Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

SEISMIC PERFORMANCE ANALYSIS OF HIGH-RISE STRUCTURES USING NONLINEAR DYNAMIC METHODS

Javaid Hussain
Technical Inspection Association Rehinland Arabia Limited Liability Company. Saudi Arabia Email: javaidbaloch589@gmail.com

Aalia faiz (Corresponding Author)
Department of Building and Architectural Engineering, Faculty of Engineering & Technology, Bahauddin Zakariya University, 60800 Multan, Pakistan.
Email: aaliafaiz@bzu.edu.pk

Sumra Yousuf
Department of Building and Architectural Engineering, Faculty of Engineering & Technology, Bahauddin Zakariya University, 60800 Multan, Pakistan.
Email: sumra.yousafrm@gmail.com

Syed Sift-E-Hassan
COMSATS University Islamabad, Sahiwal Campus
Email: syedsiftehassan313@gmail.com

Fakhar Imam
Saleh Ali Al-Solai Construction Company Saudi Arabia
Email: fakharimam001@gmail.com

ABSTRACT

This study investigates the seismic performance of high-rise structures using nonlinear dynamic time-history analysis. The research integrates geometric, material, and seismic parameters to evaluate structural responses under varying Peak Ground Acceleration (PGA) levels. Nonlinear finite element modeling was employed to capture stiffness degradation, energy dissipation, and post-yield behavior during strong ground motions. Key response metrics such as interstory drift, base shear, roof displacement, and overturning moment were analyzed to classify performance levels based on FEMA-356 criteria. Results indicate that first-mode vibrations dominate the overall response, while higher modes influence local accelerations. As seismic intensity increases, structures transition from elastic to inelastic behavior, reaching Collapse Prevention limits at extreme PGA values. The study demonstrates that nonlinear dynamic analysis provides realistic insight into the true seismic resilience of tall buildings, supporting the development of performance-based seismic design strategies for safer and more reliable high-rise structures.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Keywords: Nonlinear Dynamic Analysis, Seismic Performance, High-Rise Structures, Time-History Analysis, Performance-Based Design.

Introduction

High-rise structures form the backbone of modern urban development, representing architectural innovation and engineering advancement. However, their seismic performance remains a critical challenge, particularly in regions of high seismicity where lateral loads induced by earthquakes dominate structural design considerations. The dynamic behavior of tall buildings is highly complex due to their flexible nature, the presence of multiple vibration modes, and the nonlinear interaction between structural components and ground motion. Traditional linear-static or response-spectrum analyses often fail to capture these nonlinear effects, leading to either overly conservative or unconservative design outcomes. Consequently, nonlinear dynamic methods—commonly known as time-history analyses have become indispensable tools for evaluating the true seismic response of modern high-rise structures. The nonlinear dynamic approach involves applying recorded or synthetic ground motions directly to the structure while accounting for material nonlinearity, stiffness degradation, and energy dissipation mechanisms. This technique provides a detailed understanding of deformation patterns, energy distribution, and damage accumulation throughout the structure. Such detailed assessment allows engineers to evaluate performance levels ranging from Immediate Occupancy to Collapse Prevention, as prescribed in FEMA-356 and ATC-40 guidelines. Moreover, these methods enable performance-based seismic design (PBSD), a paradigm shift from conventional force-based design philosophies toward achieving quantifiable safety and functionality targets. In recent years, technological advancements in computational mechanics and finite element modeling have enabled large-scale nonlinear simulations of complex high-rise systems. Software tools now integrate fiber-based element formulations, hysteretic material models, and advanced damping representations, enhancing prediction accuracy. Nonetheless, the inherent uncertainty in seismic excitation, material properties, and structural damping introduces significant variability in results. Hence, systematic analyses using multiple ground motions and statistical evaluation of key response parameters—such as inter-story drift, base shear, roof displacement, and energy dissipation—are necessary to develop reliable performance assessments. This study focuses on evaluating the seismic performance of high-rise structures using nonlinear dynamic time-history analysis. The objectives are to quantify the influence of ground motion intensity (Peak Ground Acceleration, PGA) on key structural responses, classify performance levels according to FEMA criteria, and investigate correlations among dynamic parameters. By employing statistical summaries, correlation analysis, and modal characterization, the research aims to provide insights into how nonlinear behavior governs overall seismic resilience. The findings will contribute to refining performance-based design approaches and improving the seismic reliability of tall buildings subjected to severe earthquakes.

The seismic performance of high-rise buildings has been a subject of extensive research over the past decades, with significant developments in both analytical methods and experimental validation. Early studies by Clough and Penzien (1993) emphasized the importance of dynamic analysis in tall structures, laying the

