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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 steel moment-resisting frames is an important aspect of earthquake-resistant structural design because these systems are expected to resist lateral forces through strength, stiffness, ductility, and controlled inelastic deformation. This study evaluates the seismic behaviour of a G+5 steel moment-resisting frame using nonlinear static pushover analysis and nonlinear dynamic time history analysis. The structural model is developed and analysed in ETABS by considering appropriate material properties, loading conditions, seismic parameters, fixed base support, and plastic hinge behaviour. Pushover analysis is performed in both X and Y directions to assess base force capacity, storey displacement, hinge formation, and FEMA 440 equivalent linearization response. Time history analysis is carried out using earthquake acceleration input to study dynamic base shear response, displacement, storey drift, response spectrum behaviour, and hinge performance. The pushover results show that the maximum base force is 2806.759 kN in the X-direction and 3382.603 kN in the Y-direction. The maximum pushover displacement is 52.368 mm in the X-direction and 84.058 mm in the Y-direction, indicating greater flexibility in the Y-direction. Time history results show maximum drift values of 0.004166 in the X-direction and 0.006853 in the Y-direction. Since the Y-direction drift exceeds the commonly accepted limit of 0.004, stiffness enhancement and drift-control measures are required. Overall, the study concludes that the frame has adequate lateral strength and ductile behaviour, but its seismic performance is governed by deformation demand in the Y-direction.
Keywords: Steel Moment-Resisting Frame, Seismic Performance, Pushover Analysis, Time History Analysis, ETABS, Storey Drift, Base Shear, Plastic Hinge, FEMA 440, Nonlinear Analysis.

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.

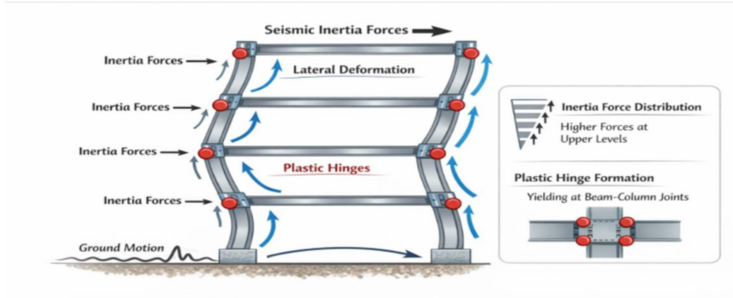

Figure 1: Conceptual illustration of seismic response mechanism in a steel moment-resisting frame showing lateral deformation pattern, inertia force distribution, and plastic hinge formation.

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

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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. FEMA 440 equivalent linearization was also used to interpret the pushover response in terms of spectral displacement, spectral acceleration, and effective period. The X-direction showed a spectral displacement of 174.67 mm, spectral acceleration of 0.545915 g, and effective period of 1.135 seconds, whereas the Y-direction showed a spectral displacement of 1599.576 mm, spectral acceleration of 0.658688 g, and effective period of 3.127 seconds. These values indicate that the Y-direction has greater flexibility and higher deformation demand, making it more critical for seismic performance evaluation.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

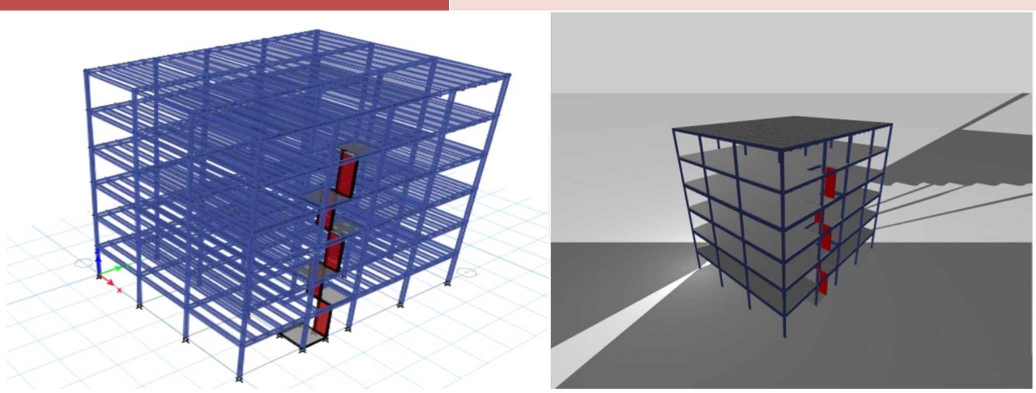

Figure 2: 3D analytical model of G+5 steel moment-resisting frame developed in ETABS software.

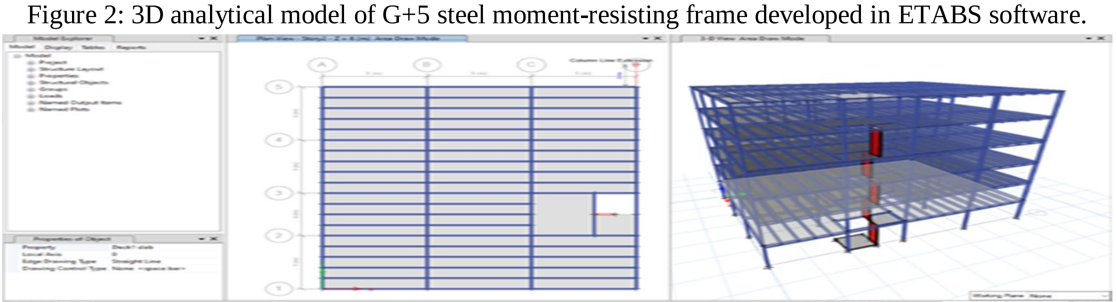

Figure 3: Plan view showing grid layout and structural configuration of the building.

