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

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Abstract: Performance-based seismic design has emerged as a critical requirement in modern structural engineering due to the limitations of conventional force-based analysis methods in accurately predicting nonlinear structural response. Steel moment-resisting frames (SMRFs) are widely used as lateral load-resisting systems in earthquake-prone regions because of their inherent ductility, energy dissipation capacity, and structural redundancy. However, realistic evaluation of their seismic performance requires advanced nonlinear analysis techniques capable of capturing stiffness degradation, plastic hinge formation, and cyclic loading effects. This research presents a comprehensive analytical framework for evaluating the seismic performance of a multi-storey steel moment-resisting frame using nonlinear static (pushover) and nonlinear dynamic (time-history) analyses performed in ETABS software. A detailed three-dimensional model incorporating material and geometric nonlinearity along with calibrated plastic hinge properties was developed. Pushover analysis revealed a maximum base shear capacity of 43,166 kN in the X-direction and 2,452 kN in the Y-direction, highlighting directional stiffness variation. Maximum inter-storey drift of 0.0153 m was observed at the first storey. Nonlinear dynamic analysis indicated higher displacement demand due to cyclic effects and higher-mode participation. Plastic hinge formation primarily occurred at beam ends, confirming strong-column–weak-beam behavior. The study demonstrates that integrated nonlinear analysis provides reliable insight into structural capacity, deformation demand, and performance level attainment under seismic loading.

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.

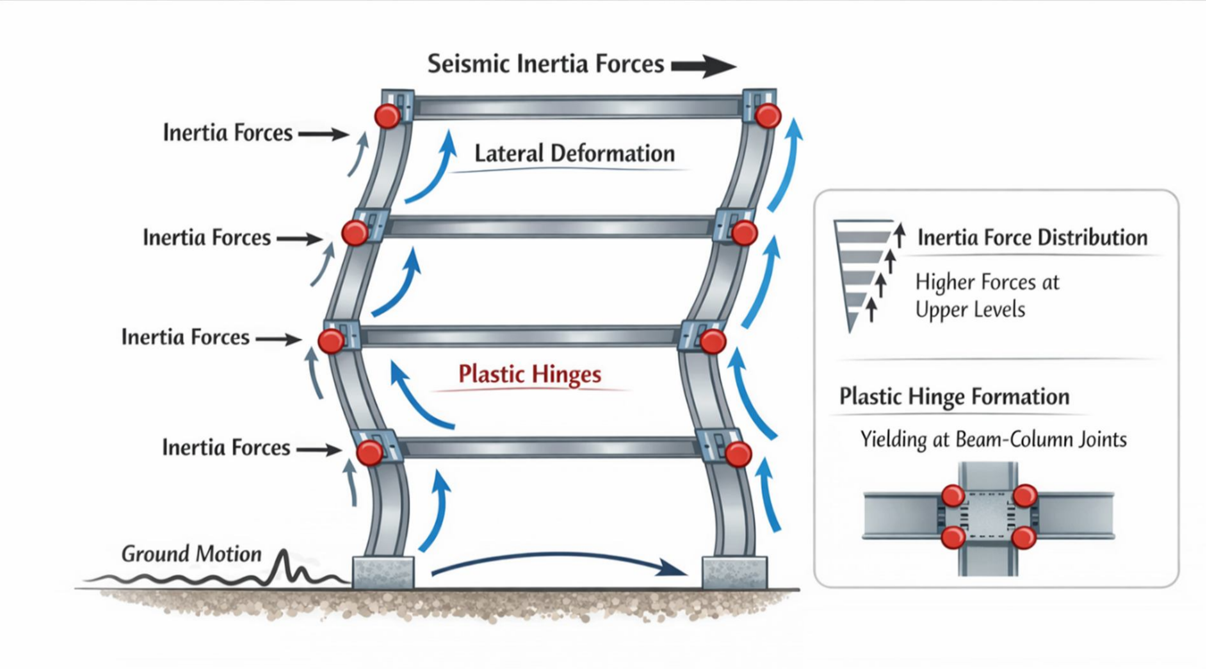

Figure 1: Conceptual illustration of seismic response mechanism in a steel moment-resisting frame showing lateral deformation pattern, inertia force distribution, and plastic hinge formation.

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 valuable 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

A. Dataset Used and Algorithm

The analytical dataset utilized in the present research comprises structural response parameters obtained from a detailed three-dimensional numerical model of a multi-storey steel moment-resisting frame developed using ETABS software. Unlike data-driven machine learning studies that rely on empirical datasets collected from field observations or digital platforms, the dataset in this research is generated through advanced nonlinear structural analysis procedures. Such analytically generated datasets are widely adopted in performance-based earthquake engineering research, as they enable systematic evaluation of structural behavior under controlled loading conditions.

