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# A Novel Ductile Energy Dissipation Device to Enhance the Seismic Performance of Chevron Braced Frames in the Near-Fault Region

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## Abstract


Concentrically Braced Frames (CBFs), particularly Chevron (inverted-V) bracing, are popular lateral load-resisting systems in steel structures due to their high stiffness and architectural adaptability. However, their seismic performance is often compromised by the premature buckling of the compressive brace under severe ground motions, leading to an unbalanced force in the beam and potential structural collapse. This study introduces and evaluates a novel, ductile energy dissipation element designed to act as a structural "fuse" to improve the behavior of Chevron Braced Frames (CBF), especially in the near-fault region. Six geometric configurations of the proposed element were first modeled and analyzed using the ABAQUS finite element software to determine the optimal dimensions and force-displacement characteristics. Subsequently, three 2D steel frames (12, 18, and 23 stories) with and without the proposed element were subjected to nonlinear time-history analysis in SAP2000. Three near-fault ground motion records (Kobe, Northridge, and Loma Prieta) were used for the analysis. The results demonstrate that the proposed element significantly enhances the seismic performance of the frames. Compared to conventional CBF, the novel system reduced the average base shear by 45%, average roof acceleration by 40%, and average brace axial force by 60%. Furthermore, the proposed element successfully concentrated all inelastic deformations within itself, preventing plastic hinge formation in the main structural members (beams, columns, and braces), ensuring a more resilient and damage-controllable structure.

**Keywords:** Chevron brace, Ductile element, Energy dissipation, Near-fault earthquake, Nonlinear dynamic analysis, Steel frame.

## 1 | Introduction

Earthquakes represent one of the most significant natural threats to the built environment, causing immense economic losses and casualties primarily due to structural collapse [1], [2]. In steel structures, Concentrically

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Braced Frames (CBFs) are widely used for their high lateral stiffness. Among CBFs, the Chevron (inverted-V) bracing configuration is particularly favored for its architectural advantage of creating large openings.

However, the seismic performance of Chevron braces is inherently limited by the buckling of the compressive diagonal member during a major earthquake. This buckling causes a sudden loss of strength and stiffness, creating a significant unbalanced vertical force in the supporting beam. This can lead to large inelastic deformations, beam failure, and potentially progressive collapse of the structure [3], [4]. Post-earthquake investigations have repeatedly highlighted the vulnerability of CBF, particularly when subjected to the high-velocity pulses characteristic of near-fault ground motions [4].

To overcome these limitations, researchers have focused on passive energy dissipation devices. These devices act as structural fuses, yielding or deforming to absorb seismic energy, thereby protecting the main load-carrying members [5], [6]. A review of the literature reveals various yielding dampers, including Added Damping and Stiffness (ADAS), Triangular Added Damping and Stiffness (TADAS), and ring-spring dampers. Abbasnia et al. [7] and Hosseini and Mirzaei [8] have shown the effectiveness of adding steel rings to CBFs. However, there is a continuous need for simple, cost-effective, and easily replaceable devices specifically designed for Chevron bracing systems.

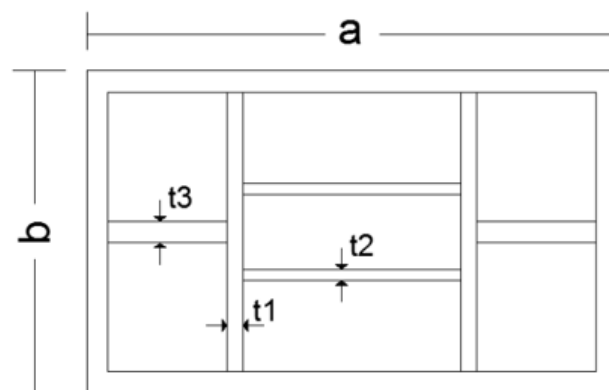
This paper presents a novel ductile energy dissipation element for Chevron braces. The primary objectives are:

- I. To propose and geometrically optimize a new energy dissipation element using finite element analysis.
- II. To evaluate the effectiveness of the proposed element in reducing seismic demands (base shear, roof acceleration, brace force) in steel frames of varying heights (12, 18, and 23 stories).
- III. To compare the plastic hinge formation mechanism in frames with and without the proposed element under near-fault ground motions.
- IV. To demonstrate that the proposed element can successfully prevent buckling and concentrate damage, significantly enhancing the seismic resilience of CBF.

## 2 | Proposed Energy Dissipation Element and Numerical Modeling

### 2.1 | Geometry of the Proposed Element

The proposed Ductile Element (DE) is a box-shaped steel component designed to be installed at the intersection of the two Chevron braces and the beam, acting as the primary energy-dissipating fuse. A total of six models (model 1 to model 6) with varying geometric parameters (especially plate thicknesses  $t_1$ ,  $t_2$ ,  $t_3$ ) were evaluated to determine the optimal configuration for stable hysteretic behavior and adequate energy dissipation capacity.



**Fig. 1. Geometric configuration of the proposed ductile energy dissipation element.**

**Table 1. Geometric dimensions of the proposed element models (Model 3 was selected for this study).**

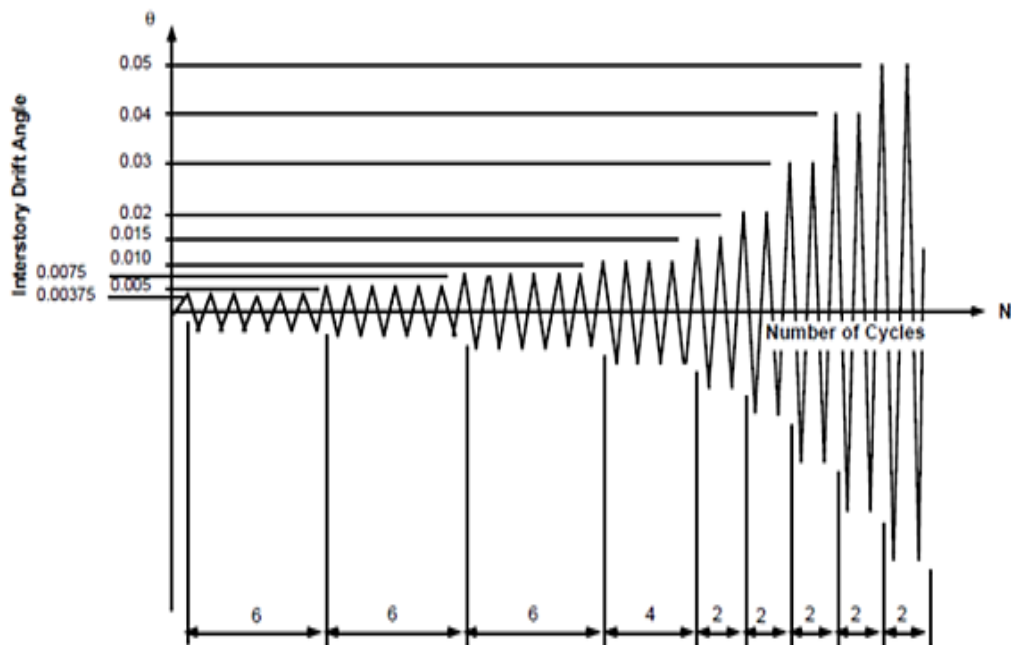
	a (mm)	b (mm)	t1 (mm)	t2 (mm)	t3 (mm)
Model 1	500	300	15	6	20
Model 2	500	300	15	8	20
Model 3	500	300	15	10	20
Model 4	500	300	20	12	20
Model 5	500	300	20	15	20
Model 6	500	300	20	20	20

Following a comparative analysis of the six models in ABAQUS, Model 3 (with  $t_1=15$  mm,  $t_2=10$  mm,  $t_3=20$  mm) was selected for all subsequent frame analyses due to its stable and full hysteretic response, high energy dissipation capacity, and suitable yield force. The material used is ST37 steel with a yield stress ( $F_y$ ) of 2400 kg/cm<sup>2</sup> and an ultimate stress ( $F_u$ ) of 3700 kg/cm<sup>2</sup>.

