International Journal of Researches on Civil Engineering with Artificial Intelligence

www.ceai.reapress.com

Int. J. Res. Civ. Eng. AI. Vol. 3, No. 3 (2026) 200–212.

Paper Type: Original Article

Numerical and Performance Analysis of Eccentric Bracing Systems with Replaceable Structural Fuses for Seismic Damage Control

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Citation:

Received: 05 January 2026 *Revised: 20 March 2026* *Accepted: 17 May 2026*	Hamidi, M., & Biklaryan, M. (2026). Numerical and performance analysis of eccentric bracing systems with replaceable structural fuses for seismic damage control. *International journal of researches on civil engineering with artificial intelligence, 3*(3), 200-212.

Abstract

This study investigates the performance of eccentric bracing systems and replaceable fuses in the seismic retrofitting of 14- and 20-story reinforced concrete frames. The main objective is to evaluate the effect of these systems on increasing energy dissipation capacity and reducing damage in high-rise structures subjected to seismic loads. The research methodology includes numerical simulations using Perform-3D software and nonlinear static and dynamic analyses based on FEMA-356, Publication No. 360, and Standard No. 2800. Three proposed models with different connection configurations between steel frames and reinforced concrete frames were designed and compared with conventional systems. The analysis results indicated that the proposed models provide superior seismic performance compared with conventional systems. The optimal model, consisting of a steel link beam connected to the reinforced concrete beam, reduced the base shear by up to 17%, the stress ratio by 40%, and the material weight by 38%. The relative lateral displacement in this model was 14% higher than that of the cross-braced system, indicating greater flexibility. The interaction between the reinforced concrete frame and the bracing system contributed 40% and 50% to lateral load resistance in the 14- and 20-story structures, respectively. Replaceable fuses significantly improved energy dissipation by concentrating stresses within the link beam. The yield base shear in the 14- and 20-story structures was 1.15 and 1.0 times the design base shear, respectively, demonstrating the high strength capacity of the structures and reduced damage potential. Due to its high constructability and rapid post-earthquake repair capability, the proposed model is recommended for seismic retrofitting of high-rise structures. The findings of this study demonstrate the superiority of the proposed systems in reducing inter-story drift, increasing load-bearing capacity, and improving seismic stability. The application of replaceable fuses and eccentric bracing systems provides an effective strategy for enhancing the seismic performance of high-rise reinforced concrete structures.

Keywords: Eccentric bracing systems, Replaceable structural fuses, Energy dissipation, High-rise structures.

1 | Introduction

In recent decades, rapid population growth, urban development, and increasing land limitations have resulted in a growing demand for high-rise buildings. Due to their considerable height, mass, and structural complexity,

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https://doi.org/10.48314/ijrceai.vi.63

high-rise structures exhibit different seismic responses compared with low-rise buildings. These structures are generally subjected to significant lateral forces, large displacement demands, and higher-mode effects during earthquakes, which makes the selection of appropriate seismic-resistant systems essential for ensuring safety and controlling structural damage [1], [2].

In modern earthquake engineering, the design philosophy has gradually shifted from conventional strength-based approaches toward performance-based seismic design. This approach focuses not only on providing sufficient strength but also on controlling structural damage, improving energy dissipation capacity, reducing residual deformations, and maintaining post-earthquake functionality. Therefore, developing structural systems capable of concentrating damage in predetermined and repairable components has become one of the main objectives in seismic design and retrofit strategies [1], [3].

Among the various lateral load-resisting systems, Eccentric Braced Frames (EBFs) have received considerable attention because they combine the stiffness advantages of concentrically braced frames with the ductility characteristics of moment-resisting frames. In these systems, seismic energy is mainly dissipated through the development of plastic deformations in the link beam, while the other structural members remain protected from severe damage [4], [5].

The link beam in an EBF acts as a structural fuse that controls nonlinear behavior and absorbs earthquake energy through shear and flexural mechanisms. The seismic performance of EBF systems is highly dependent on the geometry, length, material properties, and stiffener arrangement of the link beam. Ebrahimi Hosein Abadi and Shakib [4] investigated the behavior of eccentrically braced frames equipped with box-shaped link beams under far-fault and near-fault earthquake records. Their results indicated that proper stiffener arrangements can significantly reduce displacement demands and improve seismic performance, particularly under severe seismic excitations.

Several studies have also evaluated the influence of different eccentric bracing configurations on structural response. Nassani et al. [5] compared steel frames with different bracing systems under seismic loading and demonstrated that eccentric bracing systems provide improved ductility and energy absorption capacity compared with conventional bracing systems. Similarly, Liu et al. [6] investigated different forms of eccentrically braced steel frames and showed that variations in brace configuration and link characteristics have a significant effect on strength, stiffness, and energy dissipation behavior.

