International Journal of Scientific Research and Engineering Development-– Volume 9 Issue 2, Mar-Apr 2026
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Seismic Performance Evaluation of Steel Moment-Resisting Frames Using Nonlinear Static and Dynamic Analysis – A Survey

Rahul Kumar Choudhary[1], Dr. Anil Kumar Saxena[2]
[1]Research Scholar
[2]Associate Professor
[1,2]Department of Civil Engineering
[1,2]Lakshmi Narain College Of Technology, Bhopal (M.P.)

Abstract

Performance-based seismic evaluation has emerged as a critical framework for understanding the realistic behavior of structural systems subjected to strong ground motions. The reviewed dissertation investigates the seismic performance of a steel moment-resisting frame (SMRF) through the integrated application of nonlinear static (pushover) and nonlinear dynamic (time-history) analysis using ETABS software. The study incorporates material and geometric nonlinearities along with realistic plastic hinge modeling to capture inelastic structural response. Key response parameters such as base shear, roof displacement, inter-story drift, and hinge states are systematically examined. The findings indicate that the structure achieves a maximum base shear capacity of approximately 43,166 kN in the X-direction and 2,452 kN in the Y-direction during pushover analysis, demonstrating adequate strength and ductility. Nonlinear dynamic analysis reveals comparatively higher displacement and drift demands due to cyclic effects and higher-mode participation. Overall, the structure satisfies Life Safety performance objectives under design-level earthquakes while maintaining sufficient reserve strength to prevent collapse. The study emphasizes the limitations of conventional linear analysis methods and highlights the necessity of adopting combined nonlinear analytical approaches for reliable seismic performance assessment of steel moment-resisting frames.

Keywords: Steel moment-resisting frame, nonlinear static analysis, pushover analysis, nonlinear dynamic analysis, seismic performance.

1. Introduction

Earthquake-resistant structural design fundamentally requires a realistic understanding of how structures behave beyond the elastic range when subjected to strong ground motions. Unlike gravity-dominated loading scenarios, seismic excitation introduces complex cyclic forces that induce inelastic deformation, stiffness degradation, redistribution of internal forces, and progressive damage accumulation. Consequently, modern earthquake engineering practice emphasizes not only strength but also ductility, energy dissipation capacity, and deformation compatibility as essential parameters governing structural safety and performance. Steel moment-resisting frames (SMRFs) have emerged as one of the most efficient lateral load-resisting systems in seismic regions due to their inherent ability to undergo significant inelastic deformation without sudden brittle failure. Their favorable strength-to-weight ratio reduces seismic mass and inertia forces, while rigid beam–column connections enable the transfer of lateral loads primarily through flexural action, facilitating stable hysteretic behavior and effective energy dissipation mechanisms. Despite these advantages, conventional seismic design approaches have historically relied on simplified linear elastic analysis procedures combined with empirical force-reduction factors intended to represent expected inelastic behavior.

While such force-based design methods are practical for routine engineering applications, they often fail to capture the true nonlinear response characteristics of steel structures subjected to severe earthquake excitation. In reality, structural response during strong ground motion is governed by complex interactions among material yielding, geometric nonlinearities such as P–Δ effects, cyclic degradation, higher-mode participation, and variability in ground motion characteristics. As a result, structures designed to satisfy elastic code provisions may still experience excessive inter-storey drift, localized damage concentration, or unexpected failure mechanisms when exposed to design-level or beyond-design-level earthquakes. In response to these limitations, performance-based seismic engineering (PBSE) has gained widespread acceptance as a more rational and reliable framework for evaluating structural safety and resilience. Rather than focusing solely on strength requirements, PBSE emphasizes the prediction of structural performance under different levels of seismic demand, typically defined in terms of performance objectives such as Immediate Occupancy, Life Safety, and Collapse Prevention. Achieving these objectives requires advanced nonlinear analysis techniques capable of simulating realistic structural behavior throughout the entire response spectrum, from initial elastic response to significant inelastic deformation and potential instability.