## 2.2| Finite Element Modeling in ABAQUS

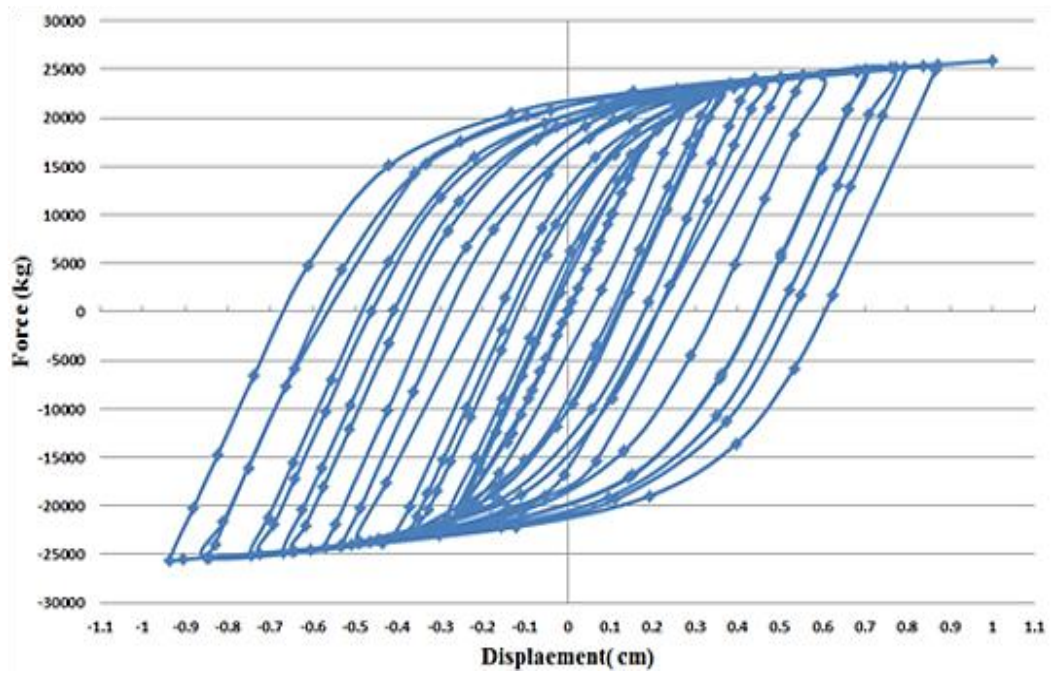
A detailed 3D finite element model of the selected element (Model 3) was created in ABAQUS to extract its accurate cyclic force-displacement behavior. The element was meshed using 10-node quadratic tetrahedral elements (C3D10). A multi-linear kinematic hardening model was used to simulate the material's cyclic plasticity.

The model was subjected to a cyclic loading protocol as specified in ATC-40 [9], as shown in Fig. 2.

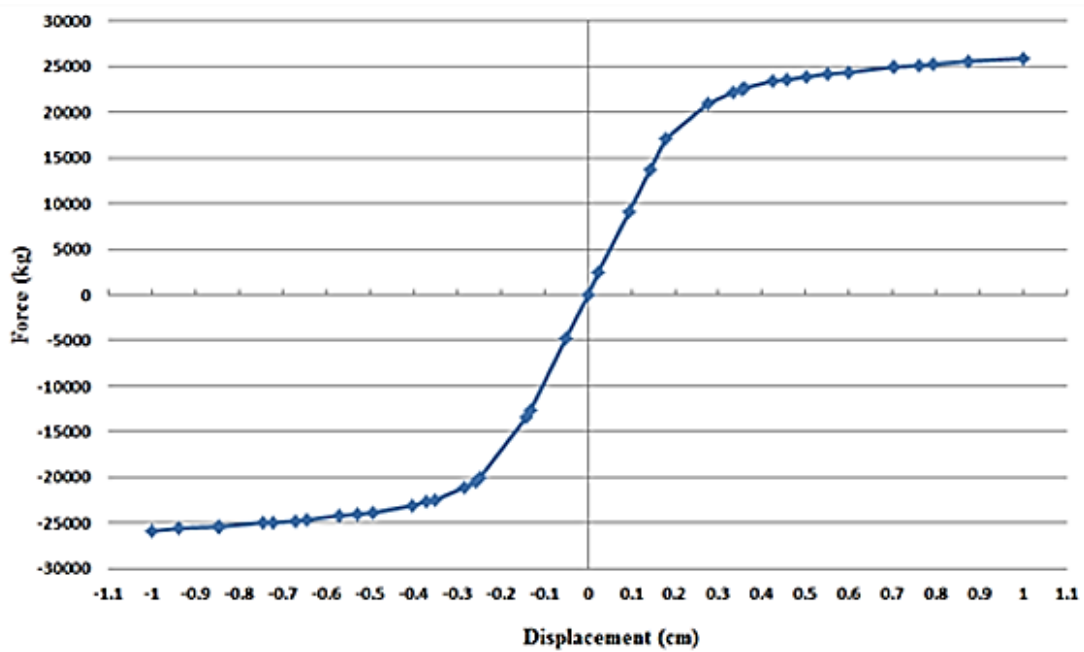


**Fig. 2. Cyclic loading protocol used for ABAQUS analysis (based on ATC-40).**

The analysis yielded the stable hysteresis loop and the backbone curve shown in Fig. 3. These curves are essential for defining the nonlinear link element in SAP2000.



a.



b.

Fig. 3. Nonlinear behavior and stress distribution of the proposed element; a. Stable hysteresis loop of the proposed element (Model 3), and b. Backbone force-displacement curve.

The von Mises stress distribution, shown in *Fig. 4*, confirms that yielding initiates and spreads within the intended ductile zones of the element.

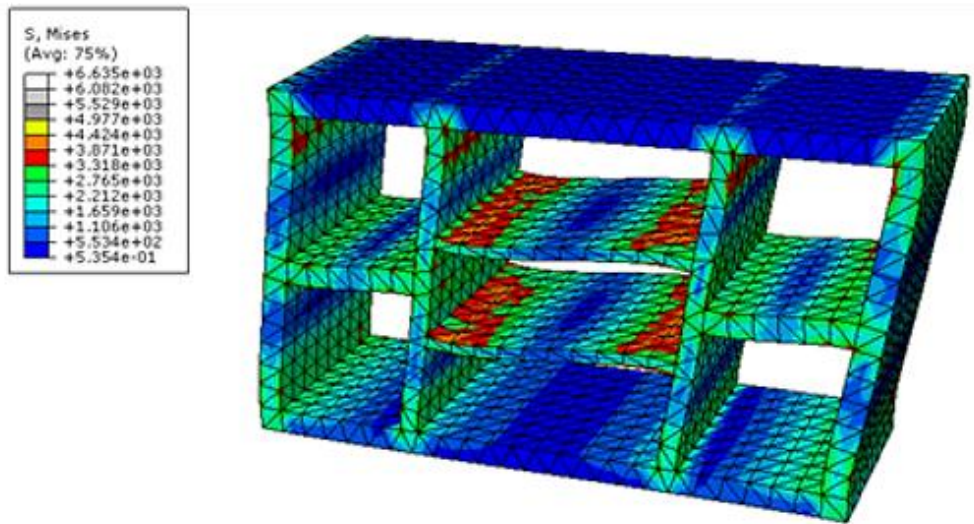


Fig. 4. Von Mises stress distribution in the proposed element under cyclic loading.

### 2.3 | Structural Frame Modeling in SAP2000

Three 2D steel frames of 12, 18, and 23 stories were designed. Each frame had 3 bays with a 5-meter span and a 3-meter story height. The design followed the Iranian Standard No. 2800 (4th Edition) [10] for a site in Tonekabon (Soil Type II). Beams were modeled with I-sections, while columns and braces were modeled with box sections.

