SEISMIC ANALYSIS OF STRUCTURES EQUIPPED WITH FRICTION DAMPERS UNDER VERTICAL EARTHQUAKE EFFECTS

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Article Info:

Abstract:

This study investigates the seismic performance of moment-resisting frames equipped with rotational friction dampers under simultaneous horizontal and vertical earthquake components. A 9-story steel moment frame was analyzed using nonlinear dynamic time history analysis with five high-magnitude earthquake records. The dampers were designed with a capacity equal to 30% of the base shear force at each story level. Results demonstrate that implementing rotational friction dampers reduces maximum roof displacement by an average of 31% and maximum base shear by 32%. The analysis was performed using OpenSees software, considering both horizontal and vertical earthquake components simultaneously. The friction dampers effectively dissipate seismic energy while maintaining the main structural elements in the elastic range, proving to be an efficient passive energy dissipation system for seismic retrofitting of structures.

Keyword:

Introduction

Modern seismic design philosophy allows structures to undergo controlled inelastic deformation during strong earthquakes, primarily through plastic hinge formation in beams and columns. While this approach ensures life safety, it often results in significant structural and non-structural damage, leading to high repair costs and extended downtime (Babaei & Karimi Ghaleh Jough, 2025a). To address these limitations, passive energy dissipation systems have gained popularity as effective alternatives for seismic protection. Friction dampers represent one of the most practical and cost-effective passive control systems. These devices dissipate seismic energy through friction between sliding surfaces, offering several advantages including stable hysteretic behavior, independence from loading frequency and temperature, and minimal maintenance requirements. The concept of friction damping was first introduced by Keightley in the 1970s, followed by significant developments by Pall and Marsh in the 1980s. Rotational friction dampers (RFD), developed by Mualla, represent an advanced form of friction-based energy dissipation systems. These devices consist of central and side steel plates with friction pad materials sandwiched between them, connected through high-strength bolts and spring washers. The damper rotates about its central axis when subjected to lateral forces, dissipating energy through friction. This research aims to evaluate the effectiveness of rotational friction dampers in reducing seismic response parameters of steel moment frames under combined horizontal and vertical earthquake excitations.

Literature Review

The concept of friction damping for seismic applications was first introduced by Keightley in the late 1970s at Montana State University, focusing on using Belleville washers and steel plates to create friction connections for building damping systems (Keightley, 1977). Building on this foundation, Pall and Marsh developed the Limited Slip Bolted (LSB) connection in the early 1980s, utilizing brake lining materials between steel plates and offering more predictable and stable behaviour (Pall & Marsh, 1982). Their extensive experimental studies demonstrated that friction dampers could significantly reduce structural response while maintaining the main structure in the elastic range.

Mualla introduced rotational friction dampers (RFD) at the Technical University of Denmark in 2000, representing a significant advancement in friction damper technology (Mualla, 2000). These devices consist of a T-shaped central plate rotating between two side plates with special friction pad materials, demonstrating stable energy dissipation characteristics and frequency-independent behavior over hundreds of loading cycles. Mualla and Nielsen conducted parametric studies identifying key design parameters affecting RFD performance, including the geometric shape ratio, bolt clamping force, friction material properties, and damper size, revealing that optimal performance could be achieved with equivalent damping ratios of 15-50% of critical damping (Mualla & Nielsen, 2002).

Recent developments have introduced innovative configurations such as elliptic-braced frames with rotational friction dampers (ELBRF-RFD), which serve as displacement-restraint bracing techniques (Daemi et al., 2024). This study introduces the quantification of seismic performance factors through incremental dynamic analysis, demonstrating significant improvements in seismic resilience. Comprehensive experimental studies involving 27 friction pad material comparison tests found that fiber-reinforced resin-based composite (FRRC) material outperformed traditional materials in achieving high friction coefficient and stable performance (Li et al., 2024). This research addressed three main challenges in RFD performance: avoiding strength fluctuation, enhancing strength, and ensuring uniform pressure distribution.

Advanced friction damper configurations have emerged, including rotational friction dampers with restoring force, consisting of rotational friction pads with heavy-duty torsional springs (Naeem & Kim, 2020). Non-preload variable friction dampers (NVFD) have been developed, which do not require preloading and combine inerter elements, featuring an amplification effect that results in more significant damping performance (Liu et al., 2024). Motion amplified rotational friction dampers (RAFD) have been proposed, which can realize several times amplified friction force for a given normal load due to the adopted amplification system (Chen et al., 2023). Analytical and experimental results demonstrate that RAFD showcases superior seismic control effectiveness compared to traditional friction dampers.

Recent comparative studies have evaluated friction, self-centering and hybrid self-centering dampers, with superelastic friction dampers operating on a parallel mechanism of shape memory alloy cables and frictional components (Yang et al., 2024; Babaei & Karimi Ghaleh Jough, 2024a). These hybrid systems demonstrate excellent performance in reducing interstory drift ratio, residual interstory drift ratio, and absolute acceleration responses, with 90% of damper deformations recovered.