Although EBFs provide excellent seismic performance, severe earthquakes may result in damage to the link beams. Since the link beam is usually considered as the primary energy-dissipating component, replacement or repair of damaged links after major earthquakes may become a time-consuming and costly process. To address this limitation, replaceable structural fuse systems have been proposed as an advanced damage-control strategy in seismic engineering.

Structural fuses are designed to concentrate nonlinear deformation and damage in specific replaceable components while preventing damage to the main structural members. This concept allows buildings to recover their functionality more rapidly after earthquakes and reduces repair costs. Hashemi and Alirezaei [3] investigated the application of energy-based components for improving seismic performance of steel frames and emphasized the effectiveness of controlled energy dissipation mechanisms in reducing structural damage.

The combination of eccentric bracing systems with replaceable fuses provides a promising approach for improving seismic resilience. Alizadeh and Asghari [7] studied self-centering eccentrically braced frames equipped with distributed fuses along the height and demonstrated that fuse-based systems can provide high energy dissipation capacity while minimizing residual displacements after earthquakes. Their findings indicated that concentrating damage in replaceable components improves repairability and enhances the overall seismic performance of structures.

For existing reinforced concrete buildings, retrofit using steel eccentric bracing systems has become an effective method for improving lateral strength and ductility. Khan and Alluqmani [8] evaluated reinforced concrete frames strengthened with eccentric steel braces and column jackets and reported significant improvements in seismic capacity, stiffness, and damage control compared with unretrofitted structures. Furthermore, Harba et al. [2] investigated reinforced concrete buildings with and without steel bracing systems under seismic loading and confirmed that additional steel bracing can substantially enhance structural performance and reduce earthquake-induced demands.

Performance evaluation of retrofitted structures requires accurate nonlinear modeling techniques capable of simulating plastic hinge formation, energy dissipation mechanisms, and damage distribution. Nonlinear analysis software such as Perform-3D provides advanced capabilities for evaluating structural behavior under seismic loading conditions. Previous studies have demonstrated the effectiveness of nonlinear static and dynamic analyses in predicting the behavior of complex structural systems and assessing performance levels under earthquake excitation [9], [10].

The evaluation of existing structures through performance-based approaches has also been investigated by several researchers. Gutiérrez Urzúa [1] studied performance-based seismic assessment and retrofit strategies for existing frames and highlighted the importance of selecting appropriate strengthening systems to achieve targeted performance objectives. Additionally, studies on reinforced concrete and steel composite systems have shown that the interaction between existing structural components and added seismic resisting systems plays a critical role in improving overall seismic behavior [11], [12].

Therefore, the main objective of this study is to investigate the numerical and performance-based behavior of high-rise reinforced concrete buildings retrofitted with eccentric bracing systems equipped with replaceable structural fuses. The effects of these systems on energy dissipation capacity, displacement response, damage concentration, and seismic performance are evaluated using nonlinear analyses in Perform-3D. The proposed retrofit strategy aims to provide an efficient solution for improving seismic resilience, reducing structural damage, and enhancing post-earthquake repairability of high-rise RC buildings.

2 | Literature Review

Extensive research has been conducted in recent years to evaluate the seismic performance of EBFs, retrofit strategies for existing structures, and energy-dissipation systems based on replaceable structural components. The following section summarizes previous studies related to eccentric bracing systems, seismic retrofit of reinforced concrete structures, nonlinear analysis methods, and performance-based design approaches.

Ebrahimi Hosein Abadi and Shakib [4] investigated the seismic behavior of eccentrically braced frames equipped with box-shaped link beams having different stiffener arrangements under far-fault and near-fault earthquake records. In their study, the nonlinear response of EBFs was evaluated by considering different configurations of stiffeners in the link beams. The results demonstrated that the arrangement of stiffeners has a significant influence on controlling link beam behavior and reducing displacement demands. The study indicated that optimized link beam details can improve energy dissipation capacity and enhance the seismic performance of EBF systems, particularly under severe near-fault ground motions.

Alizadeh and Asghari [7] investigated the seismic behavior of off-center bilinear braced frames with emphasis on capacity-limited design and energy demand parameters. Their study focused on evaluating the relationship between structural capacity, seismic demands, and energy dissipation characteristics. The results showed that controlling the capacity of energy-dissipating members can improve structural response and prevent excessive damage in primary load-carrying components. Their findings highlighted the importance of performance-based design approaches for developing efficient bracing systems.