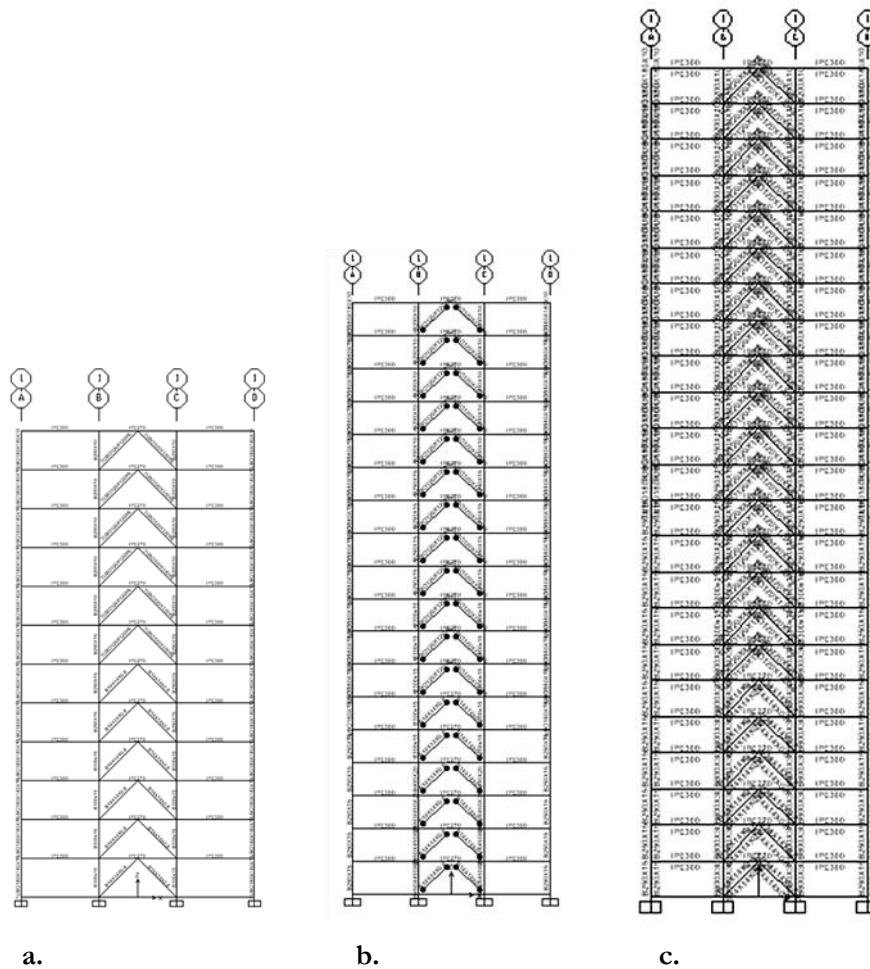


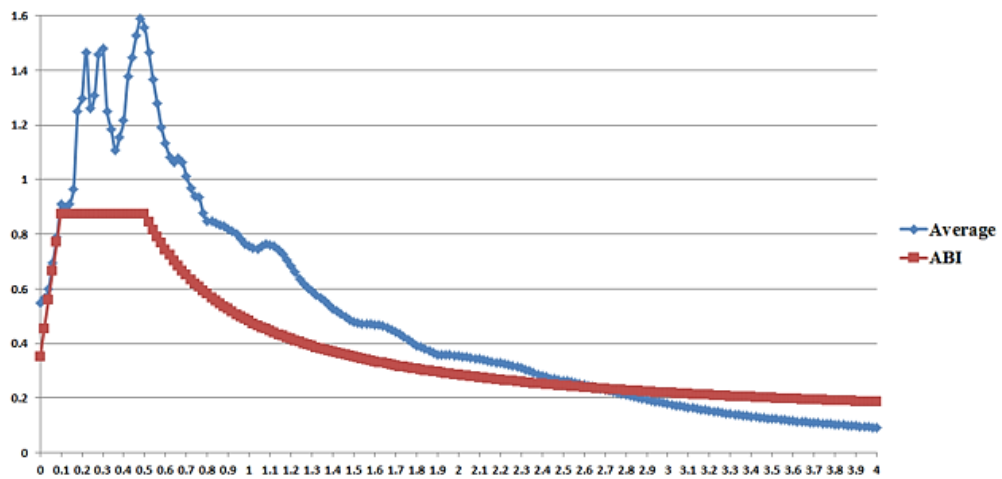
Fig. 5. Elevation of the 2D frames used for analysis; a. 12-story, b. 18-story, and c. 23-story.

## 2.4 | Ground Motion Selection and Scaling

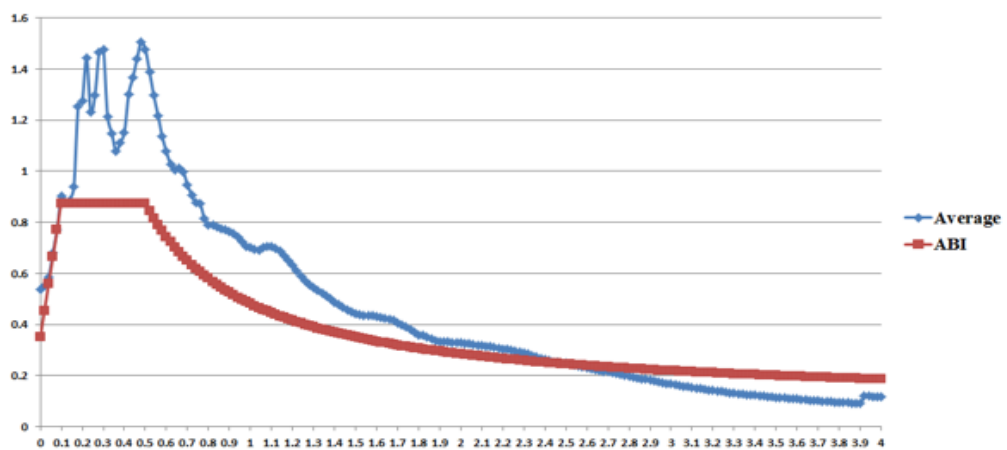
Three near-fault ground motion records were selected from the Pacific Earthquake Engineering Research Center (PEER) Ground Motion Database [11] to perform the nonlinear time-history analyses. Their characteristics are summarized in *Table 2*. The records were scaled according to the Iranian Standard No. 2800 [10] to match the design spectrum, as shown in *Fig. 6*.

**Table 2. Properties of the selected near-fault ground motion records.**

Earthquake	Near Feild		
	Kobe	Northridge	Loma Prieta
Magnitude	6.9	6.69	6.93
Station	0 Nishi-Akashi	5081 Topanga	57007 Corralitos
Data source	CUE	USGS	CDMG
Distance	7.08 (km)	10.31 (km)	0.15 (km)
PGA (g)	0.509	0.364	0.644



a.



b.

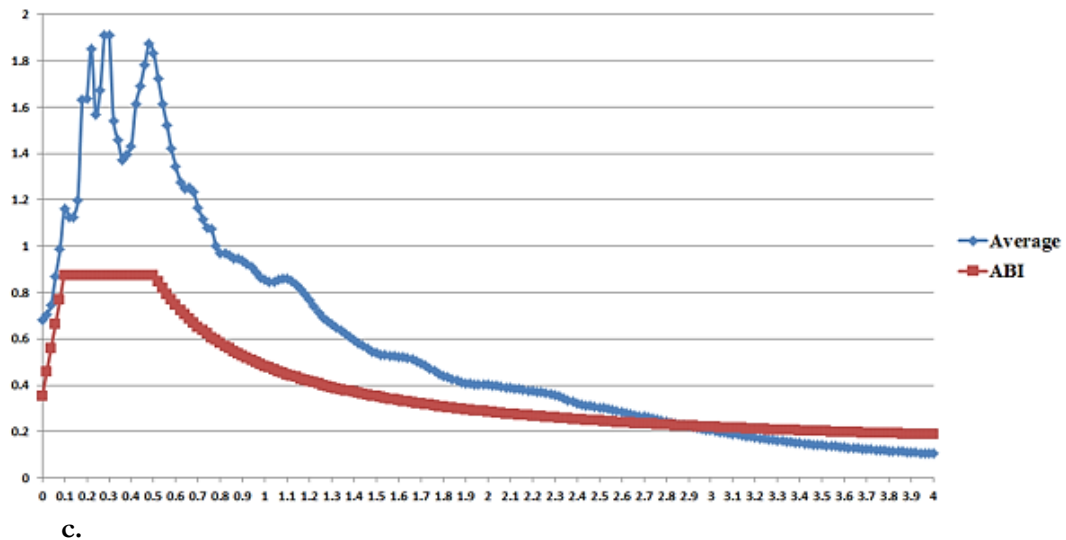


Fig. 6. Scaled response spectra of selected ground motions for the a. 12-story, b. 18-story, and c. 23-story frames.

## 2.5 | Nonlinear Modeling in SAP2000

The nonlinear behavior of the proposed element was modeled using a Multi-Linear Plastic (Kinematic) link element in SAP2000. The force-deformation properties derived from the ABAQUS analysis (see *Fig. 3*) were assigned to this link. The frames were analyzed using direct integration nonlinear time-history analysis.