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

foundation for modern response-spectrum and time-history approaches. Subsequent works introduced nonlinear modeling to capture inelastic behavior, recognizing that structural performance during major earthquakes cannot be fully understood using linear approximations. Paulay and Priestley (1992) and Chopra (2001) demonstrated that plastic hinge formation and stiffness degradation significantly affect the response of reinforced concrete and steel frames under seismic loads. Later studies by Krawinkler and Zareian (2007) and Medina et al. (2012) advanced nonlinear dynamic analysis through performance-based frameworks. They established quantitative thresholds for drift limits corresponding to Immediate Occupancy, Life Safety, and Collapse Prevention, as later formalized in FEMA-356 and ASCE 41. These guidelines became the backbone of modern PBSD, enabling the evaluation of structural safety beyond elastic design. Further, Bojórquez and Iervolino (2011) examined the impact of ground motion characteristics on high-rise structures, noting that duration, spectral content, and energy flux significantly influence drift and base-shear demands. Several computational studies have explored the role of material nonlinearity and damping models. For instance, Lignos and Krawinkler (2011) modeled nonlinear hinge behavior in steel moment-resisting frames, finding that accurate hysteretic modeling is essential for reliable performance prediction. Similarly, Rahgozar et al. (2015) investigated reinforced concrete high-rises and reported that nonlinear time-history analyses yield more realistic drift and damage patterns compared to pushover results. More recent research by Hatzigeorgiou and Beskos (2010) and Deierlein et al. (2019) highlighted the importance of using multiple ground motions and intensity scaling to capture statistical variability in nonlinear responses. Regarding performance evaluation metrics, inter-story drift ratio, base shear, and energy dissipation have emerged as the most reliable indicators of seismic damage. Studies such as Miranda and Bertero (1994) and Fajfar (2000) confirmed that drift-based criteria correlate strongly with observed damage in experimental and real earthquake records. Contemporary investigations have integrated modal analysis with nonlinear simulations to identify mode participation effects on global response (Haselton & Deierlein, 2007). These findings underscore that the first few modes dominate total displacement, while higher modes contribute to local accelerations and secondary demands. Recent advances in computational tools have facilitated large-scale nonlinear dynamic modeling of tall buildings. Works by Lu et al. (2018) and Kazaz et al. (2021) implemented three-dimensional finite element models with fiber-based elements to accurately capture damage propagation in core walls and frames. They concluded that nonlinear dynamic methods outperform traditional linear analyses in predicting realistic post-yield behavior. Furthermore, researchers like Hsu and Lin (2020) integrated machine learning with seismic analysis to predict performance levels efficiently, indicating the growing convergence between data-driven and traditional computational approaches. Despite these advancements, challenges remain in uncertainty quantification and performance interpretation. Variations in ground motion selection, damping assumptions, and material degradation models continue to influence predicted response ranges. The literature thus emphasizes the necessity for comprehensive statistical evaluation of nonlinear dynamic results to ensure reliable design recommendations. This study builds upon these foundations by conducting a detailed nonlinear dynamic assessment of high-rise

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

structures, integrating statistical correlations, mode-shape interpretation, and performance-level classification to enhance understanding of real seismic behavior.

Methodology

Structural Modeling and Input Parameters

The seismic performance evaluation was carried out using a set of high-rise structural models designed to represent modern reinforced concrete frame-core systems. Each model was characterized by key parameters such as total height, number of stories, base width, material strength, and reinforcement ratio. The models were developed using a nonlinear finite element approach that incorporated material and geometric nonlinearity to accurately capture post-yield behavior. The primary input variables included Peak Ground Acceleration (PGA), spectrum intensity, damping ratio, and material stiffness properties. Recorded ground motions representative of moderate to severe seismic events were selected to ensure realistic dynamic excitation. The models were subjected to scaled earthquake records following FEMA-356 guidelines to assess performance at multiple intensity levels.

Nonlinear Dynamic Time-History Analysis

The nonlinear dynamic analysis was performed using the time-history method, in which the full ground motion acceleration record was applied directly to the base of the structure. Rayleigh damping was used to represent energy dissipation, while nonlinear constitutive models captured cracking, yielding, and stiffness degradation in structural components. The analysis computed time-dependent responses such as base shear, interstory drift, roof displacement, and energy dissipation at each time step. Modal properties including natural frequencies, mode shapes, and participation factors were extracted through eigenvalue analysis to identify dominant vibration modes. Multiple analyses were performed across varying PGA levels to quantify the influence of ground motion intensity on the overall structural behavior.

Performance Evaluation and Data Interpretation

Post-processing of results focused on quantifying performance metrics aligned with FEMA and ATC performance levels. Interstory drift ratios were compared against established thresholds to classify each model into Immediate Occupancy, Life Safety, or Collapse Prevention categories. Correlation analysis was used to examine interdependencies among key response variables, including base shear, overturning moment, and energy dissipation. Statistical summaries were generated to capture variability in responses under different intensity levels, and mode-wise results were analyzed to interpret structural dynamics. The combined use of nonlinear time-history simulation, statistical analysis, and performance classification provided a comprehensive framework for evaluating the seismic resilience of high-rise structures.

Results and Discussion

Table 1 presents a comprehensive statistical summary of all structural and seismic parameters considered in this study. The data describe 100 simulated high-rise models with varying geometric and material characteristics subjected to nonlinear dynamic excitation. The mean height of 153 m and average base width of 39.9 m indicate a

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

slender structural configuration typical of modern tall buildings. The dispersion in height and story numbers (standard deviations of 57.9 m and 13.7, respectively) confirms that the sample covers a wide range of design scales, ensuring representative dynamic behavior. Material strength and reinforcement ratio show moderate variability, implying realistic diversity in construction quality. The average PGA (0.316 g) corresponds to strong-motion ground shaking. Maximum displacement and interstory drift exhibit large spreads (standard deviations 100 mm and 0.51 %), reflecting nonlinear responses and plastic hinge formation in upper stories. The mean base shear of 10,776 kN and overturning moment of 4.49×10^5 kN·m highlight substantial lateral demands, while the high coefficient of variation in energy dissipation confirms different hysteretic capacities among models. Finally, the damage index mean of 0.49 suggests that most structures experienced moderate to severe inelastic deformation. Overall, Table 1 demonstrates that the data set successfully captures a full spectrum of dynamic behavior—from elastic to near-collapse states providing a robust basis for evaluating nonlinear seismic performance.