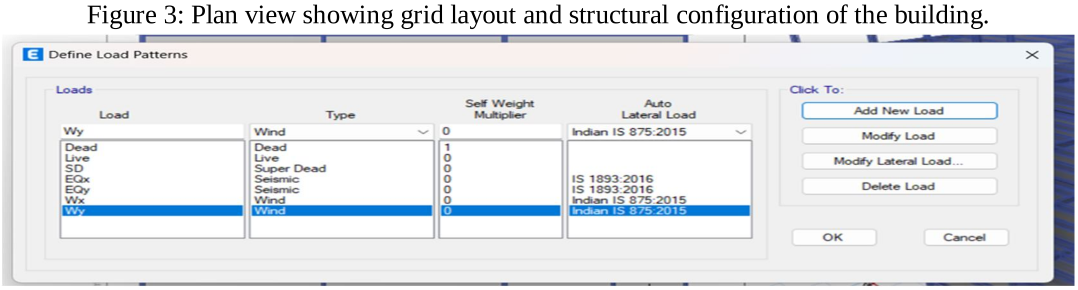

Figure 4: Definition and assignment of load patterns including dead, live, wind and seismic loads in ETABS.

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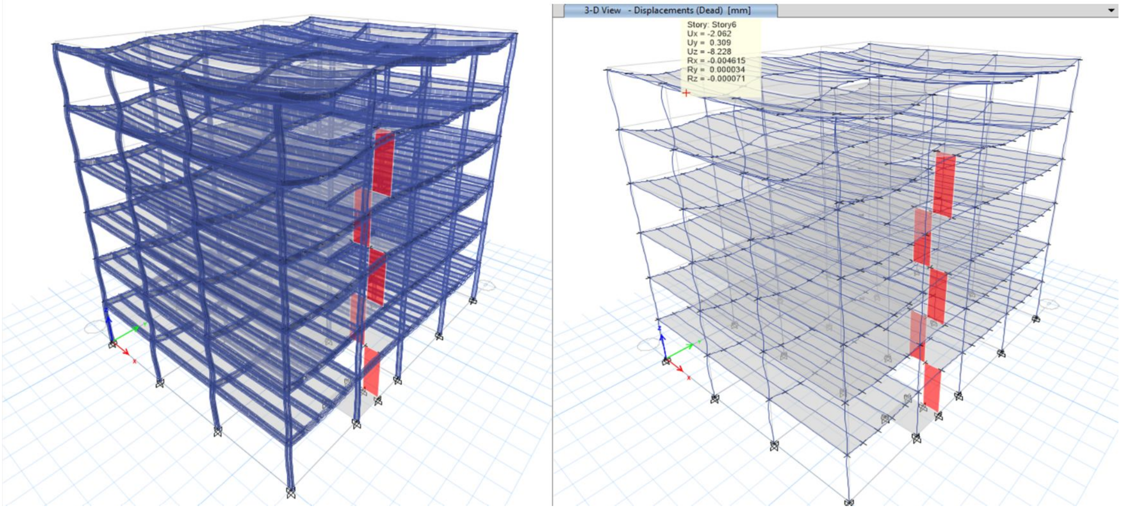

Figure 5: Deformed shape of structure under applied loading showing overall structural behavior.

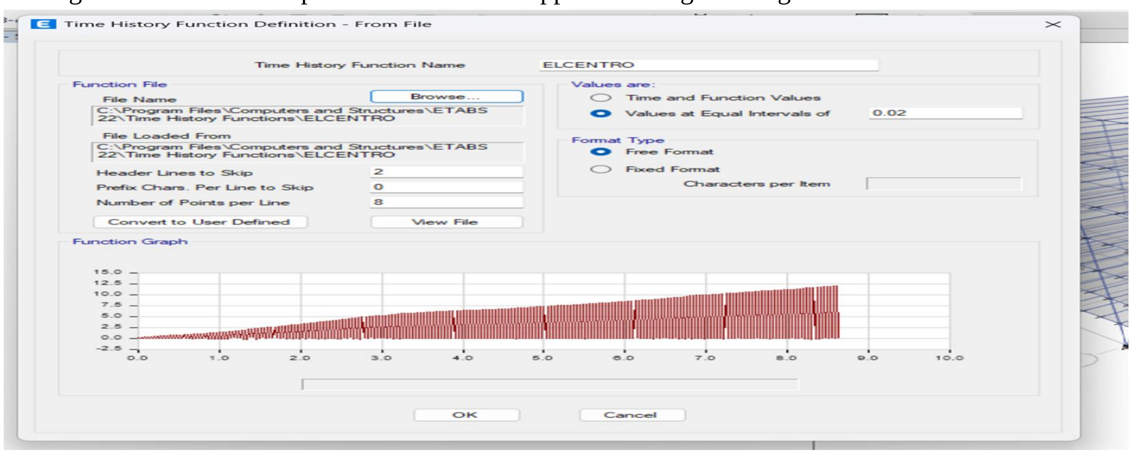

Figure 6: Acceleration versus time graph of El Centro earthquake record used as input for time history analysis.

