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Damage Steering in Architecture and Structures: The Efficiency of Vertical Links in Enhancing Building Resilience and Repairability

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Abstract

Conventional earthquake-resistant systems often undergo permanent deformations during severe seismic events, leading to the formation of plastic hinges throughout most parts of the structure. This condition makes the reuse of the building impossible, and consequently, total demolition and reconstruction become inevitable—an approach that is neither economically, environmentally, nor architecturally sustainable. In recent years, inspired by the concept of "damage steering," researchers have sought to concentrate damage in predetermined locations so that, through repair or replacement, the building remains reusable. One of the most innovative systems in this regard is the rocking frame concept. The present study investigates the efficiency of this system in steel-braced frames equipped with vertical links, focusing on how rocking mechanisms can reduce structural responses after earthquakes. The results indicate that employing eccentric bracing with vertical links significantly enhances ductility and energy dissipation, although the rocking mechanism imposes some limitations on these improvements. These findings are significant not only from a structural engineering perspective but also for architecture: preserving spatial and functional qualities after seismic events, enabling continued occupancy, and reducing the need for complete demolition. Accordingly, such systems can play a crucial role in achieving sustainable and resilient architecture.

Keywords: Vertical link, Seismic resilience, Damage steering, Rocking mechanism, Sustainable architecture.

1 | Introduction

Iran, due to its location on the seismically active Alpine–Himalayan belt and the presence of active faults, is constantly exposed to the threat of severe earthquakes [1]. In addition, the existence of old buildings in dense

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urban fabrics and the lack of sufficient supervision in new constructions increase the vulnerability of structures [2]. Under such conditions, earthquakes are not merely an engineering issue but also an urban and architectural crisis that directly affects the quality of life of citizens and the sustainability of urban contexts [3].

There is a strong necessity to design structures that, while minimizing structural damage, also prevent losses to the spatial and functional qualities of buildings [4]. In this regard, repairable systems based on the concept of *rocking mechanisms* can be considered as an innovative solution [5]. Such systems not only provide seismic safety but also enable the rapid return of buildings to service, preventing total demolition and the loss of spatial and cultural capital of cities [6], [7].

The significance of the present research lies in exploring the application of rocking mechanisms in steel-braced frames equipped with vertical links. With a focus on reducing post-earthquake structural responses, this study demonstrates how predetermined connections can act as structural fuses and yielding dampers to prevent extensive damage.

From an architectural standpoint, this system offers the advantage that a building remains functional with only the replacement or repair of a limited number of structural components. This feature is particularly crucial for public facilities such as hospitals, schools, and service centers, where the continuity of architectural functionality after a disaster is as valuable as structural safety. Therefore, it can be stated that the integration of advanced structural technologies with architecture is not only an engineering necessity but also a requirement for realizing resilient and sustainable cities.

Xu et al. [6] conducted an experimental study on a three-story, three-bay frame with five-meter bay lengths and a story height of 3.2 meters at the European Laboratory for Structural Assessment in Italy. The tested system was subjected to an earthquake simulation of 0.25 g. The lateral load was resisted in the loading direction by two parallel Eccentrically Braced Frames (EBFs) with a single shear panel, and in the orthogonal direction by two parallel Moment-Resisting Frames (MRFs). In the tested V-EBF frames (with vertical link beams), the columns were oriented along their weak axis to apply maximum shear to the vertical link. The applied loading followed displacement-control at the third floor with load distribution ratios of 1/3, 2/3, and 1 for the first to third stories, respectively. The results demonstrated favorable behavior and good ductility of the system. Comparison between the two parallel V-EBF frames showed no lateral or torsional instability, particularly in the critical region of brace–link intersections. This finding was in complete agreement with prior nonlinear buckling analysis using ANSYS. It was concluded that, with proper design of the vertical shear link, the risk of lateral or torsional instability at the lower end of the link is eliminated, and only lateral bracing at the upper end (intersection with the main beam) is necessary [8].

At the University of California, Berkeley, short link specimens were tested under cyclic loading with incremental displacement histories. In the first specimen [9], displacement increased over two cycles, and the maximum rotation before strength degradation was 0.065 radians. In the second specimen [10], subjected to single-cycle loading, the maximum rotation reached 0.097 radians. These results demonstrate that the rotation capacity of link beams depends strongly on loading type, history, and available testing facilities. In 2002, a new loading protocol for EBF link beams was proposed, derived from cyclic histories used for moment frames. This "loading history" approach was more stringent than previous protocols and showed minor inelastic rotations for short links compared to earlier findings [11], [12].

Based on analytical studies, Tabar Molehi and Zahrai [12] in 2006 investigated one-story EBFs with vertical links of different lengths, with and without web stiffeners. Frames equipped with single-panel shear links exhibited stable and full hysteretic behavior, with more than 90% of dissipated energy attributed to inelastic shear deformation of the link. It was also noted that the maximum inelastic rotation capacity directly depends on the applied loading history [13].

Di Sarno et al. [14] tested 37 specimens under various protocols. According to the AISC 2002 loading protocol, the average link rotation capacity for shear-yielding specimens was 0.075 radians, indicating the protocol's restrictive effect. However, specimens tested under the revised AISC 2005 protocol achieved average rotations of 0.11 radians, aligning more closely with code provisions and suggesting its suitability. The strain-hardening factor for these specimens ranged from 1.05 to 1.62 [14], [15]. Zahrai and Mahrouzadeh experimentally investigated the effect of shear panels on ductility and energy dissipation using locally available steel profiles by testing five vertical link specimens. The shear deformation angle before failure reached 0.128–0.156 radians. The frames exhibited good ductility with an average damping ratio of 26.7–30.6% and a response modification factor of about 7.15–10.65. Since almost all input energy was dissipated by the links, while beams, columns, and braces remained elastic, the system could be reused after an earthquake simply by replacing the damaged link. This confirms the cost-effectiveness of using vertical link beams in seismic design of new steel buildings and in retrofitting existing structures [16], [17].

2 | Verification of Modeling Accuracy and Research Method

To ensure the validity of the SAP results, a laboratory model from reference [13] was selected, and its results were compared with the finite element model. The comparative figures show that the SAP modeling demonstrates acceptable accuracy. In *Figs. 3-8*, the pushover curve of the experimental specimen is presented alongside the finite element model.

From an architectural perspective, this stage is of great importance, as it allows the study of building behavior in different plans and under real loads without the need for physical construction. With this approach, it becomes possible to predict the impact of eccentric bracing systems and vertical links on the building's interior space, the load distribution in columns and beams, and the flexibility of the plan. This information is valuable for architects and designers, as it can optimize the selection of form, dimensions, and openings based on seismic performance [18], ensuring that architectural spaces remain usable even after an earthquake.

Figs. 1 to *5* illustrate the geometric model, numerical modeling, and deformation mechanism of the laboratory specimen. It was observed that plastic hinges initially formed in the vertical links, and after the complete yielding of the braces, the structure approached the mechanism stage. From an architectural point of view, this indicates that the system can localize and control the damage points, allowing other parts of the building to remain intact without compromising the overall plan and form design.

Thus, the accuracy of the modeling enables architects to design structures that are both resilient and flexible, where seismic performance is optimized while maintaining spatial quality and ensuring usability of the spaces after an earthquake.