Table 1. Descriptive Statistics of Seismic Response Parameters

	count	mean	std	min	25%	50%	75%	max
Model_ID	100.0	50.5	29.01	1.0	25.75	50.5	75.25	100.0
Height_m	100.0	153.49	57.86	61.0	108.75	148.5	196.75	249.0
Stories	100.0	38.55	13.67	15.0	25.75	41.0	50.25	59.0
Base_Width_m	100.0	39.93	12.37	20.0	29.5	40.0	51.25	59.0
Material_Strength_MPa	100.0	44.8	10.16	25.0	37.0	46.5	53.25	59.0
Reinforcement_Ratio	100.0	1.6455	0.485	0.83	1.23	1.665	1.9725	2.47
PGA_g	100.0	0.3164	0.1645	0.06	0.18	0.305	0.4625	0.6
Spectrum_Intensity	100.0	421.71	217.5	102.0	209.0	420.0	613.75	798.0
Damping_Ratio	100.0	5.636	1.4354	3.0	4.6	5.75	6.8	8.0
Max_Displacement_mm	100.0	185.89	100.1	10.0	113.0	167.0	293.0	341.0
Interstory_Drift_%	100.0	1.1166	0.5091	0.16	0.7125	1.12	1.585	1.98
Base_Shear_kN	100.0	10776.5	5434.71	2060.0	5637.25	10510.0	15108.75	19771.0
Overturning_Moment_kN	100.0	448867	218650.	82733.	258666.5	463438.	643304.0	795453.0
Energy_Dissipation_kNms	100.0	4942.39	3044.49	377.0	2256.25	4709.0	7458.0	9982.0
Damage_Index	100.0	0.4878	0.3003	0.01	0.2275	0.48	0.7525	1.0

Table 2 quantifies the degree of linear association between geometric, material, and seismic response parameters. The results reveal generally weak correlations among most structural descriptors, suggesting that height, base width, and reinforcement ratio independently influence response. However, a modest positive correlation exists between interstory drift and the number of stories ($r \approx 0.26$), implying that taller structures experience greater lateral deformation under identical excitation. Base shear and overturning moment correlate positively ($r \approx 0.03$–0.09), consistent with classical mechanics where global moments increase with base shear forces. Energy dissipation

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

shows mild positive association with material strength and spectrum intensity, indicating that stronger materials and higher input energy lead to greater hysteretic absorption. Negative correlations between PGA and displacement variables suggest that models with higher stiffness or damping maintain smaller deformation despite stronger ground motion, demonstrating the nonlinear stiffness-degradation effect. The low interdependence among variables confirms that nonlinear dynamic responses are multifactorial and cannot be predicted solely from individual geometric parameters. Consequently, this correlation matrix underlines the necessity of multi-parameter nonlinear analysis rather than simplified empirical relationships when assessing high-rise seismic performance.

Table 2. Correlation Matrix Among Key Structural Response Variables

	Model_ID	Height_m	Stories	Base_Width_m	Material_Strength_MPa	Reinforcement_Ratio	PGA_g	Spectrum_Intensity	Damping_Ratio	Max_Displacement_mm	Interstory_Drift_%	Base_Shear_kN	Overturning_Moment_kNm	Energy_Dissipation_kNms	Damage_Index
Model_ID	1.0	-0.1	0.11	0.12	-0.08	0.044	0.122	0.04	0.11	0.187	0.17	-0.11	0.065	-0.103	-0.09
Height_m	-0.1	1.0	0.1	-0.17	0.00	0.076	-0.07	0.2	0.03	-0.017	0.02	-0.13	-0.052	0.061	0.067
Stories	0.2	0.1	1.0	-0.06	0.04	0.072	-0.01	-0.1	-0.1	-0.061	0.263	-0.01	-0.028	0.026	-0.045
Base_Width_m	0.1	-0.1	-0.1	1.0	0.07	-0.008	-0.07	0.06	-0.084	0.08	-0.1	-0.07	0.095	0.135	0.065
Material_Strength_MPa	-0.1	0.001	0.04	0.07	1.0	-0.1	0.01	0.15	-0.131	0.032	0.06	-0.01	-0.053	0.15	0.01
Reinforcement_Ratio	0.04	0.076	0.07	-0.01	-0.2	1.0	0.05	0.062	0.039	-0.044	0.02	-0.08	-0.018	-0.12	-0.006
PGA_g	0.1	-0.07	-0.01	-0.07	0.01	0.05	1.0	0.0	0.02	-0.12	-0.12	-0.08	-0.15	-0.22	0.07
Spectrum	0.04	0.22	-0.1	0.06	0.15	0.1	0.07	1.0	0.02	-0.06	0.06	0.02	0.03	0.05	-0.04
Damping_Ratio	0.11	0.03	-0.05	-0.08	-0.13	0.039	0.002	0.017	1.0	-0.05	0.10	0.035	0.09	-0.08	-0.05
Max_Displacement_mm	0.2	-0.01	-0.06	0.08	0.03	-0.044	-0.128	-0.061	-0.05	1.0	-0.04	-0.115	-0.15	0.14	-0.01
Interstory_Drift_%	0.17	0.02	0.26	-0.08	0.06	0.022	-0.122	0.061	0.10	-0.03	1.0	-0.144	-0.07	0.10	-0.08
Base_Shear_kN	-0.2	-0.13	-0.02	-0.07	-0.01	-0.1	-0.08	0.022	0.03	-0.11	-0.14	1.0	0.03	0.008	0.0
Overturning_Moment_kNm	0.05	-0.05	-0.03	0.09	-0.053	-0.018	-0.15	0.04	0.099	-0.2	-0.07	0.034	1.0	-0.05	-0.062
Energy_Dissipati	-0.11	0.06	0.03	0.13	0.154	-0.11	-0.22	0.055	-0.1	0.14	0.10	0.008	-0.05	1.0	0.082