Limited research has been conducted on friction damper performance under combined horizontal and vertical earthquake components. The analysis of current provisions indicates that the absence of clear guidelines on the use of the vertical seismic component can be strongly non-conservative for certain structures. Chen et al. reported that although peak vertical accelerations are generally lower than horizontal components, recent worldwide earthquakes have demonstrated cases where vertical accelerations exceed horizontal values, particularly in near-fault regions. Such observations indicate that neglecting vertical excitation may lead to underestimation of seismic demand. From an architectural and structural configuration perspective, Manoukas showed that transfer structures introducing vertical irregularity significantly increase structural vulnerability to vertical ground motion effects (Chen et al., 2025; Manoukas, 2026).

Most studies have focused primarily on horizontal excitation effects, leaving a gap in understanding the influence of vertical ground motion on damper effectiveness (Babaei et al., 2024; Babaei & Karimi Ghaleh Jough, 2025b). Recent studies indicate that the ground motion vertical component is typically ignored in analysis, even though damage observed in recent earthquakes suggests that vertical accelerations may significantly influence structural response (Di Michele et al., 2020; Karimi Ghaleh Jough & Babaei, 2025a; Babaei & Karimi Ghaleh Jough, 2024c).

Recent developments in machine-learning technology have rapidly progressed in earthquake seismology, achieving great success in catalog development, seismicity analysis, and ground-motion prediction (Mousavi & Beroza, 2024). Artificial intelligence has emerged as a powerful tool for structural health monitoring that considerably improves accuracy, robustness, and operational efficiency (Karimi Ghaleh Jough & Babaei, 2025b). These advances are being integrated with traditional finite element modeling approaches using platforms like OpenSees for enhanced seismic analysis capabilities.

Recent multi-hazard studies have investigated the effectiveness of friction dampers for connected steel buildings under uncorrelated seismic ground motion and wind excitations (Malhotra et al., 2020). Results show that friction dampers are more effective for low-rise buildings under seismic ground motions, whereas the same control devices show effectiveness for high-rise buildings under wind effects. Comprehensive assessments have been conducted on damper performance in mainshock-aftershock sequences, demonstrating stable performance over multiple cycles.

The integration of optimization algorithms with finite element analysis has enabled optimal damper placement strategies. Genetic algorithms implemented in MATLAB with nonlinear time-history analyses performed in OpenSees have been used to determine optimal placement of energy dissipation devices in steel moment-resisting frames. These computational advances, combined with improved understanding of damper mechanics and material properties, have significantly enhanced the practical application of friction dampers in seismic protection systems.

Current research gaps include the need for more comprehensive studies on vertical earthquake component effects, advanced material development for improved friction properties, integration of artificial intelligence for optimal design and placement, and understanding multi-hazard performance under combined loading scenarios. The present research addresses the gap in understanding vertical earthquake effects by investigating the seismic performance of steel moment frames equipped with rotational friction dampers under simultaneous horizontal and vertical earthquake excitations, providing insights into the actual effectiveness of these systems under realistic loading conditions (Chopra, 2007).

Popov (Popov et al., 1995) investigated slotted bolted connections as an alternative friction damper configuration, demonstrating good energy dissipation characteristics and practical implementation advantages for steel frame applications.

Performance under Vertical Ground Motion

Limited research has been conducted on friction damper performance under combined horizontal and vertical earthquake components. Most studies have focused primarily on horizontal excitation effects, leaving a gap in understanding the influence of vertical ground motion on damper effectiveness and overall structural response.

Chopra (Chopra, 2017b) emphasized the importance of vertical ground motion effects in earthquake engineering, particularly for structures with long spans or specific dynamic characteristics. However, systematic studies on friction damper performance under combined loading scenarios remain limited in the literature. Recent analytical studies have begun to address this research gap. When horizontal and vertical components act simultaneously near

causative faults, larger plastic rotations in structural beams are obtained compared to those resulting from considering only horizontal components. Furthermore, vertical ground motion might increase or decrease horizontal maximum displacement depending on axial load ratios of structural elements and will increase maximum inter-story drift while changing its distribution. The challenge becomes more complex for friction dampers due to their velocity-dependent and pressure-sensitive nature. Ground motion parameters including spectral response acceleration, peak ground acceleration, and effective peak velocity correlate well with displacement demand, though friction damper response cannot maintain optimality when subjected to different seismic excitations owing to passive properties. The interaction between vertical motion-induced axial load variations and friction interface behavior represents a critical research area requiring comprehensive experimental and analytical investigation.