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

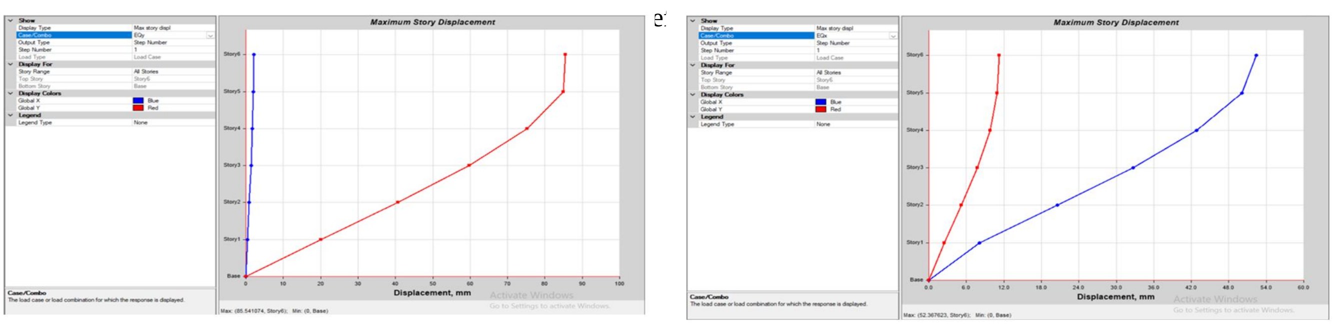

Figure 7: Storey displacement profile under Y& X -direction pushover analysis.

The pushover analysis results show that the G+5 steel moment-resisting frame develops a regular lateral deformation pattern under seismic loading. The storey displacement response increases from the base to the top storey, which indicates typical frame action under lateral load. The maximum displacement is higher in the Y-direction than in the X-direction, showing that the Y-direction is comparatively more flexible and more critical for deformation control.

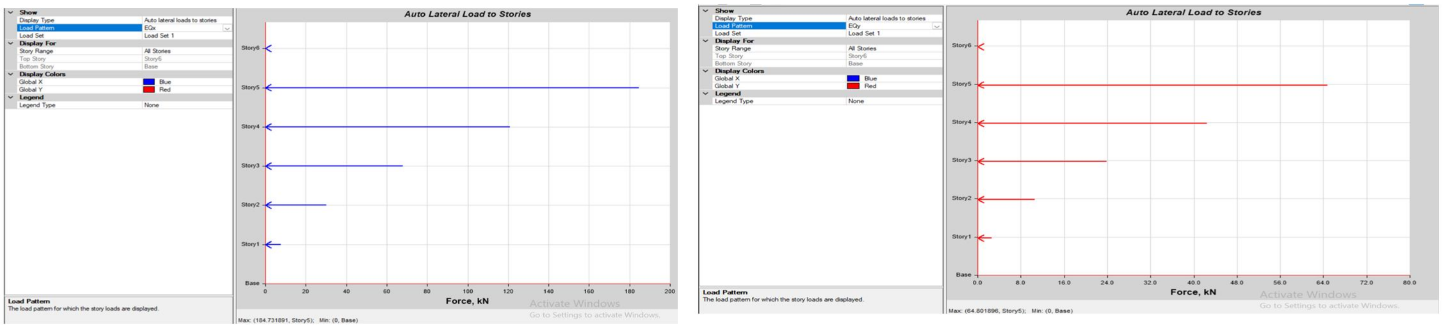

Figure 8: Storey shear response under X & Y-direction pushover analysis.

The base force versus monitored displacement response represents the nonlinear lateral capacity of the frame. The results indicate that the structure develops considerable base force resistance in both principal directions. However, the higher displacement demand in the Y-direction shows that seismic performance should not be evaluated only from strength capacity; deformation demand and drift response must also be considered.

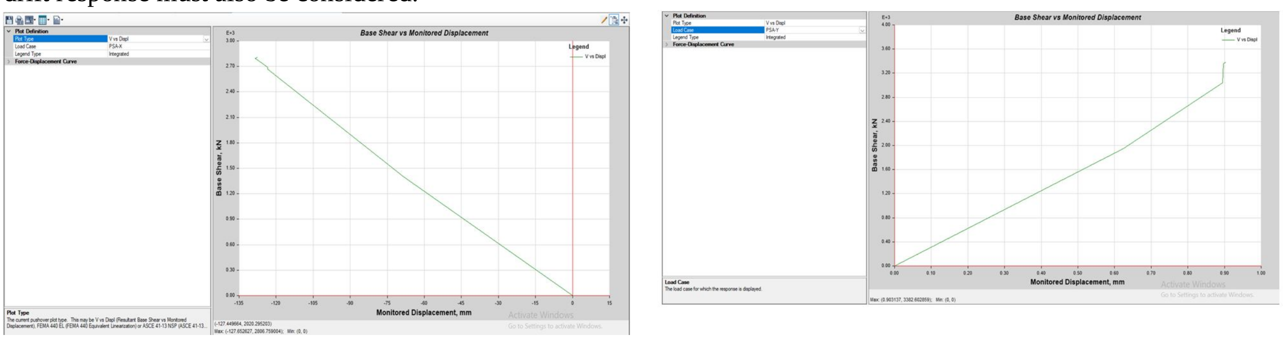

Figure 9: Base force versus monitored displacement under X & Y-direction pushover analysis.