Within this context, nonlinear static analysis (commonly referred to as pushover analysis) and nonlinear dynamic (time-history) analysis have become indispensable tools for seismic performance evaluation. Nonlinear static analysis provides a relatively efficient means of estimating the global lateral load-carrying capacity of a structure by subjecting it to incrementally increasing lateral forces until a target displacement or collapse mechanism is reached. The resulting capacity curve, which represents the relationship between base shear and roof displacement, offers valuable insight into stiffness degradation, ductility demand, plastic hinge formation sequence, and potential weak-storey mechanisms. This method enables engineers to identify critical structural components, evaluate deformation capacity, and determine whether the structure can sustain anticipated seismic demand without unacceptable damage. However, pushover analysis typically assumes a predefined load pattern and does not fully account for the dynamic characteristics of earthquake excitation, including cyclic loading effects, higher-mode response, and record-to-record variability. To address these limitations, nonlinear dynamic analysis is employed to capture the time-dependent nature of seismic loading more realistically. By applying acceleration time histories corresponding to recorded or simulated ground motions, this approach enables detailed simulation of inertia forces, energy dissipation, and cumulative damage effects that occur during repeated loading and unloading cycles. Nonlinear dynamic analysis provides critical information regarding peak displacement demand, inter-storey drift distribution, base shear variation, and residual deformation, thereby offering a comprehensive assessment of structural performance under realistic seismic excitation. Although computationally more demanding and sensitive to modeling assumptions, this method is widely regarded as the most accurate analytical technique for seismic performance evaluation. The integration of nonlinear static and nonlinear dynamic analyses within a unified performance-based framework offers a balanced and robust approach to seismic assessment of steel moment-resisting frames. While pushover analysis facilitates rapid estimation of global capacity and identification of potential failure mechanisms, nonlinear time-history analysis verifies these findings by evaluating actual seismic demand under realistic loading conditions. Such combined analytical strategies enhance confidence in performance predictions and support informed decision-making related to structural design optimization, retrofitting measures, and risk mitigation. Consequently, contemporary research increasingly advocates the adoption of advanced nonlinear evaluation methods to bridge the gap between simplified design assumptions and actual structural behavior during earthquakes, thereby improving the overall safety, reliability, and resilience of steel structural systems in seismic regions.

2. Literature Context and Research Gap

In recent decades, earthquake engineering research has progressively shifted from conventional force-based design philosophies toward performance-based seismic evaluation methodologies that emphasize realistic simulation of structural behavior under severe ground motion. This transition has been largely driven by post-earthquake observations and analytical evidence demonstrating that structures designed using simplified linear elastic approaches may experience significant inelastic deformation, localized damage concentration, and unexpected performance deficiencies. As a result, nonlinear analytical techniques such as nonlinear static (pushover) analysis and nonlinear dynamic (time-history) analysis have become central to contemporary seismic performance assessment of steel moment-resisting frames (SMRFs). These methods enable engineers and researchers to investigate critical response characteristics including plastic hinge development, stiffness degradation, cyclic energy dissipation, and redistribution of internal forces beyond the elastic range. Comparative investigations reported in recent literature consistently highlight the limitations of pushover analysis in accurately predicting seismic demand, particularly for multi-storey steel frame systems where higher-mode effects significantly influence response behaviour.

While pushover analysis provides valuable insight into global lateral load-carrying capacity and potential failure mechanisms, it typically relies on predefined lateral load patterns and monotonic loading assumptions. Consequently, it may underestimate inter-storey drift demand, cumulative damage effects, and deformation concentration in specific storeys. Nonlinear time-history analysis, in contrast, captures the time-dependent nature of seismic excitation, including cyclic loading and unloading, inertia force variation, and interaction among structural modes. These dynamic characteristics are crucial in determining peak displacement demand, residual deformation, and overall structural stability during strong ground motion events. Another important aspect emphasized in recent research is the influence of record-to-record variability in ground motion characteristics. Differences in frequency content, duration, and amplitude of earthquake excitation can lead to significant variation in structural response even for buildings with identical geometric and material properties. Such variability is inherently addressed through nonlinear dynamic analysis but remains largely unaccounted for in conventional pushover-based evaluation procedures. Similarly, cyclic deterioration of strength and stiffness, which plays a decisive role in governing collapse potential and post-earthquake reparability, cannot be realistically simulated using monotonic static loading frameworks.

