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

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***Abstract:** The seismic performance of building structures is a critical aspect of structural engineering, particularly in regions prone to earthquakes. This study presents a comprehensive evaluation of a G+5 steel moment-resisting frame using nonlinear static (pushover) and nonlinear dynamic (time history) analysis methods. The structural model is developed in ETABS software with appropriate material properties, loading conditions, and boundary assumptions in accordance with relevant Indian Standard codes. Initially, linear static analysis is performed to verify the structural model and to understand its elastic response under applied loads. This is followed by pushover analysis, which is used to assess the inelastic behavior of the structure by applying incremental lateral loads and evaluating the formation of plastic hinges. The capacity curve obtained from pushover analysis provides insight into the strength, stiffness, and deformation capacity of the structure. To simulate realistic earthquake conditions, nonlinear time history analysis is carried out using the El Centro ground motion record with a time step of 0.02 seconds. The structural response is evaluated in terms of displacement, base reaction, and storey drift. The results indicate that the structure exhibits stable and controlled behavior under dynamic loading, with displacement and drift values remaining within permissible limits. The hinge formation pattern confirms a desirable ductile mechanism, with yielding occurring primarily in beams before columns. The comparison of results obtained from static and dynamic analyses shows strong consistency, validating the accuracy of the modelling and analysis approach. Overall, the study demonstrates that steel moment-resisting frames provide adequate strength, stiffness, and ductility to resist seismic forces effectively. The combined use of pushover and time history analysis offers a reliable approach for realistic seismic performance evaluation of structures.*

***Keywords:** Steel moment-resisting frame, nonlinear static analysis, time-history analysis, seismic performance, plastic hinge, story drift.*

I. INTRODUCTION

Earthquakes represent one of the most significant natural hazards affecting structural safety, urban infrastructure, and human life. The seismic performance of buildings depends not only on their strength but also on their ability to undergo controlled inelastic deformation without experiencing sudden collapse. Traditional seismic design approaches primarily rely on linear elastic analysis combined with response reduction factors to approximate nonlinear structural behavior. Although such approaches simplify the design process, they often fail to capture realistic structural response under strong ground motions. Consequently, modern earthquake engineering practice increasingly emphasizes performance-based seismic evaluation methodologies that incorporate advanced nonlinear analysis techniques.

Steel moment-resisting frames (SMRFs) have gained widespread acceptance as effective lateral load-resisting systems in seismic regions due to their superior ductility, high strength-to-weight ratio, and architectural flexibility. In these structural systems, beams and columns are rigidly connected, enabling lateral forces to be resisted primarily through flexural action rather than bracing or shear walls. During seismic excitation, SMRFs are designed to dissipate energy through the formation of plastic hinges at predetermined locations, typically at beam ends. This controlled yielding mechanism, known as the strong-column–weak-beam philosophy, ensures that global structural stability is maintained while preventing catastrophic failure. However, the actual seismic behavior of steel moment-resisting frames is influenced by multiple interrelated factors such as stiffness distribution, structural geometry, connection detailing, and ground motion characteristics. Linear analysis methods are unable to adequately represent these complexities, particularly when structures experience significant inelastic deformation. As a result, nonlinear static analysis and nonlinear dynamic analysis have become essential tools in performance-based seismic engineering. Nonlinear static (pushover) analysis provides insight into global strength capacity, deformation characteristics, and potential failure mechanisms by applying incrementally increasing lateral loads.

In contrast, nonlinear dynamic (time-history) analysis captures the time-dependent variation of structural response under realistic earthquake records, thereby accounting for inertia forces, cyclic degradation, and higher-mode participation. The integration of these two analysis techniques enables a comprehensive evaluation of both structural capacity and seismic demand. Advanced structural analysis software such as ETABS facilitates detailed modeling of nonlinear material behavior, geometric nonlinearity, and plastic hinge properties, allowing engineers to assess performance levels such as Immediate Occupancy, Life Safety, and Collapse Prevention.

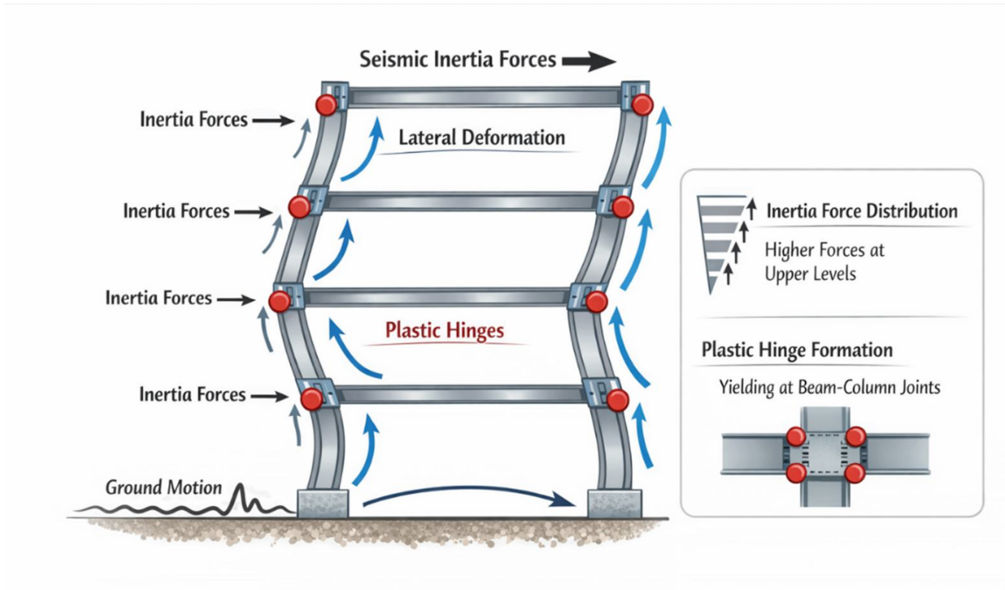

Figure 1: Conceptual illustration of seismic response mechanism in a steel moment-resisting frame showing lateral deformation pattern, inertia force distribution, and plastic hinge formation.