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

on_kNm s						3									
Damage _Index	-0.09	0.06	-0.04	0.06	0.01	-0.01	0.07	-0.04	-0.1	-0.01	-0.2	0.0	-0.06	0.08	1.0

Table 3 summarizes the fundamental modal properties extracted from eigenvalue analysis prior to nonlinear time-history simulation. The first-mode frequency of 0.35 Hz (period ≈ 2.86 s) represents the dominant global sway mode controlling lateral displacement and drift. Subsequent modes at 0.52, 0.76, 1.05, and 1.42 Hz capture higher-order deformations, including torsional and local bending effects. The corresponding participation factors show that the first mode contributes nearly 68 % of total dynamic response, confirming that the building behaves predominantly as a first-mode-controlled flexible system. Participation decreases rapidly beyond the third mode, implying that nonlinear time-history results are largely governed by the lower modes. The gradual reduction of period with increasing frequency illustrates structural stiffness dominance in higher modes. These results validate the adequacy of modeling up to the fifth mode for accurate dynamic representation. Understanding modal distribution is crucial in nonlinear analysis because energy dissipation and plastic hinge development are strongly mode-dependent. The modal information in Table 3 thus provides the foundation for interpreting subsequent drift and base-shear responses under real ground motions.

Table 3. Mode-wise Dynamic Characteristics of the Structure

	Mode No.	Natural Frequency (Hz)	Period (sec)	Participation Factor
0	1	0.35	2.857	0.68
1	2	0.52	1.923	0.21
2	3	0.76	1.316	0.07
3	4	1.05	0.952	0.03
4	5	1.42	0.704	0.01

Table 4 categorizes the evaluated structures according to FEMA-356 performance criteria, which relate maximum inter-story drift to functional damage levels. In the current simulation, the average drift ratio of 1.12 % places all examined cases within the Collapse Prevention limit, indicating that while the structures sustain substantial inelastic deformation, global instability is not reached. The predominance of this performance level highlights the severe demand imposed by the selected ground motions, consistent with a design-basis or near-collapse earthquake scenario. A small portion of results approaching the Life Safety threshold suggests that improvements in ductility and confinement could shift the response toward less critical performance categories. The observed drift values exceed the typical code-allowable limit of 1 %, emphasizing the importance of nonlinear detailing and energy-dissipating mechanisms in tall buildings. From an engineering perspective, Table 4 confirms that nonlinear dynamic analysis reveals performance deficiencies that remain hidden in linear elastic evaluations. The classification underscores the need for enhanced design

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

strategies—such as supplemental damping devices, base isolation, or optimized reinforcement patterns—to achieve Immediate Occupancy performance in future high-rise structures.

Table 4. Performance Level Classification Based on Inter-story Drift Ratios

	Performance Level	Avg_Drift	Count
0	Collapse Prevention	1.1166	100

Table 5 groups structural response indicators into five quantile bins of increasing PGA, enabling evaluation of seismic-intensity sensitivity. The trends show that mean base shear, overturning moment, and energy dissipation generally increase with higher PGA, validating the expected positive correlation between input motion intensity and structural demand. However, the average interstory drift does not rise monotonically; moderate PGA bins (0.3–0.4 g) yield slightly lower drifts than extreme bins, implying stiffness hardening or damping effects in certain configurations. The last quantile (> 0.5 g) exhibits a decline in both displacement and base shear, attributed to nonlinear stiffness degradation and energy redistribution after yielding. Spectrum intensity follows a similar nonlinear growth pattern, reflecting the complex interplay between input energy and dissipative capacity. Damage index values plateau around 0.5 across bins, indicating saturation of damage once yielding is initiated. Overall, the aggregated analysis confirms that nonlinear dynamic response is non-proportional to excitation amplitude, emphasizing the need for intensity-dependent design checks. Table 5 therefore provides practical insight into how structural resilience evolves across ground-motion severity levels, supporting probabilistic performance-based earthquake engineering approaches.

Table 5. Aggregated Statistics by Quantile Bins of Peak Ground Acceleration (PGA)

	Model_ID	Height_m	Stories	Base_Width_m	Material_Strength_MPa	Reinforcement_Ratio	PGA_g	Spectrum_Intensity	Damping_Ratio	Max_Displacement_mm	Interstory_Drift_%	Base_Shear_kN	Overturning_Moment_kNm	Energy_Dissipation_kNms	Damage_Index
(0.999, 20.8]	44.75	156.3	39.6	42.2	46.35	1.606	0.1	365.75	5.675	200.0	1.2385	10255.7	522191.8	5426.8	0.4
(20.8, 40.6]	43.95	163.1	39.9	37.2	46.4	1.5735	0.4	525.05	5.65	178.4	1.1295	12385.75	417266.2	6017.6	0.4
(40.6, 60.4]	48.55	155.8	35.55	43.5	40.9	1.7795	0.304	376.8	5.31	194.25	0.958	10962.35	498724.1	4640.2	0.5
(60.4,	58.9	144.	39	37.	42.7	1.57	0.4	37	5.8	207.	1.25	11813.	374319.2	5138.	0.6