Research Gaps and Motivation

While extensive research has been conducted on friction dampers under horizontal excitation, the combined effects of horizontal and vertical earthquake components on damper performance require further investigation. Most existing studies focus on single-component loading, potentially underestimating or overestimating the actual performance under realistic earthquake scenarios.

The present research addresses this gap by investigating the seismic performance of steel moment frames equipped with rotational friction dampers under simultaneous horizontal and vertical earthquake excitations, providing insights into the actual effectiveness of these systems under realistic loading conditions.

Methodology

This study employed a comprehensive numerical investigation to evaluate the seismic performance of steel moment frames equipped with rotational friction dampers under simultaneous horizontal and vertical earthquake excitations. A nine-story steel moment frame was modeled using the OpenSees finite element platform, incorporating nonlinear material properties with Steel02 constitutive models and fiber-based cross-sections to accurately capture the inelastic structural response. The rotational friction dampers were strategically positioned in the central bay of each floor to maintain structural symmetry and minimize torsional effects. The capacity of the rotational friction dampers was selected as 30% of the story shear demand based on established practice in friction-based energy dissipation systems. Previous experimental and numerical studies have shown that sizing friction dampers within a moderate fraction of the story or base shear (typically on the order of 20–40%) provides effective response reduction without excessively increasing structural stiffness or force demand on primary members (Mualla & Belev, 2015). In line with performance-based seismic design principles adopted in guidelines such as FEMA 356, the selected capacity represents a balanced design choice that ensures efficient energy dissipation while preserving the intended global behavior of the moment-resisting frame.

Five ground motion records were carefully selected from the PEER Strong Motion Database based on specific criteria including magnitude range (6.0-7.0), epicentral distance (20-45 km), and soil conditions (Type III with shear wave velocity 175-375 m/s). Each record was scaled according to FEMA 356 procedures to ensure compatibility with the design response spectrum (FEMA, 2000). In performance-based seismic assessment and nonlinear dynamic analysis,

using a minimum of five spectrally matched records is widely adopted to capture response variability and reduce dispersion in engineering demand parameters. The analysis protocol consisted of nonlinear time history analyses performed on both the bare frame and the damper-equipped frame configurations under simultaneous application of horizontal and vertical earthquake components. Rayleigh damping with 5% critical damping ratio was implemented for the first and third modes to represent inherent structural damping. Key response parameters including maximum roof displacement and base shear were extracted and compared between the two configurations to quantify the damper effectiveness. The methodology incorporated geometric nonlinearity and P-Delta effects to ensure realistic representation of large displacement behavior under severe seismic excitation.

Analysis Procedure

The nine-story steel moment frame was modeled using OpenSees finite element software, beginning with geometric specifications as shown in Figure 1. The structure featured 4-meter bay spans and 3.2-meter story heights, designed according to Iranian Standard 2800 (4th edition) with regular configuration to permit two-dimensional modeling. Steel material properties were defined using Steel02 constitutive models with yield strength of 2400 kg/cm² and elastic modulus $E = 2 \times 10^6$ kg/cm², as illustrated in Figure 2. The material model employed a bilinear stress-strain relationship with gradual transition from elastic to inelastic behavior, avoiding the abrupt yielding characteristic of Steel01 models.
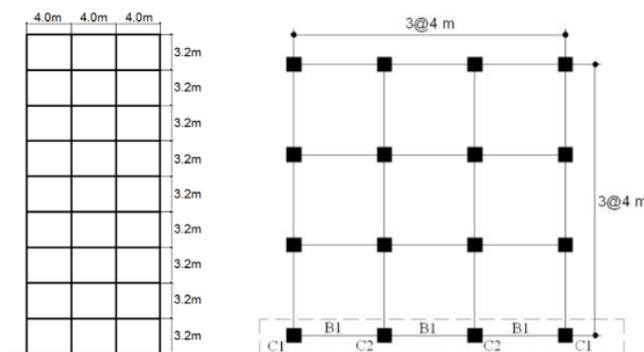

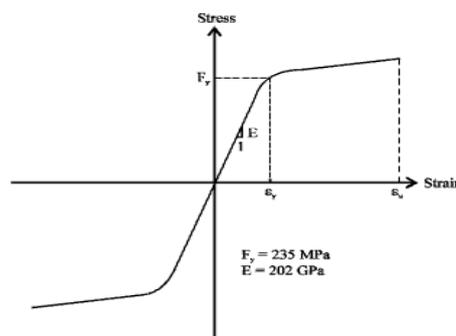**Figure 1: Three-Dimensional View and Geometric Specifications of The Moment Frame**