The present study aims to evaluate the seismic performance of a steel moment-resisting frame using integrated nonlinear static and dynamic analyses. By systematically examining response parameters such as base shear capacity, story drift demand, roof displacement, and hinge state progression, the research contributes toward improved understanding of structural behavior and supports the adoption of performance-based seismic design practices.

II. REVIEW OF LITERATURE

Seismic performance evaluation of steel moment-resisting frames (SMRFs) has been a major area of research in earthquake engineering, particularly following observations from damaging earthquakes that revealed the limitations of conventional force-based design approaches. Traditional seismic design methodologies were primarily developed to ensure structural safety by preventing collapse through the use of simplified linear elastic analysis combined with response reduction factors. While such approaches provided practical solutions for routine design, they were often unable to accurately represent the nonlinear response characteristics of structures subjected to strong ground motions [1]. Consequently, modern research has increasingly focused on performance-based seismic evaluation frameworks that enable realistic assessment of deformation demand, damage progression, and collapse potential.

Early experimental investigations played a critical role in shaping current understanding of steel frame seismic behavior. Following the 1994 Northridge earthquake, widespread brittle fractures in welded beam-column connections prompted extensive research into connection performance and ductile detailing requirements. Studies conducted under the SAC Joint Venture research program demonstrated that improved connection design could restore reliable inelastic rotation capacity and stable hysteretic behavior in steel moment frames [2]. These findings reinforced the importance of controlled plastic hinge formation and adherence to strong-column–weak-beam philosophy for achieving satisfactory seismic performance. Analytical studies further highlighted the inadequacy of linear elastic analysis methods in predicting realistic deformation demand. Krawinkler emphasized that structural response under severe seismic loading is governed by nonlinear phenomena such as stiffness degradation, strength deterioration, and redistribution of internal forces following yielding [3]. Nonlinear static analysis, commonly referred to as pushover analysis, was introduced as an efficient tool for estimating global structural capacity and identifying potential collapse mechanisms.

The capacity spectrum method proposed by Freeman provided a framework for relating pushover-derived capacity curves to seismic demand spectra, thereby facilitating performance-based evaluation of structural systems [4]. Despite its widespread adoption, pushover analysis has been shown to possess inherent limitations, particularly in capturing higher-mode effects and cyclic degradation. Chopra and Goel demonstrated that invariant lateral load patterns assumed in conventional pushover procedures may lead to inaccurate estimation of inter-storey drift demand in multi-storey structures [5]. Their research indicated that deformation demand predicted by pushover analysis often differs significantly from that obtained through nonlinear dynamic analysis, especially in mid-rise and irregular steel frames. Similar observations were reported by Gupta and Krawinkler, who found that drift concentration in lower storeys under dynamic loading conditions was not adequately captured by static procedures [6].

Nonlinear dynamic analysis has therefore been recognized as the most reliable approach for seismic performance assessment. Time-history analysis enables simulation of actual earthquake ground motion records, allowing engineers to capture inertia effects, cyclic loading behavior, and record-to-record variability [7]. Medina and Krawinkler demonstrated that displacement demand in steel moment frames varies significantly depending on ground motion characteristics such as frequency content and duration, highlighting the importance of considering multiple records in performance-based evaluation [8]. These findings underscore the limitations of simplified analysis methods and emphasize the need for demand-based assessment techniques.

Recent research has focused on improving modeling accuracy in nonlinear analysis. Lignos and Krawinkler investigated the collapse behavior of steel moment-resisting frames using extensive nonlinear dynamic simulations, demonstrating that cumulative damage and cyclic deterioration play decisive roles in governing collapse potential [9]. Their work highlighted that monotonic pushover analysis cannot adequately represent strength and stiffness degradation occurring under repeated loading cycles. Zareian and Medina further emphasized the influence of modeling assumptions, including hinge property selection and damping representation, on predicted seismic response [10].

Such studies have contributed to the development of more realistic hinge models and improved analytical formulations in commercial software. The influence of structural configuration and irregularity has also been widely examined. Tremblay and co-researchers reported that steel moment-resisting frames with vertical stiffness irregularities exhibit significant drift concentration in lower storeys under nonlinear dynamic loading [11]. Chen et al. demonstrated that higher-mode participation substantially increases displacement demand in upper storeys of mid-rise steel frames, indicating that first-mode pushover procedures may underestimate response in taller structures [12]. These findings highlight the importance of comprehensive three-dimensional modeling and multi-directional seismic evaluation.

Another important aspect addressed in literature is residual deformation and post-earthquake reparability. Eatherton and Hajjar showed that structures satisfying life safety drift limits may still experience excessive residual displacement, leading to functional impairment and high repair costs [13]. Their research emphasized that residual drift can only be realistically captured through nonlinear dynamic analysis, reinforcing the need for integrated analytical approaches. Jalayer and Cornell proposed probabilistic performance-based frameworks that incorporate uncertainty in ground motion characteristics and structural capacity, thereby enabling more robust seismic risk assessment [14].

Recent advancements have also explored the use of advanced signal processing and wavelet-based techniques for analyzing nonlinear seismic response. Kamgar and colleagues demonstrated that near-fault ground motions containing velocity pulses impose significantly higher displacement demand on steel frames compared to far-field records [15]. Similarly, Safari Honar et al. investigated dynamic response characteristics of multi-storey steel structures and concluded that higher-mode effects play a critical role in governing inter-storey drift distribution [16]. These studies collectively emphasize that realistic seismic evaluation requires consideration of ground motion variability and dynamic amplification effects. Performance-based seismic design guidelines such as FEMA 356 and FEMA P-695 have further contributed to standardizing nonlinear analysis procedures and performance criteria [17].

These documents provide recommendations for hinge modeling, drift limits, and collapse evaluation methodologies. Research by Haselton et al. demonstrated that collapse probability in steel frames is strongly influenced by cumulative damage effects and record-to-record variability, supporting the adoption of incremental dynamic analysis techniques for critical structures [18].

Although substantial progress has been made, several research gaps remain. Many studies rely on either nonlinear static or nonlinear dynamic analysis in isolation, limiting the ability to correlate structural capacity with realistic seismic demand [19]. Furthermore, insufficient attention is often given to quantitative interpretation of response parameters such as base shear capacity, displacement demand, and hinge state progression obtained from advanced software analysis. Comparative studies integrating both analytical approaches within a unified performance-based framework remain relatively limited.