Jouneghani and Haghollahi [9] evaluated the seismic behavior of steel moment frames equipped with elliptical braces using Incremental Dynamic Analysis (IDA). The study investigated structural performance under different seismic intensity levels and assessed parameters such as strength, ductility, and collapse potential. The results showed that appropriate bracing systems can significantly improve seismic reliability by increasing lateral resistance and reducing structural demands.

Hashemi and Alirezaei [3] studied the effectiveness of energy-based components for improving the seismic performance of steel frames. Their research emphasized the role of energy dissipation mechanisms in controlling nonlinear structural response. The results indicated that incorporating energy-dissipating elements can reduce damage concentration in main structural members and improve the overall seismic performance of buildings.

Salmasi and Sheidaii [10] investigated the resistance of eccentrically braced frames against progressive collapse. Their study evaluated the influence of eccentric bracing systems on structural robustness and load redistribution capability. The findings demonstrated that EBF systems can provide considerable resistance against abnormal loading scenarios due to their ductility and energy absorption characteristics. The researchers concluded that eccentric bracing can improve structural resilience under extreme loading conditions.

Nassani et al. [5] performed a comparative assessment of steel frames equipped with different bracing systems under seismic effects. Their research compared various bracing configurations and evaluated their effects on structural strength, stiffness, and deformation capacity. The results showed that eccentric bracing systems provide a balanced combination of stiffness and ductility, making them suitable for seismic-resistant design, especially in structures requiring both strength and energy dissipation capacity.

Liu et al. [6] investigated the seismic behavior of different forms of eccentrically braced steel frames. Their research focused on evaluating the effects of different EBF configurations on structural response parameters, including strength, stiffness, ductility, and energy dissipation. The results confirmed that the geometry and arrangement of bracing members significantly influence seismic performance. The study emphasized the importance of selecting appropriate EBF configurations for achieving improved structural behavior under earthquake loading.

Gutiérrez Urzúa [1] conducted a performance-based seismic assessment of existing frames and investigated retrofit strategies using advanced strengthening systems. The study emphasized the importance of evaluating existing structures based on performance objectives rather than only strength criteria. The results indicated that retrofit systems should be selected based on their ability to control damage, improve ductility, and achieve desired performance levels under different earthquake intensities.

Nassirpour [13] investigated the performance-based seismic assessment of masonry-infilled steel frame structures. Although the main focus of the study was infilled frame behavior, the research highlighted the importance of considering nonlinearity, interaction between structural components, and realistic modeling approaches in seismic assessment. The study demonstrated that accurate numerical simulation is essential for predicting structural behavior under earthquake loading.

Milad [14] studied the influence of infill walls on the seismic behavior of steel framed structures. The results showed that nonstructural components can significantly affect stiffness, strength, and deformation characteristics of structural systems. This study emphasized the necessity of considering actual structural conditions during nonlinear seismic evaluations.

Davani et al. [15] evaluated the performance of strap-braced cold-formed steel frames using IDA. Their research investigated the relationship between seismic intensity and structural response parameters. The results demonstrated that performance-based evaluation methods such as IDA provide a comprehensive approach for determining structural capacity and identifying critical damage states.

Khan and Alluqmani [8] investigated reinforced concrete frames strengthened with eccentric steel braces and column jackets. Their study focused on improving the seismic performance of existing RC structures through retrofit techniques. The results indicated that adding eccentric steel braces significantly increased lateral strength, stiffness, and energy dissipation capacity. The interaction between the existing concrete frame and the added steel bracing system was identified as an important factor influencing retrofit efficiency.

Wang et al. [11] experimentally investigated the seismic behavior of steel frame–precast steel reinforced concrete infill wall systems. Their research evaluated the lateral resistance mechanism and deformation characteristics of composite structural systems. The results indicated that hybrid systems can provide enhanced seismic performance through effective interaction between different structural components.

Keerthana and Parthasarathi [16] investigated the structural efficiency of tubular steel systems combined with variable moment-resisting bracing configurations. Their research emphasized the role of structural configuration and member arrangement in improving lateral resistance. The findings confirmed that optimized bracing layouts can contribute to improved strength and deformation control under seismic loading.

Li et al. [17] developed and experimentally evaluated steel beam-through framed connections with curved knee braces for improving seismic performance. The study investigated the behavior of innovative connections and their ability to dissipate seismic energy. The results demonstrated that properly designed energy-dissipating components can improve ductility and delay damage development in primary structural members.