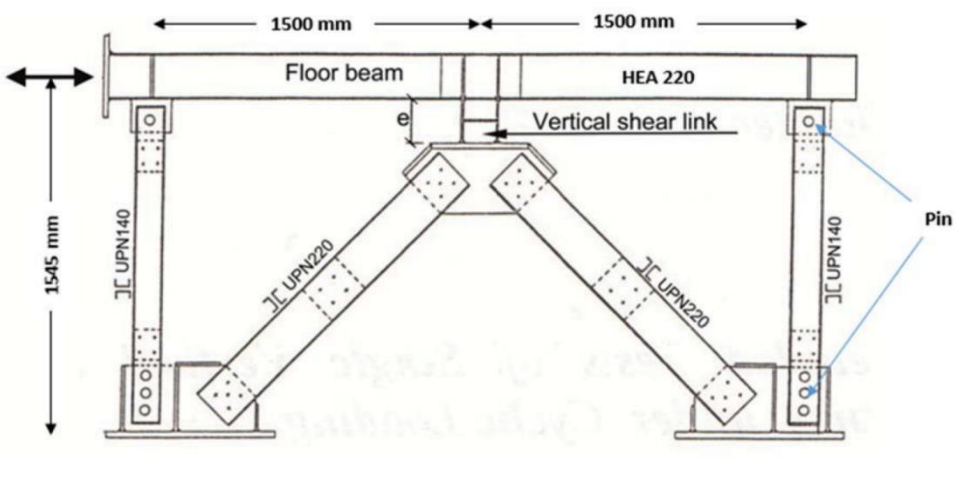

Fig. 1. Geometric specifications and sections of the experimental model.

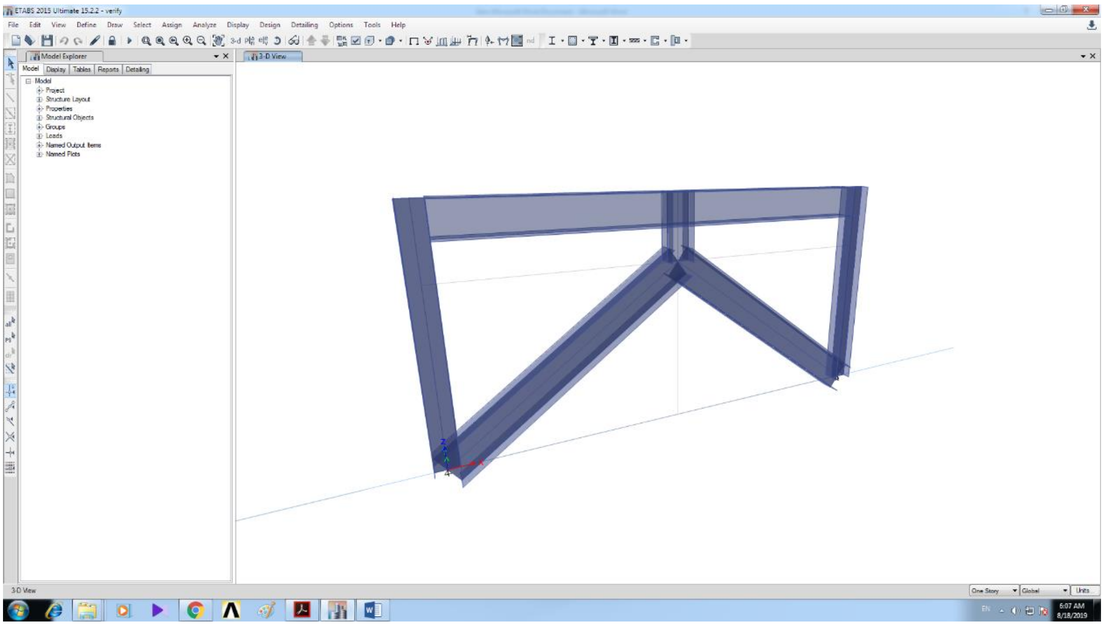

Fig. 2. Numerical modeling sample of the laboratory specimen.

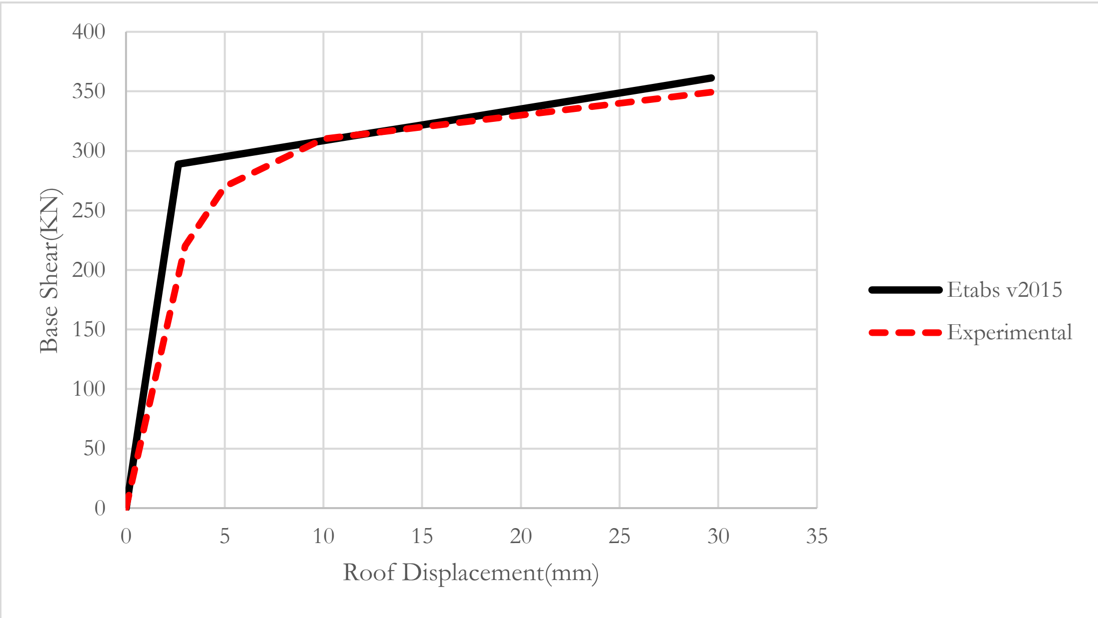

Fig. 3. Comparison of experimental and numerical model results by the author.