In the context of developing countries, localized seismic evaluation studies are particularly necessary due to differences in design practices, seismic zoning, and soil conditions. Research conducted on steel moment-resisting frames designed according to regional codes has highlighted the need for context-specific performance assessment to ensure structural safety and resilience [20]. Overall, existing literature consistently demonstrates that while pushover analysis provides vluable insight into global strength capacity and failure mechanisms, nonlinear dynamic analysis remains indispensable for capturing realistic seismic demand and cumulative damage effects. The present study builds upon these research findings by integrating nonlinear static and nonlinear dynamic analysis techniques within a comprehensive analytical framework. By systematically evaluating response parameters such as base shear capacity, story drift distribution, roof displacement demand, and plastic hinge formation patterns, the research aims to contribute toward improved understanding of seismic performance of steel moment-resisting frames and support the adoption of performance-based seismic design methodologies

III. RESEARCH METHODOLOGY

The methodology adopted in this study involves structural modelling, load definition, and analysis using ETABS software. The structure is modelled as a G+5 steel moment-resisting frame with a total height of 18 meters. Standard ISMB sections are used for beams and columns, and material properties are assigned based on E250 grade steel. Loads are applied as per Indian Standard codes, including dead load, live load, wind load, and seismic load. The seismic parameters are defined according to IS 1893:2016, ensuring realistic representation of earthquake forces. Pushover analysis is carried out by applying incremental lateral loads in both X and Y directions. Plastic hinges are assigned at beam and column ends to simulate nonlinear behavior. The capacity curve obtained from this analysis is used to evaluate the strength and deformation capacity of the structure. Time history analysis is performed using the El Centro earthquake record. The ground motion is applied in both directions with a time step of 0.02 seconds. The response of the structure is recorded in terms of displacement, base reaction, and drift over time.

Table 1: Key Structural and Analysis Parameters

Parameter	Value
Number of Storeys	G + 5
Storey Height	3 m
Total Height	18 m
Material	Steel (E250)
Analysis Type	Pushover + Time History
Ground Motion	El Centro
Time Step	0.02 sec
Zone Factor	0.36

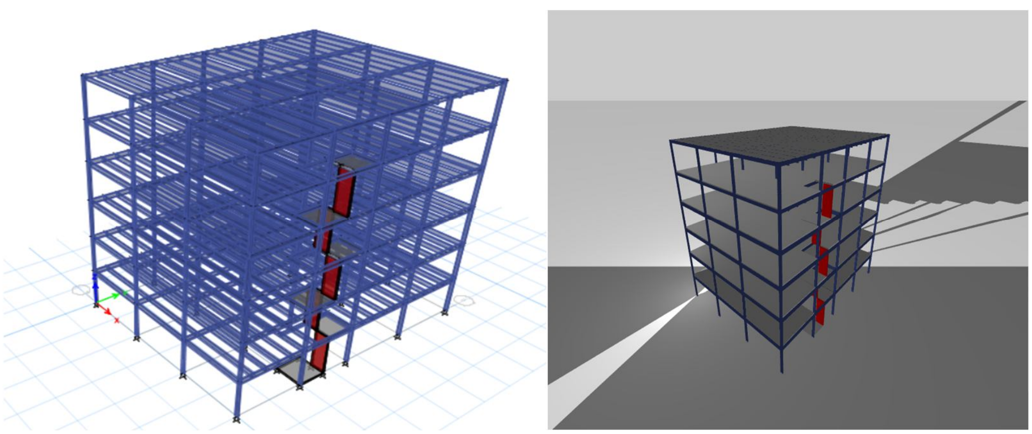

Figure 2: 3D analytical model of G+5 steel moment-resisting frame developed in ETABS software.

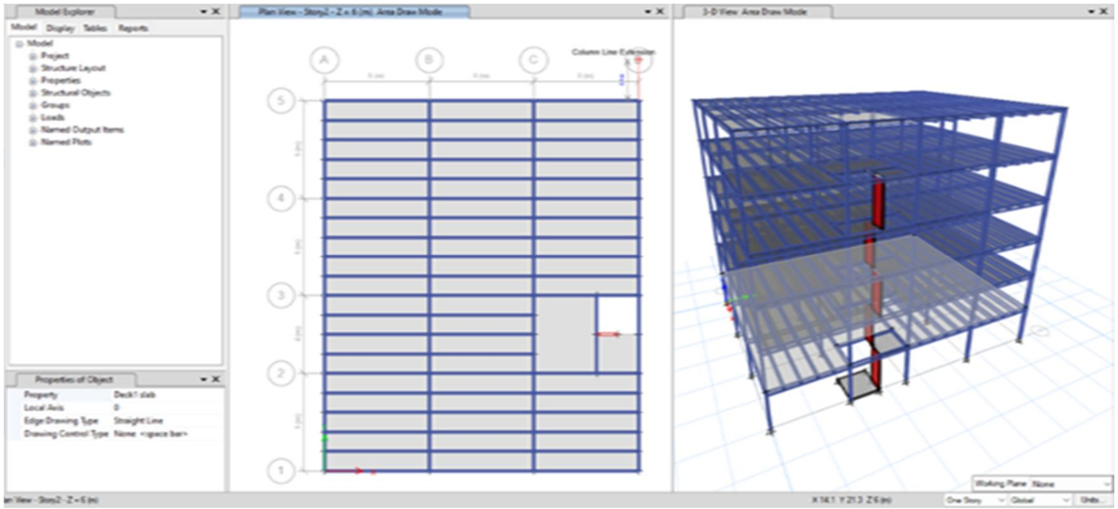

Figure 3: Plan view showing grid layout and structural configuration of the building.