Figure 2: Stress-Strain Curve of Steel02 Material

The 9-story steel moment frame utilized varying cross-sections optimized for each floor level. The lower three stories (1-3) employed IPB280 and IPB360 sections for interior and exterior columns respectively, with IPE360 beams. The middle stories (4-6) used IPB240 and IPB300

columns with IPE360 and IPE300 beams respectively. The upper three stories (7-9) incorporated IPB240 and IPB280 columns with IPE300 beams throughout. This section distribution follows typical design practice where heavier sections are used in lower stories to accommodate higher load demands, transitioning to lighter sections in upper levels. NonlinearBeamColumn elements with five integration points were employed for all frame members, incorporating P-Delta effects through local-to-global coordinate transformations. Nodal masses were concentrated at beam-column joints based on tributary area calculations, incorporating dead loads (2400 kg/m) and 20% of live loads (800 kg/m) as specified in seismic design provisions.
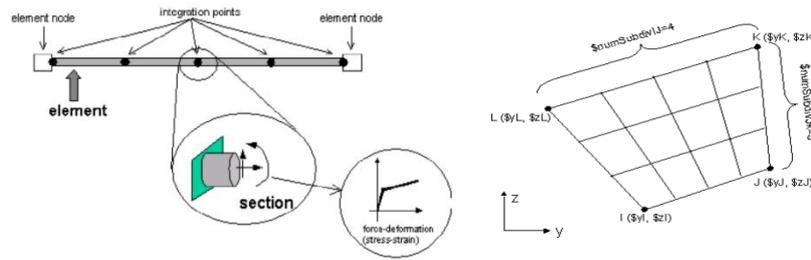

Figure 3: Method Of Defining Fiber Sections in Opensees

The loading sequence commenced with static gravity analysis followed by dynamic earthquake analysis. Five ground motion records were selected from the PEER database based on magnitude range (6.0-7.0), epicentral distance (20-45 km), and site conditions (Type III soil with Vs = 175-375 m/s), as summarized in Table 1. Each record was scaled according to FEMA 356 procedures, ensuring minimum spectral acceleration values over the period range of 0.2T to 1.5T exceeded code-specified design spectra. Rayleigh damping with 5% critical damping ratio was implemented using the first and third modal frequencies according to Equations 1 and 2.

Table 1: Specifications Of Accelerograms Applied to The Structure

| Earthquake Record	PGA (g)	Time	Duration
Landers (1992)	0.13	0.005	38
Chi-Chi Taiwan (1999)	0.137	0.004	44.52
El Mayor-Cucapah (2010)	0.227	0.005	39.44
Darfield New Zealand (2010)	0.176	0.005	31
Kobe (1995)	0.214	0.01	28

$$C = \alpha M + \beta K \tag{1}$$

$$\beta = \frac{2\xi_1\omega_1 - 2\xi_m\omega_m}{\omega_1^2 - \omega_m^2} \tag{2}$$

Rotational friction dampers were modeled using the moment-rotation relationship shown in Figure 4, with capacity determined as 30% of story shear force following established optimization guidelines. Bracing elements with cross-sectional areas specified in Table 2 were designed to ensure 30% stiffness contribution from the damping system. The dampers were positioned in the central bay of each floor to maintain structural symmetry and minimize torsional effects, as depicted in Figure 4.

Table 2: Base Shear Force and Capacity of Dampers Used in Different Floors of The Structures

Story	Base Shear (ton)	Damper Capacity (ton)	Brace Cross-Section
9	24.08	7.22	2.02
8	28.77	8.63	2.47
7	32.89	9.87	2.7
6	36.42	10.93	2.99
5	39.38	11.81	3.31
4	41.76	12.53	3.43
3	43.54	13.06	3.4
2	44.73	13.42	3.4
1	45.33	13.6	6.28
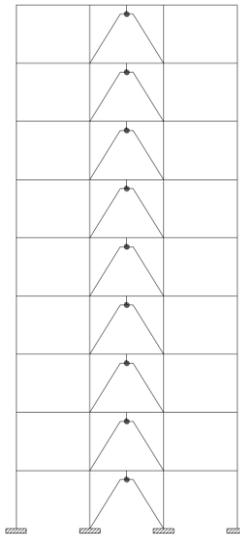
Figure 4: Damper Placement Layout in The Moment Frame

Result and Discussion

The seismic response analysis presented in this study examines the structural behavior of a building system under five distinct earthquake ground motion records: Landers, Chi-Chi, El Mayor, Darfield (New Zealand), and Kobe. These earthquakes represent diverse seismic characteristics in terms of magnitude, frequency content, duration, and intensity, providing a comprehensive evaluation of structural performance under varying seismic excitations. The analysis focuses on two critical response parameters: maximum structural displacement and base shear forces, which are fundamental indicators of structural performance and safety under seismic loading conditions. Figure 5 compares maximum structural displacements across the five earthquake records. Chi-Chi earthquake produces the highest displacement (0.300 m), attributed to its long-duration, near-field characteristics with significant velocity pulses. Darfield shows the second-highest response (0.258 m), reflecting intense ground motion characteristics. Landers demonstrates moderate displacement (0.200 m), while El Mayor and Kobe produce lower responses (0.151 m and 0.140 m, respectively). The variation indicates