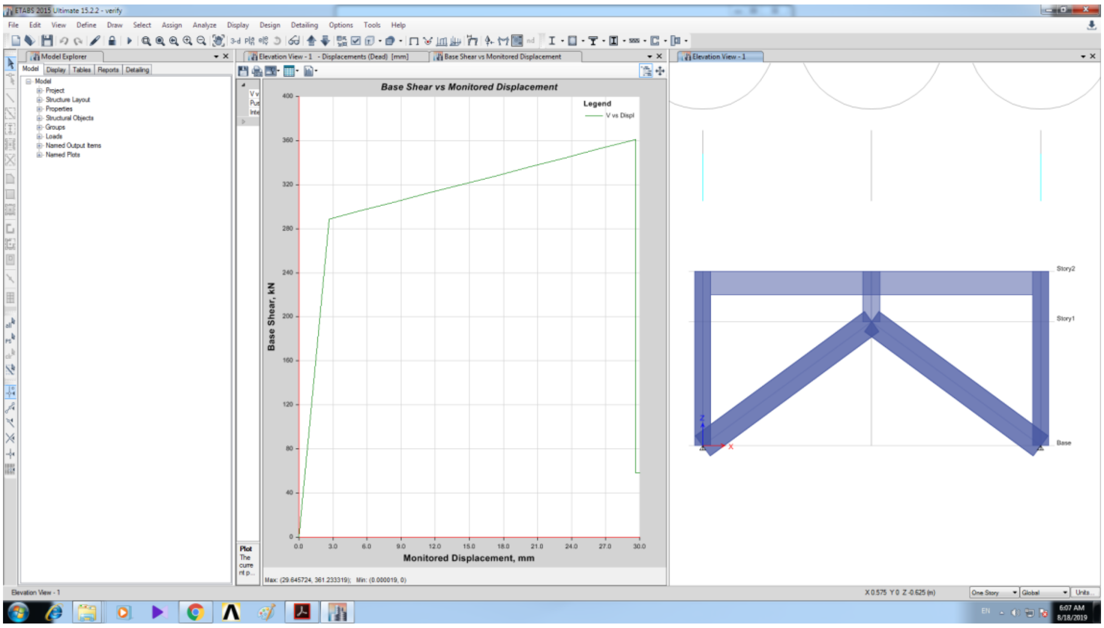

Fig. 4. Numerical analysis of the laboratory specimen.

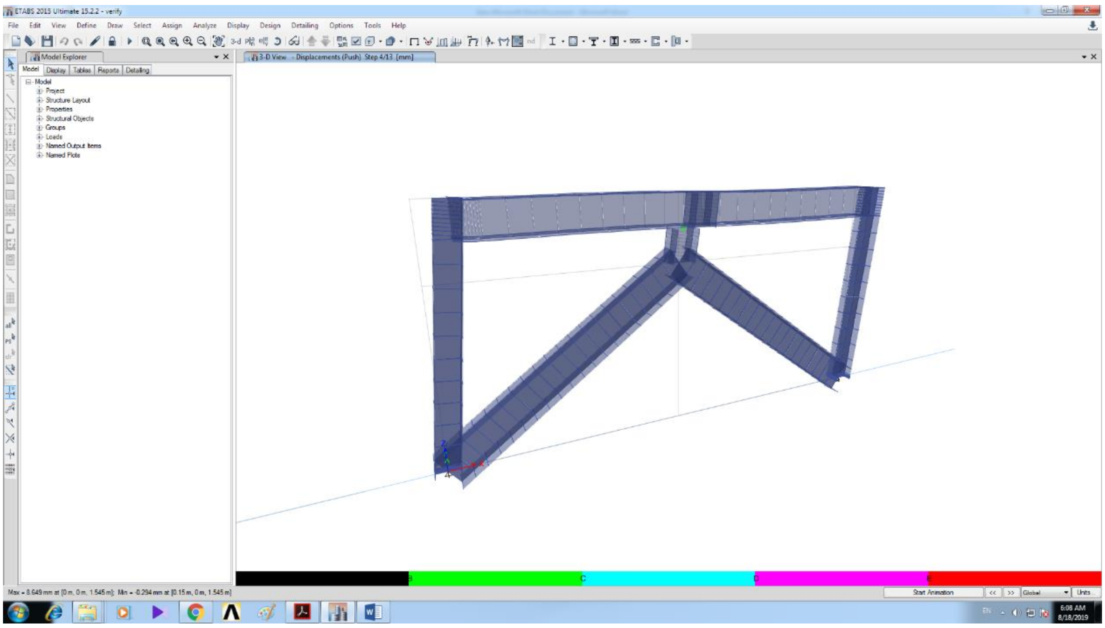

Fig. 5. Mechanism of deformation and plastic hinge formation in the laboratory specimen.

3 | Analysis and Interpretation of Results

In this study, the structure was modeled in two configurations: an EBF with vertical links, and a rocking frame system. Nonlinear static pushover analyses revealed that plastic hinges initially form in the links, which act as predetermined fuses. The controlled yielding of the braces enhances the ductility and energy absorption capacity of the structure. From an architectural perspective, this feature is highly significant, as controlling the damage mechanism ensures that critical parts of the building remain intact, allowing for continued use of the spaces after an earthquake. This advantage is particularly vital for public, educational, and service buildings, where interruption of use would result in high costs and social impact.

Modal analysis results indicated that although the rocking system limits ductility and energy dissipation, it provides better control over deformations and prevents widespread damage to other structural elements. From an architectural design standpoint, this enables preservation of spatial organization and building layout even after seismic events.

Table 1. Results of Seismic Parameter Calculations for Model 1.

Ultimate Strength	Ductility	Energy Dissipation	Model Name
2148 KN	12.34	921500 KN.mm	MODEL 2
1633 KN	6.12	261100 KN.mm	MODEL 3

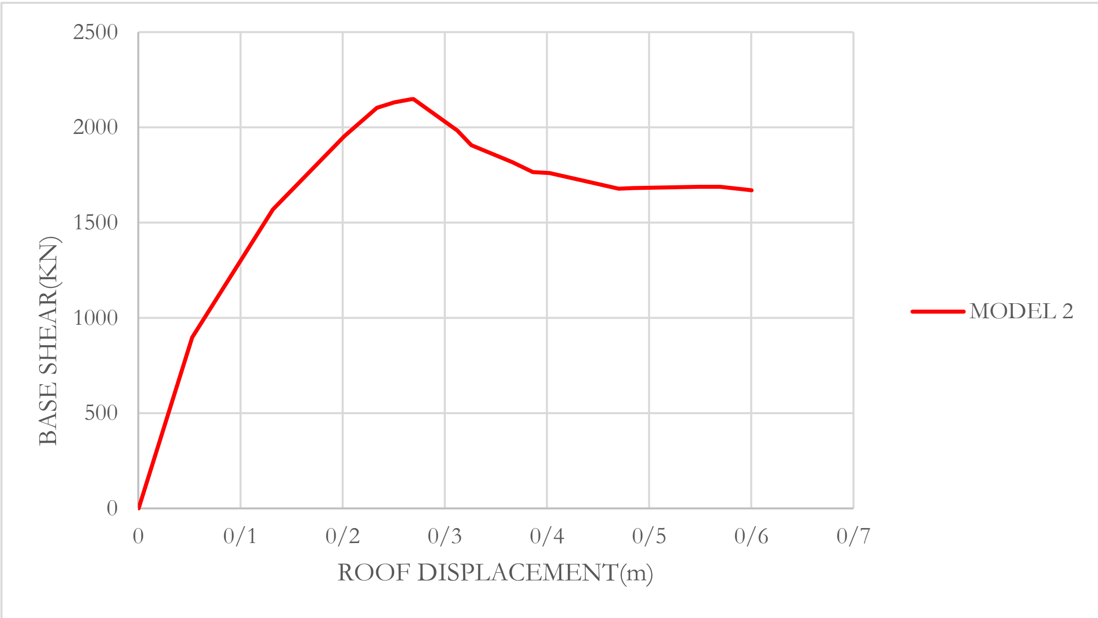

Fig. 6. Load-displacement curves of the second model variants.