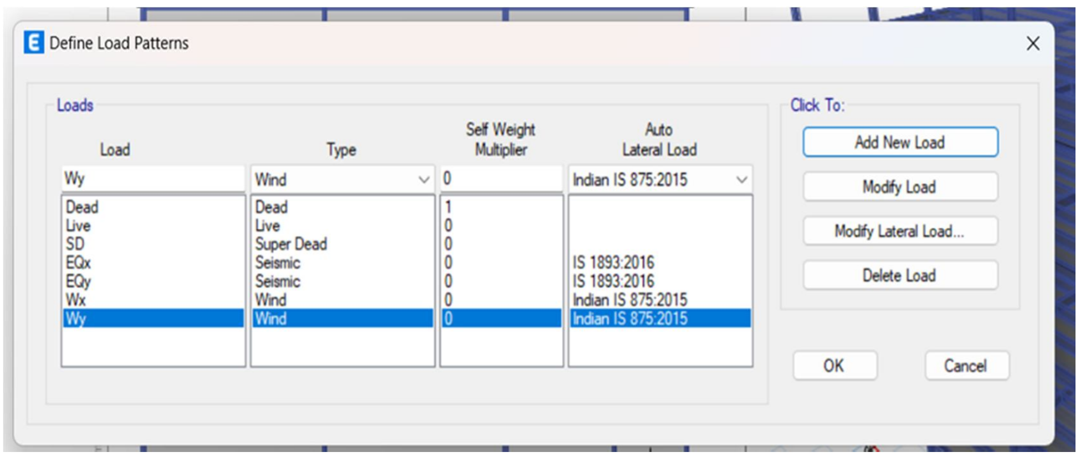

Figure 4: Definition and assignment of load patterns including dead, live, wind and seismic loads in ETABS.

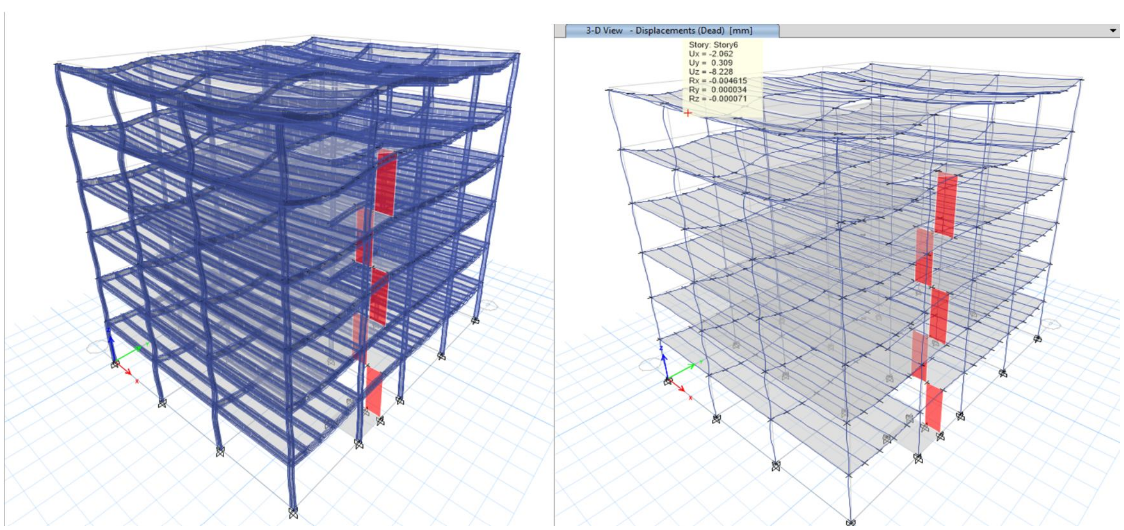

Figure 5: Deformed shape of structure under applied loading showing overall structural behavior.

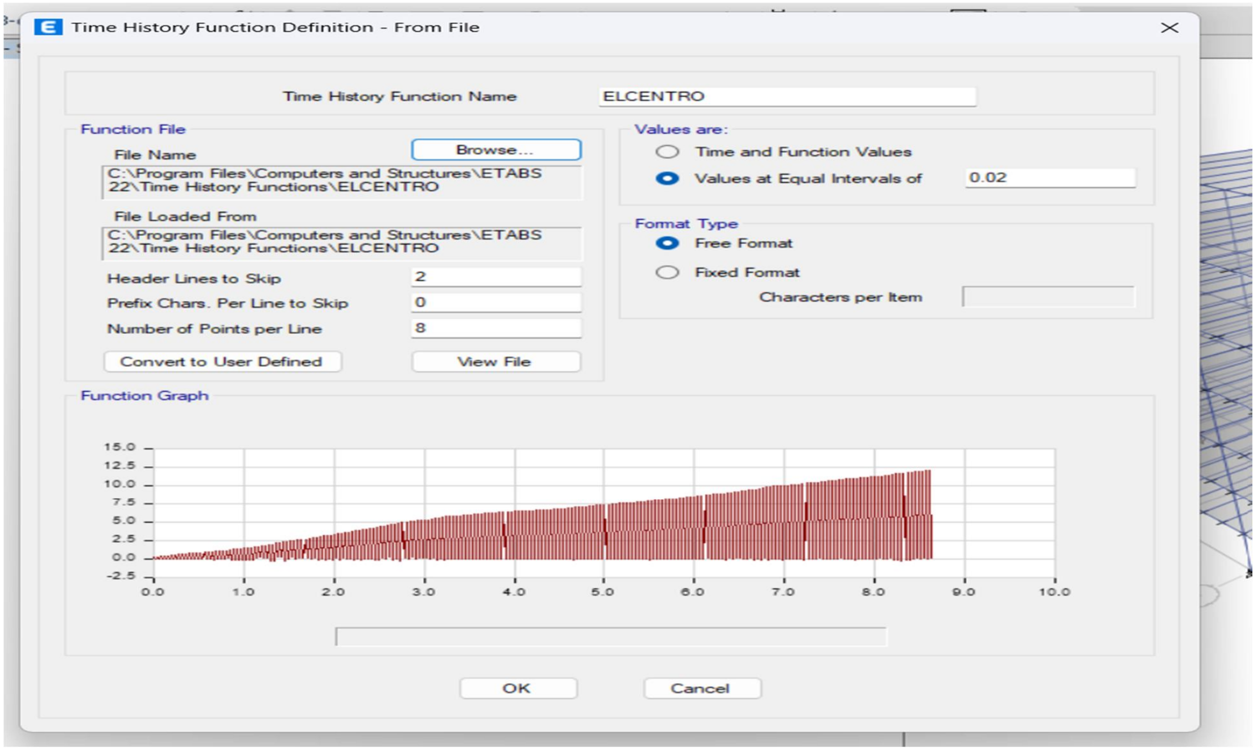

Figure 6: Acceleration versus time graph of El Centro earthquake record used as input for time history analysis.