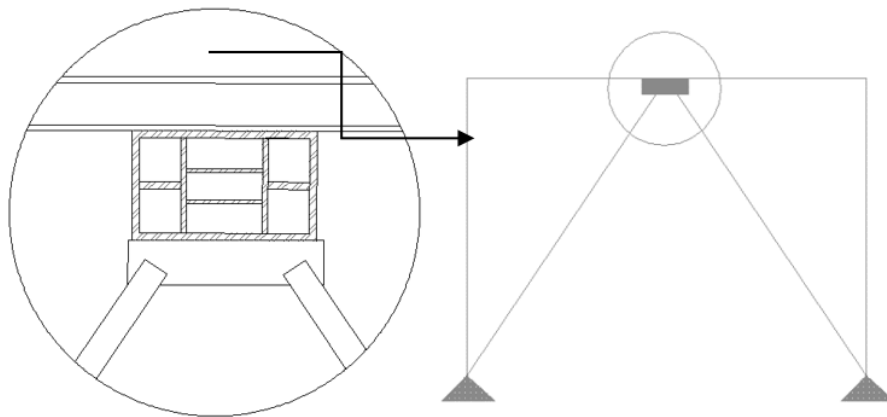


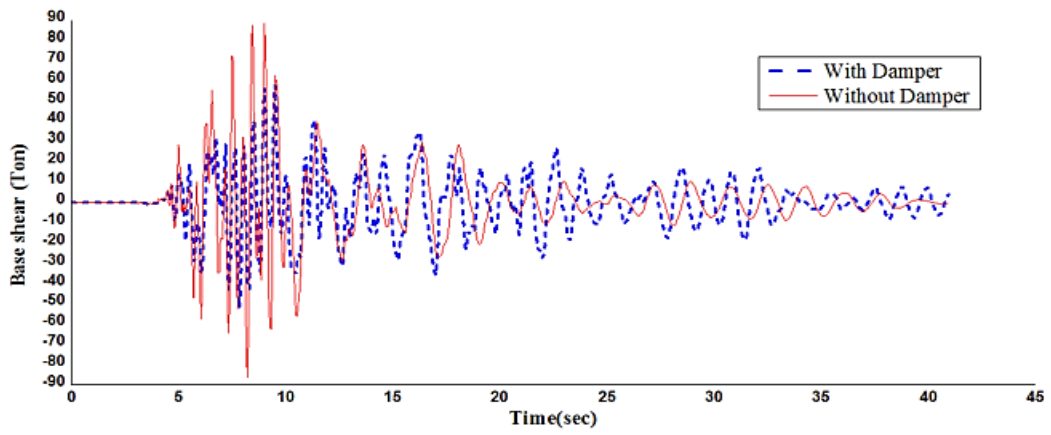
Fig. 7. Installation location of the proposed ductile element at the Chevron brace intersection.

## 3 | Results and Discussion

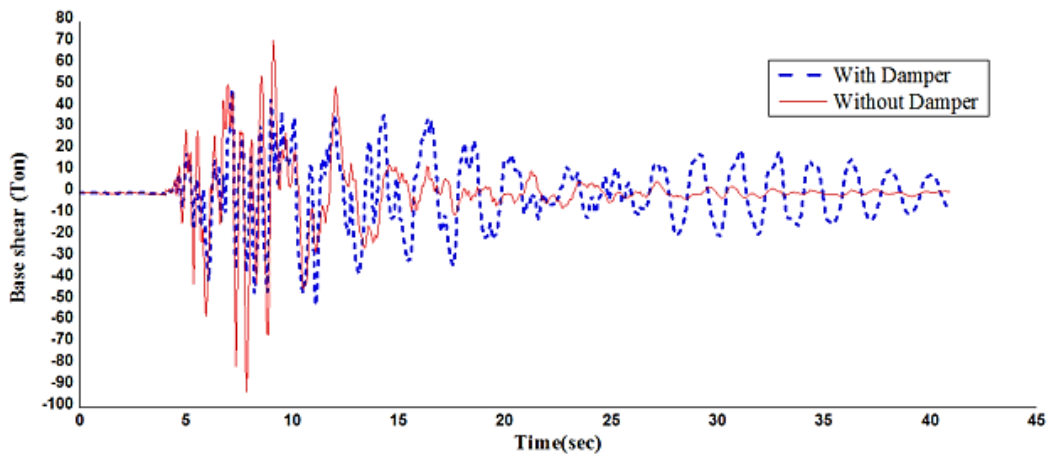
The nonlinear time-history analysis results for the conventional CBF and the frames equipped with the proposed (CBF-DE) are compared in this section.

### 3.1 | Base Shear

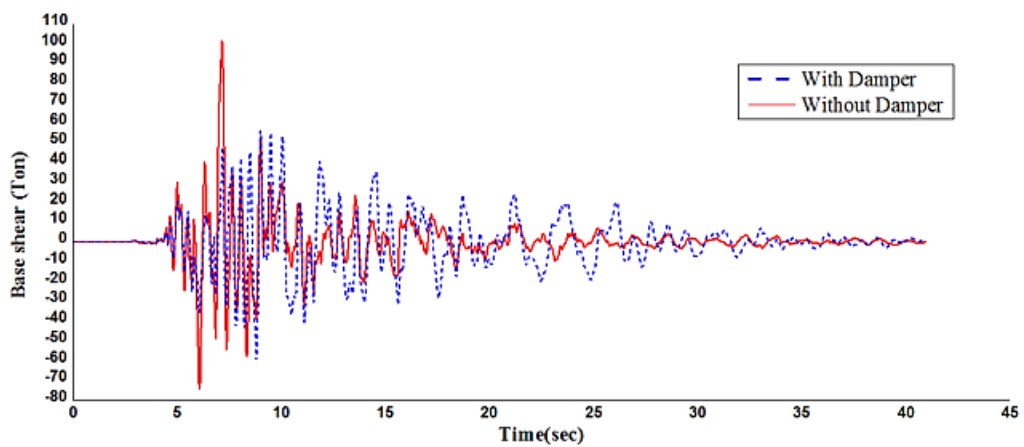
The proposed element significantly reduced the base shear demand in all frames and for all three ground motions, as shown in *Figs. 8-10*. For instance, under the Kobe earthquake (see *Fig. 8*), the maximum base shear was reduced from 89 tons to 53 tons for the 12-story frame, and from 102 tons to 58 tons for the 23-story frame. On average, the base shear was reduced by 45% across all cases



a.

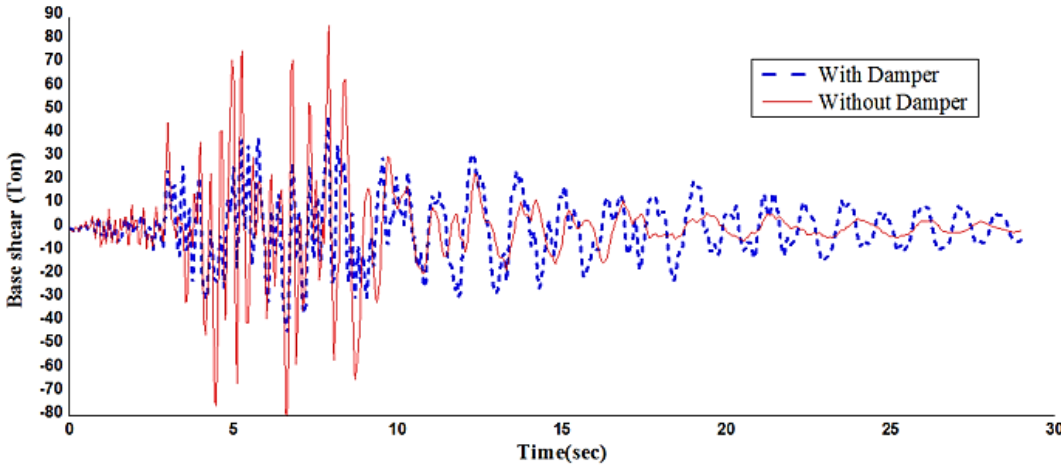


b.

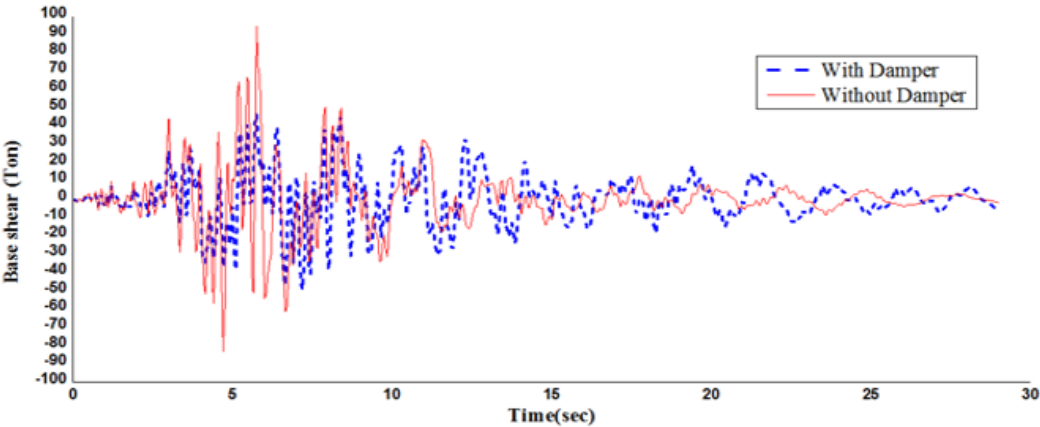


c.