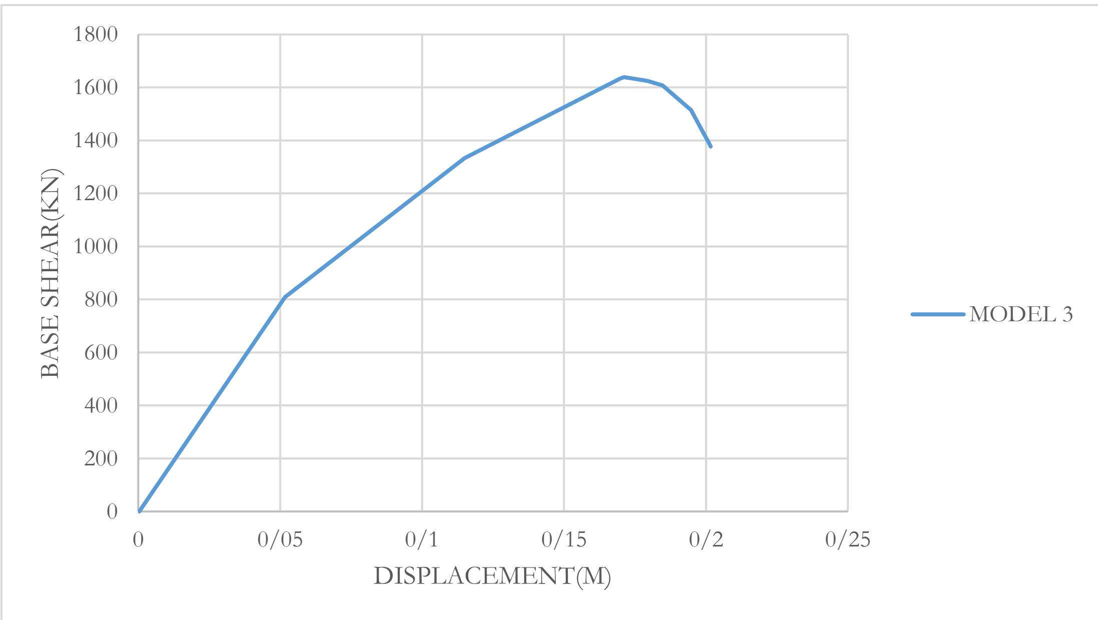

Fig. 7. Load-displacement curves of the third model variants.

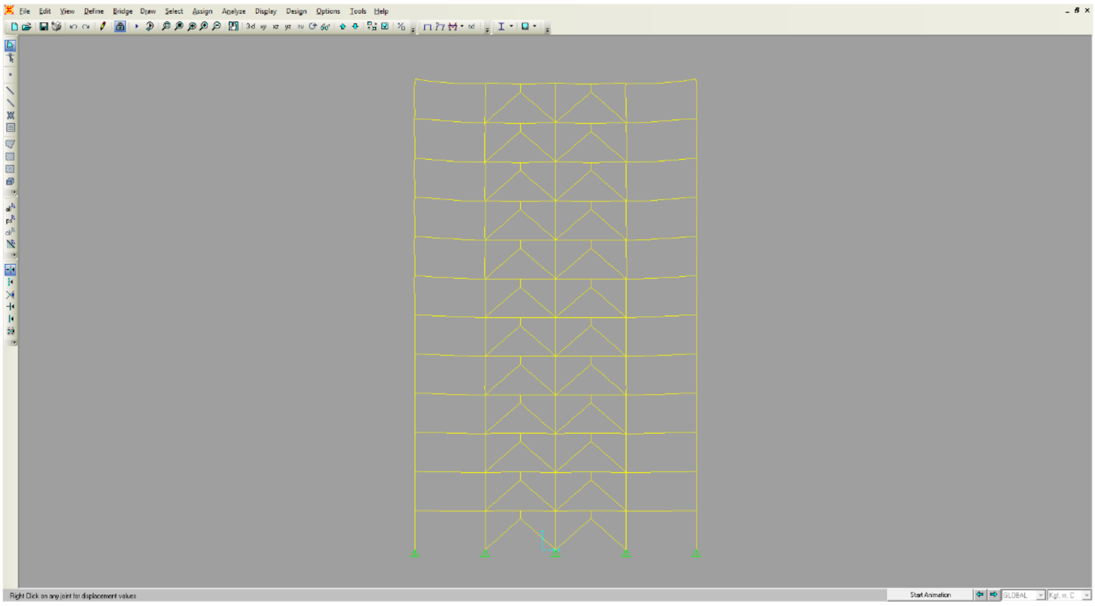

Fig. 8. Yield mechanism and hinge formation of model 2- under gravity loading.

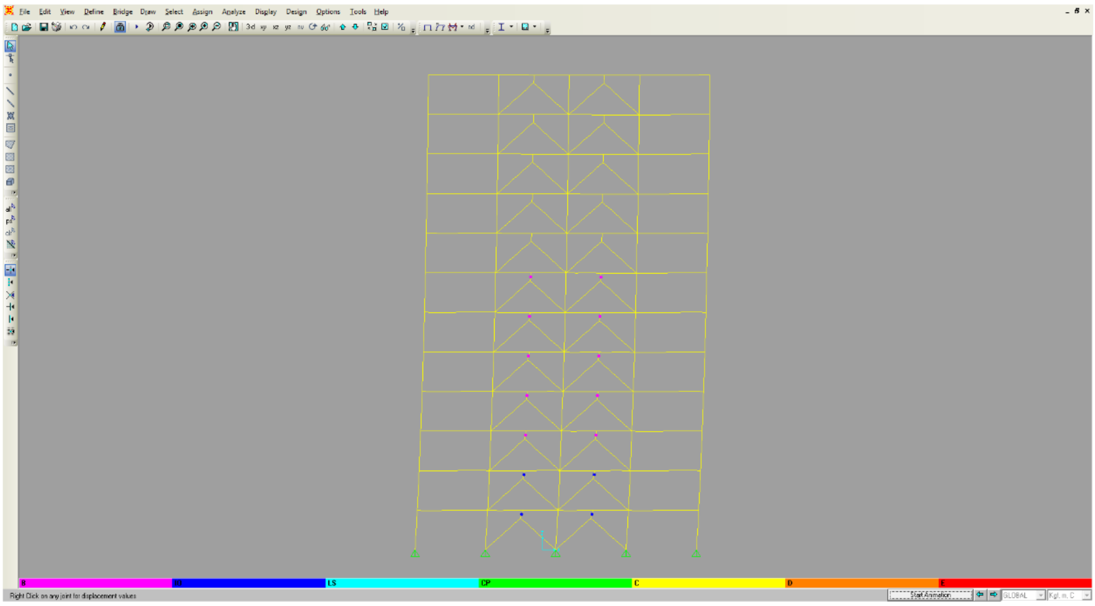

Fig. 9. Yield mechanism and hinge formation of model 2 - first stage.