IV. RESULTS AND DISCUSSION

The results obtained from the analysis provide valuable insight into the structural behavior under seismic loading. Linear static analysis indicates that the structure behaves elastically under normal loading conditions, with displacement increasing gradually from the base to the top storey. Pushover analysis shows that the structure exhibits stable nonlinear behavior. The capacity curve indicates sufficient strength and deformation capacity. Plastic hinges are observed to form first in beams, followed by columns, confirming the strong-column weak-beam mechanism. Time history analysis reveals that the structure responds dynamically to earthquake loading with controlled oscillatory motion. The displacement varies with time, reaching peak values at intervals corresponding to maximum ground acceleration. The response gradually reduces due to damping effects.

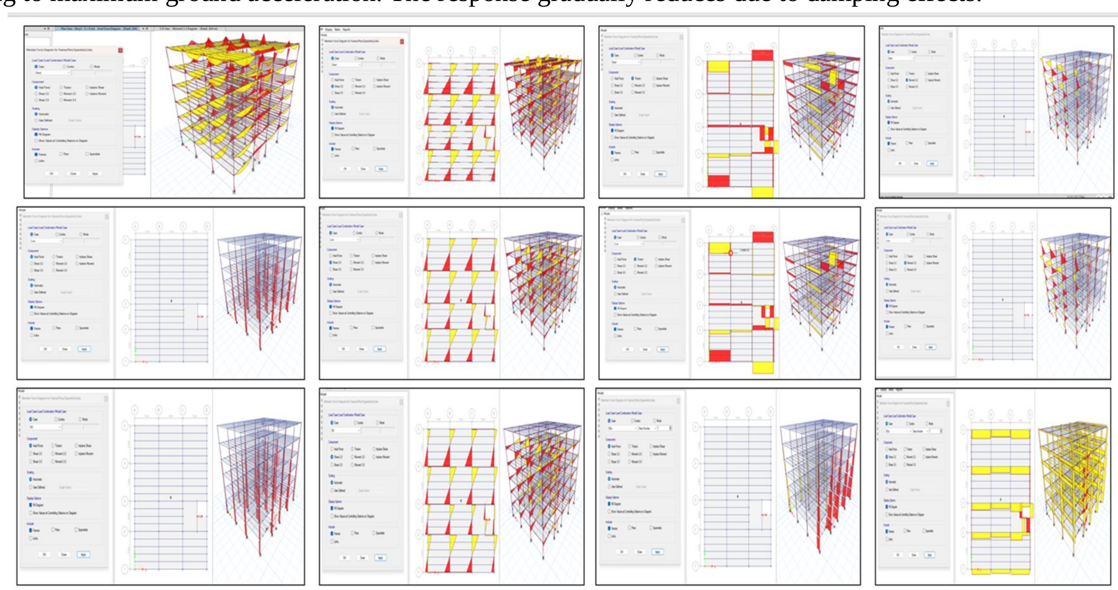

Figure 7: Pushover capacity curve showing relationship between base shear and roof displacement.

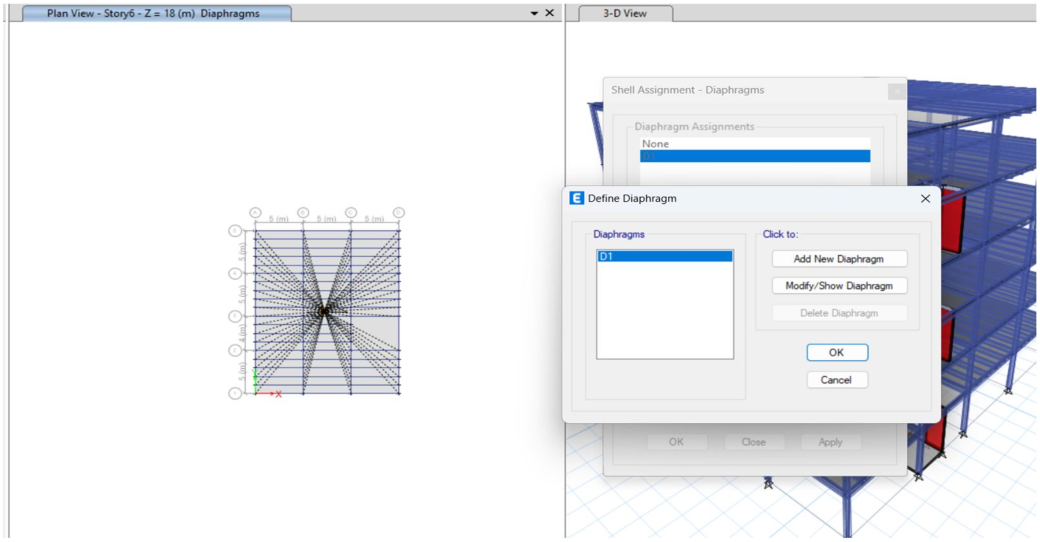

Figure 8: Plastic hinge formation pattern indicating progressive inelastic behavior of structural members.