Harba et al. [2] evaluated the seismic performance of multi-story reinforced concrete flat plate buildings with and without steel bracing systems. Their findings showed that incorporating steel bracing systems significantly improves lateral stiffness, reduces seismic demands, and enhances structural performance. The study confirmed the effectiveness of steel bracing as a retrofit solution for reinforced concrete buildings.

Yacin et al. [12] reviewed performance evaluation methods for reinforced concrete infilled frames under earthquake scenarios. Their study highlighted the importance of advanced numerical modeling, experimental validation, and performance-based assessment methods for accurately predicting structural response. The authors emphasized that considering interaction between different structural components is essential for reliable seismic evaluation.

Overall, previous studies demonstrate that EBFs are among the effective seismic-resistant systems due to their high ductility and energy dissipation capacity. However, conventional EBF systems may experience damage concentration in link beams, which can increase repair time after severe earthquakes. Therefore, integrating replaceable structural fuses with eccentric bracing systems represents a promising approach for improving post-earthquake repairability and reducing permanent damage. Furthermore, the application of nonlinear analysis tools such as Perform-3D provides an effective framework for evaluating the seismic performance of retrofitted high-rise reinforced concrete structures and investigating the interaction between existing RC frames and newly added steel bracing systems.

3 | Research Model Description

The overall strengthening of reinforced concrete frames using bracing systems is appropriate when structural deficiencies are caused by lateral loads or the resulting displacements. However, if structural weaknesses originate from gravity loads, strengthening of deficient structural members becomes necessary.

Therefore, the first step in selecting a retrofitting strategy is identifying the type of deficiency in the existing structure. Once it is confirmed that the weakness of the reinforced concrete frame is related to lateral loads, various strengthening alternatives using steel bracing systems and proposed innovative approaches are investigated.

For this purpose, in the existing reinforced concrete frame models, the structural resistance against lateral forces is evaluated by calculating the lateral load factor, and the level of structural deficiency is determined. After identifying the percentage of weakness, appropriate systems are selected to compensate for these deficiencies.

The investigated models were developed as realistic three-dimensional structures consisting of reinforced concrete moment-resisting frames. These models include:

I. Five 5-meter spans in the X direction

II. Four 5-meter spans in the Y direction

III. A story height of 3.5 meters

The structures were considered as high-rise examples with 14 and 20 stories, respectively.

Figs. 1 and *2* illustrate the plan layouts of the models and the locations of braced bays.

Considering the influence of steel bracing systems on the stress ratio of reinforced concrete frame members, the number and location of braces were selected in such a way that local strengthening of structural components was not required.

For modeling the link beams in eccentric bracing systems (Models M3 to M6), FEMA Beam elements were used. These elements, designed according to the requirements of Publication No. 360 and FEMA-356, allow the definition of plastic hinges at both ends of the beam and are suitable for simulating the nonlinear behavior of link beams.

The FEMA Beam element was configured to separately or simultaneously represent the shear and flexural behavior of the link beam depending on its length.

For Model M3 (concrete link beam), concrete material properties with a compressive strength of 24 MPa were considered. For Models M4, M5, and M6 (steel link beams), steel material properties with a yield stress of 400 MPa were incorporated into the element definitions.

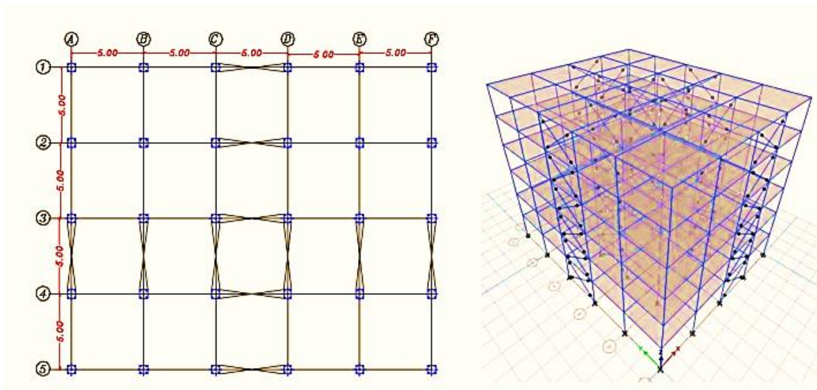

Fig. 1. Structural plan and analytical models investigated in this study.