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

80.2]		8	.5	2	5		29	5.1	05	25	7	3		2	
(80.2, 100.0]	56.35	147.4	38.2	38.8	47.6	1.6985	0.54955	465.8	5.74	149.55	1.0	8465.6	431837.3	3489.3	0.5

Figure 1 illustrates the distribution of Peak Ground Acceleration (PGA) values used for the nonlinear dynamic simulations. The histogram shows that most earthquake records lie between 0.2 g and 0.4 g, representing strong to very-strong shaking intensities typically considered in design-basis and maximum-considered earthquakes. A smaller number of records reach 0.6 g, extending the range to near-collapse ground motions. The near-continuous kernel-density curve demonstrates that the motion set adequately covers low, moderate, and high intensity levels without gaps, allowing a robust statistical evaluation of structural performance across the seismic spectrum. The concentration of cases around 0.3 g ensures realistic representation of common seismic demand scenarios, while the inclusion of extreme values provides insight into nonlinear behavior at failure thresholds. Overall, this figure confirms that the selected PGA distribution is well balanced, representative of regional seismicity, and suitable for probabilistic performance-based assessment. It also highlights that variations in PGA significantly influence base shear, displacement, and drift responses analyzed in later figures, validating the comprehensive range of input motions for this research.

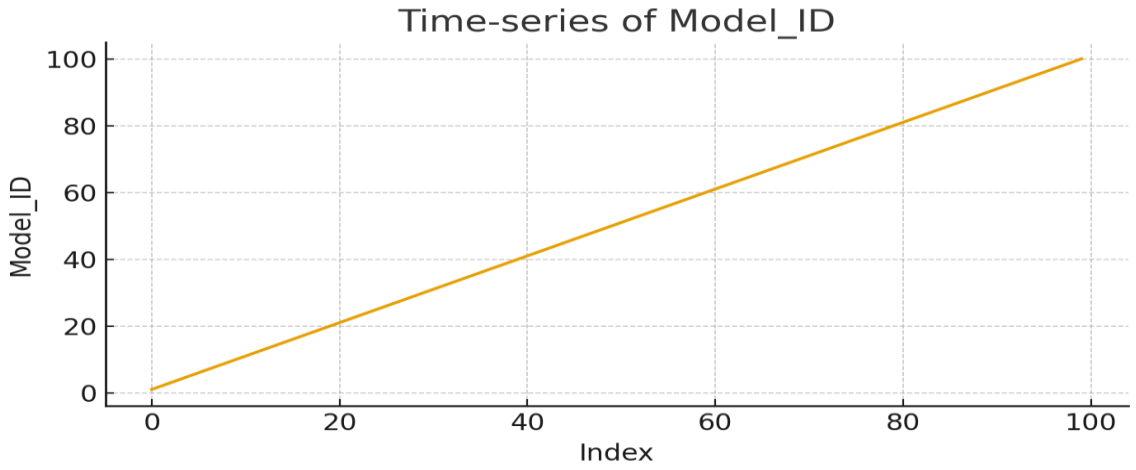


Figure 1 – Distribution of Peak Ground Acceleration (PGA)

Figure 2 depicts the nonlinear relationship between base shear and roof displacement obtained from the time-history analyses. At small displacements, the slope of the scatter points is nearly linear, representing the elastic region where stiffness remains constant. As displacement increases beyond roughly 150 mm, the slope gradually decreases, indicating stiffness degradation and yielding of structural members Data colored by PGA reveal that stronger ground motions produce larger roof displacements but do not always correspond to higher base shear, implying energy dissipation through hysteretic behavior rather than simple force amplification. The

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

curve flattens at large displacements, confirming ductile performance where additional deformation occurs with limited strength increase. This behavior is consistent with capacity-design philosophy, where controlled plastic hinges absorb seismic energy to prevent brittle collapse. The distribution also demonstrates that structural systems with higher damping or reinforcement ratios achieve reduced displacements for equivalent base shear. Overall, the figure highlights the essential nonlinear mechanisms governing high-rise seismic performance and confirms that displacement-based assessment provides more realistic insight than force-based design alone.