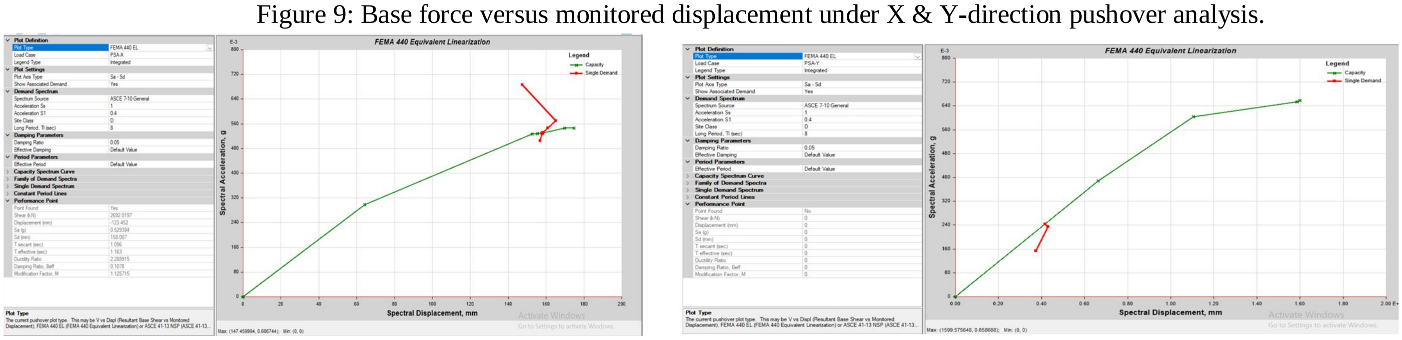

Figure 10: FEMA 440 equivalent lineariz

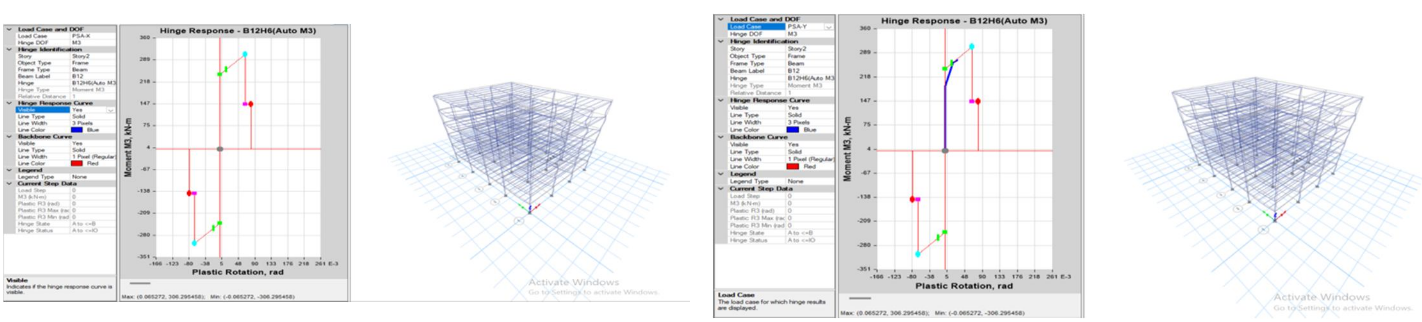

Figure 11: Beam hinge formation under X & Y-direction pushover analysis

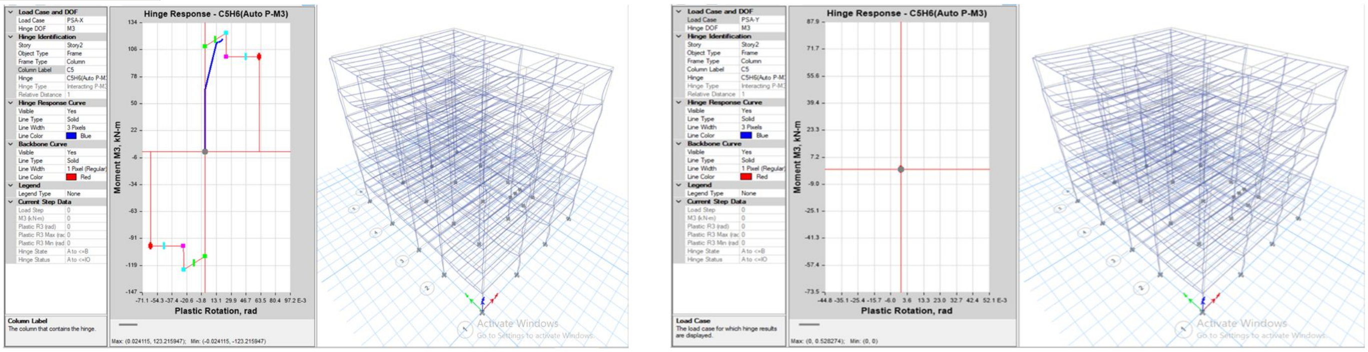

Figure 12: Column hinge formation under X & Y-direction pushover analysis

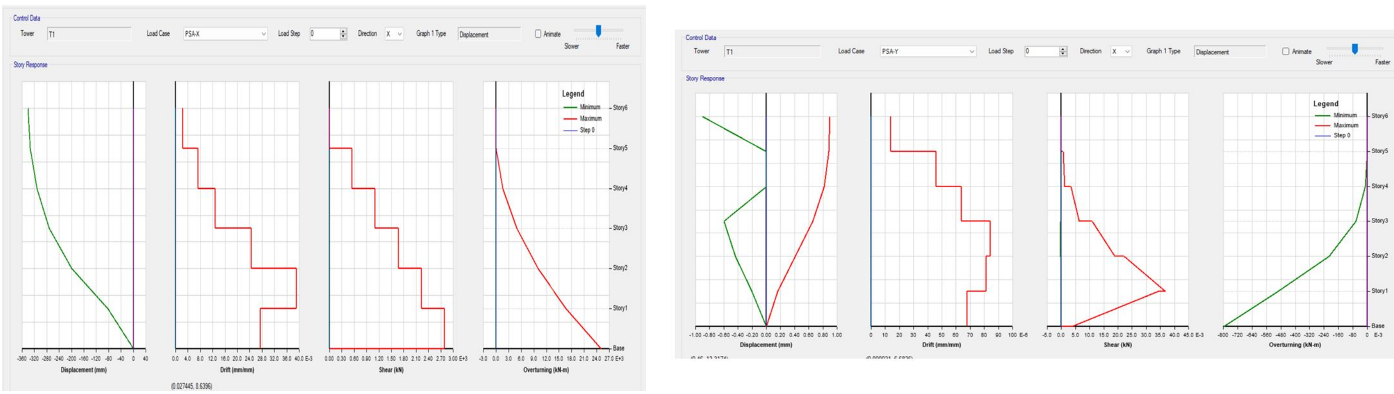

Figure 13: Combined storey response under X & Y-direction pushover analysis

The combined pushover response confirms that the frame has adequate lateral strength and controlled hinge formation. The beam and column hinge patterns indicate ductile behaviour, but the FEMA 440 response and displacement results show that the Y-direction has greater flexibility. Therefore, the Y-direction should be considered the governing direction for performance improvement. Time history analysis provides a realistic evaluation of the frame response under earthquake excitation. The base shear response varies continuously with time due to cyclic