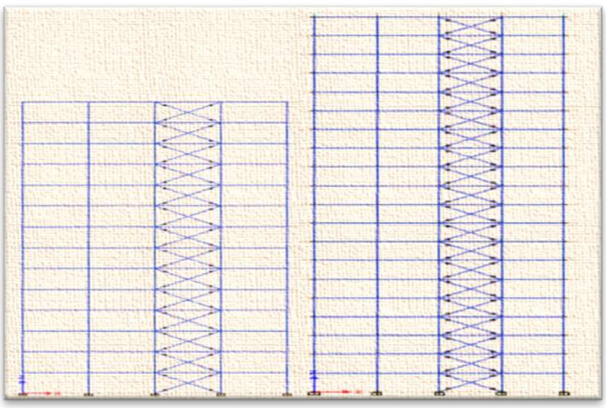

Fig. 2. Examples of seismic retrofit configurations for 14- and 20-story buildings.

4 | Research Methodology and Modeling

According to *Figs. 3-5*, the capacity curves and the formation sequence of plastic hinges for models M0 to M6 of a fourteen-story building are illustrated. Based on the data presented in *Figs. 3* and *4*, comparison of the performance of models M1 and M2 (consisting of reinforced concrete frames strengthened with concentric bracing systems) with the reference model M0 indicates that the deficiencies existing in the original reinforced concrete structure have been effectively compensated.

Furthermore, the dual behavior of the structural system demonstrates that the strength capacity of the existing structure has increased by approximately 10% compared with the standard reinforced concrete frame. The first plastic hinge was formed due to brace buckling, occurring at the Serviceability performance level.

In the evaluation of Model M3, which consists of a reinforced concrete frame retrofitted with an eccentric bracing system and a concrete link beam, the results based on *Fig. 5* show that the first plastic hinge developed within the concrete link beam region. Subsequently, the reinforced concrete flexural beam entered the plastic stage under a base shear approximately twice that of the original reinforced concrete frame.

Furthermore, analysis of the pushover curves of the retrofitted models (as presented in *Figs. 6* to *8*) and comparison of the newly proposed models M4 to M6 with the reference model M0 indicate that the application of these strengthening systems results in the formation of plastic hinges in the reinforced concrete beams while providing greater lateral energy dissipation compared with the unretrofitted reinforced concrete frame.

The results demonstrate that the proposed retrofitting approaches improve the seismic response of reinforced concrete structures by enhancing lateral resistance, increasing energy absorption capacity, and controlling the location of plastic damage in predetermined regions.

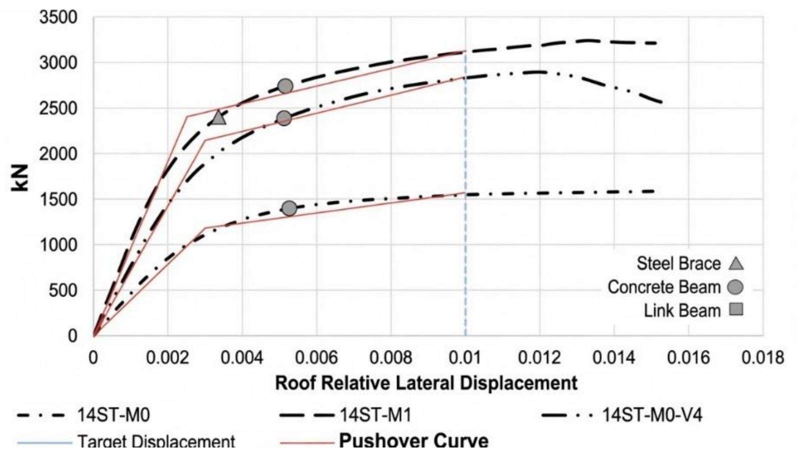

Fig. 3. Evaluation of the capacity curves and yielding sequence in models M0 and M1: A case study of a 14-story building.

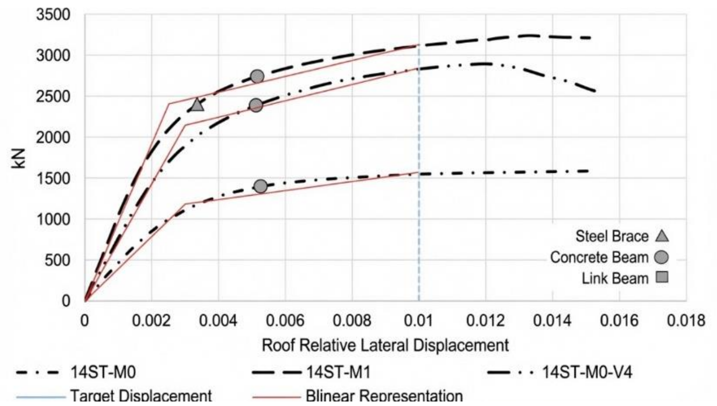

Fig. 4. Evaluation of the capacity curves and yielding sequence in the M0 and M2 models for a 14-story building.