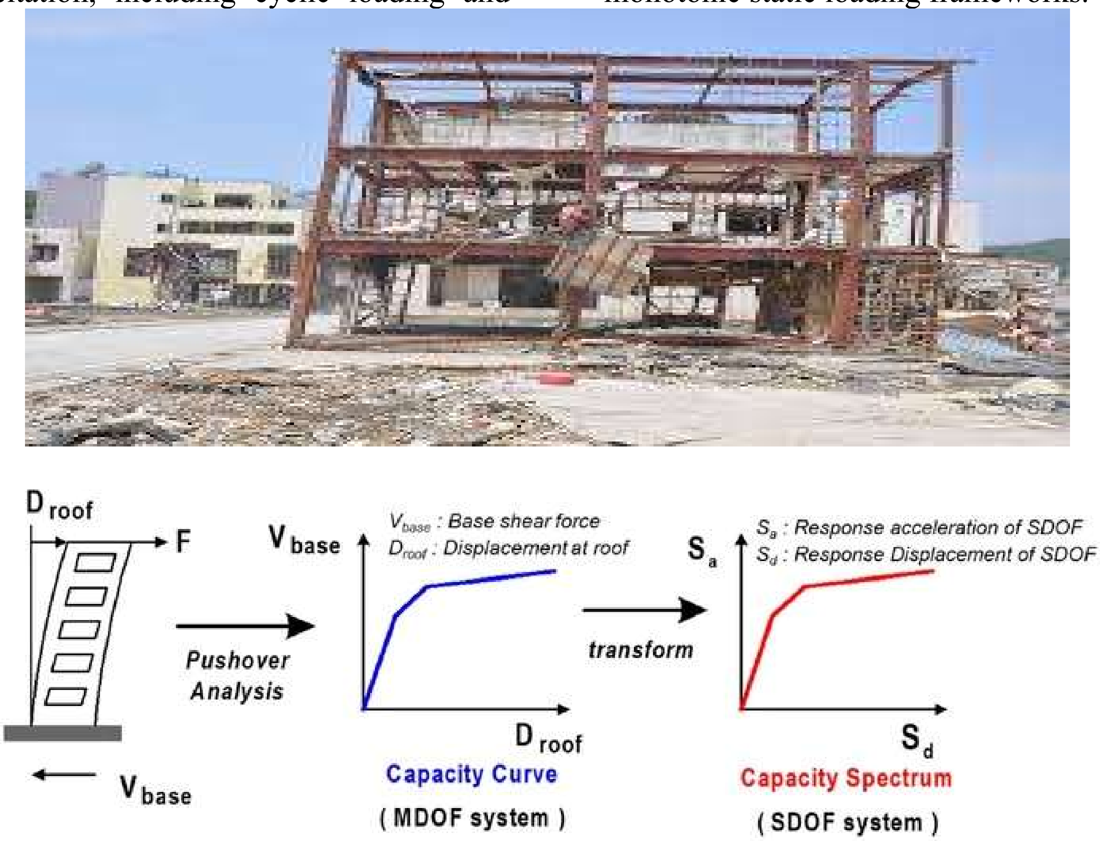

Figure 1.1: Typical steel moment-resisting frame system and seismic response behavior

These limitations collectively underscore the necessity of adopting integrated analytical strategies that combine capacity-based and demand-based assessment approaches. The reviewed dissertation identifies several critical research gaps within the existing body of knowledge. One major gap is the limited integration of nonlinear static and nonlinear dynamic analyses within a unified performance evaluation framework. Although many studies employ either pushover or time-history analysis independently, comparatively fewer investigations systematically correlate capacity estimates obtained from static procedures with demand predictions derived from dynamic simulations. This lack of integration restricts the ability to comprehensively evaluate seismic performance and may lead to incomplete or unconservative design conclusions. Another significant gap pertains to the insufficient utilization of quantitative response parameters extracted from advanced structural analysis software. While modern computational tools enable detailed modelling of material nonlinearity, geometric effects, and plastic hinge behaviour, numerous studies still focus primarily on qualitative interpretations rather than rigorous data-driven assessment. Parameters such as base shear capacity, peak roof displacement, inter-storey drift ratios, hinge rotation demand, and residual deformation provide valuable insight into structural performance but are not consistently analysed in a systematic manner. Furthermore, existing literature often lacks detailed examination of drift concentration phenomena and potential soft-storey mechanisms that may develop under nonlinear response conditions. Such localized deformation patterns can critically influence damage progression and collapse vulnerability, particularly in steel moment-resisting frames where stiffness distribution and connection detailing govern inelastic behaviour. Additionally, there remains a notable need for localized performance-based seismic evaluation studies that reflect regional seismic hazard characteristics, design practices, and codal provisions applicable to specific contexts such as Indian seismic zones. By addressing these identified gaps, the reviewed work contributes to advancing the understanding of seismic performance of SMRF systems through comprehensive analytical investigation. The adoption of realistic modelling strategies, systematic extraction of response parameters, and performance-based evaluation criteria enables a more accurate and holistic assessment of structural behaviour under earthquake loading. Consequently, the study strengthens the foundation for integrating advanced nonlinear analysis techniques into practical seismic design and assessment methodologies.

