https://doi.org/10.12989/scs.2022.43.5.553

[10] Elgammal, A., El-Khoriby, S., & Seleemah, A. (2024). Seismic retrofitting of existing reinforced concrete buildings using aluminium shear links and eccentric steel chevron braces. *Arabian journal for science and engineering*, *49*(10), 1–35. https://doi.org/10.1007/s13369-024-08908-8

[11] Xiong, M., Xiong, J., Hu, S., Liu, Y., & Wang, K. (2024). Experiment and analysis on seismic performance of a self-centering Y-eccentrically braced frames structure. *Journal of building engineering*, *97*, 110683. https://doi.org/10.1016/j.jobe.2024.110683

[12] Saleh, Y. N., Mourad, S. A., & Ibrahim, A. M. (2024). Topology optimization of vertical shear links in eccentrically braced frames. *Structures*, *66*, 106821. https://doi.org/10.1016/j.istruc.2024.106821

[13] Louzai, A., & Abed, A. (2025). A simplified design procedure for seismic retrofitting of RC frames with setbacks using eccentric steel braces having vertical shear link elements. *Bulletin of earthquake engineering*, *23*(6), 2805–2838. https://doi.org/10.1007/s10518-025-02163-4

[14] Tonyali, Z. (2025). Energy-based optimization of short-link EBFs under pulse-type ground motions using the concept of uniform damage distribution (UDD). *Structures*, *81*, 110171. https://doi.org/10.1016/j.istruc.2025.110171

[15] Yu, H., Zhang, Y., Li, Y., Ma, Z., & Su, J. (2026). Study on seismic performance of eccentrically braced steel frames with replaceable truss-type link. *Journal of building engineering*, *124*. https://doi.org/10.1016/j.jobe.2026.115977

[16] Saleh, Y. N., Mourad, S. A., Salem, H. G., & Ibrahim, A. M. (2026). Computational study on stiffened topology-optimized shear links for eccentrically braced frames. *Bulletin of earthquake engineering*, *24*(7), 5223–5255. https://doi.org/10.1007/s10518-026-02417-9

[17] Wiranatha, I. G. E., Wijaya, M. N., & Susanti, L. (2026). The seismic performance of vertical link in reinforced concrete eccentric braced frame (EBF) with GGBFS as partial cement replacement. *Evergreen*, *13*(3), 1159–1172. https://doi.org/10.5109/7441043