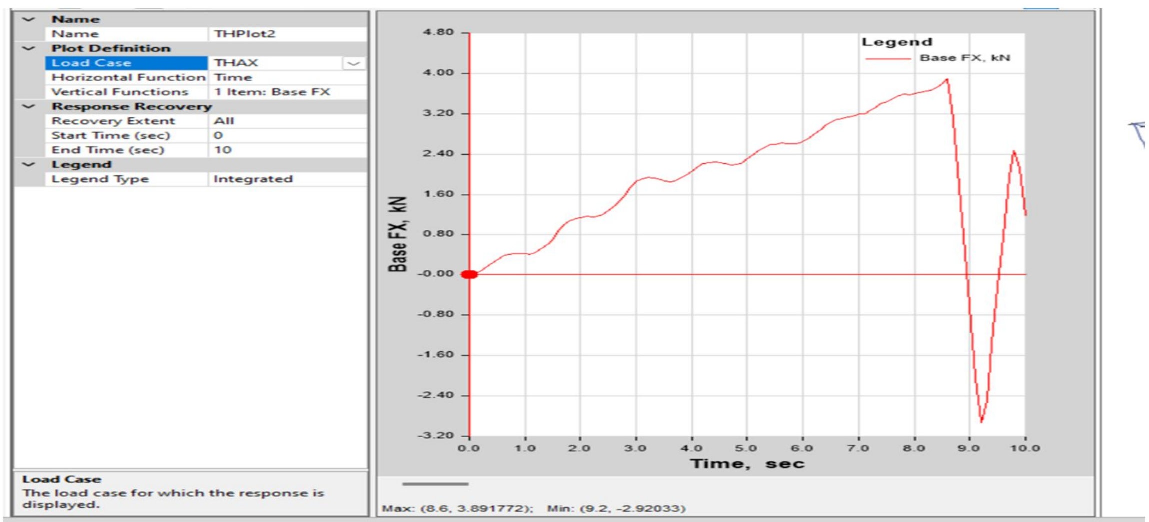

Figure 9: Time history response showing variation of displacement with respect to time under earthquake loading.

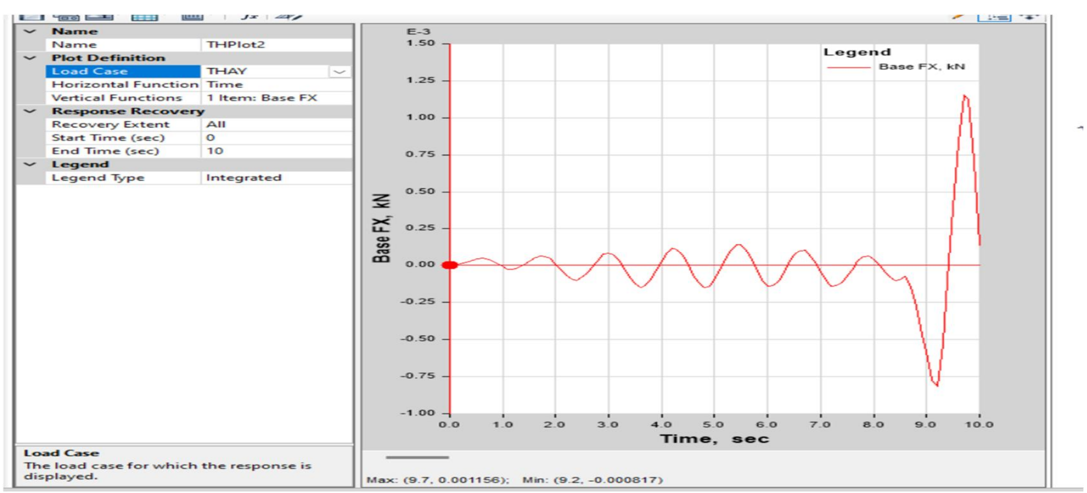

Figure 10: Variation of base reaction with time indicating dynamic force transfer during seismic excitation.

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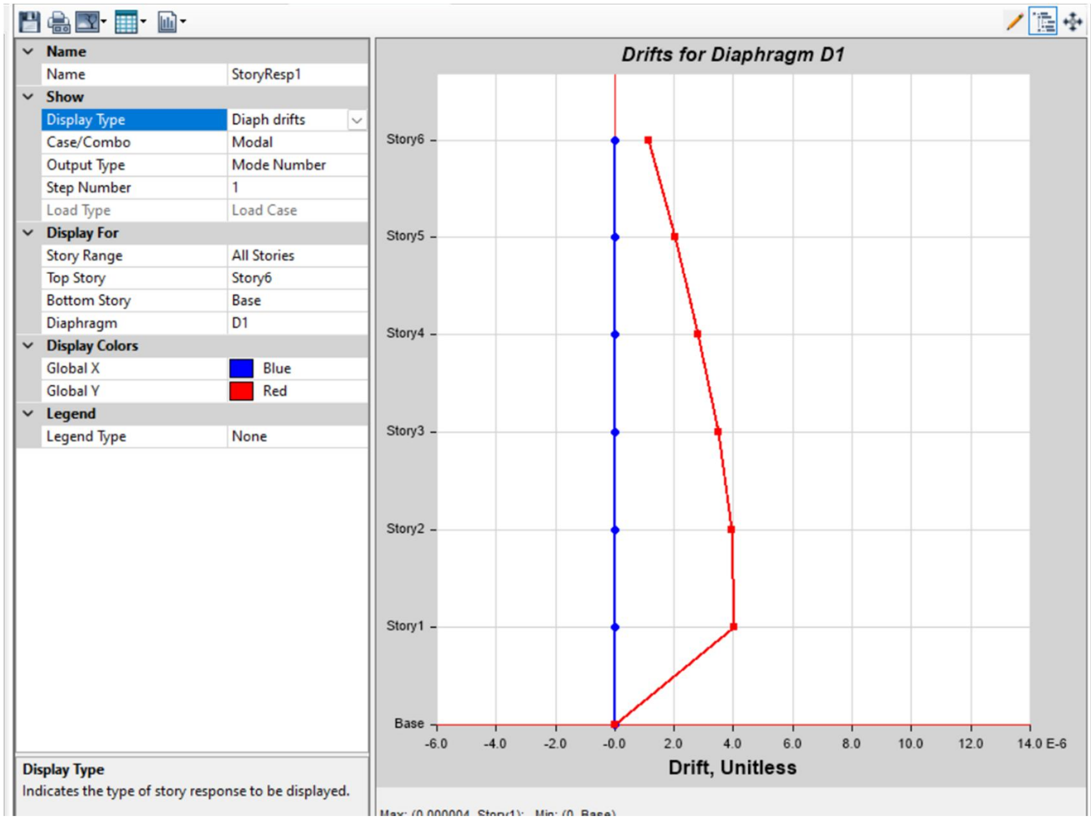

Figure 11: Storey drift variation with time showing relative displacement between consecutive floors during earthquake motion.