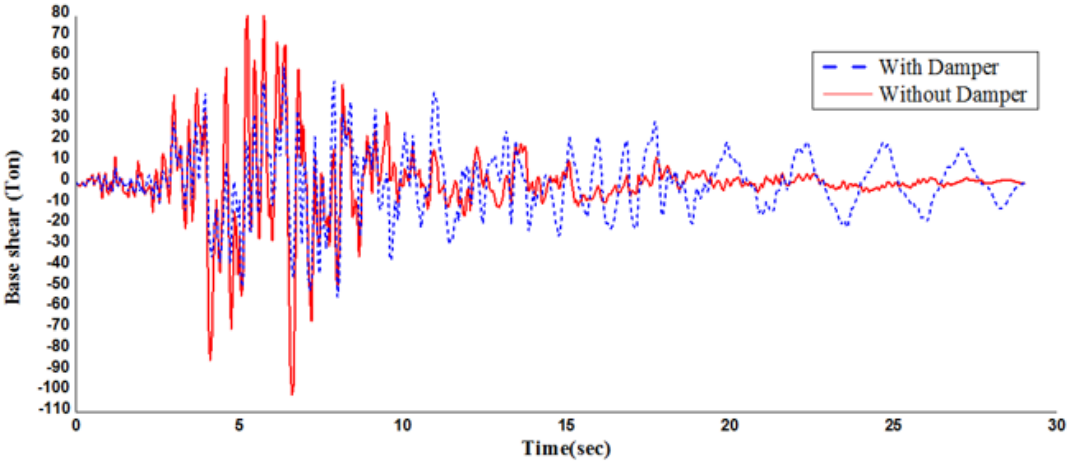
Fig. 8. Comparison of base shear (Kobe); a. 12-story, b. 18-story, and c. 23-story.



a.

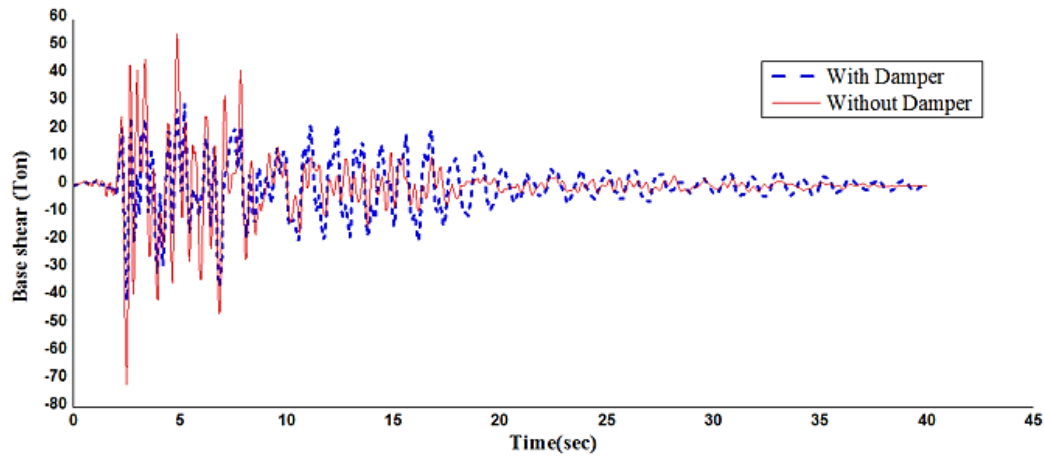


b.

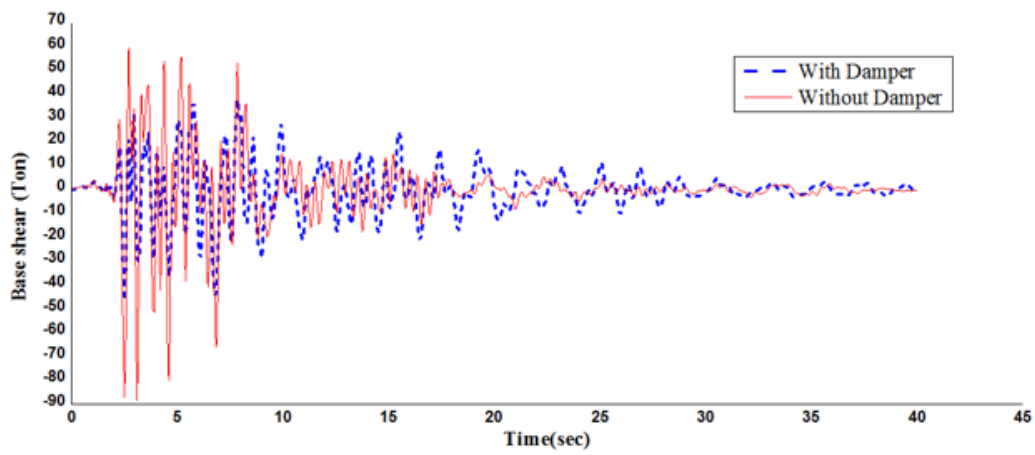


c.

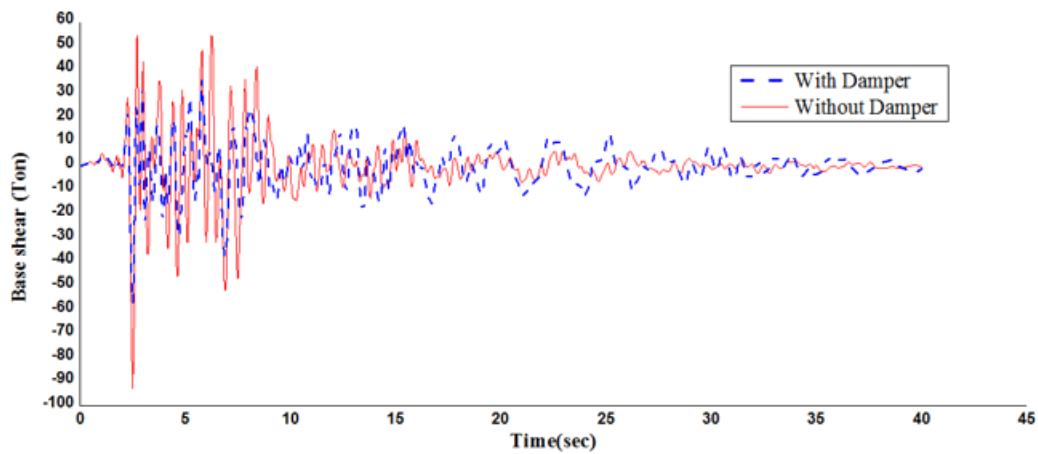
Fig. 9. Comparison of base shear (Northridge); a. 12-story, b. 18-story, and c. 23-story.



a.



b.

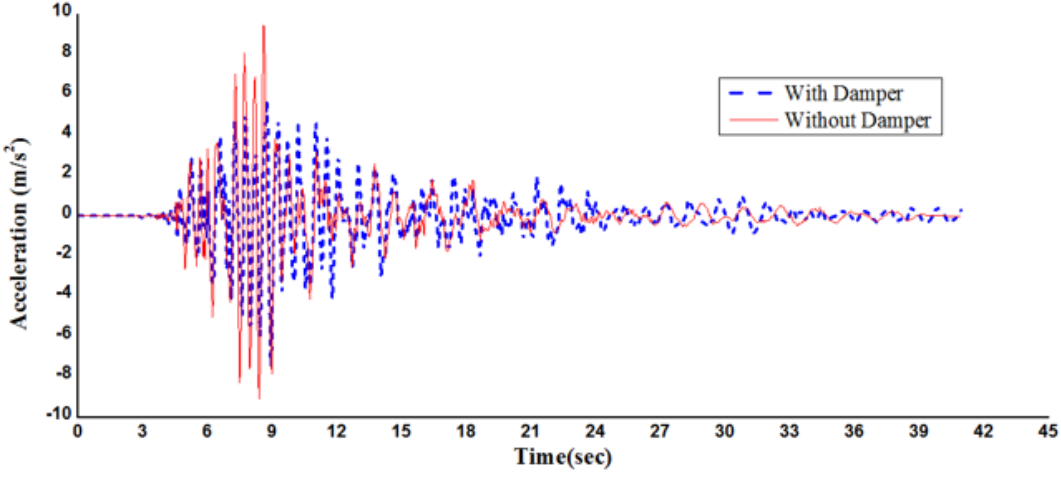


c.