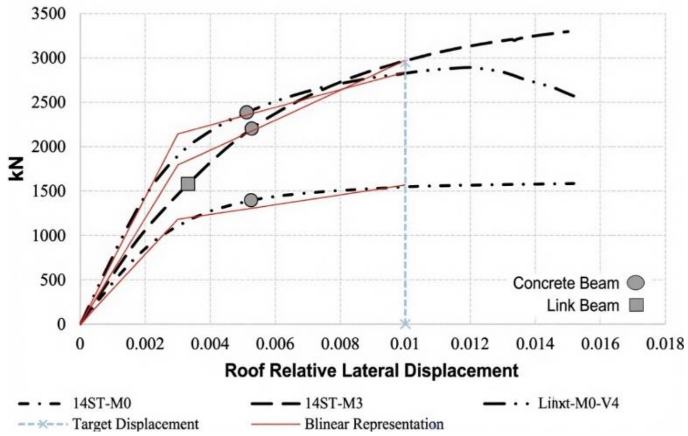

Fig. 5. Evaluation of the capacity curves and yielding sequence in the M0 and M3 models for a 14-story building.

4.1 | Investigation of the Sequence of Plastic Hinge Formation

Recent studies on models M4 to M6 have revealed an interesting behavioral pattern. Based on these observations, the first region where a plastic hinge is formed is the steel link beam, and this phenomenon occurs during the early stages of rapid loading (the Immediate Occupancy/Serviceability performance region).

Although in these retrofitted models the formation of plastic hinges in the concrete frame members occurs with a slight delay compared with the unstrengthened reinforced concrete frame, it is noteworthy that plastic hinge formation in the concrete beams of these models also takes place during the same rapid loading phase.

This behavior indicates that the proposed systems successfully concentrate inelastic deformation within the intended energy-dissipating components, particularly the steel link beams, while delaying damage development in the main reinforced concrete members. Therefore, the use of replaceable link elements provides better control over the location and progression of seismic damage.

4.2 | Evaluation of the Strength Performance of the Proposed Models

The results obtained from comparing the newly proposed models (M4 to M6) with a standard-designed reinforced concrete frame indicate that these innovative models are capable of providing the required strength level for the structure.

In other words, the implementation of the strengthening techniques employed in these models leads to achieving a desirable load-carrying capacity compared with conventional structural systems.

The proposed retrofitting models improve structural performance by increasing lateral resistance, enhancing energy dissipation capacity, and ensuring that damage is concentrated in predetermined and replaceable components rather than in the primary structural members. These characteristics make the proposed systems suitable alternatives for improving the seismic performance of existing reinforced concrete structures.

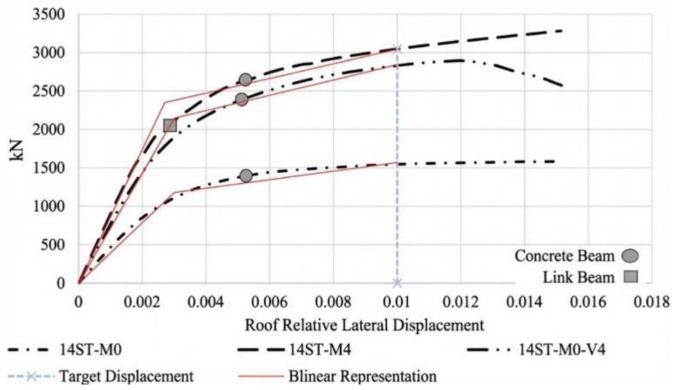

Fig. 6. Evaluation of the capacity curves and yielding sequence in the M0 and M4 models for a 14-story building.

4.3 | Investigation of the Seismic Behavior of Reinforced Concrete Frames Retrofitted with Innovative Approaches

In the innovative retrofitting approaches identified as M4, M5, and M6, it was observed that both the target displacement and the corresponding base shear force of the structure increased significantly. For example, in Model M6, the base shear force developed at the target displacement was approximately twice that observed in the original reinforced concrete frame.

Fig. 7 illustrates the formation of plastic hinges and the yielding process in the structural components of a 14-story reinforced concrete frame retrofitted using two different scenarios.

In the models utilizing conventional reinforced concrete frame retrofitting methods (M1, M2, and M3), when a displacement corresponding to 1.5 times the target inter-story drift was applied, not only did the steel braces reach their yielding state, but the main components of the existing reinforced concrete frame, including beams and columns, also entered the yielding stage.

In contrast, in the models retrofitted with the proposed innovative systems, yielding was concentrated primarily within the steel link beam. Meanwhile, the other main structural components remained within their elastic response range.