that displacement demands are highly dependent on earthquake frequency content and duration rather than magnitude alone.
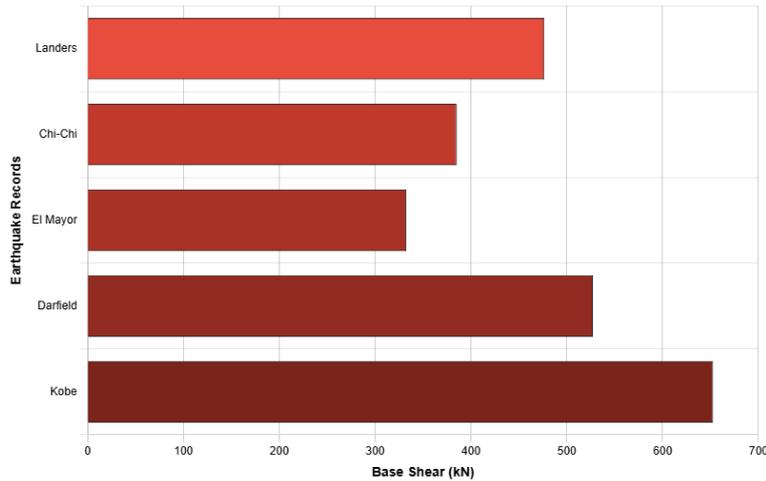

Figure 5: Maximum Structural Displacement Comparison Across Five Earthquake Records.

Figure 6 illustrates base shear force demands using horizontal bars. Kobe earthquake generates the highest base shear (652.6 kN), significantly exceeding other records due to its high-frequency content and intense accelerations. This explains Kobe's devastating impact despite lower displacement values. Darfield produces the second-highest base shear (527.4 kN), followed by Landers (476.5 kN). Chi-Chi and El Mayor show lower force demands (385.1 kN and 332.7 kN), indicating different dynamic response mechanisms dominated by displacement rather than acceleration.
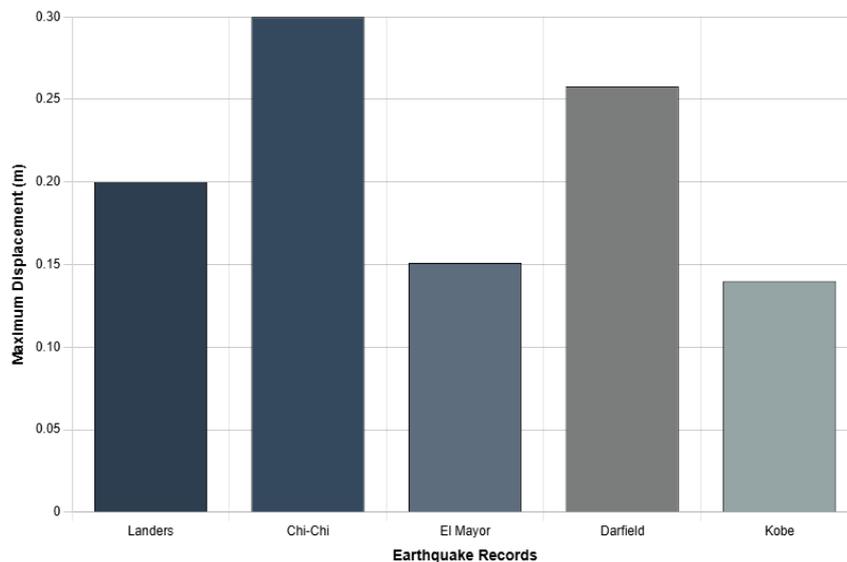

Figure 6: Base Shear Force Comparison Showing Structural Force Demands Under Different Earthquake Ground Motions

Figure 7 presents a dual-axis representation combining displacement and base shear responses to reveal the complex relationship between these two fundamental seismic response parameters. The chart employs bars for displacement values (left axis) and a connected line

with markers for base shear forces (right axis), enabling direct comparison and correlation analysis.

The most significant observation from this combined representation is the apparent inverse relationship between displacement and base shear responses. While Chi-Chi earthquake produces the maximum displacement (0.300 m), it generates a moderate base shear force (385.1 kN). Conversely, Kobe earthquake exhibits the minimum displacement (0.140 m) while producing the maximum base shear force (652.6 kN). This inverse correlation suggests fundamentally different dynamic response mechanisms governing these two parameters.