The structural dataset includes key seismic response parameters such as base shear capacity, overturning moment demand, inter-storey drift ratios, roof displacement, and plastic hinge state progression obtained from nonlinear static and nonlinear dynamic analyses. These parameters collectively provide a comprehensive representation of both global and local structural performance under earthquake loading.

The structural model consists of beams and columns connected through rigid moment-resisting joints, enabling lateral forces to be resisted primarily through flexural action. Material properties for structural steel were assigned in accordance with codal recommendations, incorporating elastic modulus, yield strength, and realistic stress–strain relationships to simulate inelastic deformation.

Geometric nonlinearity was activated to account for P–Δ effects, which significantly influence displacement demand in multi-storey frames. Plastic hinges were introduced at critical locations such as beam ends and column bases using calibrated hinge definitions available in ETABS. These hinge properties were selected to represent performance states including elastic response, immediate occupancy, life safety, and collapse prevention.

The analytical algorithm followed in this research can be described as a structured performance-based evaluation procedure. Initially, gravity loads including dead load and an appropriate percentage of live load were applied to establish realistic mass distribution.

Subsequently, nonlinear static (pushover) analysis was conducted by incrementally applying lateral loads in both principal directions until significant stiffness degradation and hinge formation were observed. This procedure enabled the generation of capacity curves and identification of global strength parameters. Following pushover analysis, nonlinear dynamic (time-history) analysis was performed using representative earthquake ground motion records scaled to match design spectrum characteristics. The algorithm captured time-dependent variation of response parameters, enabling realistic assessment of cyclic loading effects and higher-mode participation. The integration of these analytical procedures formed the basis for generating a robust dataset for seismic performance evaluation.

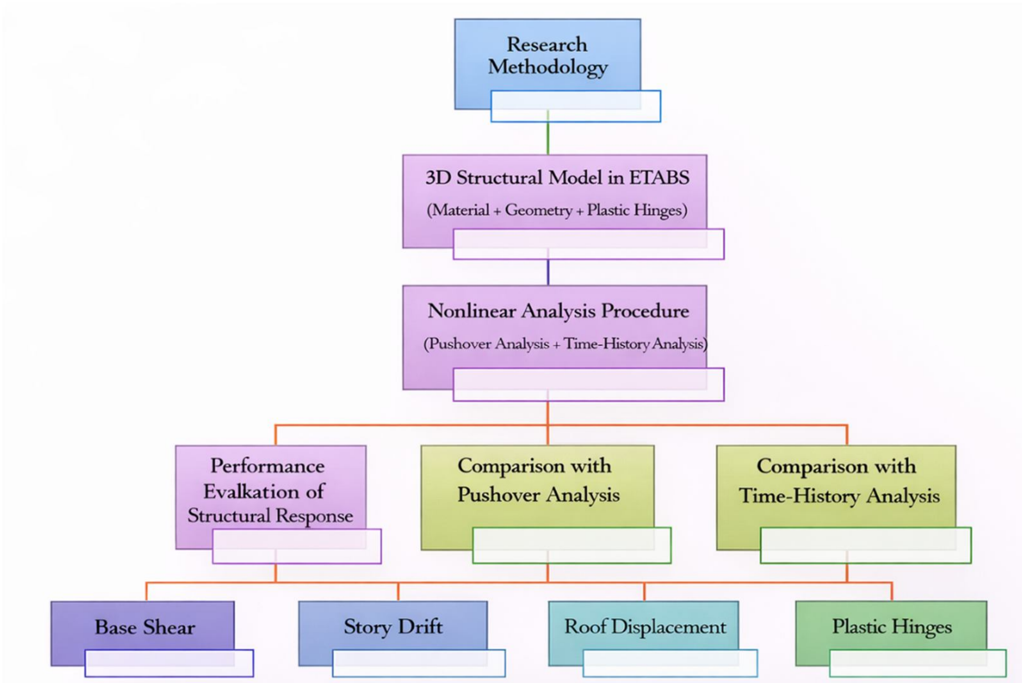

Figure 2: Flowchart illustrating the overall nonlinear seismic performance evaluation process, including structural modeling, load definition, pushover analysis, time-history analysis, response extraction, and performance level assessment.

