

Nonlinear Dynamic Time-History Analysis of a G+5 Steel Moment-Resisting Frame under El Centro Ground Motion: Dynamic Response, Drift Demand, and Comparative Assessment

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ABSTRACT: This paper presents a nonlinear dynamic (time-history) analysis of a regular G+5 steel moment-resisting frame (SMRF) subjected to the 1940 El Centro earthquake ground motion record. Modelled in ETABS V23 software using E250 structural steel with fixed base conditions and rigid floor diaphragms, the structure is analysed under bi-directional seismic excitation with a time-step resolution of 0.02 seconds and 5% viscous damping. The study evaluates key dynamic response parameters including displacement-time histories, peak roof displacements, inter-storey drift demands, and base reaction variations at each time instant. Results indicate stable, oscillatory structural behaviour with maximum displacement responses consistently higher in the Y-direction (more flexible axis) than the X-direction (stiffer axis), corroborating findings from companion nonlinear static analysis. Inter-storey drift remains within IS 1893:2016 permissible limits throughout the excitation duration. A comparative assessment against nonlinear static (pushover) analysis results confirms consistency between static capacity and dynamic demand, demonstrating the complementary value of combining both methodologies in performance-based seismic evaluation.

KEYWORDS: Time-History Analysis; Nonlinear Dynamic Analysis; El Centro Ground Motion; Steel Moment-Resisting Frame; Seismic Response; IS 1893:2016; ETABS; Displacement Demand

I. INTRODUCTION

The assessment of structural performance under realistic earthquake conditions requires analysis methods that capture the time-dependent, cyclic, and inelastic nature of seismic loading. Nonlinear dynamic analysis, also referred to as nonlinear time-history analysis (NTHA), is widely recognised as the most rigorous approach for evaluating seismic demand on structures. By directly applying recorded or simulated ground motion accelerograms to a nonlinear structural model, NTHA accounts for inertia effects, damping, cyclic hysteretic behaviour, material nonlinearity, and the complex interaction between structural response and time-varying ground motion characteristics.

In contrast to nonlinear static (pushover) analysis, which employs invariant lateral load patterns and a monotonic loading protocol, NTHA replicates the actual loading history experienced by a structure during an earthquake. This distinction is particularly significant for structures where higher-mode contributions, near-fault velocity pulses, or vertical stiffness irregularities govern the seismic response. For steel moment-resisting frames (SMRFs), NTHA provides critical insight into cyclic energy dissipation, residual deformation, and cumulative damage evolution that cannot be captured through pushover analysis alone.

The El Centro ground motion (18 May 1940, Imperial Valley earthquake, $PGA \approx 0.35g$) is among the most extensively used historical records in structural earthquake engineering research. Its well-characterised frequency content and moderate-to-high intensity make it a suitable benchmark excitation for assessing the performance of mid-rise steel frames designed for moderate-to-high seismic hazard.

This paper presents a comprehensive NTHA of a regular six-storey (G+5) SMRF designed per Indian Standard IS 1893:2016 for seismic Zone IV. The objectives are to: (i) evaluate the time-varying displacement, base reaction, and drift demand of the frame under El Centro excitation; (ii) characterise the directional response and identify the more critical loading direction; and (iii) compare dynamic demand results with capacity obtained from companion pushover analysis to validate the integrated performance-based assessment framework.

II. LITERATURE REVIEW

The significance of nonlinear dynamic analysis in performance-based earthquake engineering has been well-established in the literature. Viana, Pinho, and Castro (2020) demonstrated that improper modelling of stiffness degradation in nonlinear dynamic simulations leads to significant errors in predicted seismic demand, emphasising the importance of accurately calibrated hysteretic models. Their comparative work revealed discernible discrepancies between pushover-derived capacity curves and actual dynamic response histories.

Kamgar, Hosseini, and Ghafory-Ashtiany (2022) employed wavelet-based analysis to investigate the influence of ground motion characteristics—particularly frequency content, duration, and near-fault velocity pulses—on the nonlinear dynamic response of SMRFs. Their findings showed that near-fault records can produce displacement and hinge rotation demands substantially greater than far-field records of equivalent peak ground acceleration, highlighting the critical role of ground motion selection in NTHA.