The displacement-to-base shear relationship can be explained through the lens of structural dynamics and frequency content analysis. Large displacement responses typically indicate significant fundamental mode participation, characterized by lower frequencies and longer periods. In contrast, high base shear forces often result from higher-mode contributions, involving shorter periods and higher frequencies. Ground motions with rich low-frequency content (like Chi-Chi) tend to excite fundamental modes effectively, producing large displacements with moderate forces. Conversely, ground motions with significant high-frequency content (like Kobe) activate higher-order modes, resulting in substantial force amplification with limited displacement response.

The Darfield earthquake presents an interesting case, showing both high displacement (0.258 m) and high base shear (527.4 kN) responses. This suggests that Darfield ground motion contains broad-band frequency content capable of exciting multiple vibration modes simultaneously, resulting in significant response amplification across both displacement and force parameters. The Landers earthquake demonstrates moderate values for both parameters (0.200 m displacement, 476.5 kN base shear), indicating balanced frequency content affecting various structural modes. El Mayor earthquake shows consistently low responses for both parameters, suggesting limited energy content across all relevant frequency ranges. This relationship analysis has profound implications for seismic design philosophy. Structures designed primarily for displacement limits (such as drift-controlled systems) may experience unexpected force demands under certain ground motions. Similarly, force-based design approaches may inadequately address displacement-controlled failure modes under specific seismic scenarios.
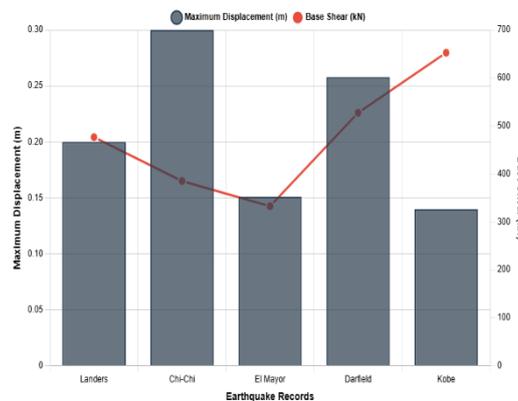

Figure 7: Dual-Axis Comparison Showing the Relationship Between Maximum Displacement (Bars) And Base Shear Forces (Line with Markers) For Each Earthquake Record

Table 3 provides a comprehensive quantitative summary of the seismic response analysis, including maximum displacement, base shear forces, and their calculated ratios. The displacement-to-base shear ratio serves as a normalized parameter for comparing relative structural behavior across different earthquake scenarios. The displacement/base shear ratios reveal significant variation, ranging from 0.214×10^{-3} (Kobe) to 0.779×10^{-3} (Chi-Chi), representing a 264% difference between extreme values. Chi-Chi earthquake exhibits the highest ratio, confirming its displacement-dominated response characteristics. This elevated ratio indicates efficient fundamental mode excitation with limited higher-mode participation. The Kobe earthquake demonstrates the lowest ratio, consistent with its force-dominated response pattern. The low ratio suggests predominant higher-mode contributions resulting in substantial force amplification relative to displacement response. This characteristic is particularly important for understanding potential brittle failure modes under Kobe-type ground motions.

The intermediate ratios observed for Darfield (0.489×10^{-3}), El Mayor (0.454×10^{-3}), and Landers (0.420×10^{-3}) indicate more balanced response characteristics. These earthquakes produce moderate-to-low ratios, suggesting mixed-mode participation with varying degrees of displacement and force contributions. The statistical analysis of the displacement/base shear ratios provides insight into the expected range of structural behavior under different seismic scenarios. The mean ratio of 0.471×10^{-3} with a standard deviation of 0.189×10^{-3} indicates substantial variability requiring careful consideration in design applications. These quantitative relationships are essential for developing performance-based seismic design criteria, establishing appropriate acceptance limits for both displacement and force-based assessment procedures, and understanding the complex interplay between ground motion characteristics and structural response mechanisms. The data presented in Table 3 supports the development of empirical relationships for preliminary design estimation and provides benchmark values for validating numerical modeling approaches in seismic analysis applications.

Table 3: Quantitative Summary of Seismic Response Parameters Showing Maximum Displacement, Base Shear Forces, And Their Ratios for Structural Performance Evaluation

Earthquake Record	Maximum Displacement (m)	Base Shear (kN)	Displacement/Base Shear Ratio ($\times10^{-3}$)
Landers	0.2	476.5	0.42
Chi-Chi	0.3	385.1	0.779
El Mayor	0.151	332.7	0.454
Darfield	0.258	527.4	0.489
Kobe	0.14	652.6	0.214