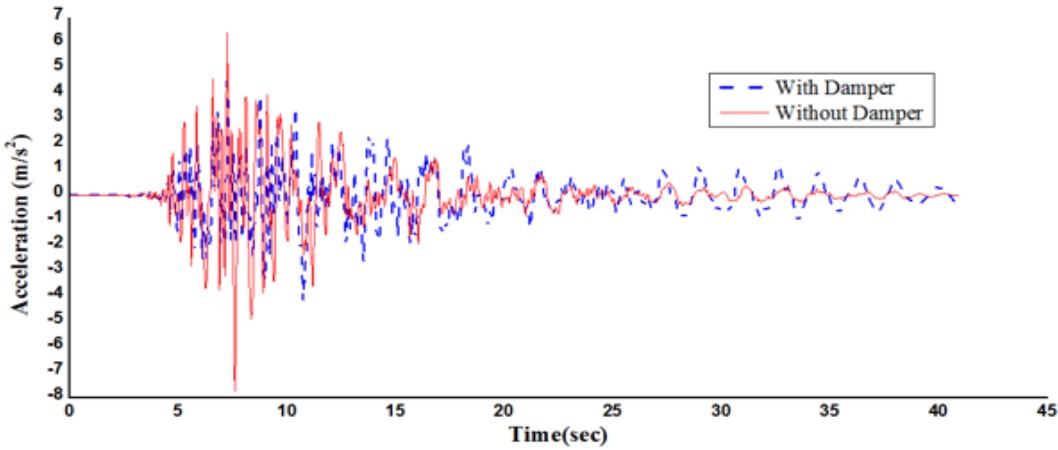
Fig. 10. Comparison of base shear (Loma Prieta); a. 12-story, b. 18-story, and c. 23-story.

### 3.2 | Roof Acceleration

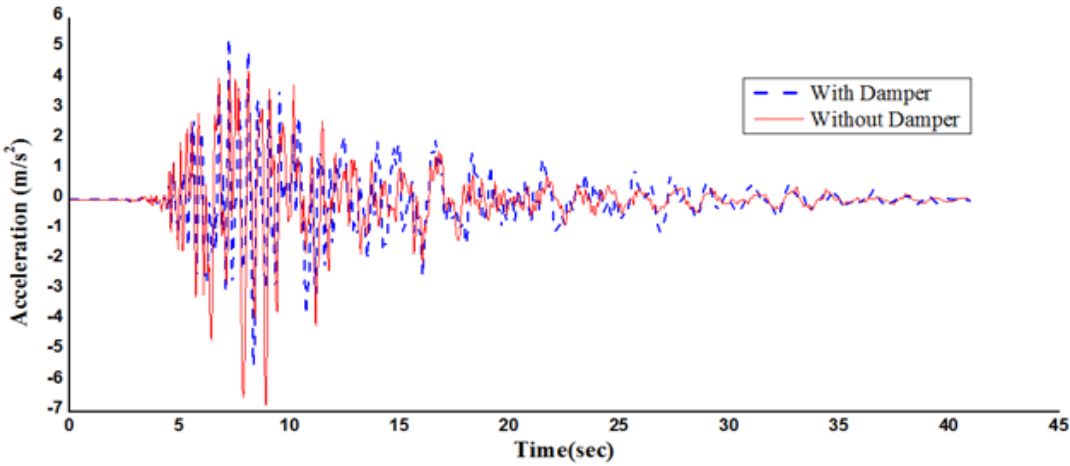
The element also effectively controlled the roof acceleration, reducing it by an average of 40%. This is a critical benefit for the functionality of non-structural components and the comfort of occupants.



a.

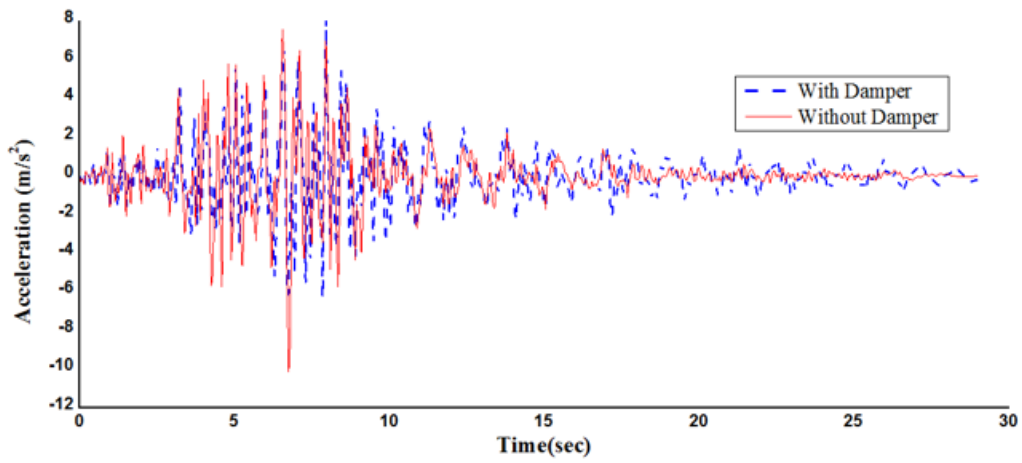


b.

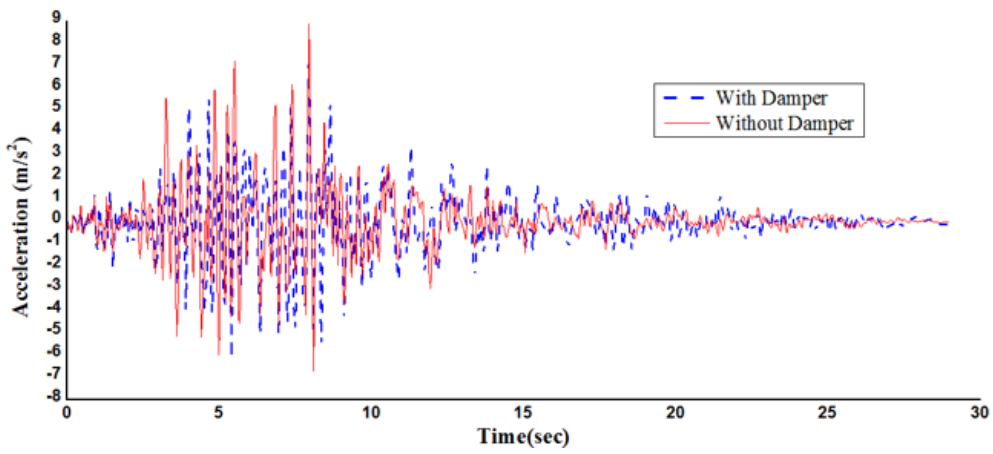


c.

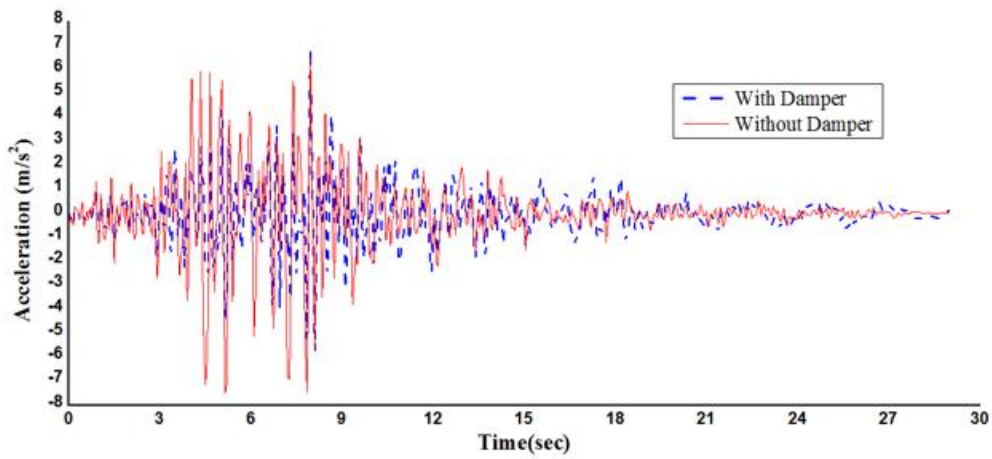
Fig. 11. Comparison of roof acceleration (Kobe); a. 12-story, b. 18-story, and c. 23-story.



a.