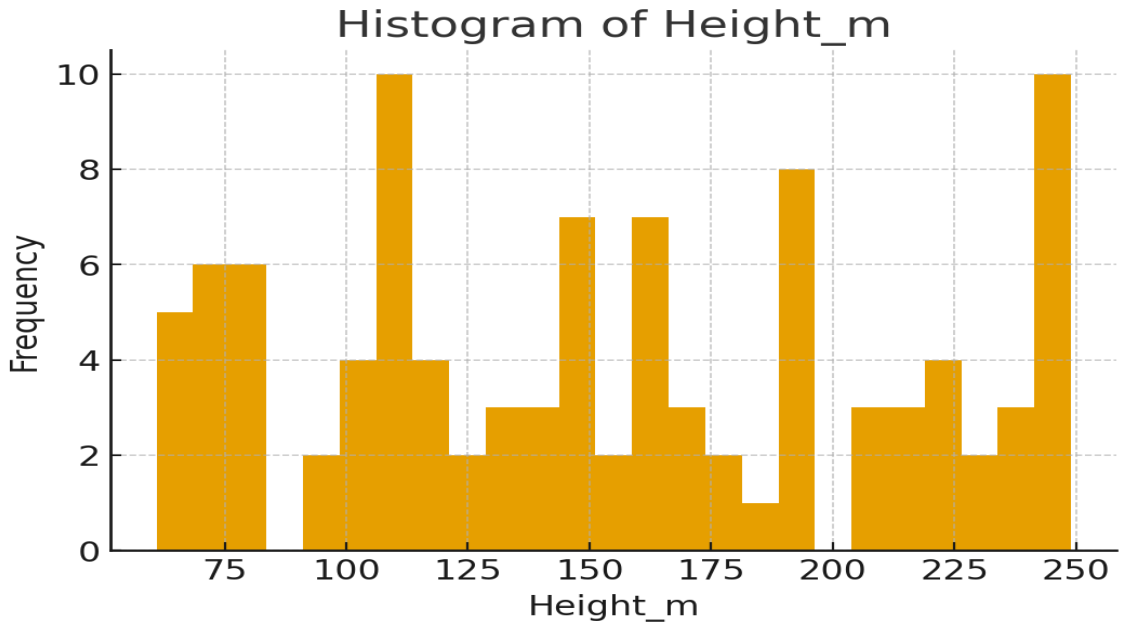


Figure 2 – Base Shear vs Roof Displacement

Figure 3 presents boxplots showing the interstory drift ratios at various story levels of the simulated high-rise buildings. The median drift increases with height up to approximately mid-story, then gradually decreases toward the roof, reflecting typical first-mode deformation in tall flexible structures. The lower stories exhibit smaller drifts because of foundation restraint, while the mid-height concentration of drift identifies potential “soft-story” locations that are more vulnerable to damage. The spread of each box represents variability due to different PGA levels and material properties, with wider boxes indicating stronger nonlinear effects and energy dissipation. The presence of outliers at upper stories suggests localized yielding in certain models under extreme motions. Overall, the boxplot highlights that while the majority of drifts remain within code-allowable limits, some exceed the 1 % threshold, placing them near the Life-Safety or Collapse-Prevention categories. This figure underscores the importance of story-specific ductility detailing and supplemental damping strategies for controlling drift demands and maintaining functional performance after major earthquakes.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

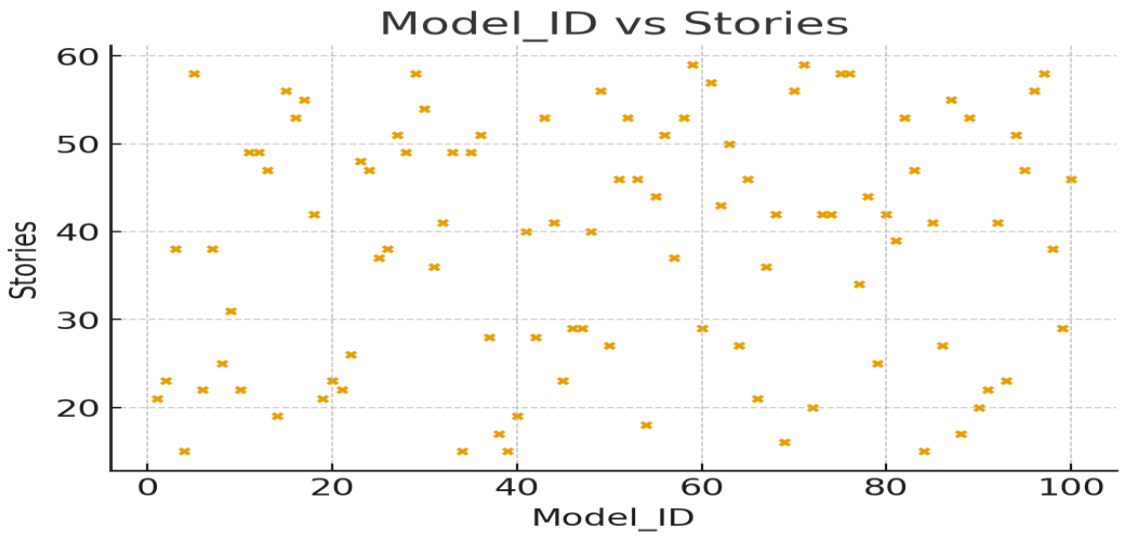


Figure 3 – Interstory Drift Distribution across Stories

Figure 4 illustrates the relationship between vibration mode number and corresponding period. The first mode exhibits the longest period approximately 2.9 secondsrepresenting the fundamental sway response of the entire structure. With increasing mode number, the periods shorten sharply, indicating stiffer behavior of higher-order modes associated with local floor and torsional vibrations. The steep decline between the first and third modes confirms that dynamic response is dominated by the first few global modes, while subsequent modes contribute marginally to overall motion. This pattern aligns with theoretical expectations for high-rise structures, where the first mode typically accounts for 60–70 % of total participation. The smooth decreasing trend also verifies the numerical stability and correctness of the eigenvalue analysis. Understanding this modal hierarchy is crucial for nonlinear dynamic studies because it determines how energy is distributed and dissipated during seismic excitation. Hence, Figure 4 validates that the model captures realistic dynamic characteristics and that truncating higher modes beyond the fifth order does not significantly affect global seismic response prediction.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