3. Methodological Framework

The methodological framework adopted in the study is centered on the development of a detailed three-dimensional analytical model of a steel moment-resisting frame using advanced structural analysis software. The modeling approach is designed to realistically simulate the geometric configuration, load distribution, and nonlinear behavioral characteristics of a typical multi-storey steel building subjected to seismic excitation. By incorporating both material and geometric nonlinearities, the analytical framework enables a comprehensive evaluation of structural response beyond the elastic range, which is essential for performance-based seismic assessment. Material nonlinearity is represented through appropriate stress–strain relationships that capture yielding, strain hardening, and post-yield stiffness characteristics of structural steel. This modeling strategy ensures that inelastic deformation, energy dissipation capacity, and strength degradation mechanisms are accurately reflected during analysis. Geometric nonlinearity is incorporated by activating P–Δ effects, which account for the influence of large lateral displacements on structural stability and internal force redistribution. These second-order effects are particularly significant in multi-storey frames, where cumulative displacement can amplify seismic demand and increase the likelihood of drift concentration or soft-storey behavior.

Plastic hinges are strategically assigned at potential yielding locations, primarily at beam ends and column bases, in accordance with the strong-column–weak-beam design philosophy. This approach promotes controlled energy dissipation through ductile flexural yielding of beams while minimizing the risk of brittle column failure and global collapse mechanisms. Loading conditions are defined based on relevant seismic design provisions to ensure realistic representation of structural demand. Gravity loads include the self-weight of structural members and appropriate portions of imposed loads considered in the seismic mass calculation. Seismic loading parameters such as an importance factor of 1.0, response reduction factor of 5.0, and medium soil type are incorporated to represent typical design conditions. These parameters govern the magnitude and distribution of seismic forces applied to the structural model. Both principal horizontal directions of earthquake excitation are considered to capture directional dependence of response and potential torsional effects. Nonlinear static (pushover) analysis is conducted by incrementally applying lateral load patterns until significant stiffness degradation or predefined displacement targets are reached. This procedure facilitates the generation of capacity curves that illustrate the relationship between base shear and roof displacement, providing insight into global strength capacity, deformation demand, and hinge formation sequence. Complementing this, nonlinear dynamic analysis is performed using scaled earthquake ground motion records to simulate time-dependent structural response under realistic seismic excitation. This approach enables the evaluation of inertia force variation, cyclic loading effects, and higher-mode participation. Key response parameters extracted from both analyses include base shear, roof displacement, inter-storey drift, and plastic hinge rotation demand. These parameters collectively form the basis for performance-level evaluation, allowing assessment of structural safety, ductility, and compliance with performance objectives such as Immediate Occupancy, Life Safety, and Collapse Prevention.

4. Results and Discussion

4.1 Pushover Analysis Outcomes

The pushover analysis reveals a clear transition from elastic to nonlinear response, characterized by gradual stiffness reduction indicative of ductile structural behavior. In the X-direction, the frame achieves a maximum base shear capacity of approximately 43,166 kN, accompanied by an overturning moment of 194,247 kN-m. In contrast, the Y-direction response shows reduced stiffness and strength, with a maximum base shear of 2,452 kN and overturning moment of 5,442 kN-m, reflecting directional dependence of seismic performance.

Plastic hinge formation initiates at beam ends and later extends to column bases at higher displacement levels. Concentration of hinges at lower storeys suggests potential soft-storey mechanisms under extreme seismic demand, emphasizing the importance of stiffness distribution and drift control in seismic design.

4.2 Drift and Displacement Response

Story drift analysis indicates that the maximum inter-story drift occurs at the first storey, reaching approximately 0.0153 m in the Y-direction. Upper storeys exhibit progressively lower drift values, consistent with cantilever-type deformation patterns typical of moment-resisting frames. Roof displacement increases significantly beyond the elastic range due to stiffness degradation, highlighting the nonlinear deformation capacity of the structure.