loading and force reversal. The dynamic response confirms that the structure remains stable under the selected ground motion, but the displacement and drift results must be checked carefully to identify the critical direction.

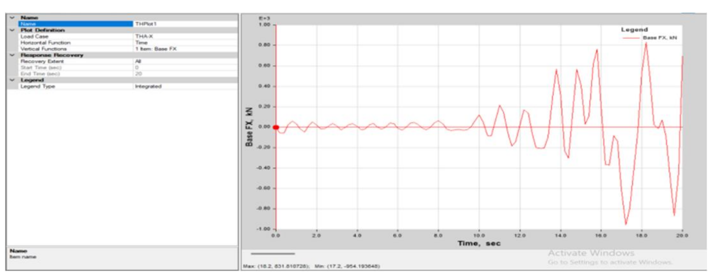

Figure 14: Time history response of base shear under applied ground motion

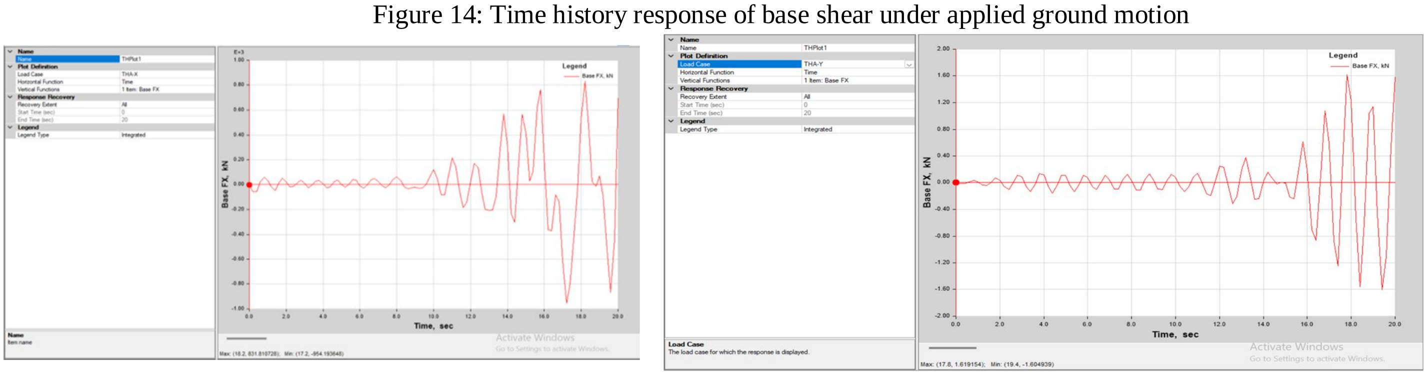

Figure 15: Base shear response with time in X & Y-direction from time history analysis

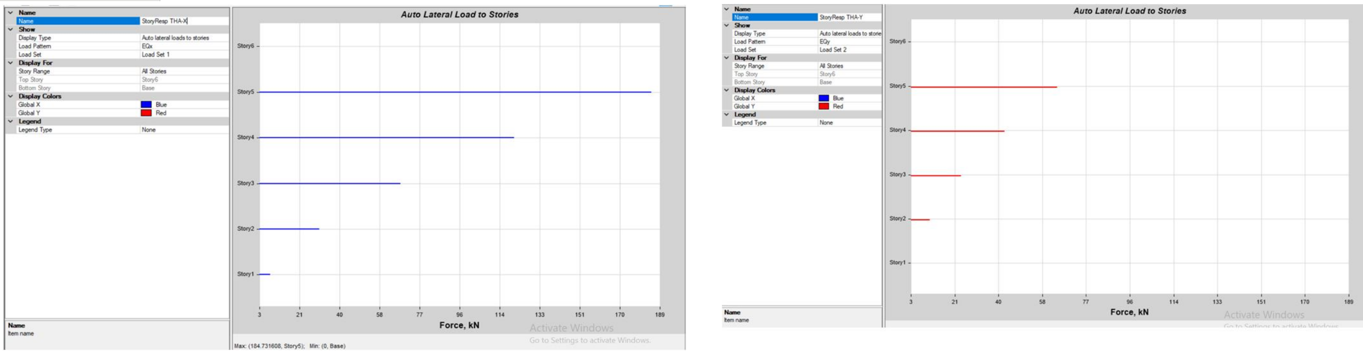

Figure 16: Storey base shear response in X & Y-direction from time history analysis

Storey drift is a key parameter for seismic performance because it is directly related to structural and non-structural damage. The maximum drift in the X-direction is close to the permissible limit, while the Y-direction drift exceeds the commonly accepted limit of 0.004. This indicates that the frame requires stiffness enhancement and drift-control measures in the Y-direction.