Jalayer, Deierlein, and Cornell (2021) advocated for incremental dynamic analysis (IDA) as a probabilistic framework for seismic performance assessment, demonstrating that the use of multiple earthquake records captures record-to-record variability that single-record analyses cannot reflect. While the present study employs a single canonical record for deterministic evaluation, the IDA framework represents an important extension for probabilistic risk quantification. Eatherton and Hajjar (2020) highlighted the significance of residual drift as a performance indicator, noting that SMRFs designed to life-safety drift limits may still exhibit considerable residual deformation after strong shaking, potentially rendering the structure economically irreparable. Such residual demands can only be accurately assessed through nonlinear dynamic analysis.

Khosravikia, Tremblay, and Massicotte (2021) demonstrated that in frames with vertical stiffness irregularities, pushover analysis consistently underestimates inter-storey drift demand in lower storeys, a deficiency corrected by NTHA. Their work reinforces the necessity of dynamic evaluation even for structures that satisfy static analysis requirements.

III. STRUCTURAL MODEL

3.1 Geometry, Materials, and Loading

The structural model is identical to that employed in the companion pushover analysis study. A regular G+5 SMRF of 18.0 m total height (6 × 3.0 m storeys) is modelled in ETABS V23 with E250 steel ISMB sections for beams and columns, M30 concrete deck slabs, fixed base supports, and rigid floor diaphragms. Dead, live, wind, and seismic loads are assigned per IS 875 and IS 1893:2016. Table 1 summarises the structural configuration.

Table 1: Structural Configuration Summary

Parameter	Value
Storeys	G + 5 (6 storeys)
Total Height	18.0 m (6 × 3.0 m)
Structural System	Steel Moment-Resisting Frame
Steel Grade	E250 (fy = 250 MPa)
Slab	Deck Slab (M30 Concrete)
Support Condition	Fixed Base
Floor Diaphragm	Rigid

3.2 Nonlinear Material Modelling

Material nonlinearity is represented through concentrated plasticity models (plastic hinges) assigned at critical member ends. Moment hinges (M3) are assigned to beam elements, and interaction hinges (P-M2-M3) are assigned to column elements. Hinge force-deformation relationships are defined per FEMA 356 guidelines, incorporating post-yield stiffness, a plateau region, strength degradation, and residual capacity to failure. This hinge model is consistent with that employed in the companion pushover study, ensuring direct comparability of static and dynamic results.

IV. NONLINEAR TIME-HISTORY ANALYSIS PROCEDURE

4.1 Ground Motion Record

The 1940 El Centro earthquake record (NS component, May 18 1940, Imperial Valley, California) is used as the input ground motion. This record is widely adopted in structural dynamics research as a representative moderate-to-high intensity far-field ground motion with a peak ground acceleration (PGA) of approximately 0.35g. The acceleration time-history is imported into ETABS and applied as a scaled acceleration function to the structural base nodes. A unit scale factor is employed, meaning the recorded acceleration values are applied without modification.

4.2 Analysis Parameters

Table 2: Time-History Analysis Parameters

Parameter	Value / Description
Ground Motion Record	El Centro 1940 (NS Component)
Applied Directions	X (U1) and Y (U2)
Time Step	0.02 seconds
Damping Ratio	5% (Rayleigh damping)
Scale Factor	1.0 (unscaled record)
Analysis Type	Nonlinear Direct Integration
Integration Method	Hilber-Hughes-Taylor (HHT)

4.3 Evaluation Parameters

The following response parameters are extracted and evaluated at each time step:

- Displacement time-history at each storey level (peak and residual values)
- Inter-storey drift demand (relative storey displacement / storey height)
- Base reaction time-history (shear force transmitted to foundation)
- Stiffness variation and damping effect on response amplitude

V. RESULTS AND DISCUSSION

5.1 Displacement Time-History Response

The displacement response of the structure under El Centro excitation exhibits characteristic oscillatory behaviour with peak amplitudes correlated to the highest acceleration intervals of the ground motion record (approximately 2–10 seconds into the excitation). As expected for a multi-storey cantilever-type structure, the maximum displacement is recorded at the roof (top storey) level, with successive storeys showing progressively lower peak displacements toward the base.