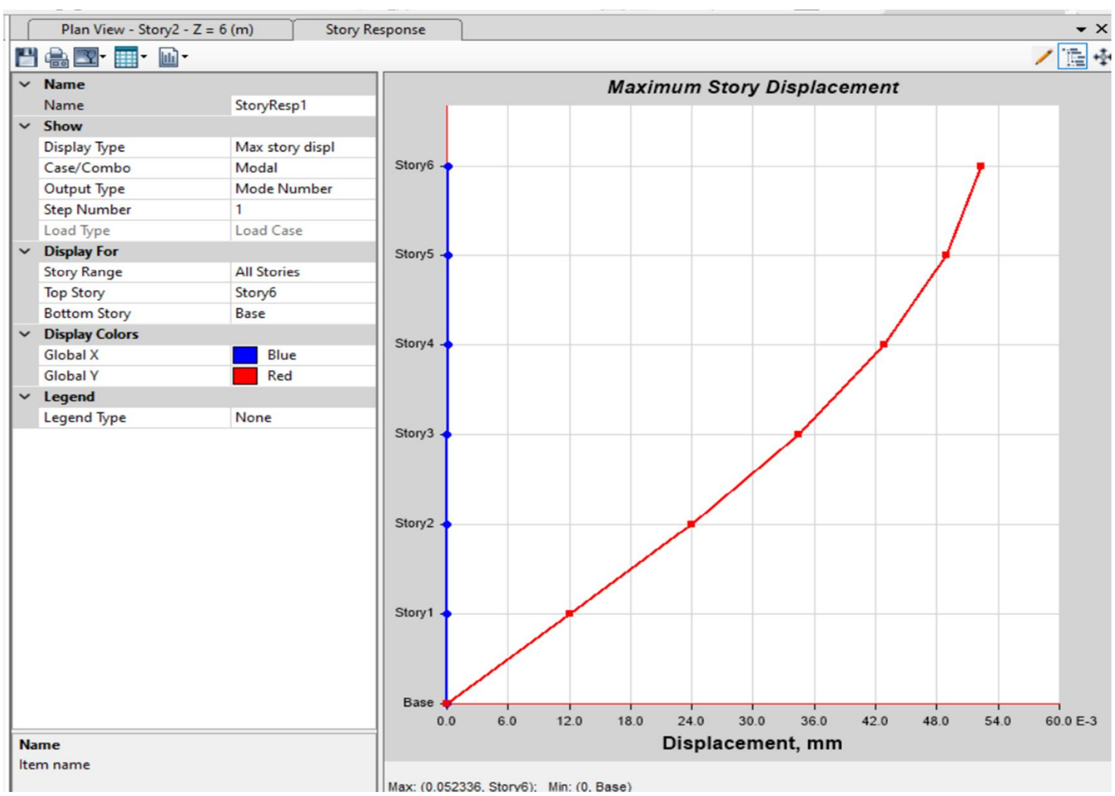

Figure 12: Storey displacement profile along building height showing maximum deformation at the top storey.

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Table 2: Summary of Key Results

Parameter	X-Direction	Y-Direction
Base Shear (kN)	411.53	160.56
Max Displacement (mm)	41.5	111.5
Drift	Within limits	Within limits
Behavior	Stiff	Flexible

The comparison of results from different analyses shows strong consistency. The displacement and base shear values obtained from pushover analysis are close to those from linear analysis, while time history analysis provides peak dynamic response within a similar range.

The structure demonstrates good seismic performance, with no signs of instability or excessive deformation. The results confirm that the structure is capable of resisting seismic