B. Performance Evaluation Matrix

The seismic performance of the steel moment-resisting frame was evaluated using a comprehensive matrix of global and local response parameters derived from nonlinear analysis results. Base shear capacity was considered a primary indicator of global lateral strength.

The pushover analysis revealed a maximum base shear capacity of 43,166 kN in the X-direction and 2,452 kN in the Y-direction, demonstrating directional variation in stiffness and strength. Overturning moment demand at the base was also extracted, with peak values reaching 194,247 kN-m in the X-direction and 5,442 kN-m in the Y-direction. These parameters were used to assess whether the structural system possessed adequate reserve strength beyond design-level seismic demand.

Roof displacement and inter-storey drift were evaluated to quantify deformation demand and potential damage concentration. Maximum inter-storey drift of 0.0153 m was observed at the first storey, indicating increased flexibility at lower levels. Drift distribution patterns along the building height were analyzed to identify soft-storey tendencies and stiffness irregularities. Plastic hinge rotation demand and hinge state progression were monitored throughout the analyses to evaluate local ductility requirements. The majority of hinges remained within Life Safety performance limits, while only limited hinge formation approached Collapse Prevention state at maximum displacement levels.

The performance evaluation matrix further incorporated comparison between capacity-based results obtained from pushover analysis and demand-based results obtained from nonlinear dynamic analysis. Time-history results indicated higher peak displacement demand due to cyclic effects and higher-mode participation, confirming the limitations of static procedures in capturing realistic seismic response.

Structural stability was assessed by examining strength degradation trends and hinge distribution patterns. The absence of widespread column hinging or global instability indicated satisfactory seismic performance.

Overall, the adopted methodology integrates structural modeling accuracy, nonlinear analysis procedures, and quantitative performance evaluation criteria to provide a comprehensive assessment framework. The structured analytical algorithm ensures reproducibility of results and enables systematic interpretation of seismic response parameters. By combining capacity estimation with realistic demand prediction, the research methodology supports performance-based seismic design principles and contributes to improved understanding of nonlinear behavior in steel moment-resisting frame structures.

IV. RESULTS AND DISCUSSION

A. Pushover Capacity Response Analysis

The nonlinear static pushover analysis provided critical insight into the global lateral load-carrying capacity and deformation characteristics of the steel moment-resisting frame. The capacity curve obtained in the X-direction exhibited a well-defined transition from linear elastic response to nonlinear inelastic behavior, followed by gradual stiffness degradation. The structure achieved a maximum base shear capacity of 43,166 kN, accompanied by an overturning moment demand of 194,247 kN-m at the base. This substantial strength capacity indicates that the frame possesses adequate resistance to design-level seismic forces and maintains significant reserve strength beyond the elastic range. The post-yield slope reduction observed in the pushover curve confirms desirable ductile behavior, which is essential for performance-based seismic design.

In contrast, the pushover response in the Y-direction showed comparatively lower stiffness and strength, with a peak base shear of 2,452 kN and base moment of 5,442 kN-m. This directional variation highlights the influence of structural configuration and stiffness distribution on seismic performance. Plastic hinge formation patterns revealed that yielding initiated primarily at beam ends in lower storeys, followed by gradual hinge propagation to intermediate levels as displacement demand increased. Such hinge distribution confirms adherence to the strong-column–weak-beam philosophy and indicates controlled energy dissipation without premature column failure.