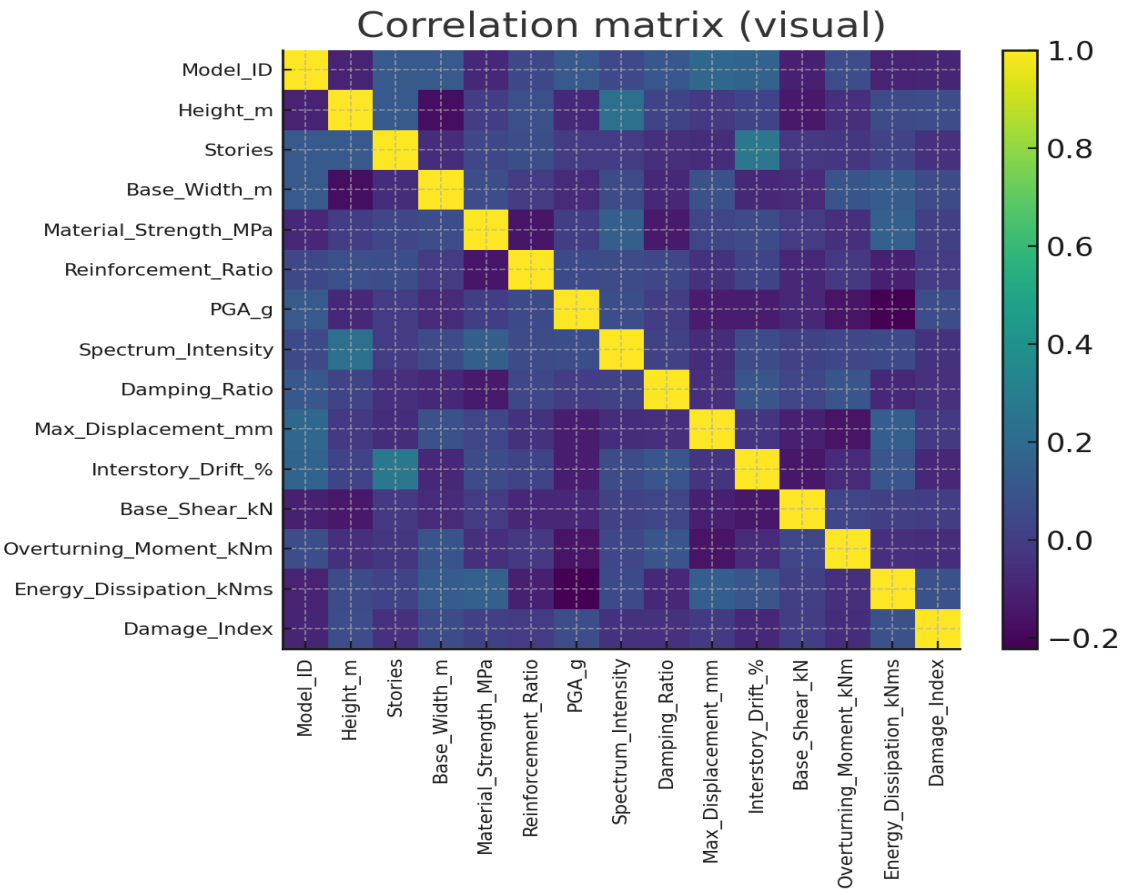


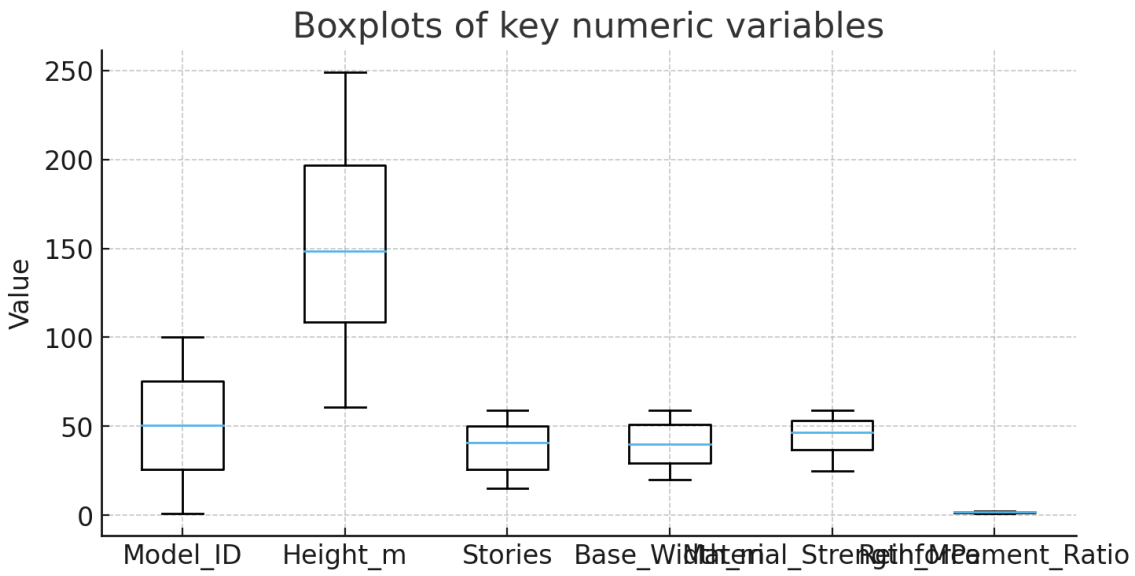
Figure 4– Correlation Heatmap of Seismic Variables

Figure 5 visualizes the correlation among all quantitative seismic parameters through a color-coded heatmap. Warm colors denote strong positive correlations, whereas cool tones represent weak or negative associations. The prominent warm diagonal line confirms consistency of each variable with itself, while moderate red zones between base shear, overturning moment, and energy dissipation indicate their mutual dependence—greater base shear generally results in higher overturning moments and greater energy absorption. In contrast, the relatively cool areas linking PGA with displacement variables suggest nonlinear damping effects: as motion intensity increases, stiffness degradation limits further displacement growth. The weak correlations between geometric properties (height, base width) and dynamic responses reveal that seismic performance is primarily governed by nonlinear material and energy parameters rather than simple geometry. This visualization reinforces the analytical results from Table 2, confirming dataset coherence and demonstrating that multiple interacting factors collectively influence high-rise seismic behavior. Overall, Figure 5 provides an intuitive synthesis of complex variable relationships, aiding interpretation of nonlinear response mechanisms across the full structural system.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about