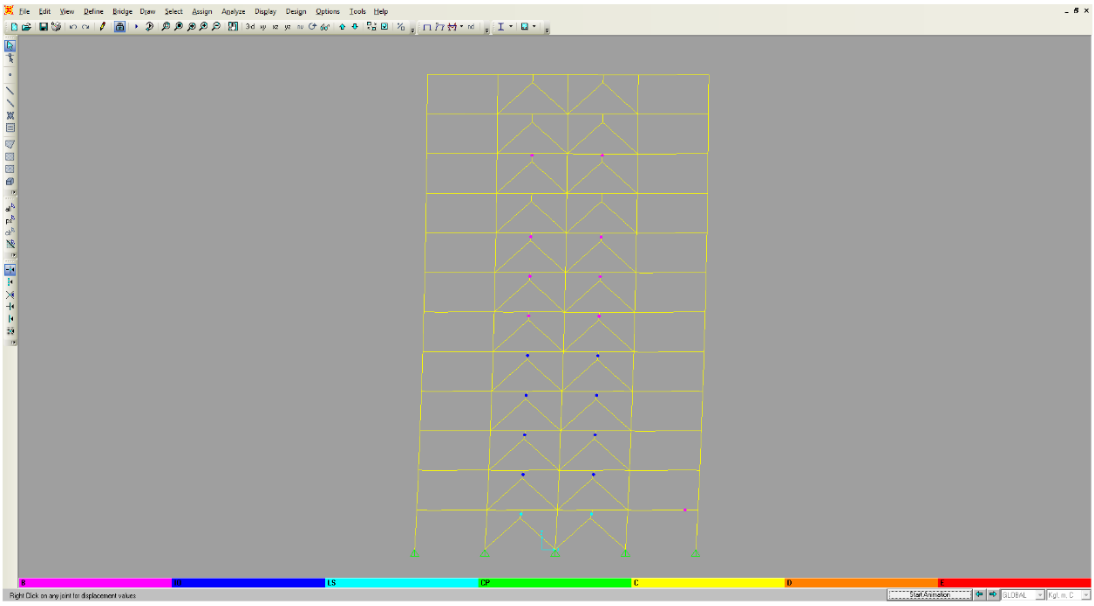

Fig. 10. Yield mechanism and hinge formation of model 2- second stage.

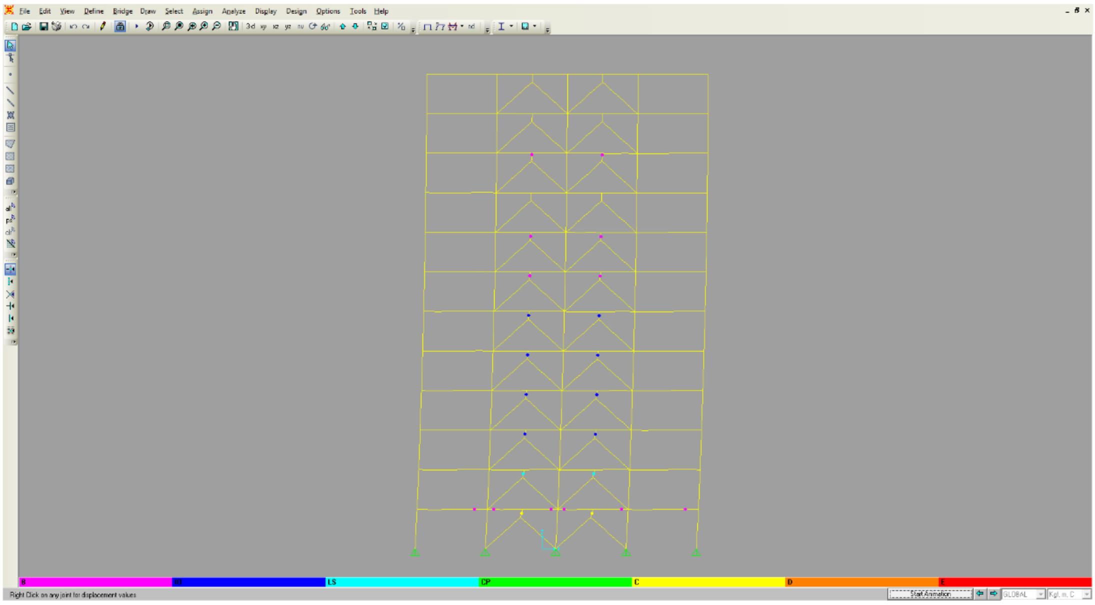

Fig. 11. Yield mechanism and hinge formation of model 2- third stage.

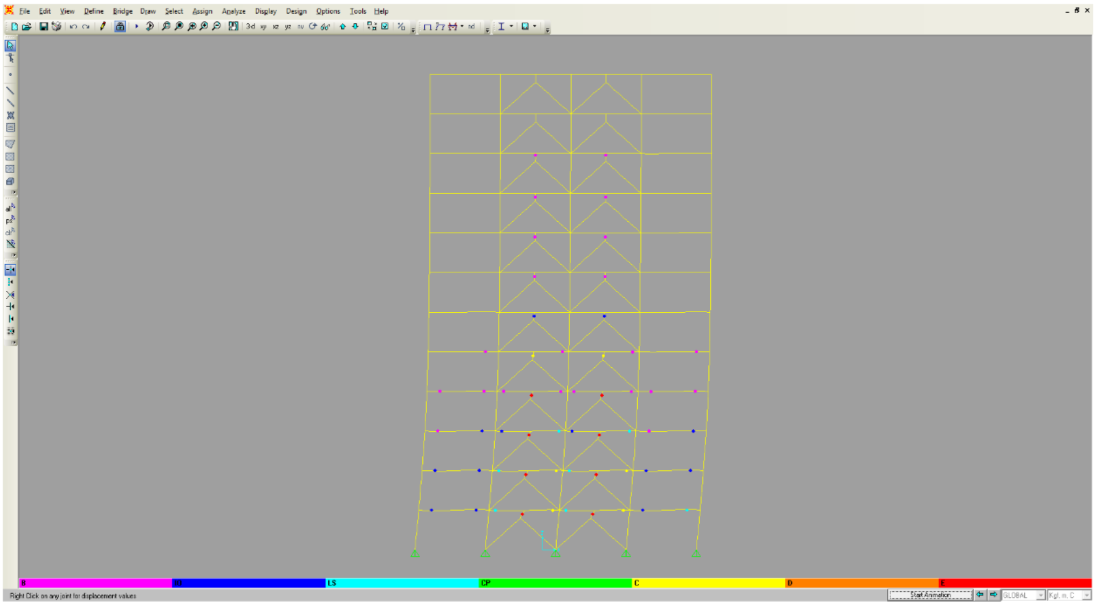

Fig. 12. Yield mechanism and hinge formation of model 2- fourth stage.

Figs. 6- 20 present the numerical results:

I. Energy Dissipation: Eccentric bracing with vertical links significantly increases energy dissipation, whereas the rocking mechanism limits this increase.

II. Ductility: Vertical links increased ductility by up to 1.22 times compared to the concentric specimen, although the rocking mechanism reduces this effect.

III. Ultimate Strength: The presence of eccentric bracing and vertical links decreased the ultimate strength of the structure, while the rocking mechanism amplified this reduction by up to 55%.

The architectural implication of these results is clear: selecting an appropriate system can balance optimal seismic performance with maintaining spatial quality. Using vertical links and eccentric bracing enables designing more open spaces, larger openings, and flexible floor plans without compromising safety, while the rocking system ensures that post-earthquake damage is confined to predetermined locations, keeping the building functional.