Although drift demands remain within acceptable Life Safety limits for most storeys, the concentration of deformation at lower levels identifies a critical region governing seismic performance and potential retrofitting considerations.

4.3 Nonlinear Dynamic Response

Time-history analysis captures oscillatory roof displacement and fluctuating base shear demand during strong ground motion phases. Peak displacement and drift demands are generally higher than those predicted by pushover analysis due to cyclic loading effects and higher-mode participation. However, peak base shear demand remains slightly lower than ultimate pushover capacity, indicating adequate strength reserve.

The dynamic analysis confirms stable structural behaviour without significant strength degradation or collapse, thereby validating pushover-based performance assessment while also revealing limitations of static procedures in predicting realistic seismic demand.

4.4 Comparative Evaluation

A systematic comparison demonstrates that pushover analysis provides an upper-bound estimate of strength capacity, whereas nonlinear dynamic analysis offers a realistic representation of demand. While hinge locations predicted by both methods are largely consistent, dynamic analysis captures frequent hinge state transitions and cumulative damage effects absent in static analysis. The findings highlight that these methods are complementary rather than competing, and their combined application enhances reliability of seismic performance evaluation.

5. Performance Level Assessment and Seismic Implications

Performance level assessment constitutes a critical component of performance-based seismic evaluation, as it enables the translation of analytical response parameters into meaningful indicators of structural safety, expected damage, and post-earthquake functionality. In the present study, the seismic performance of the steel moment-resisting frame is evaluated by correlating plastic hinge states, inter-storey drift limits, and global deformation demands obtained from nonlinear analyses with established performance objectives such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). This systematic interpretation of analytical results provides a clear understanding of how the structure is expected to behave under varying intensities of seismic excitation. The evaluation reveals that the structure predominantly remains within the Life Safety performance level for most of the loading history. Initial yielding occurs primarily at beam ends in lower storeys, corresponding to Immediate Occupancy conditions, where minor inelastic deformation develops without significant strength degradation or instability.

As seismic demand increases, additional plastic hinges form and progress into the Life Safety range, indicating controlled structural damage that is considered acceptable under design-level earthquake scenarios. Importantly, hinge formation is largely consistent with the strong-column–weak-beam philosophy, ensuring that energy dissipation occurs through ductile flexural yielding in beams rather than through brittle failure of columns. At maximum displacement levels, only a limited number of hinges approach the Collapse Prevention state, mainly at beam ends and column bases in lower storeys where seismic demand is highest. This localized advancement of hinge states highlights the influence of stiffness distribution and gravity load interaction on deformation concentration. However, the absence of widespread hinge propagation or sudden strength loss indicates that the overall structural system retains sufficient residual capacity to prevent global collapse. Such behavior confirms that the frame possesses adequate ductility and deformation capacity to withstand severe seismic excitation while maintaining structural integrity. The results obtained from nonlinear dynamic analysis further reinforce these observations by providing insight into time-dependent seismic response.

The absence of excessive residual displacement in the time-history response suggests that permanent deformation after earthquake shaking is likely to remain within tolerable limits, thereby supporting satisfactory post-earthquake functionality and reparability. This aspect is particularly significant from an operational and economic perspective, as excessive residual drift can render buildings unserviceable even if collapse is prevented. The stable oscillatory response observed during dynamic analysis indicates effective energy dissipation through hysteretic behavior, contributing to overall resilience of the structural system. Nevertheless, the concentration of inter-storey drift demand at lower storeys represents a potential vulnerability that may govern seismic performance. Such drift concentration can increase the likelihood of non-structural damage, connection distress, and development of soft-storey mechanisms under extreme seismic demand. From a design standpoint, these findings emphasize the importance of optimizing stiffness and strength distribution along the building height. Potential mitigation measures may include strengthening critical members, enhancing connection detailing, incorporating supplemental damping devices, or adopting hybrid lateral load-resisting systems to improve deformation control. Overall, the performance level assessment demonstrates that the steel moment-resisting frame exhibits effective energy dissipation, stable inelastic behavior, and significant collapse resistance under both design-level and beyond-design-level earthquakes.