This characteristic enables the structure to maintain its integrity after an earthquake and provides the capability for rapid repair and quick return to serviceability. By concentrating seismic damage in replaceable components, the proposed systems reduce permanent damage to the primary structural members and improve the overall seismic resilience of reinforced concrete high-rise structures.

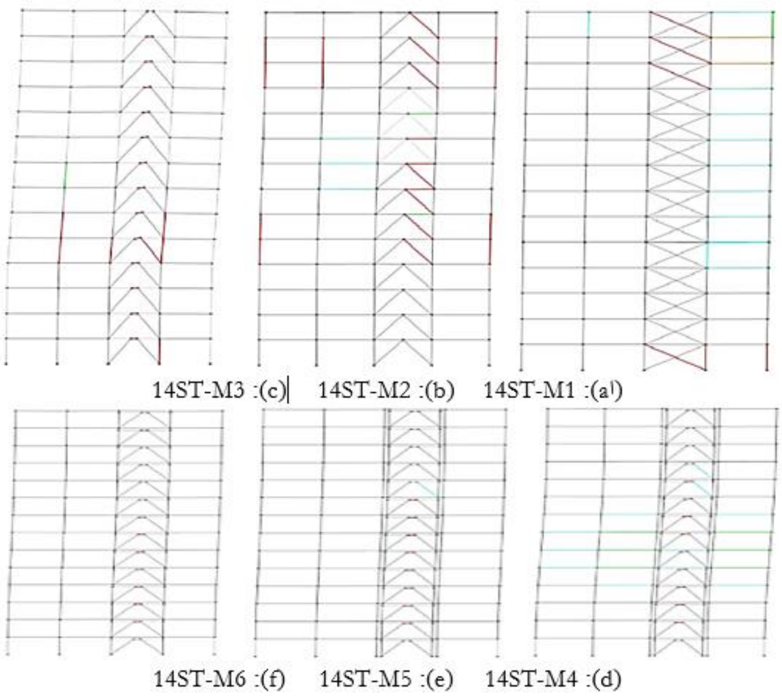

Fig. 7. Investigation of deformation patterns and plastic hinge formation sequence in the 14-story retrofitted reinforced concrete frame models.

4.4 | Analysis of Target Displacement Stability in a 20-Story Structure with Various Retrofitting Systems

According to *Table 1*, the values of the coefficients associated with the target displacement for a 20-story structure are presented. Examination of these coefficients indicates that despite variations in the type of retrofitting system employed, the magnitude of the target inter-story drift remains almost unchanged without any significant variation.

This observation demonstrates that the selection of different strengthening approaches has a limited influence on the target displacement demand of the structure. In other words, the proposed retrofitting systems are capable of improving the strength and energy dissipation characteristics of the structure while maintaining a relatively stable displacement demand.

The consistency of target displacement values among different retrofitting models indicates that the proposed systems can enhance seismic performance without causing undesirable increases in deformation demands. This behavior is particularly important in high-rise structures, where controlling lateral displacement and inter-story drift is one of the primary design considerations.

Table 1. Analysis of target displacement coefficients in 20-story buildings.

Type of Structure	g	K_i (kN/cm) (E5)	K_e (kN/cm) E5	T_i	T_e	C_0	C_1	C_2	C_3	S_a	Delta Target (Cm)
20ST-MO	9.81	37287	36260		2.48	1.30	1.00	1.10	1.00	0.25	54
20ST-M0-V4 -V4	9.81	61005	59243	1.55	1.58	1.30	1.00	1.10	1.00	0.35	48
20ST-M1	9.81	80640	59383	2.38	2.77 1.3	2.77 1.3	1.00	1.10	1.00	0.25	51
20ST-M2	9.81	59888	57218	2.38	2.43	1.3	1.00	1.10	1.00	0.25	52
20ST-ME	9.81	57023	54125	2.40	2.40 1.3	2.40 1.3	1.00	1.10	1.00	0.23	60

Table 1. Continued.

Type of Structure	g	K_i (kN/cm) (E5)	K_e (kN/cm) E5	T_i	T_e	C_0	C_1	C_2	C_3	S_a	Delta Target (Cm)
20ST-M4	9.81	66984	53226	2.38	2.40 1.3	2.40 1.3	1.00	1.10	1.00	0.23	60
20ST-M5	9.81	54650	52836	2.42	2.46 1.3	2.46 1.3	1.00 1.10	1.00 1.10	1.00	0.25	54
20ST-M6	9.81	65345	49967	2.42	2.77	1.3	1.00	1.10	1.00	0.23	62

5 | Conclusion

Considering the increasing importance of braced retrofitting systems in the seismic rehabilitation of structures, this study investigated and evaluated the performance of an innovative system consisting of a steel frame equipped with eccentric bracing. By emphasizing the capability of restoring building functionality after moderate-intensity earthquakes and reducing seismic damage, this system is introduced as a promising approach in seismic design.