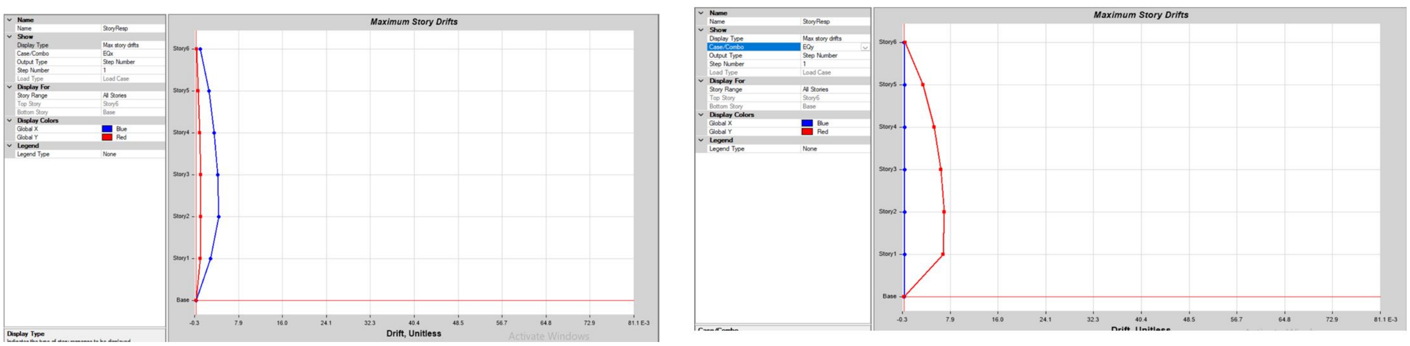

Figure 17: Storey drift response in X & Y-direction from time history analysis

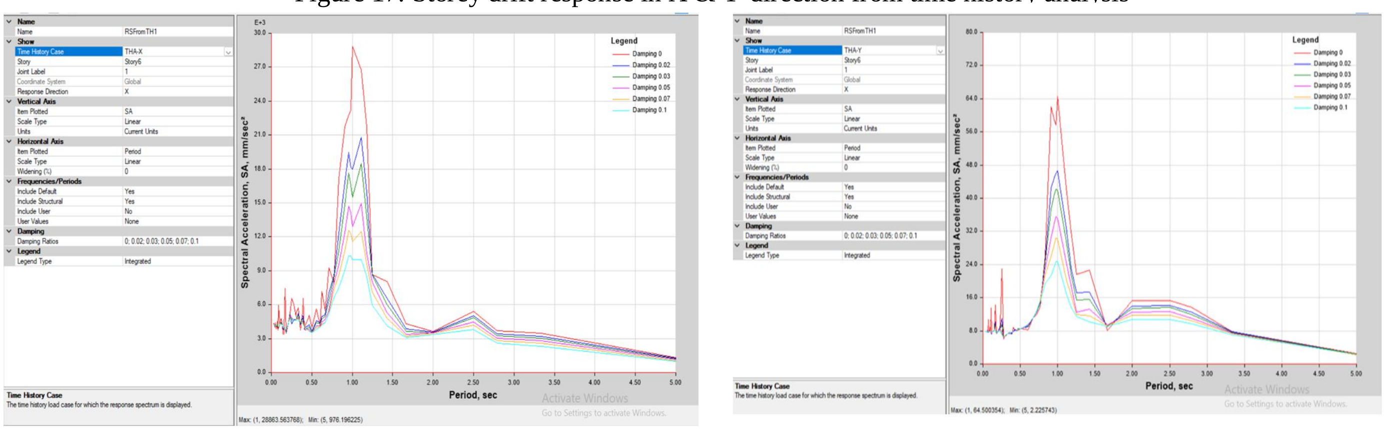

Figure 18: Response spectrum curve in X & Y-direction.