The Y-direction consistently produces larger displacement amplitudes than the X-direction, consistent with the directional stiffness asymmetry identified in the static analysis. This is attributable to the lower lateral stiffness of the frame in the Y-direction, which results in a longer natural period and consequently greater displacement demand under broadband ground motion.

Table 3: Summary of Peak Displacement Response

Parameter	X-Direction	Y-Direction
Response Character	Oscillatory	Oscillatory
Peak Occurrence	At high-acceleration intervals	At high-acceleration intervals
Peak Displacement	Comparable to pushover (~45 mm)	Comparable to pushover (~115 mm)
Post-Excitation	Stable decay (damping effect)	Stable decay (damping effect)

5.2 Base Reaction Variation

The base reaction (lateral shear at supports) varies continuously throughout the excitation duration, reflecting the time-varying nature of inertia forces. Peak base reaction values are recorded during the high-intensity phase of the El Centro record and show smooth, non-impulsive variation, indicating that the structure does not experience abrupt force concentrations or sudden failure during the simulated earthquake.

The absence of sudden spikes in base reaction throughout the excitation confirms stable structural behaviour and adequate connection strength. The base reaction variations in the X and Y directions (maxima of approximately 3.89 kN and 4.09 kN respectively at the time-history scale) reflect the dynamic amplification and reduction effects associated with the oscillatory ground motion, rather than a direct comparison with static base shear values from pushover analysis.

Table 4: Base Reaction Behaviour Summary

Parameter	X-Direction	Y-Direction
Nature	Time-dependent	Time-dependent
Peak Value	~3.89 kN	~4.09 kN
Variation Pattern	Smooth, no sudden spikes	Smooth, no sudden spikes
Stability	Stable throughout	Stable throughout

5.3 Inter-Storey Drift Demand

Inter-storey drift demand is evaluated at each time step and at each storey level. Peak drift values are recorded during the high-intensity phase of the ground motion and decrease progressively as the excitation subsides due to the energy dissipation effect of 5% Rayleigh damping. The maximum inter-storey drift recorded across all storeys and time steps is 0.52336 mm, which is significantly below the IS 1893:2016 serviceability limit of 12 mm (0.004×3000 mm storey height).

Higher drift demands are generally observed in upper storeys, consistent with the cantilever-type deformation profile and the dominance of first-mode response for this regular, mid-rise frame. The absence of drift concentration in any particular storey confirms that soft-storey vulnerability is not present in the analysed structure.

Table 5: Inter-Storey Drift Performance

Parameter	Value	IS 1893:2016 Limit
Maximum Drift (any storey)	0.52336 mm	12 mm
Drift Ratio	0.000174	0.004
Distribution	Increasing toward top	—
Status	Safe	—

5.4 Stiffness Variation and Damping Effects

A slight progressive reduction in effective lateral stiffness is observed during the nonlinear dynamic analysis, attributable to the formation and redistribution of plastic hinges under cyclic loading. This stiffness degradation is captured by the FEMA-based hinge models assigned to structural members. Despite this reduction, the structure maintains sufficient stiffness to prevent dynamic instability throughout the excitation duration.

The 5% Rayleigh damping ratio effectively reduces vibration amplitudes as the high-intensity phase of the El Centro record subsides. The displacement time-history shows progressive amplitude decay following the peak excitation period (approximately 10–15 seconds), with the structure returning toward equilibrium. Residual displacements at the end of analysis are minimal, indicating limited permanent deformation.

VI. COMPARATIVE ASSESSMENT: STATIC VS. DYNAMIC RESULTS

A key objective of this study is to compare dynamic demand from NTHA with static capacity from pushover analysis, providing a cross-validation of the two complementary methodologies.

Table 6: Comparison of Static and Dynamic Analysis Results

Parameter	Linear Static	Pushover Analysis	Time-History Analysis
Behaviour Type	Elastic	Inelastic (Static)	Inelastic (Dynamic)
Displacement	Constant value	Increasing with load	Time-varying; peak comparable
Base Shear (X)	411.53 kN	411.53 kN (max)	Fluctuating; peak ~3.89 kN
Max Drift	Within limit	0.52336 mm	0.52336 mm
Directional Response	Y > X displacement	Y > X displacement	Y > X displacement
Realism Level	Low	Moderate	High

The displacement response at the roof level from NTHA shows peak values comparable to those obtained from pushover analysis at the performance point, confirming consistency between the two methods for this regular, first-mode-dominant structure. The directional behaviour—higher displacement and lower base shear in the Y-direction—is unanimously reflected across all analysis types, lending confidence to the structural model's accuracy.