Based on the hinge formation mechanism, it is observed that in the studied structure, hinge formation begins at the links. This initial yielding contributes significantly to the ductility of the structure, and the yielding stages progress until the complete yielding of the lateral load-resisting system leads to overall structural yielding.

For a more detailed assessment and to predict the structural deformations, this section examines the modal deformations of the first five modes of the structure.

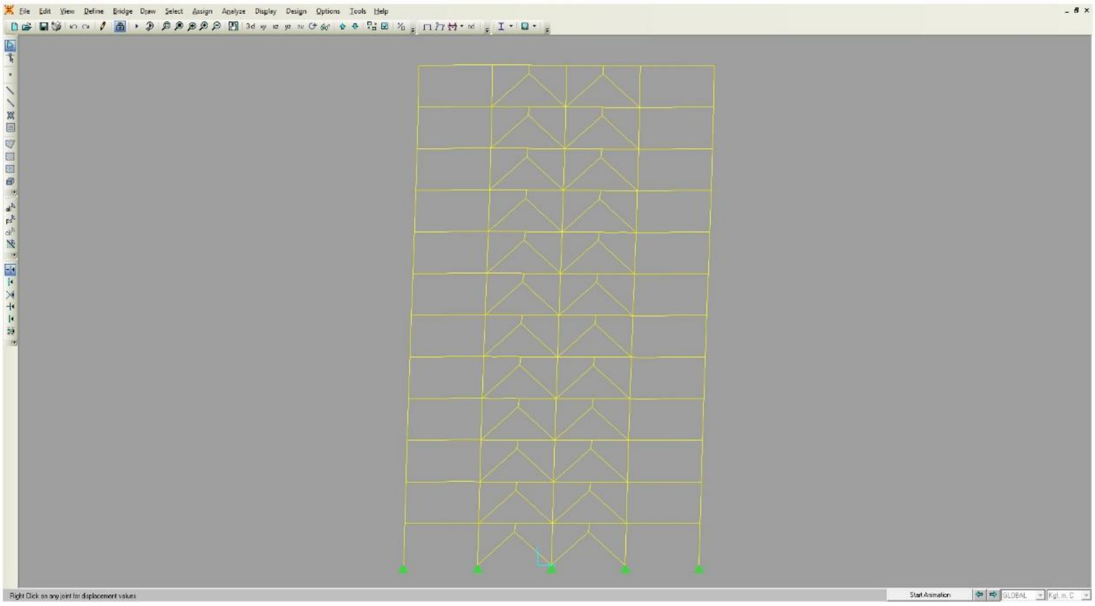

Fig. 13. Mode shape deformation of the first mode of the studied structure.

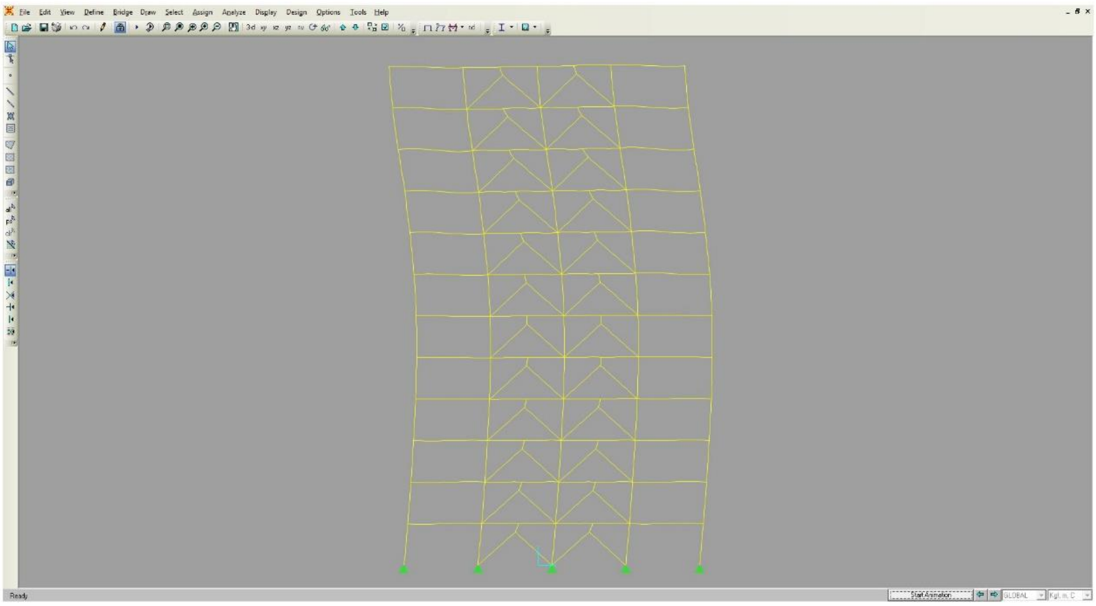

Fig. 14. Mode shape of the second vibration mode of the analyzed structure.

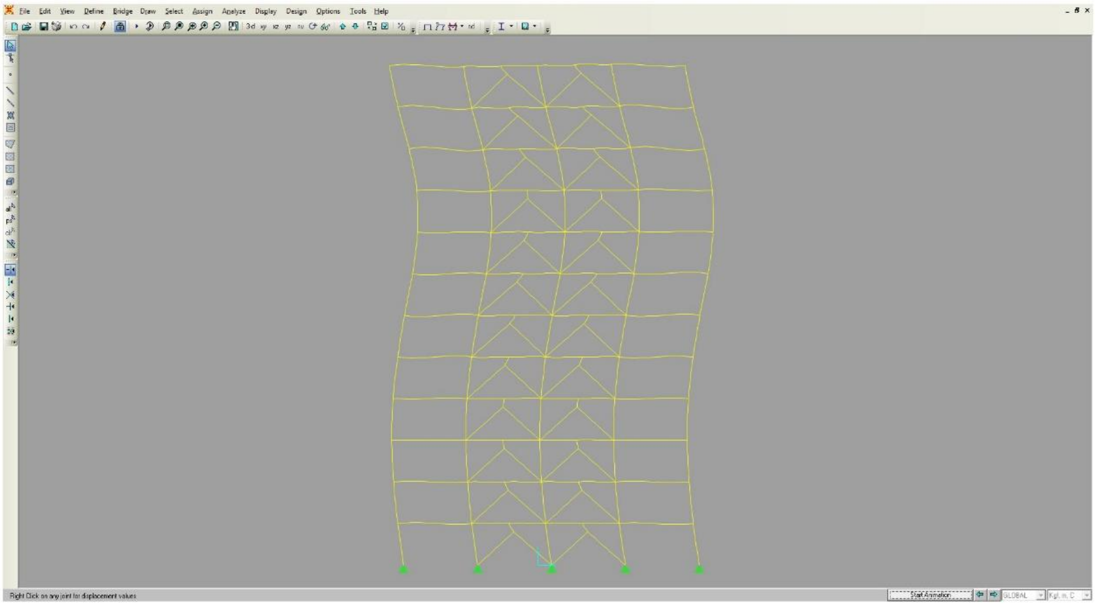

Fig. 15. Mode shape of the third vibration mode of the analyzed structure.