Figure 8. To better evaluate the structural performance of the controlled building, an additional engineering demand parameter, namely the maximum inter-story drift ratio (IDR), is introduced. The IDR responses of the controlled (with rotational friction dampers) and uncontrolled (bare) nine-story frame are compared for the selected earthquake records. The results indicate an average reduction of approximately 23% in maximum inter-story drift due to the installation of friction dampers, while all drift ratios of the controlled structure remain below the allowable limit of 0.02 specified by the seismic design guideline.
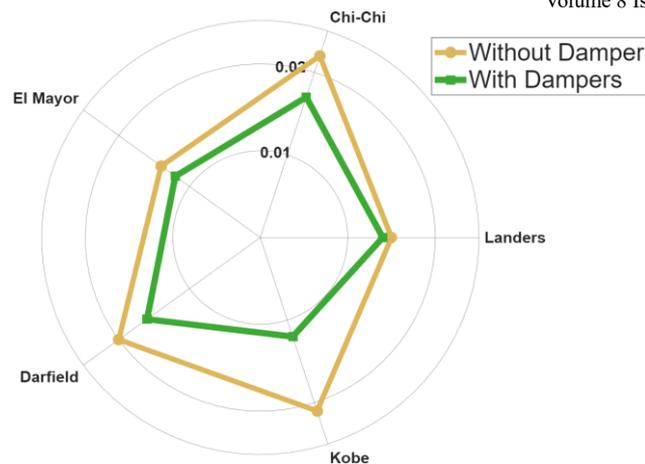
Figure 8. Comparison Of Maximum Inter-Story Drift Ratios (IDR) Of the Nine-Story Frame with And Without Rotational Friction Dampers Under Five Earthquake Records.

From a practical engineering perspective, the results of this study demonstrate that rotational friction dampers can effectively control seismic response while satisfying deformation-based design requirements specified in current seismic guidelines. The controlled structure exhibited inter-story drift ratios below the commonly adopted allowable limit of 0.02, indicating acceptable performance under combined horizontal and vertical earthquake excitations. These findings support the applicability of rotational friction dampers as a viable seismic retrofitting solution for existing steel moment-resisting frames, as they can be implemented without significant alteration of the primary structural system. Furthermore, the observed influence of vertical ground motion highlights the importance of considering simultaneous horizontal and vertical components in performance-based seismic evaluation and retrofit design.

Conclusion

This study demonstrates the effectiveness of rotational friction dampers in enhancing the seismic performance of steel moment frames under combined horizontal and vertical earthquake excitations. The research reveals significant improvements in structural response control, with the dampers achieving an average 31% reduction in maximum roof displacement across five earthquake records, though performance variations were observed based on specific earthquake characteristics. This displacement control capability demonstrates the dampers' effectiveness in limiting structural deformation during seismic events.

The force reduction capabilities of the rotational friction dampers proved equally impressive, delivering a consistent 32% average reduction in maximum base shear across all test scenarios. This substantial force reduction indicates effective load limitation on primary structural elements, which translates to reduced stress demands on the main structural system. The dampers exhibited reliable performance characteristics, maintaining stable energy dissipation behavior across different earthquake intensities and frequency contents, demonstrating their robustness under varying seismic conditions.

The design methodology validation confirmed that the 30% capacity design rule proves effective for achieving significant response reductions while maintaining overall system stability. This finding provides valuable guidance for practical implementation of these

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dampers in real-world applications. From a practical standpoint, the rotational friction dampers can be readily integrated into existing moment frame systems, making them particularly suitable for seismic retrofitting applications where structural enhancement is needed without major modifications to the primary structural system.

The research confirms that rotational friction dampers represent a viable and effective passive energy dissipation system for seismic protection of steel structures. Future research should investigate the performance under near-field earthquakes and explore optimization strategies for different structural configurations to further advance the application of this promising seismic protection technology.

References

Babaei, S., & Karimi Ghaleh Jough, F. (2025a). Retrofitting for Resilience: Seismic Rehabilitation and Life Cycle Cost Analysis of A Reinforced Concrete School in Nicosia After The 2023 Turkey Earthquakes. Konya Journal of Engineering Sciences, 13(4), 1232-1251. doi:10.36306/konjes.1626828

Babaei, S., & Karimi Ghaleh Jough, F. (2024a). Parametric Study of Vertically Isolated Steel Braced Frames Controlled by Shape Memory Alloys. Journal of Applied Engineering Sciences, 14(2), 194-201. doi:10.2478/jaes-2024-0024

Babaei, S., & Karimi Ghaleh Jough, F. (2025b). Seismic Rehabilitation of a Reinforced Concrete School in Northern Cyprus Following the 2023 Turkey Earthquake Sequences. Gazi University Journal of Science Part A: Engineering and Innovation, 12(1), 213-227. doi:10.54287/gujsa.1590807

Babaei, S., Karimi Ghaleh Jough, F., Beydola, A., & Habib, A. (2024). Seismic Rehabilitation and Nonlinear Analysis of a Reinforced Concrete School in Nicosia Following the 2023 Kahramanmaraş Earthquake Sequences. Paper presented at the 3rd National Civil Engineering Symposium, Kyrenia, Northern Cyprus.