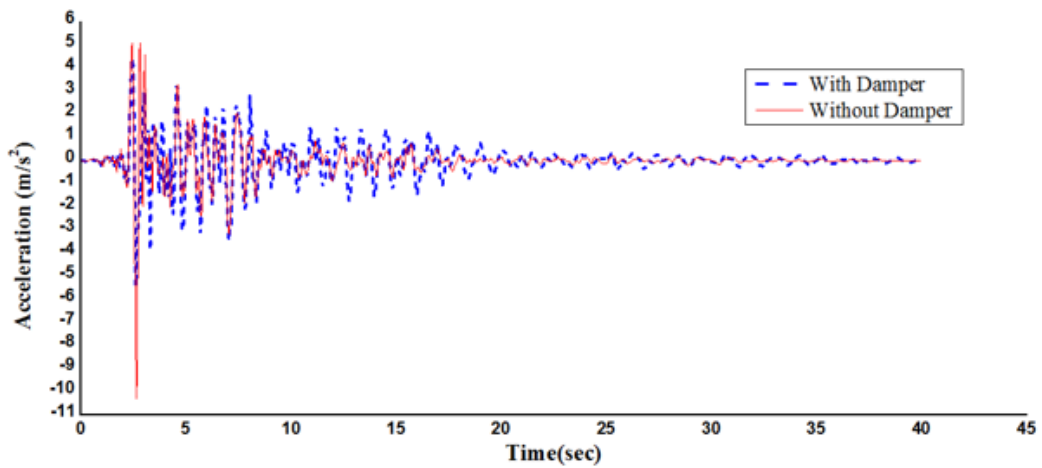


b.

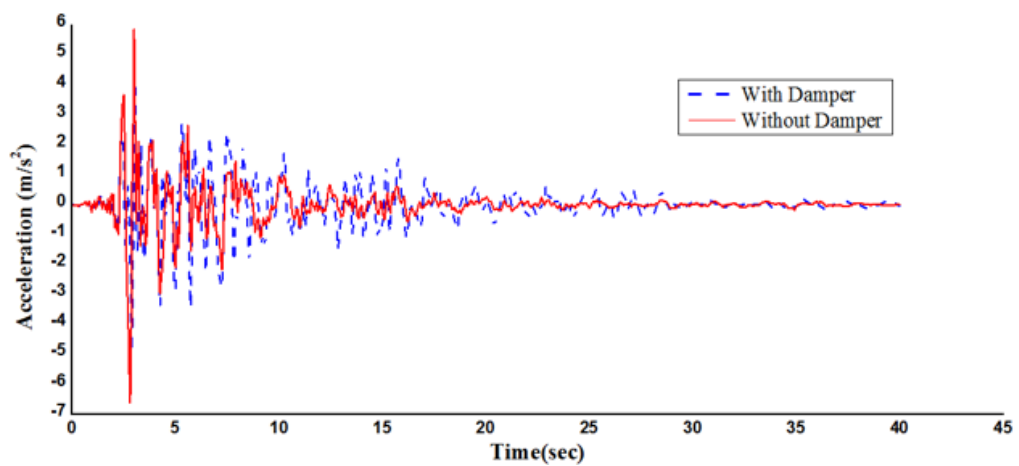


c.

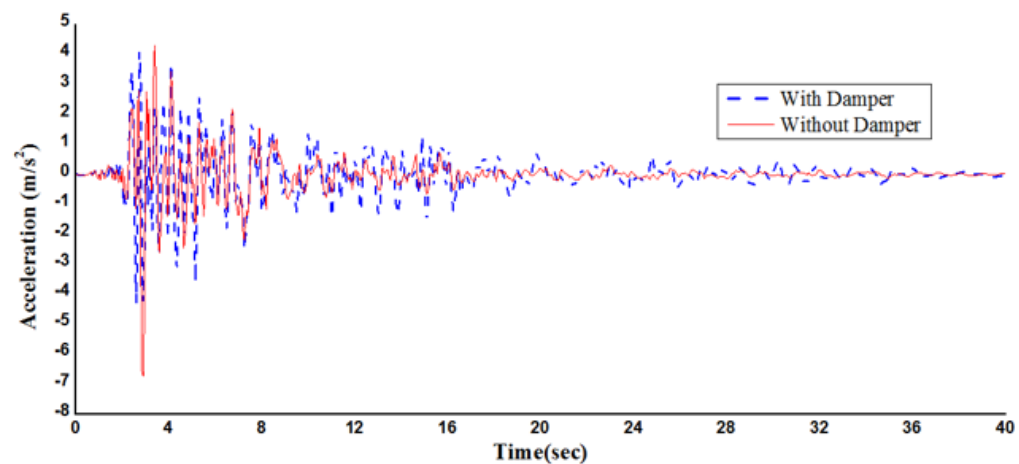
Fig. 12. Comparison of roof acceleration (Northridge); a. 12-story, b. 18-story, and c. 23-story.



a.



b.



c.

Fig. 13. Comparison of roof acceleration (Loma Prieta); a. 12-story, b. 18-story, and c. 23-story.

### 3.3 | Brace Axial Force

One of the primary goals was to protect the main braces from buckling. The results show a substantial reduction, averaging 60%, in the axial force demand on the ground floor brace. This confirms that the DE successfully absorbs a significant portion of the seismic energy, shielding the primary structural members.

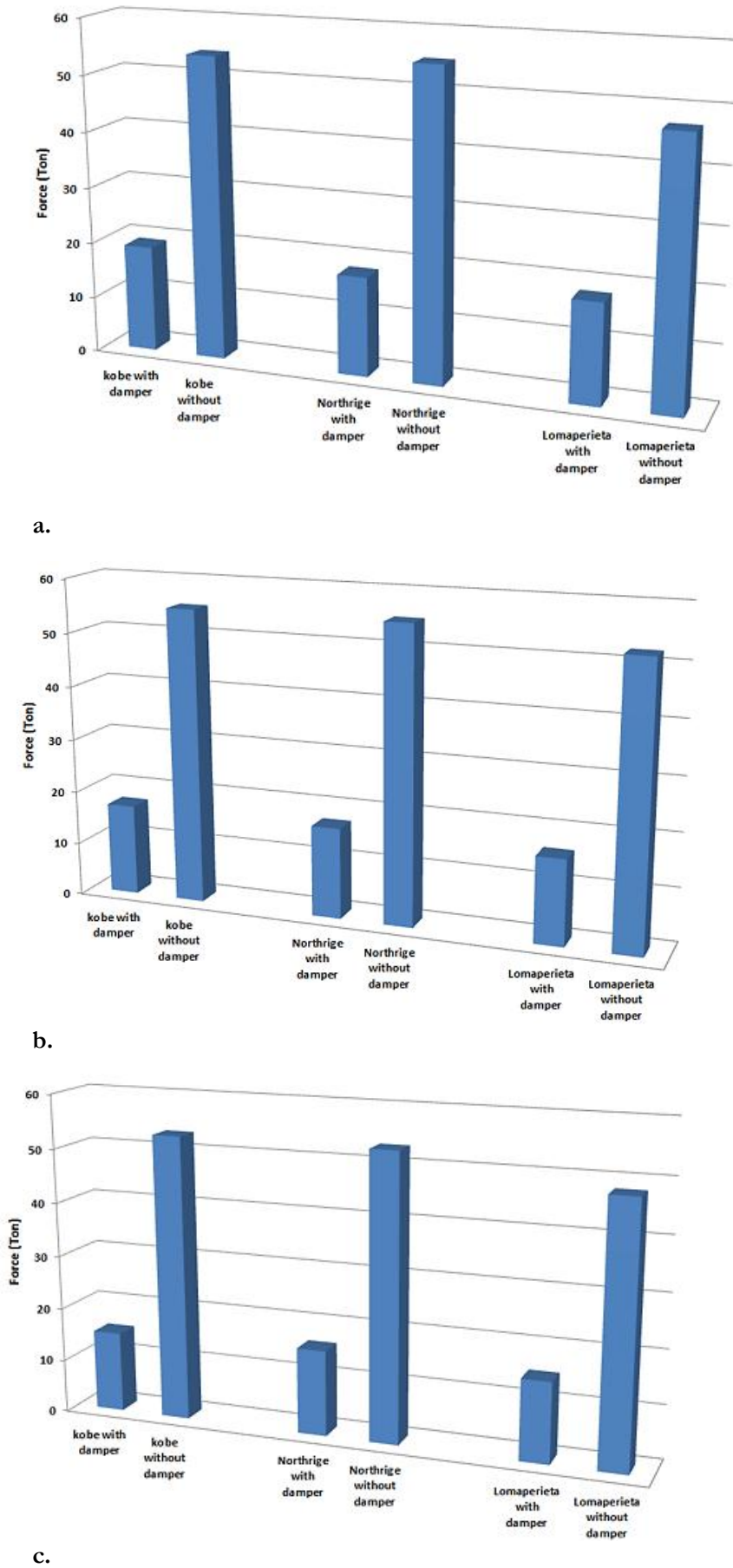


Fig. 14. Comparison of maximum ground floor brace axial force for; a. 12-story, b. 18-story, and c. 23-story frames under all three ground motions.