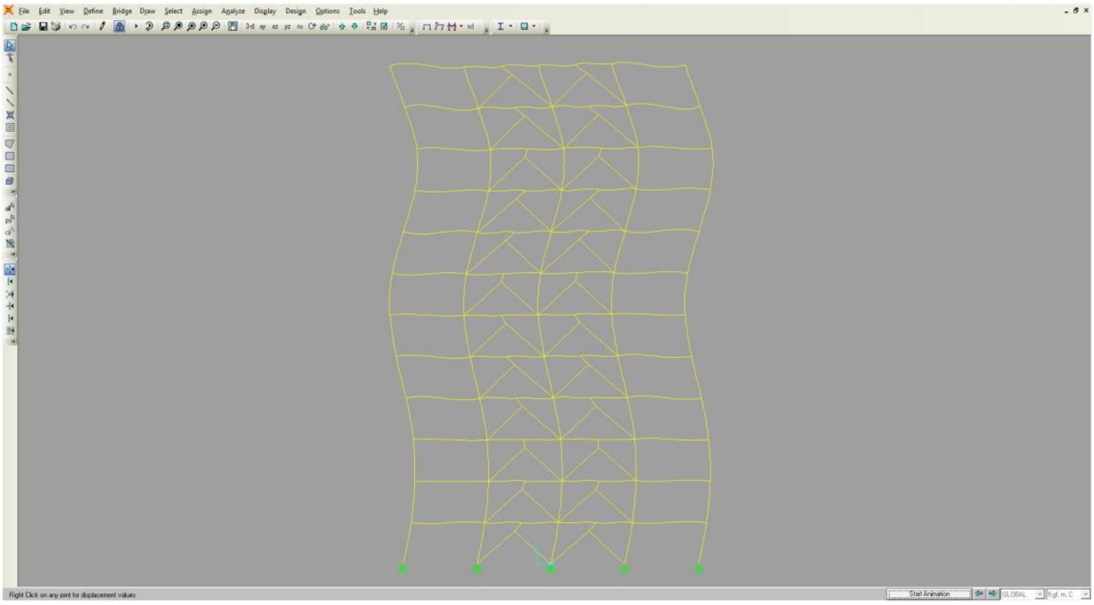

Fig. 16. Mode shape of the fourth vibration mode of the analyzed structure.

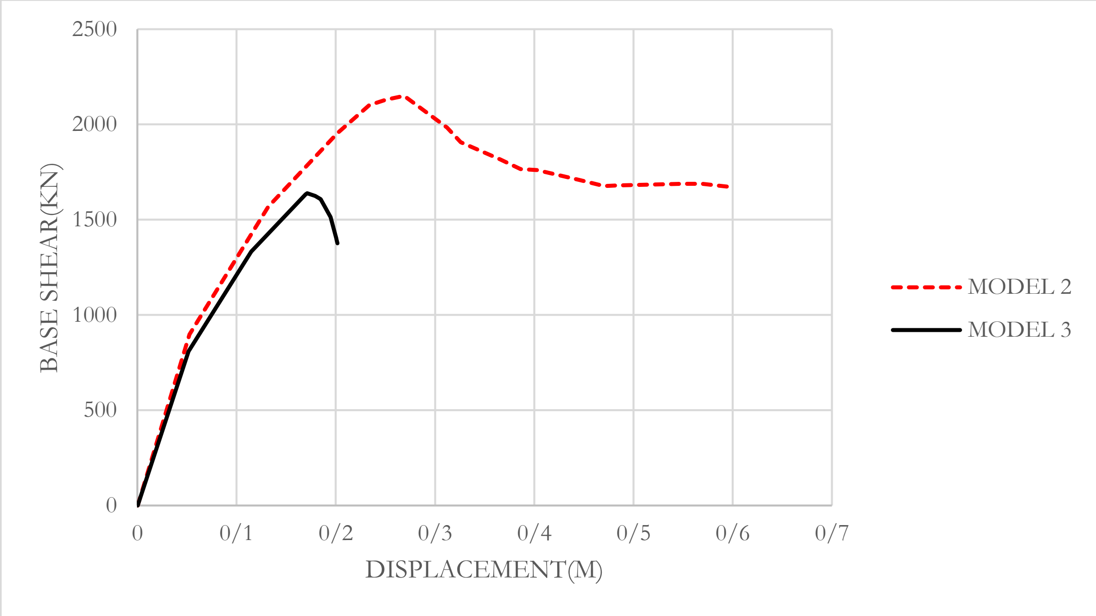

Fig. 17. Comparison of the effect of rocking motion on the structural performance.

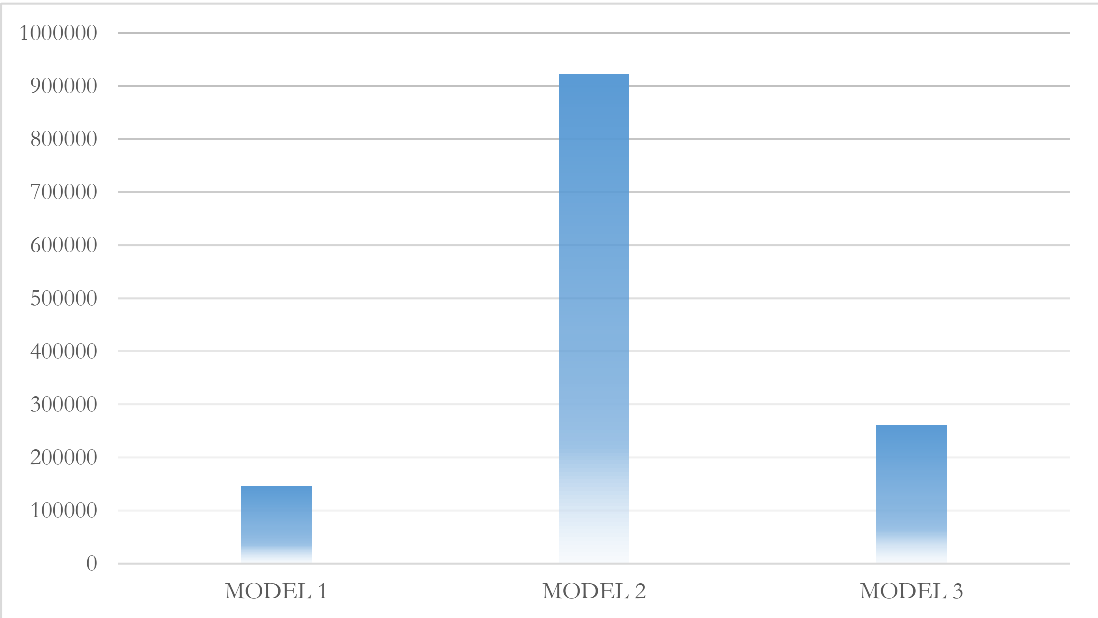

Fig. 18. Comparative bar chart of energy absorption obtained from nonlinear analysis of the models in this study.

Based on the comparative bar chart of the nonlinear analysis results, it can be observed that the presence of an eccentric bracing system and a vertical link member significantly increases the energy absorption capacity of the structure. In this study, a 5.2-fold increase in energy absorption was observed compared to the concentric bracing model. However, the presence of rocking motion reduced the energy absorption capacity, limiting this increase to about 78%.