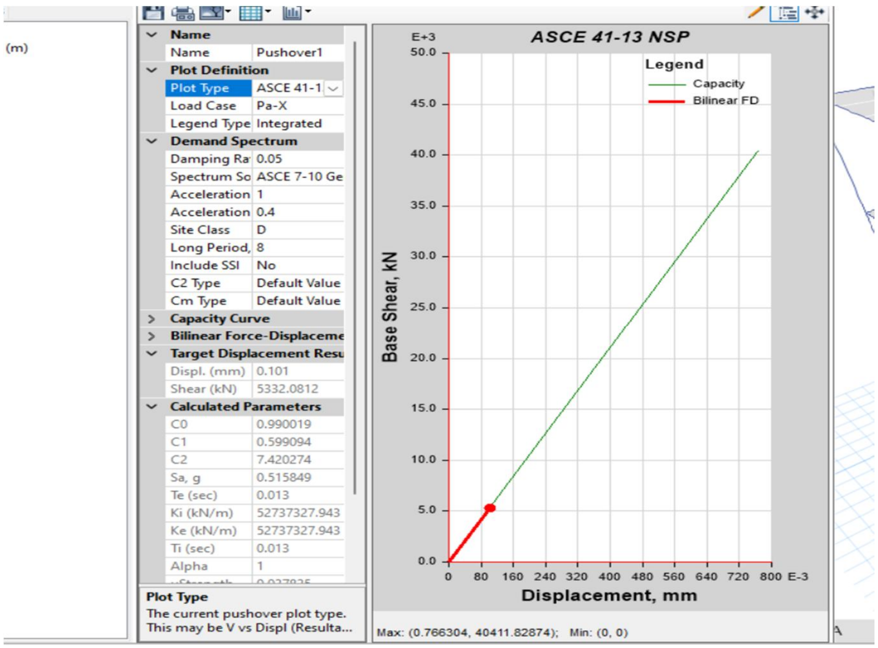

Figure 3: Pushover capacity curve showing nonlinear base shear versus roof displacement relationship and corresponding hinge development.

B. Story Drift and Roof Displacement Behaviour

Inter-storey drift response extracted from nonlinear analysis results provided a detailed understanding of deformation demand distribution along the building height. The maximum drift was recorded at the first storey level, with a peak value of 0.0153 m observed under Y-direction pushover loading. This concentration of deformation at lower storeys indicates increased flexibility and potential soft-storey tendencies under severe seismic demand. Such behavior is commonly observed in moment-resisting frame structures where stiffness distribution varies along the height.

In the X-direction, drift values were more uniformly distributed across storeys, reflecting higher lateral stiffness and strength capacity. The drift profile exhibited a cantilever-type deformation pattern, with progressively decreasing drift toward upper levels. Roof displacement demand increased significantly after yielding due to stiffness degradation, highlighting the nonlinear response characteristics of the frame. When correlated with hinge formation patterns, these displacement trends provide a clear representation of damage progression and performance level attainment. Although higher drift demand was observed at lower storeys, the overall drift values remained within acceptable limits corresponding to Life Safety performance criteria for steel moment-resisting frames.

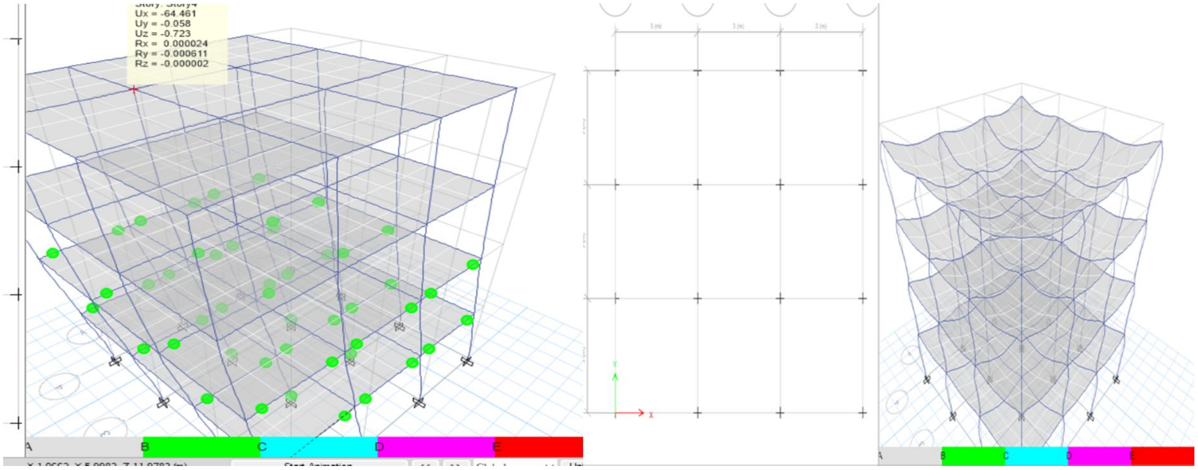

Figure 4: Story-wise drift distribution and roof displacement profile obtained from nonlinear analysis.

C. Plastic Hinge Formation and Performance State Evaluation (≈200 words)

Plastic hinge monitoring during nonlinear analysis enabled detailed evaluation of local damage progression and ductility demand in structural members. Initial hinge formation occurred at beam ends in lower storeys, corresponding to the onset of yielding under increasing lateral loads. These hinges initially remained within the Immediate Occupancy performance level, indicating minor inelastic deformation with negligible strength degradation. As loading progressed, additional hinges formed in intermediate storeys, and several hinges transitioned into the Life Safety performance range, reflecting controlled damage and effective energy dissipation. At higher displacement levels, limited hinge formation was observed at column bases, particularly at lower storeys where deformation demand was highest. However, the overall hinge distribution remained consistent with the intended strong-column–weak-beam mechanism. Only a small number of hinges approached Collapse Prevention state at maximum displacement demand, and no sudden brittle failure was observed. This indicates that the structural system maintains global stability even under severe seismic excitation. The hinge-based performance assessment complements global response evaluation and confirms that the frame possesses adequate ductility and deformation capacity for performance-based seismic design.