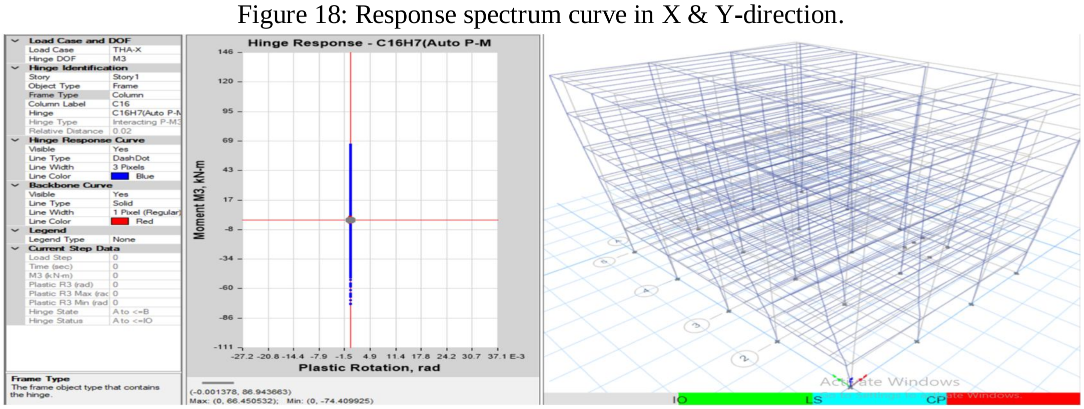

Figure 19: Column hinge formation under time history analysis

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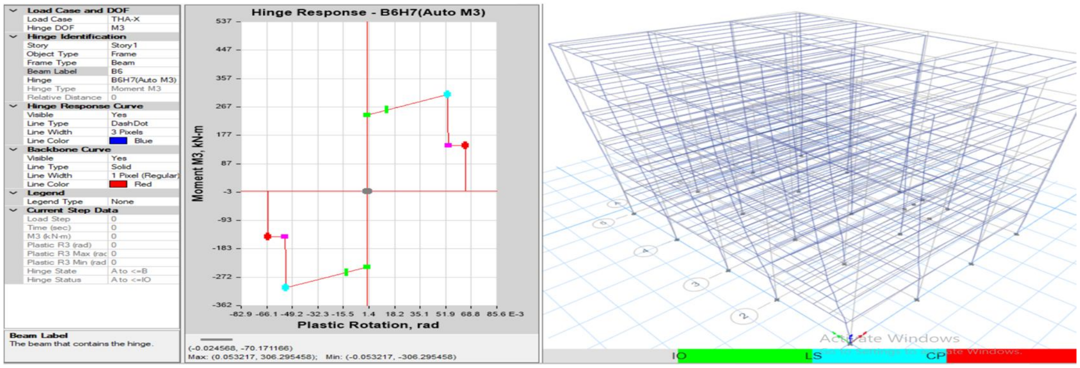

Figure 20: Beam hinge formation under time history analysis

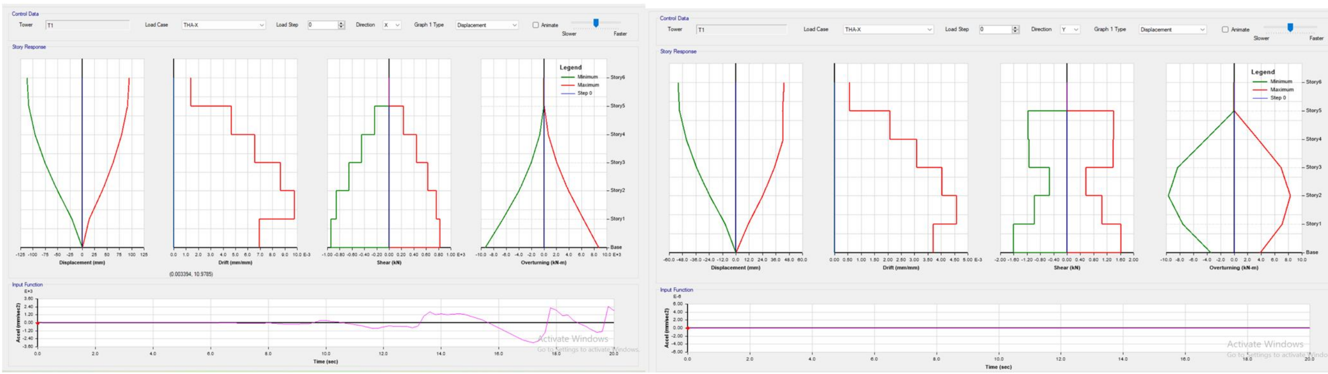

Figure 21: Combined time history storey response in X & Y-direction

Overall, the results obtained from pushover and time history analyses show that the steel moment-resisting frame has adequate strength and ductile behaviour. However, the Y-direction consistently shows higher displacement, longer effective period, and greater drift demand. Hence, the final seismic performance is governed by deformation control rather than strength deficiency, and improvement in Y-direction stiffness is recommended.

Table 2: Comparative Summary of PSA and TSA Results

Parameter	PSA (Pushover Static Analysis)	TSA (Time History Analysis)	Comparative Interpretation
Type of analysis	Nonlinear static analysis	Nonlinear dynamic analysis	PSA shows structural capacity, while TSA shows actual earthquake-time response.
Loading nature	Incremental lateral load	El Centro earthquake acceleration-time input	TSA is more realistic because earthquake force varies with time.
Maximum base force / base shear in X-direction	2806.759 kN	831.8107 kN positive, -954.194 kN negative	PSA capacity is higher than TSA demand, showing adequate lateral strength in X-direction.
Maximum base force in Y-direction	3382.603 kN	1.6192 kN positive, -1.6049 kN negative	Y-direction shows lower dynamic force response than X-direction, but higher displacement and drift demand.
Maximum displacement in X-direction	52.368 mm	38.158 mm	X-direction displacement remains comparatively controlled.
Maximum displacement in Y-direction	84.058 mm	84.058 mm	Y-direction shows larger displacement and higher flexibility.
Storey drift in X-direction	Not directly evaluated as governing parameter	0.004166	X-direction drift is close to the permissible limit.
Storey drift in Y-direction	Higher deformation tendency indicated	0.006853	Y-direction drift exceeds the usual 0.004 limit and requires stiffness improvement.
FEMA 440 spectral displacement	X = 174.67 mm, Y = 1599.576 mm	Not applicable	FEMA 440 confirms higher flexibility in Y-direction.
Hinge behaviour	Plastic hinges develop under increasing lateral load	Beam and column hinges mostly remain in lower damage range	Hinge response indicates ductile behaviour, but Y-direction drift remains critical.
Critical direction	Y-direction	Y-direction	Both analyses identify Y-direction as the governing direction.
Overall performance	Adequate strength capacity	Stable dynamic response with drift concern	Structure is strong, but Y-direction drift control is required.

The comparative evaluation of PSA and TSA results shows that the structure has adequate lateral strength and stable dynamic behaviour. However, both analyses identify the Y-direction as the critical direction due to larger displacement, longer effective period, and higher storey drift. Therefore, the seismic performance of the frame is governed mainly by deformation control rather than strength deficiency. Stiffness enhancement or drift-control measures are recommended in the Y-direction.