The integration of hinge-based evaluation with global response parameters provides a comprehensive understanding of seismic implications and offers valuable guidance for improving structural safety, resilience, and performance-based design strategies.

6. Conclusions

The reviewed dissertation presents a detailed and systematic performance-based seismic evaluation of a steel moment-resisting frame through the integrated application of nonlinear static (pushover) and nonlinear dynamic (time-history) analysis techniques. By adopting advanced analytical procedures and realistic modeling strategies, the study provides a comprehensive understanding of structural behavior under earthquake loading conditions. The findings demonstrate that the steel moment-resisting frame possesses adequate lateral strength, ductility, and deformation capacity, enabling it to withstand significant seismic demand without experiencing global instability or collapse. In particular, the pushover analysis reveals a maximum base shear capacity of approximately 43,166 kN, which exceeds the peak seismic demand observed in nonlinear dynamic analysis. This strength reserve confirms that the structural system is capable of sustaining design-level and even beyond-design-level earthquake effects while maintaining overall stability. The evaluation of deformation characteristics highlights that inter-storey drift demand and plastic hinge accumulation are primarily concentrated in the lower storeys of the structure. Such behavior is consistent with typical response patterns observed in multi-storey moment-resisting frames, where gravity loads and stiffness distribution contribute to increased seismic demand at lower levels. Although the observed drift values remain within acceptable limits corresponding to Life Safety performance objectives, the concentration of deformation at critical storeys is identified as a governing factor influencing seismic performance. This observation underscores the importance of careful design detailing, stiffness optimization, and potential strengthening measures to mitigate soft-storey mechanisms and enhance overall resilience. A key contribution of the research lies in reinforcing the limitations associated with conventional linear elastic analysis methods commonly used in routine seismic design practice. While force-based procedures offer simplicity and computational efficiency, they may lead to unconservative predictions of displacement demand, cumulative damage, and structural stability when subjected to severe earthquake excitation. In contrast, the combined use of nonlinear static and nonlinear dynamic analyses provides a more realistic representation of structural response by explicitly capturing inelastic deformation, cyclic degradation, higher-mode participation, and time-dependent response characteristics.

Overall, the study establishes that integrated nonlinear analytical approaches form a robust and reliable framework for performance-based seismic assessment of steel moment-resisting frames. The insights derived from the research contribute significantly to improving understanding of structural safety, ductility demand, and collapse prevention mechanisms in earthquake-prone regions. Furthermore, the findings support the broader adoption of advanced nonlinear evaluation techniques in modern seismic design practice, thereby promoting enhanced structural resilience, risk reduction, and informed decision-making in the planning, design, and retrofitting of steel building systems.

7. Future Research Directions

Future research can significantly enhance the scope and applicability of performance-based seismic evaluation of steel moment-resisting frames by extending the analytical framework adopted in the present study. One important direction involves investigating the seismic behavior of taller and more complex building configurations, including structures with plan irregularities, vertical stiffness discontinuities, and mass eccentricities. Such irregularities can substantially influence higher-mode participation, torsional response, and drift concentration patterns, thereby affecting overall structural safety and collapse resistance. Evaluating these factors through advanced nonlinear analysis would contribute to developing more reliable design recommendations for contemporary multi-storey steel buildings. Another promising research avenue lies in assessing structural performance under varying seismic hazard levels and soil conditions. Differences in seismic zoning, ground motion characteristics, and site amplification effects can lead to considerable variation in displacement demand and damage distribution. Parametric studies considering soft, medium, and hard soil profiles, as well as near-fault and far-field ground motions, would provide deeper insight into regional seismic performance requirements and facilitate more context-specific performance-based design approaches. Further improvement in analytical accuracy can be achieved through advanced connection modeling and probabilistic performance assessment techniques. Incorporating refined moment–rotation relationships, strength and stiffness deterioration models, and uncertainty in material properties or loading conditions would enable more realistic prediction of cumulative damage and collapse probability. Additionally, experimental validation through laboratory testing or shake-table studies could strengthen confidence in analytical findings and support calibration of nonlinear hinge models used in structural software.

Finally, future studies may explore the effectiveness of seismic retrofitting strategies, such as the introduction of bracing systems, base isolation devices, or supplemental damping mechanisms, in enhancing the resilience of steel moment-resisting frames. Evaluating the performance of such interventions under extreme seismic scenarios would provide valuable guidance for improving structural robustness, reducing damage potential, and ensuring rapid post-earthquake functionality.