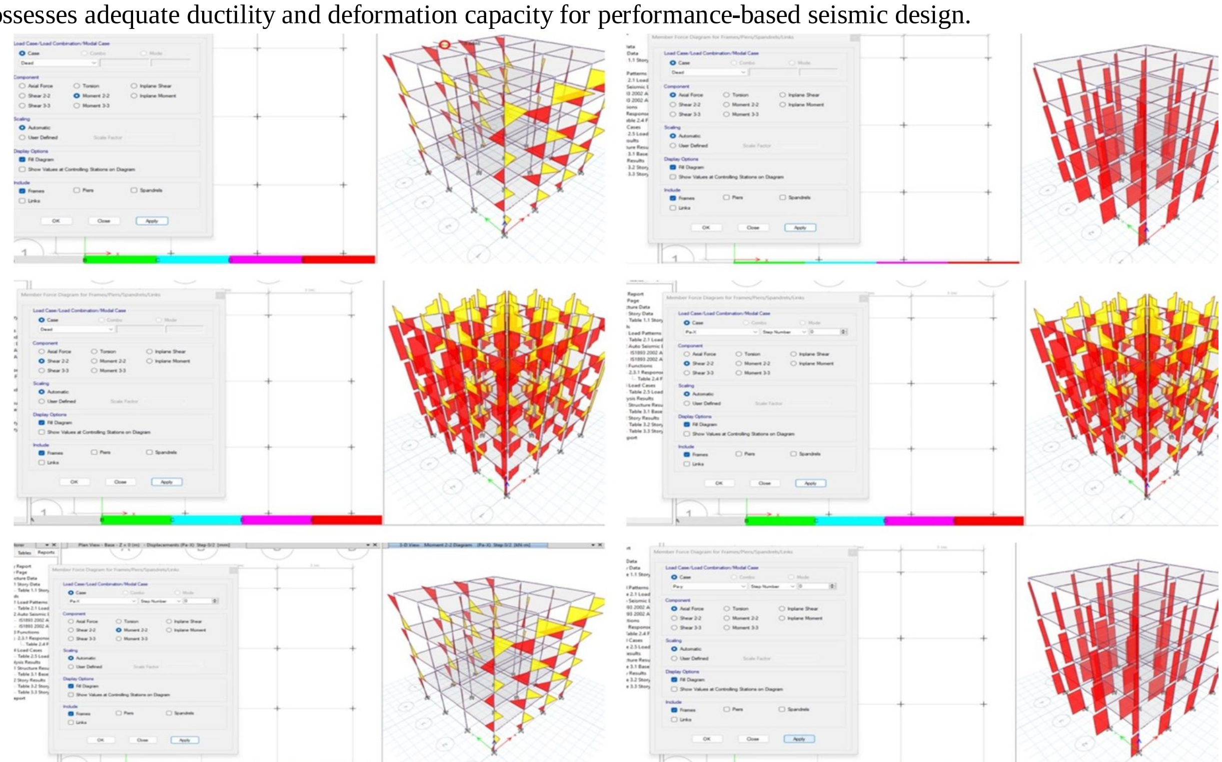

Figure 5: Plastic hinge distribution along frame height illustrating performance level transitions from elastic to collapse prevention.

D. Nonlinear Dynamic Time-History Response

Nonlinear dynamic analysis provided a realistic representation of structural response under earthquake ground motion excitation. Time-history results indicated significant fluctuation in base shear demand during the strong-motion phase, reflecting the dynamic nature of seismic loading. Peak base shear demand remained slightly lower than the ultimate capacity obtained from pushover analysis, confirming that the structure possesses sufficient strength reserve. Roof displacement time-history plots exhibited pronounced oscillatory behavior, with peak displacement occurring during maximum inertia force development.

Compared to nonlinear static analysis, dynamic analysis predicted higher peak displacement and inter-storey drift demand due to cyclic loading effects and higher-mode participation. Drift concentration was again observed at lower storeys, particularly at the first storey level, confirming trends identified in pushover analysis. The magnitude of drift demand varied depending on ground motion characteristics, demonstrating sensitivity of structural response to input excitation. Despite localized yielding at beam ends, the structure maintained overall integrity and did not experience excessive strength degradation or instability. These findings validate the effectiveness of nonlinear dynamic analysis in capturing realistic seismic demand and highlight its importance in performance-based structural evaluation.