Babaei, S., & Karimi Ghaleh Jough, F. (2024b). A Comprehensive Evaluation of Tuned Vertical Isolation System for Seismic Risk Mitigation. Journal of Applied Engineering Sciences, 14(1), 27-34. doi:10.2478/jaes-2024-0004

Chen, L., Wang, B., & Zhou, X. (2023). Analytical and experimental investigation of a motion amplified rotational friction damper. Engineering Structures, 289, 116265.

Chen, W., Wang, J., Dai, K., Hassanein, M. F., & Sharbati, R. (2025). Seismic rocking fragility analysis of unanchored nonstructural components under combined horizontal and vertical near-fault ground motions. Journal of Building Engineering, 107, 112645. https://doi.org/10.1016/j.jobe.2025.112645

Chopra, A. K. (2007). Dynamics of structures: Theory and applications to earthquake engineering (3rd ed.). Pearson Prentice Hall.

Chopra, A. K. (2017). Dynamics of structures: Theory and applications to earthquake engineering (5th ed.). Pearson Education.

Daemi, F., Habibi, M. R., Tavana, M. H., & Eivani, H. (2024). Seismic performance factors of elliptic-braced frames with rotational friction dampers through IDA. Practice Periodical on Structural Design and Construction, 29(4).

Di Michele, F., Cantagallo, C., & Spacone, E. (2020). Effects of the vertical seismic component on seismic performance of an unreinforced masonry structure. Bulletin of Earthquake Engineering, 18, 1635–1656.

Federal Emergency Management Agency. (2000). Prestandard and commentary for the seismic rehabilitation of buildings (FEMA 356). Washington, DC.

Karimi Ghaleh Jough, F., & Babaei, S. (2025a). Seismic performance evaluation of space-frame structures using nonlinear static and time-history analyses. [Uzay kafes yapılarının sismik performansının doğrusal olmayan statik ve zaman-tarih analizleri ile değerlendirilmesi]. Niğde Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi, 14(2), 659-667. doi:10.28948/ngumuh.1633034

Karimi Ghaleh Jough, F., & Babaei, S. (2025b). Fuzzy Logic Applications in Advanced Seismic Collapse Prediction of Steel Moment Frames Accounting for Sources of Uncertainty. Paper presented at the International Conference on Engineering, Natural Sciences, and Technological Developments (ICENSTED 2025), Bayburt, Türkiye.

Keightley, W. O. (1977). Vibrational energy absorption for structures. Proceedings of the 6th World Conference on Earthquake Engineering, New Delhi, India.

Li, J., Zhang, Y., Wang, X., & Chen, M. (2024). Experimental study of rotational friction damper for seismic response control: Friction material comparison and configuration optimization. Engineering Structures, 300, 117235.

Liu, Y., Wang, Z., Li, H., & Zhang, J. (2024). Design, manufacturing, and testing of a non-preload variable friction damper for seismic application of buildings. Structural Control and Health Monitoring, 2024, 9573096.

Malhotra, A., Garg, A., & Behl, A. (2020). Effectiveness of friction dampers in seismic and wind response control of connected adjacent steel buildings. Shock and Vibration, 2020, 8304359.

Manoukas, G. (2026). Implications of vertical ground motion on reinforced concrete frame buildings with beams supporting columns. Structures, 84, 111051. https://doi.org/10.1016/j.istruc.2025.111051

Mousavi, S. M., & Beroza, G. C. (2024). Recent advances in earthquake seismology using machine learning. Earth, Planets and Space, 76, 27.

Mualla, I. H. (2000). Experimental and computational evaluation of a novel friction damper device (Doctoral dissertation, Technical University of Denmark, Copenhagen).

Mualla, I. H., & Nielsen, L. O. (2002). A friction damping system for earthquake motions. Earthquake Engineering and Structural Dynamics, 31(8), 1489–1514.

Mualla, I., & Belev, B. (2015). Analysis, design and applications of rotational friction dampers for seismic protection. Budownictwo i Inżynieria Środowiska, 199. https://doi.org/10.7862/rb.2015.199

Naeem, A., & Kim, J. (2020). Seismic retrofit of structures using rotational friction dampers with restoring force. Advances in Structural Engineering, 23(15), 3321–3334.

Pall, A. S., & Marsh, C. (1982). Response of friction damped braced frames. Journal of Structural Division, ASCE, 108(ST6), 1313–1323.

Popov, E. P., Grigorian, C. E., & Yang, T.-S. (1995). Developments in seismic structural analysis and design. Engineering Structures, 17(3), 187-197.

Standard 2800. (2012). Iranian Code of Practice for Seismic Resistant Design of Buildings. Iran: BHRC.

Yang, W., Huang, J., Li, K., & Chen, S. (2024). Comparative seismic performance evaluation of friction, self-centering and hybrid self-centering dampers. Journal of Constructional Steel Research, 218, 108686.