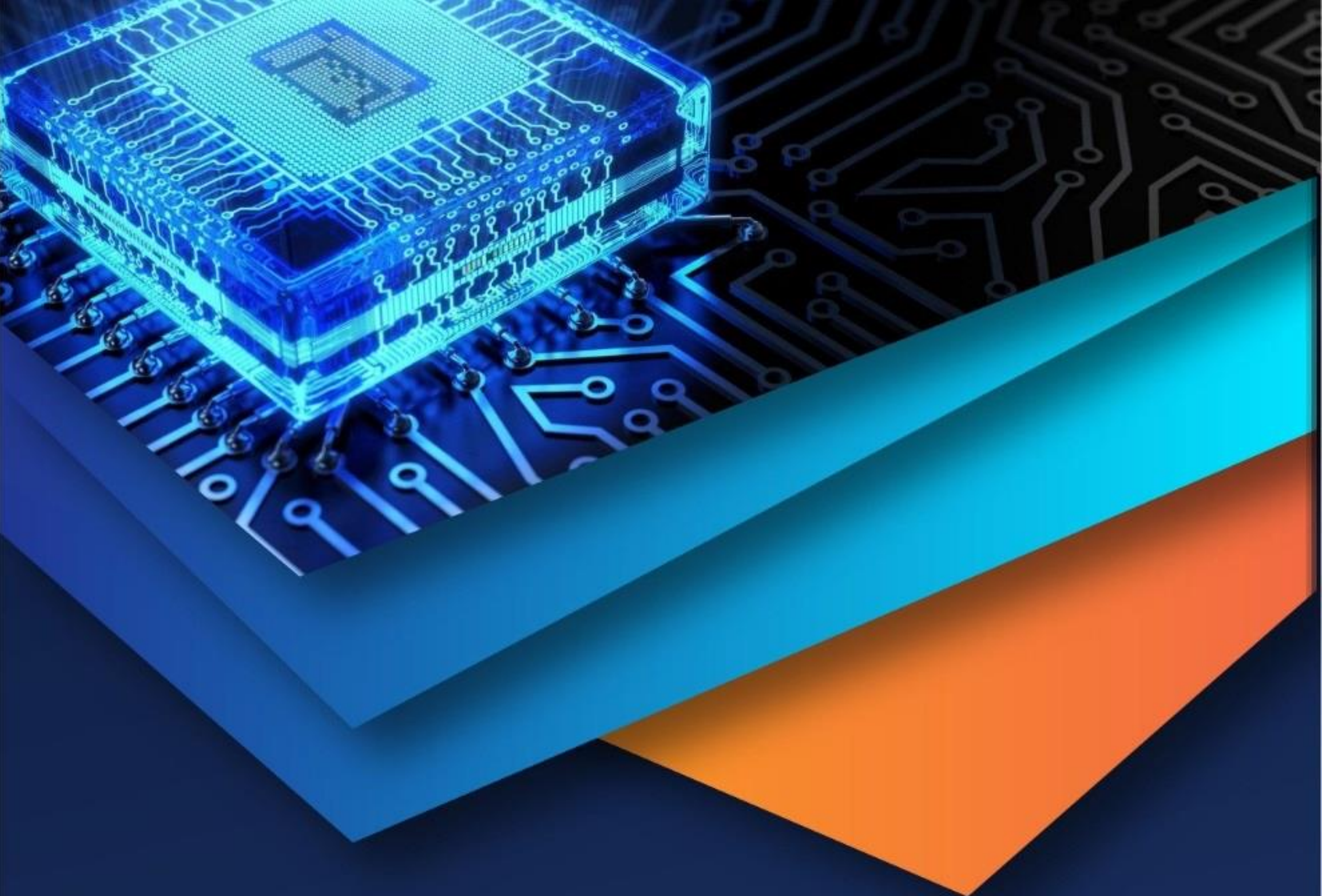
V. CONCLUSION

This study presents a detailed evaluation of the seismic performance of a G+5 steel moment-resisting frame using nonlinear static and dynamic analysis methods. The results confirm that the structure exhibits stable and reliable behavior under seismic loading. The pushover analysis demonstrates that the structure has adequate strength and ductility, with hinge formation occurring in a desirable sequence. The time history analysis further validates the performance by simulating real earthquake conditions and showing controlled dynamic response. The displacement and drift values are within permissible limits, ensuring both safety and serviceability. The consistency between different analysis methods confirms the accuracy of the modelling and analysis. Overall, the study highlights the effectiveness of steel moment-resisting frames in resisting seismic forces. The combined use of pushover and time history analysis provides a comprehensive understanding of structural behavior and enhances the reliability of performance evaluation.

REFERENCES

[1] Chopra, A. K. (2017). Dynamics of Structures (5th ed.). Pearson Education.
[2] Krawinkler, H. (2000). Seismic demands for performance evaluation of steel moment resisting frame structures. Engineering Structures, 22(7), 760–773.
[3] Gupta, A., & Krawinkler, H. (2000). Behavior of ductile SMRFs at low drift levels. Journal of Structural Engineering, 126(3), 346–353.
[4] Freeman, S. A. (1998). The capacity spectrum method as a tool for seismic design. Proceedings of the 11th European Conference on Earthquake Engineering.
[5] Chopra, A. K., & Goel, R. K. (2004). A modal pushover analysis procedure. Earthquake Engineering & Structural Dynamics, 33(8), 903–927.
[6] Medina, R. A., & Krawinkler, H. (2005). Strength demand issues in ductile moment frames. Earthquake Engineering & Structural Dynamics, 34(4-5), 497–524.
[7] FEMA 356. (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Federal Emergency Management Agency.
[8] FEMA P-695. (2009). Quantification of Building Seismic Performance Factors. FEMA.
[9] Lignos, D. G., & Krawinkler, H. (2011). Deterioration modeling of steel components. Journal of Structural Engineering, 137(11), 1291–1302.
[10] Zareian, F., & Medina, R. A. (2010). Proper modeling of structural damping. Journal of Structural Engineering, 136(3), 298–307.
[11] Tremblay, R., Poncet, L., & Bruneau, M. (2008). Seismic response of steel moment frames. Journal of Constructional Steel Research, 64(7-8), 819–832.
[12] Chen, C., Wang, Z., & Li, Y. (2022). Higher-mode effects on mid-rise steel frames. Engineering Structures, 250, 113356.
[13] Eatherton, M. R., & Hajjar, J. F. (2010). Residual drift considerations. Journal of Structural Engineering, 136(6), 681–691.
[14] Jalayer, F., Cornell, C. A., & Deierlein, G. G. (2003). Probabilistic seismic demand assessment. Earthquake Engineering & Structural Dynamics, 32(12), 1993–2012.

[15] Kamgar, R., Hosseini, S. M., & Ghafory-Ashtiany, M. (2022). Wavelet-based nonlinear seismic analysis. Engineering Structures, 252, 113128.
[16] Safari Honar, F., Rezaei, M., & Fanaie, F. (2023). Nonlinear dynamic seismic assessment of steel frames. Buildings, 13(1), 1–18.
[17] Sebaq, M. S., Bakhshi, A., & Fanaie, F. (2023). Damage indices in steel moment frames. International Journal of Steel Structures, 23(2), 455–470.
[18] Haselton, C. B., Baker, J. W., & Lignos, D. G. (2011). Collapse safety of steel frames. Journal of Structural Engineering, 137(12), 1438–1448.
[19] Antoniou, S., & Pinho, R. (2004). Development of adaptive pushover procedures. Journal of Earthquake Engineering, 8(4), 491–514.
[20] Vamvatsikos, D., & Cornell, C. A. (2002). Incremental dynamic analysis. Earthquake Engineering & Structural Dynamics, 31(3), 491–514.
[21] Bruneau, M., Uang, C.-M., & Whittaker, A. (2011). Ductile Design of Steel Structures. McGraw-Hill.
[22] Hamburger, R. O., & Moehle, J. P. (2006). Performance-based seismic design. Earthquake Spectra, 22(S2), S1–S11.
[23] Lee, K., & Foutch, D. A. (2002). Performance evaluation of steel frame buildings. Journal of Structural Engineering, 128(7), 850–859.
[24] Ricles, J. M., Zhang, X., & Lu, L.-W. (2004). Seismic performance of moment connections. Journal of Structural Engineering, 130(9), 1365–1374.
[25] Popov, E. P., & Youssef, N. F. (1998). Cyclic behavior of steel connections. Journal of Structural Engineering, 124(3), 269–277.



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