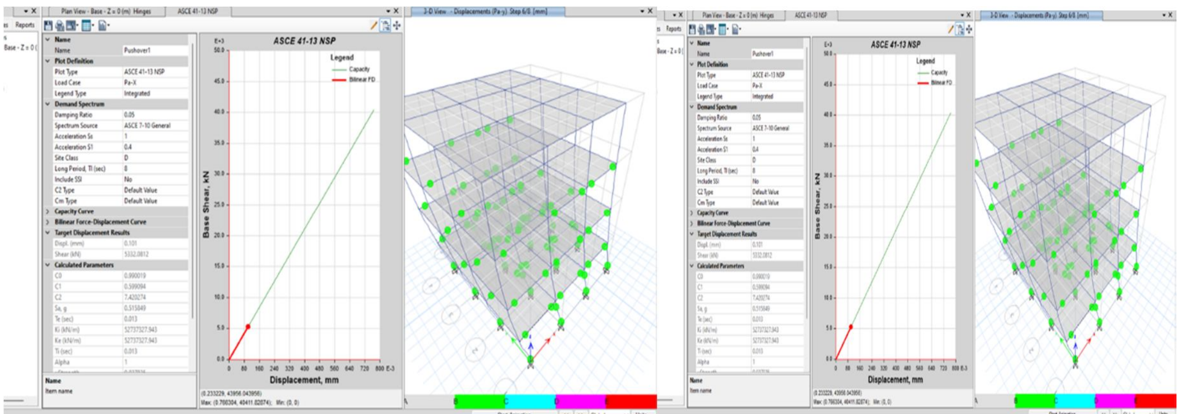

Figure 6: Time-history plots showing variation of base shear and roof displacement during earthquake excitation.

E. Comparative Response Table and Interpretation

Parameter	Nonlinear Static Analysis	Nonlinear Dynamic Analysis
Base Shear	Capacity = 43,166 kN (X-dir.)	Fluctuating demand, lower than capacity
Roof Displacement	Lower estimate	Higher peak displacement
Story Drift	Concentrated at lower storeys	More realistic cyclic drift demand
Plastic Hinges	Gradual formation	Repeated hinge state transitions
Cyclic Effects	Not captured	Fully captured

The comparative evaluation of nonlinear static and nonlinear dynamic analysis results provides valuable insight into the strengths and limitations of each method in seismic performance assessment. Pushover analysis offers a clear representation of global structural capacity and enables identification of critical performance points such as yielding initiation and ultimate strength. The capacity curve derived from pushover analysis demonstrates that the steel moment-resisting frame possesses substantial lateral strength and ductility. However, the monotonic nature of pushover loading inherently limits its ability to capture cyclic degradation, inertia effects, and higher-mode response characteristics. Nonlinear dynamic analysis, on the other hand, reflects actual demand imposed by earthquake ground motions and therefore provides a more realistic estimation of displacement and drift demand. The time-dependent variation of response parameters observed in dynamic analysis highlights the influence of ground motion frequency content and duration on structural performance. While base shear demand remained within capacity limits, peak displacement values were consistently higher than those predicted by static procedures. This discrepancy underscores the importance of incorporating dynamic analysis in performance-based design frameworks. Plastic hinge patterns obtained from both analyses showed similar locations of yielding; however, dynamic analysis revealed more frequent hinge state transitions due to repeated loading cycles. Such cyclic behavior plays a critical role in governing cumulative damage and potential strength deterioration. The comparative results therefore demonstrate that nonlinear static and dynamic analyses should be viewed as complementary tools rather than alternatives. The integration of both methods enables a comprehensive evaluation of structural safety, deformation demand, and collapse resistance.

F. Discussion

The analytical results obtained in this study clearly demonstrate the importance of adopting performance-based seismic evaluation methodologies for steel moment-resisting frame structures. The nonlinear static analysis results confirm that the frame possesses adequate lateral strength and ductility to resist design-level seismic forces. The substantial base shear capacity of 43,166 kN in the X-direction indicates that the structural system can mobilize significant resistance beyond the elastic range. This reserve strength is critical for preventing collapse during extreme seismic events. The gradual stiffness degradation observed in the pushover curve further indicates desirable ductile behavior, which is essential for energy dissipation in seismic design.