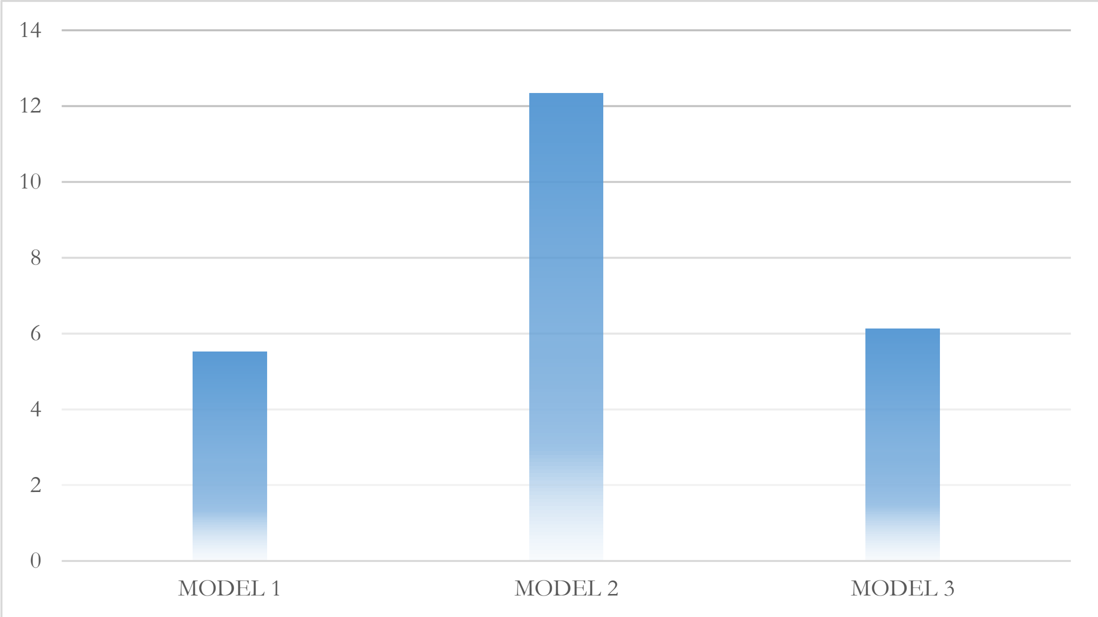

Fig. 19. Comparative bar chart of ductility obtained from the nonlinear analysis of the models in this study.

Based on the comparative bar chart of the nonlinear analysis results, it can be observed that the presence of an eccentric bracing system and a vertical link member significantly increases the ductility of the structure. In this study, a 1.22-fold increase in ductility was observed compared to the concentric bracing model. However, the presence of rocking motion reduced the structural ductility, limiting this increase to only about 10%.

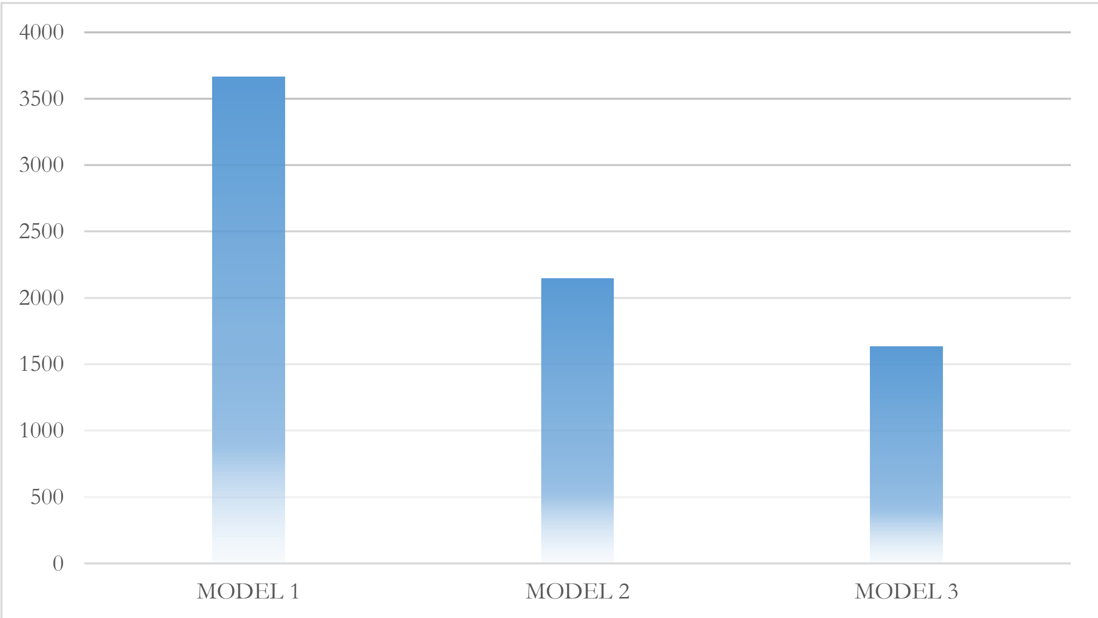

Fig. 20. Comparative bar chart showing the ultimate strength results obtained from the nonlinear analysis of the models in this study.

Based on the comparative bar chart of the nonlinear analysis results, it can be observed that the presence of an eccentric bracing system and a vertical link member reduces the ultimate strength of the structure. In this study, a 41% reduction in ultimate strength was observed compared to the concentric bracing model.

However, the presence of rocking motion amplified this effect, causing a reduction in ultimate strength of up to 55%.

4 | Conclusion

The results of this study showed that:

Plastic hinges primarily form in the bracings and vertical links, which concentrate damage in controlled locations. From an architectural perspective, this feature ensures that the overall spatial organization of the building remains intact and allows the structure to be reused after the earthquake with only localized repairs.

Eccentric bracing with vertical links significantly increases the structure's energy absorption capacity and ductility, with a 5.2-fold increase in energy absorption and a 1.22-fold increase in ductility compared to the concentric bracing model. From an architectural point of view, this finding enables more flexible spatial design, as the structure can accommodate larger deformations without collapse.

However, the rocking motion system reduced energy absorption (by up to 78%) and ultimate strength (by up to 55%). While this may be considered a technical limitation, it provides an architectural advantage: the concentration of damage in specific, replaceable components. As a result, the building can quickly return to service after an earthquake.

The findings indicate that implementing these systems can play a key role in the seismic design of new buildings and the retrofitting of existing structures in Iran. From an architectural and urban planning perspective, this translates into enhanced urban resilience, reduced need for widespread demolition, and preservation of the spatial identity of urban fabrics.

From a sustainability standpoint, repairability instead of complete demolition leads to resource savings, reduced construction waste, and lower environmental impacts. This highlights one of the most important connections between structural engineering and sustainable architecture.

In summary, systems incorporating vertical links and rocking motion not only improve seismic performance but also offer new architectural opportunities: more flexible spatial layouts, continued usability after a disaster, and the realization of resilient and sustainable buildings in the Iranian urban context.

The presence of eccentric bracing and vertical link members significantly increases structural ductility, with a 1.22-fold increase observed compared to the concentric model. However, rocking motion reduces the structure's ductility, limiting this increase to only about 10%.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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