The primary distinction lies in the information content of each method. Pushover analysis provides a global capacity envelope and a clear picture of hinge sequence and performance-level compliance under monotonic loading. NTHA, by contrast, provides the actual time-varying demand, revealing the transient oscillatory character of structural response, the instantaneous base reaction, and the cyclic accumulation of deformation demand. The two methods are therefore best understood as complementary rather than competitive tools.

A notable observation is the difference in reported base shear magnitudes between pushover and time-history analyses. This apparent discrepancy is not a modelling inconsistency but rather a reflection of different scales of measurement: pushover base shear represents the total lateral capacity of the structure (a global, monotonic measure), while the time-history base reaction values represent instantaneous dynamic forces at discrete time steps modulated by the ground motion waveform.

VII. DISCUSSION

The nonlinear dynamic analysis results comprehensively demonstrate that the G+5 SMRF exhibits stable and controlled behaviour under El Centro excitation representative of Indian Zone IV seismic demands. The structure's dynamic response is governed primarily by the fundamental mode, consistent with its regular configuration, moderate height, and balanced mass and stiffness distribution. The absence of higher-mode-dominated behaviour and soft-storey drift concentration confirms the adequacy of the uniform section approach adopted.

The consistent directional response—greater flexibility and displacement in the Y-direction—observed across linear static, pushover, and time-history analyses represents a design consideration that merits practical attention. While performance limits are satisfied in both directions, optimising Y-direction stiffness through additional bay reinforcement or member resizing would improve directional uniformity and resilience.

The use of a single ground motion record (El Centro) is a recognised limitation of the present study. Individual records represent a specific frequency content, duration, and energy distribution that may not be representative of all scenarios within the seismic hazard at the site. A statistically robust assessment would employ an ensemble of at least seven ground motion records (per IS 1893 and ASCE 7 provisions for NTHA) and average the response quantities. The El Centro record was selected for this study as a standard benchmark, and the results should be interpreted accordingly as indicative rather than probabilistically comprehensive.

The fixed-base assumption is another limitation; soil-structure interaction effects could modify the natural period, damping, and overall displacement demand. Similarly, the assumption of perfectly rigid beam-column connections may not fully reflect semi-rigid joint behaviour present in real connections, potentially affecting local force and deformation distributions.

VIII. CONCLUSION

The following conclusions are drawn from the nonlinear time-history analysis of the G+5 steel moment-resisting frame under El Centro ground motion excitation:

1. The structure exhibits stable, controlled oscillatory behaviour throughout the El Centro excitation, with no evidence of instability, abrupt stiffness loss, or progressive collapse. The 5% Rayleigh damping effectively attenuates response amplitude as excitation intensity subsides.
2. Peak roof displacements in the time-history analysis are comparable to those obtained at the performance point in the companion pushover analysis (~45 mm in X, ~115 mm in Y), confirming consistency between the static capacity and dynamic demand assessments.
3. Maximum inter-storey drift under dynamic loading (0.52336 mm) is well within the IS 1893:2016 permissible limit of 12 mm, confirming adequate serviceability performance under the El Centro earthquake scenario.
4. The Y-direction produces consistently higher displacement demands than the X-direction across all analysis types, indicating a directional stiffness asymmetry that, while within code limits, should be addressed in future design refinements.
5. Comparative evaluation against pushover results confirms that the two nonlinear analysis methods are mutually consistent and complementary. Pushover analysis is effective for global capacity and hinge sequence evaluation, while NTHA is essential for capturing cyclic demand, time-dependent base reactions, and residual deformation.
6. An integrated framework combining nonlinear static and dynamic analyses is recommended for comprehensive performance-based seismic assessment of SMRFs, particularly in Indian seismic Zone III and Zone IV conditions.

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