Story drift analysis revealed concentration of deformation at lower storeys, particularly at the first storey level where maximum drift of 0.0153 m was recorded. Such drift concentration highlights the influence of stiffness distribution on seismic response and suggests that lower storey behavior often governs overall structural performance. Although drift demand remained within acceptable Life Safety limits, the observed deformation pattern indicates potential vulnerability that may require attention in design or retrofitting strategies. Enhancing stiffness uniformity or incorporating supplemental damping systems could help mitigate such localized deformation demand.

Plastic hinge formation patterns provided valuable insight into local damage progression and ductility requirements. The predominance of beam-end hinging confirms effective implementation of the strong-column–weak-beam philosophy, ensuring that energy dissipation occurs through controlled flexural yielding rather than column failure. Limited hinge formation at column bases under extreme loading conditions indicates that the frame maintains overall stability even at high displacement levels. These findings align with modern performance-based seismic design principles, which emphasize controlled damage rather than purely elastic response.

Nonlinear dynamic analysis further highlighted the limitations of relying solely on static procedures for seismic performance evaluation. Higher displacement demand predicted by time-history analysis demonstrates the significance of cyclic loading effects and higher-mode participation. The variability of response observed across different time intervals emphasizes the influence of ground motion characteristics on structural behavior. These results reinforce the necessity of incorporating realistic dynamic analysis in performance-based frameworks to ensure reliable safety assessment.

Overall, the study confirms that integrated nonlinear static and dynamic analysis provides a robust methodology for evaluating seismic performance of steel moment-resisting frames. By combining capacity estimation with realistic demand prediction, engineers can make informed design decisions that enhance structural resilience and reduce seismic risk.

V. CONCLUSION

This research presented a comprehensive analytical investigation into the seismic performance of a steel moment-resisting frame using integrated nonlinear static (pushover) and nonlinear dynamic (time-history) analysis techniques. The primary motivation of the study was to address the inherent limitations associated with conventional force-based seismic design methods, which often rely on simplified linear elastic assumptions and do not adequately capture the complex nonlinear behavior exhibited by structures during strong earthquake ground motions. By adopting a performance-based evaluation framework and utilizing advanced modeling capabilities available in ETABS software, the study successfully demonstrated a realistic approach for assessing structural strength capacity, deformation demand, and damage progression.

The results obtained from nonlinear static analysis clearly indicate that the steel moment-resisting frame possesses significant lateral load-carrying capacity and exhibits desirable ductile behavior. The maximum base shear capacity of approximately 43,166 kN in the X-direction confirms that the structural system has sufficient reserve strength beyond the elastic range, which is critical for ensuring collapse resistance during severe seismic events. The gradual stiffness degradation observed in the pushover capacity curve further validates the effectiveness of the structural configuration in promoting controlled inelastic deformation. In contrast, the comparatively lower strength capacity observed in the Y-direction highlights the importance of evaluating seismic response in multiple principal directions to capture the influence of stiffness distribution and geometric configuration on structural performance.

Story drift analysis revealed that deformation demand was primarily concentrated at lower storeys, with a peak inter-storey drift of approximately 0.0153 m recorded at the first storey level. Although this drift demand remained within acceptable limits corresponding to Life Safety performance objectives, the observed deformation concentration suggests that lower storey behavior plays a governing role in seismic response of moment-resisting frame systems. Plastic hinge formation patterns further reinforced this observation, as yielding initiated predominantly at beam ends in lower and intermediate storeys before gradually propagating to other regions under increased displacement demand. This hinge distribution confirms adherence to the strong-column–weak-beam philosophy, ensuring that energy dissipation occurs through ductile flexural yielding rather than brittle column failure.

The nonlinear dynamic analysis provided deeper insight into the realistic time-dependent response of the structure under earthquake excitation. The results demonstrated higher peak displacement and drift demand compared to pushover predictions due to cyclic loading effects and higher-mode participation. Despite these increased demands, the structural system maintained overall stability and did not exhibit significant strength degradation or collapse tendencies. This finding emphasizes the necessity of incorporating nonlinear dynamic analysis in performance-based seismic evaluation to capture cumulative damage effects and record-to-record variability.

A key contribution of the study lies in the comparative assessment of nonlinear static and nonlinear dynamic analysis outcomes. The results confirm that while pushover analysis is highly effective for estimating global strength capacity and identifying potential failure mechanisms, dynamic analysis is essential for accurately predicting deformation demand and cyclic response characteristics. The integrated use of both methods therefore provides a balanced and reliable framework for seismic performance evaluation.