V. CONCLUSION

This study evaluated the seismic performance of a G+5 steel moment-resisting frame using nonlinear static pushover analysis and nonlinear dynamic time history analysis. The analysis was carried out to understand the structural behaviour beyond the elastic range and to assess important response parameters such as storey displacement, base shear, storey drift, FEMA 440 equivalent linearization response, response spectrum behaviour, and plastic hinge formation. The results indicate that the steel moment-resisting frame develops adequate lateral strength in both principal directions and demonstrates stable nonlinear behaviour under seismic loading.

The pushover analysis showed that the structure has considerable base force capacity, with maximum pushover base force values of 2806.759 kN in the X-direction and 3382.603 kN in the Y-direction. The maximum pushover storey displacement was observed as 52.368 mm in the X-direction and 84.058 mm in the Y-direction, indicating that the Y-direction is comparatively more flexible. FEMA 440 equivalent linearization results further confirmed this directional difference, as the Y-direction showed significantly higher spectral displacement and longer effective period than the X-direction.

The time history analysis also supported the pushover observations. The dynamic base shear response showed cyclic force reversal during earthquake excitation, while the displacement and drift results identified the Y-direction as the governing direction. The maximum storey drift was 0.004166 in the X-direction and 0.006853 in the Y-direction. Since the Y-direction drift exceeds the commonly accepted drift limit of 0.004, the structure requires stiffness enhancement and drift-control measures in that direction. However, the hinge response indicated that beam and column hinges generally remained within acceptable lower damage states under the considered time history response.

Overall, the study concludes that the G+5 steel moment-resisting frame possesses adequate strength and ductile behaviour, but its seismic performance is governed by deformation demand in the Y-direction. Therefore, improvement measures such as increased member stiffness, better beam-column connection rigidity, bracing systems, or supplemental damping devices are recommended to achieve better drift control and enhanced seismic reliability.

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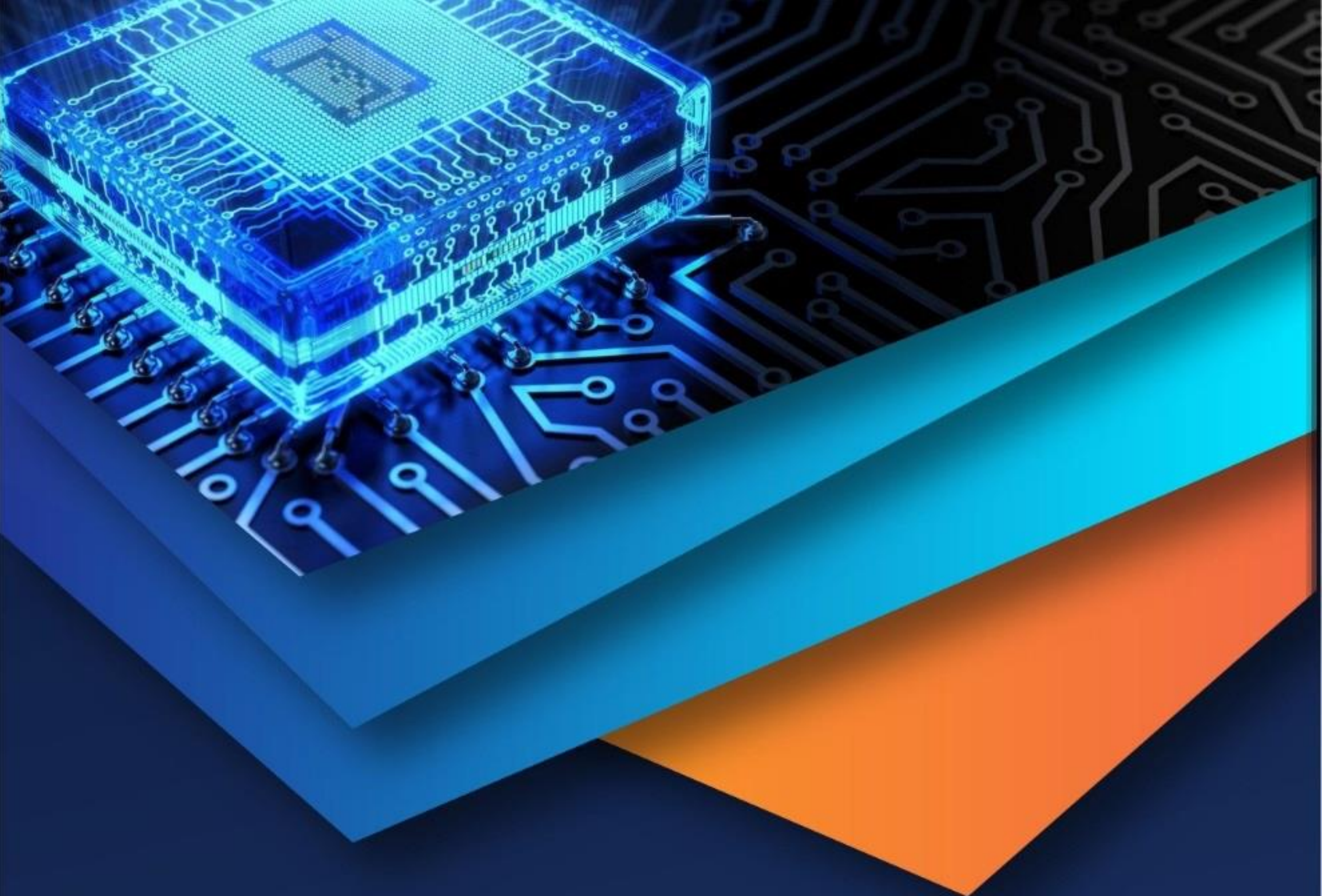

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