In this study, the proposed retrofitting system (a steel braced frame with eccentric bracing and a link beam) was evaluated and compared with conventional braced retrofitting systems. For this purpose, several retrofitting models for reinforced concrete frames were defined and analyzed, including:

I. A model with diagonal bracing configuration (M1).

II. A model with X-shaped bracing configuration (M2).

III. A model using eccentric bracing with a concrete link beam (M3).

IV. A model utilizing eccentric bracing with a steel link beam connected to steel columns embedded within the surrounding frame (M4).

V. A reinforced concrete frame retrofitted with eccentric bracing and a steel link beam connected to the frame, including two intermediate steel columns between the frame and the steel beam (M5).

VI. A reinforced concrete frame retrofitted with eccentric bracing and a steel link beam connected to the surrounding frame (M6).

A common characteristic among these models is the use of a steel frame element surrounding the bracing system, which facilitates its connection to the existing reinforced concrete frame.

The key findings of this study indicate that the proposed innovative retrofitting method, based on steel frames equipped with eccentric bracing and intermediate link beams, represents an appropriate solution for seismic strengthening of various buildings due to its favorable seismic performance and rapid recovery capability after earthquakes.

Compared with traditional bracing methods, this system demonstrates higher efficiency, particularly in earthquake-prone regions, due to its ease of implementation and availability of construction materials. Its superior seismic performance also highlights the importance of applying performance-based design approaches alongside conventional force-based design methods.

Throughout the analyses, significant interaction between the bracing system and the reinforced concrete frame was observed. The bracing members played a more effective role in resisting lateral loads at lower stories, whereas the reinforced concrete frame contributed more significantly at upper stories. The application of the proposed retrofitting systems reduced the stress ratios in reinforced concrete frame members, although this effect decreased as the building height increased.

The linear dynamic response spectrum analysis demonstrated a reduction in inter-story drift in the retrofitted models. The proposed system, consisting of eccentric bracing with a steel link beam, provided greater drift reduction compared with the reference model. Investigation of the frame–brace interaction showed that the contribution of the reinforced concrete frame to lateral load resistance increased in the proposed models.

Nonlinear static analysis confirmed increased stiffness, improved nonlinear behavior of the reinforced concrete frame, and enhanced energy absorption capacity in the proposed system. Furthermore, implementation of this system delayed the formation of plastic hinges in reinforced concrete beams and resulted in improved performance under similar lateral displacement demands.

The nonlinear dynamic analyses also indicated reductions in inter-story drift and lateral force demands in the retrofitted models. In conventional retrofitting methods, the concrete link beam reached the plastic range; however, the proposed dual system significantly improved both elastic stiffness and structural ductility. The high resistance of this system against yielding base shear was also confirmed.

In this research, the primary objective was to investigate the influence of eccentric bracing systems and replaceable structural fuses on improving energy dissipation capacity and reducing damage in high-rise structures subjected to lateral loads. Since the seismic behavior of structures requires advanced design strategies, the application of combined seismic-resistant systems can provide safer and more economical performance under critical loading conditions.

Replaceable structural fuses, as detachable energy-dissipating components, enable damage concentration in specific structural regions, thereby reducing repair costs and improving the functional durability of buildings after earthquakes. Combining these fuses with eccentric bracing systems, which are among the effective lateral load-resisting systems, enhances structural ductility and reduces irreversible damage.

To accurately evaluate the behavior of these systems, numerical modeling and nonlinear analyses were employed. The use of advanced software such as Perform-3D enabled detailed simulation of structural behavior under various loading conditions and provided a deeper understanding of the influence of this combined system on reducing structural damage.

The results demonstrate that the application of eccentric bracing systems combined with replaceable structural fuses can significantly enhance structural performance against lateral forces. These systems improve energy dissipation capacity, reduce structural damage, and increase ductility, thereby playing a significant role in enhancing the safety and durability of high-rise structures.

The combination of these two systems not only improves seismic performance but also reduces damage to structural members and increases post-earthquake repairability. Furthermore, this approach can reduce the time and cost required for structural repair and reconstruction.

Overall, the findings of this study confirm the importance of implementing innovative retrofitting systems in the design and rehabilitation of earthquake-resistant structures and demonstrate their potential for improving seismic performance and reducing damage caused by dynamic loading.

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