From a practical design perspective, the findings highlight the importance of controlling stiffness irregularities, enhancing lower storey strength distribution, and considering supplemental damping or retrofitting measures to further improve seismic resilience. Future research may extend the analytical framework to include taller structures, plan irregularities, varying soil conditions, probabilistic performance assessment, and experimental validation of analytical results. Overall, this study contributes to advancing performance-based seismic design practices and reinforces the effectiveness of steel moment-resisting frames as robust lateral load-resisting systems in earthquake-prone regions.

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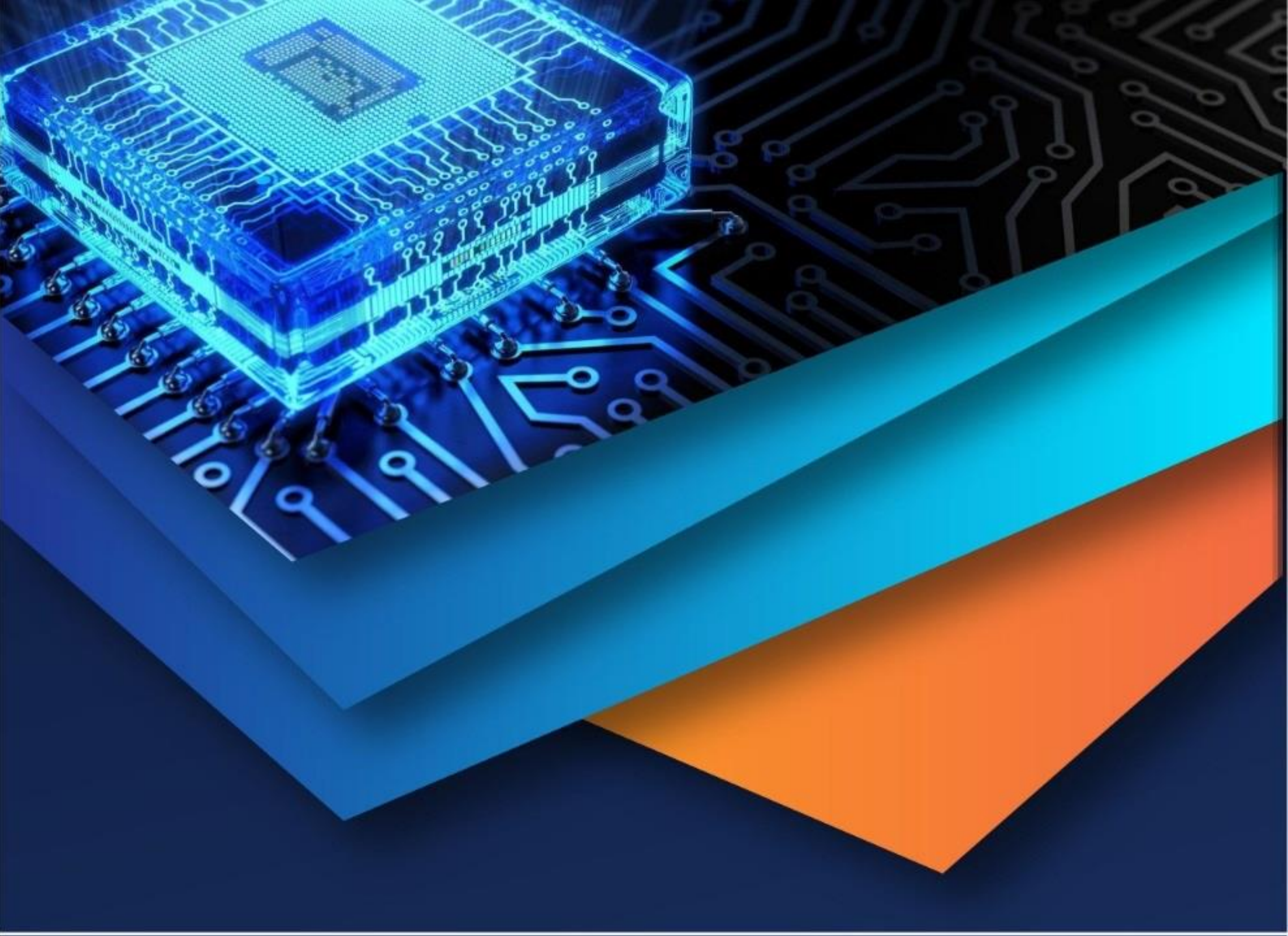

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