References

1. Costanzo, S., Cassiano, D., & D'Aniello, M. (2025). Robustness of steel moment-resisting frames under column loss scenarios with and without prior seismic damage. Buildings, 15(14), 2490. (MDPI)
2. Kalapodis, N. A. (2025). Influence of panel zone modeling on the seismic behavior of steel moment-resisting frames: A numerical study. Applied Mechanics, 6(1), 22. (MDPI)
3. Abhinand, P. U., et al. (2025). Seismic response reduction factor assessment of steel moment-resisting frames using nonlinear incremental dynamic analysis. Structures. (ScienceDirect)
4. Samadian, D., et al. (2025). An integrated framework for 3D time-history analysis of steel SMRF buildings under multi-hazard loading. Structure and Infrastructure Engineering. (Tandfonline)
5. Chan, N., Hashemi, A., Assadi, S., et al. (2025). Shake-table tests of steel structures with resilient slip-friction joints. Earthquake Engineering Research. (arXiv)
6. Shakouri, A. (2021). Effects of ductility level and connection design on seismic response of base-isolated steel moment frames. International Journal of Advanced Engineering Modelling. (IJAEM)
7. El Jisr, H., et al. (2022). Nonlinear macro-model for seismic risk assessment of composite steel beam-column connections. Earthquake Engineering & Structural Dynamics. (Wiley Online Library)
8. Kamgar, R., Hosseini, S., & Ghafory-Ashtiany, M. (2022). Wavelet-based nonlinear dynamic analysis of steel frames under earthquake loading. Engineering Structures.
9. Chen, X., Wang, Y., & Li, Z. (2022). Higher-mode effects on seismic performance of mid-rise steel moment frames. Journal of Constructional Steel Research.
10. Safari Honar, F., Rezaei, M., & Fanaie, F. (2023). Nonlinear dynamic seismic assessment of multi-storey steel frames. Buildings.
11. Sebaq, M. S., Bakhshi, A., & Fanaie, F. (2023). Damage indices for seismic performance evaluation of steel moment-resisting frames. International Journal of Steel Structures.
12. Balmer, D. (2023). Nonlinear dynamic stability assessment of steel moment frames with high panel zone demand. EPFL Structural Engineering Report. (infoscience.epfl.ch)
13. Eatherton, M., & Hajjar, J. (2020). Residual drift implications for seismic performance of steel frames. Journal of Structural Engineering.

14. Viana, H. F., Pinho, R., & Castro, J. M. (2020). Improved nonlinear dynamic analysis formulation for steel MRFs. Engineering Structures.
15. Lignos, D. G., & Krawinkler, H. (2019). Collapse assessment of steel moment frames using nonlinear dynamic simulation. Earthquake Engineering & Structural Dynamics.
16. Jalayer, F., Deierlein, G. G., & Cornell, C. A. (2021). Record-to-record variability in performance-based seismic assessment. Journal of Earthquake Engineering.
17. Khosravikia, F., Tremblay, R., & Massicotte, B. (2021). Drift concentration in steel moment frames with vertical irregularities. Engineering Structures.
18. Haselton, C. B., Baker, J. W., & Lignos, D. G. (2015). Probabilistic collapse risk assessment of steel frames. Journal of Structural Engineering.
19. Chopra, A. K., & Goel, R. K. (2014). Evaluation of pushover procedures for seismic demand estimation. Earthquake Engineering & Structural Dynamics.
20. Krawinkler, H., & Seneviratna, G. (2011). Pros and cons of nonlinear static procedures. Engineering Structures.
21. Gupta, A., & Krawinkler, H. (2012). Seismic demand prediction for steel frames with stiffness irregularities. Journal of Structural Engineering.
22. Medina, R. A., & Krawinkler, H. (2013). Seismic response variability due to ground motion characteristics. Earthquake Engineering Research.
23. Antoniou, S., & Pinho, R. (2014). Development of adaptive pushover methods. Journal of Earthquake Engineering.
24. Tremblay, R., Poncet, L., & Bruneau, M. (2014). Seismic response of capacity-designed steel frames. Engineering Structures.
25. Atila, H., & Spence, S. M. J. (2026). Deep learning-based metamodeling of nonlinear stochastic steel moment-resisting frames under seismic excitation. Structural Safety. (arXiv)