### 3.4 | Plastic Hinge Formation

The plastic hinge formation patterns, presented in *Figs. 15-17*, provide the most compelling evidence of the proposed element's effectiveness. In the conventional CBF, numerous plastic hinges formed in the braces (at LS and IO levels) and even in some columns under the Loma Prieta earthquake. In stark contrast, the frames equipped with the CBF-DE exhibited no plastic hinges in any primary structural member (beams, columns, or main braces). All inelastic deformation, and hence all damage, was successfully concentrated within the replaceable DE itself. This demonstrates a true structural fuse mechanism and ensures the frame remains nearly elastic and fully functional after a major seismic event.

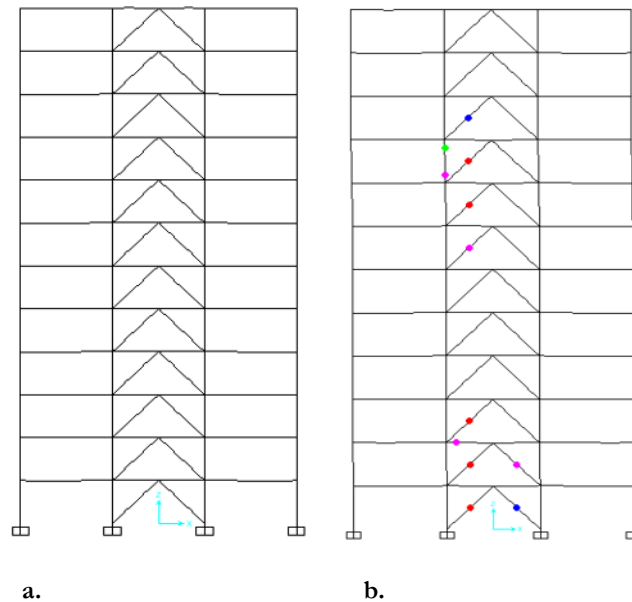


Fig. 15. Plastic hinge formation (Kobe, 12-story); a. Frame with proposed element (No hinges), and b. Conventional Chevron frame (Hinges in braces).

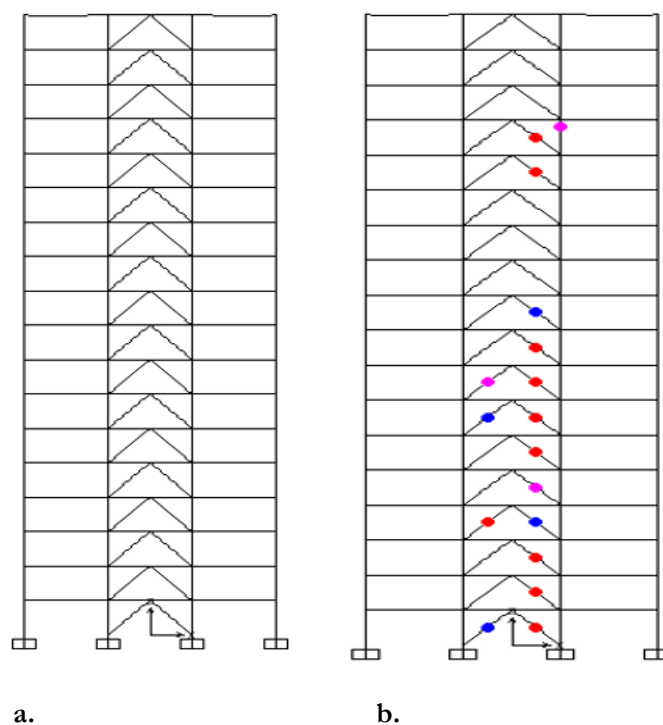


Fig. 16. Plastic hinge formation (Northridge, 18-story); a. Frame with proposed element (No hinges), and b. Conventional Chevron frame (Hinges in braces).

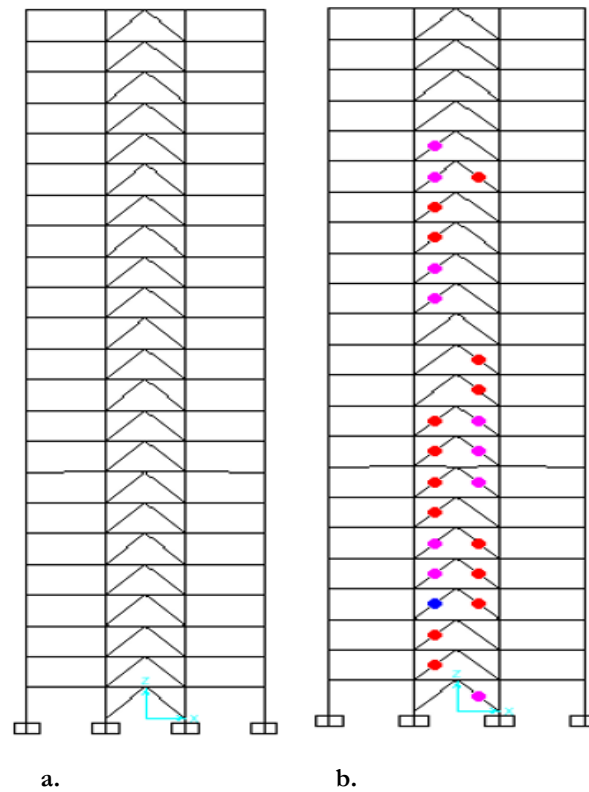


Fig. 17. Plastic hinge formation (Loma Prieta, 23-story); a. Frame with proposed element (No hinges), and b. Conventional Chevron frame (Hinges in braces).

## 4 | Discussion

The findings of this research align with and extend the established literature on passive energy dissipation. The performance observed is comparable to that reported for TADAS, ADAS, and ring spring dampers [5–8]. For instance, similar reductions in base shear (up to 40-50%) have been reported for other yielding damper systems. The main novel contribution of this paper, however, is the specific geometric configuration and the demonstration of its effectiveness in frames of varying heights (up to 23 stories) under near-fault records. A key advantage of the proposed element over traditional BRBs is its location at the brace-beam intersection, which may simplify manufacturing, inspection, and replacement after an earthquake. This focus on "damage concentration and replaceability" is a central tenet of modern performance-based earthquake engineering and resilience-based design [12–14]. Recent studies by Hosseini Bay et al. [15] on trapezoidal dampers also support the concept, but the box-type design presented here offers a different, potentially more robust, mechanism.

## 5 | Conclusions

This study proposed and evaluated a novel ductile energy dissipation element for improving the seismic performance of Chevron braced steel frames. Based on the nonlinear finite element analysis and nonlinear time-history analysis under near-fault ground motions, the following conclusions are drawn:

- I. The proposed element exhibits a stable and repeatable hysteretic behavior, making it an excellent candidate for a structural fuse.
- II. Frames equipped with the proposed element (CBF-DE) showed significantly reduced seismic demand. Average reductions were 45% in base shear, 40% in roof acceleration, and 60% in brace axial force compared to conventional CBF.

- III. Most importantly, the proposed element successfully prevented the formation of plastic hinges in the main structural members (beams, columns, and primary braces). All inelastic damage was concentrated within the easily replaceable device, ensuring the frame's post-earthquake reparability and resilience.
- IV. The proposed element is a simple, cost-effective, and reliable solution for significantly enhancing the seismic performance and damage-control capability of CBF, especially in seismically active regions like Iran.

## 6 | Suggestions for Future Research

- I. Conduct full-scale experimental testing on the proposed element to validate the numerical findings of this study.
- II. Investigate the performance of the proposed system under a wider range of far-field and pulse-type near-fault ground motion records.
- III. Develop a simplified analytical model and design guidelines for engineers to easily size and implement the element in practice.
- IV. Study the low-cycle fatigue behavior of the element to assess its reparability after multiple moderate seismic events.

## Acknowledgments

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## Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

All data generated or analyzed during this study are included within this published article. Additional modeling files and analysis results are available from the corresponding author upon reasonable request.

## Authors' Contributions

S. M. Momeni: Conceptualization, Methodology, Investigation, Writing – Original Draft Preparation, Project Administration.

H. Dashti Naserabadi: Finite Element Modeling, Validation, Formal Analysis, Software.

Gh. Gorji Bandpey: Data Curation, Structural Analysis, Visualization, Interpretation of Results.

H. Alaei: Writing – Review & Editing, Supervision, Validation, Technical Review.

All authors have read and approved the final version of the manuscript.

## Funding

This research received no external funding.

## Consent for Publication

All authors have reviewed and approved the manuscript and consent to its publication.

## Ethics Approval and Consent to Participate

This study did not involve human participants, animals, or personal data requiring ethical approval. Therefore, formal ethics committee approval and participant consent were not required. The research was conducted in accordance with accepted academic and scientific research standards.

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