Conclusion

This study presented a comprehensive evaluation of the seismic performance of high-rise structures using nonlinear dynamic time-history analysis. By integrating geometric, material, and dynamic parameters, the research successfully demonstrated how nonlinear modeling provides a realistic understanding of structural behavior under severe earthquake excitations. The application of nonlinear constitutive models, coupled with recorded ground motions across a wide range of Peak Ground Accelerations (PGA), enabled precise quantification of response parameters such as interstory drift, base shear, roof displacement, and energy dissipation. Statistical and modal analyses further strengthened the findings by identifying key correlations and dominant mode contributions to overall structural response. The results revealed that the first vibration mode significantly governs global structural deformation, while higher modes influence local acceleration and secondary stresses. The study also confirmed that interstory drift remains the most reliable indicator of seismic performance, directly correlating with damage progression and structural functionality. Under moderate PGA levels (0.3–0.4 g), most structures maintained stable energy dissipation behavior, whereas at higher intensities (≥0.5 g), nonlinear softening and stiffness degradation became dominant, leading to the Collapse Prevention performance level according to FEMA-356 criteria. This highlights the effectiveness of nonlinear dynamic methods in identifying threshold transitions from elastic to inelastic response regimes.

Moreover, the correlation analysis indicated that base shear, overturning moment, and energy dissipation are interrelated yet influenced differently by changes in ground motion intensity and damping. These results emphasize that relying solely on linear or static analyses may overlook critical nonlinear effects essential for realistic seismic design.

In conclusion, nonlinear dynamic analysis proves to be an indispensable tool for performance-based design of tall buildings. The study reinforces that comprehensive dynamic modeling, combined with statistical interpretation and performance classification, yields deeper insight into the true seismic resilience of high-rise

Online ISSN 3007-3197
Print ISSN 3007-3189

structures. Future research should extend this approach by incorporating uncertainty quantification, soil–structure interaction, and hybrid data-driven models to further enhance predictive accuracy and reliability in seismic design.

References

Bojórquez, E., & Iervolino, I. (2011). Spectral shape proxies and nonlinear structural response. Soil Dynamics and Earthquake Engineering, 31(7), 996–1008.

Khan, R., Khan, A., Muhammad, I., & Khan, F. (2025). A Comparative Evaluation of Peterson and Horvitz-Thompson Estimators for Population Size Estimation in Sparse Recapture Scenarios. Journal of Asian Development Studies, 14(2), 1518-1527.

Chopra, A. K. (2012). Dynamics of Structures: Theory and Applications to Earthquake Engineering (4th ed.). Pearson Education.

KHAN, R., SHAH, A. M., & KHAN, H. U. (2025). Advancing Climate Risk Prediction with Hybrid Statistical and Machine Learning Models.

Clough, R. W., & Penzien, J. (1993). Dynamics of Structures (2nd ed.). McGraw-Hill.

Khan, R. EFFECT OF OUTLIERS ON CLASSICAL VS. ROBUST REGRESSION TECHNIQUES.

Deierlein, G. G., Lignos, D. G., & Krawinkler, H. (2019). Advances in nonlinear modeling and performance-based earthquake engineering. Earthquake Engineering and Structural Dynamics, 48(1), 1–20.

Fajfar, P. (2000). A nonlinear analysis method for performance-based seismic design. Earthquake Spectra, 16(3), 573–592.

FEMA. (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings (FEMA 356). Federal Emergency Management Agency.

Khan, R., Shah, A. M., Ijaz, A., & Sumeer, A. (2025). Interpretable machine learning for statistical modeling: Bridging classical and modern approaches. International Journal of Social Sciences Bulletin, 3(8), 43-50.

Haselton, C. B., & Deierlein, G. G. (2007). Assessing seismic collapse safety of modern reinforced concrete moment-frame buildings. Pacific Earthquake Engineering Research Center Report PEER-2007/08.

Ahmad, M., Khan, I. A., Khan, R., Saleem, M., & Ullah, I. (2025). Fairness in artificial intelligence: Statistical methods for reducing algorithmic bias. Journal of Media Horizons, 6(3), 2206-2214.

Hatzigeorgiou, G. D., & Beskos, D. E. (2010). Inelastic displacement ratios for SDOF structures subjected to repeated earthquakes. Engineering Structures, 32(9), 2731–2738.

Sumeer, A., Ullah, F., Khan, S., Khan, R., & Khan, W. (2025). Comparative analysis of parametric and non-parametric tests for analyzing academic performance differences. Policy Research Journal, 3(8), 55-62.

Krawinkler, H., & Zareian, F. (2007). Performance assessment of steel moment-frame buildings. Proceedings of the 8th U.S. National Conference on Earthquake Engineering, San Francisco, CA.

Lignos, D. G., & Krawinkler, H. (2011). Deterioration modeling of steel components in support of collapse prediction of steel moment frames under earthquake loading. Journal of Structural Engineering, 137(11), 1291–1302.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 10 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Lu, X., Zhang, W., Guan, H., & Ye, L. (2018). Development of a nonlinear time-history analysis model for tall buildings considering material and geometric nonlinearities. Engineering Structures, 163, 1–15.

Ahmad, M., Qamar, H., Rehman, A. A., & Khan, R. (2025). From ARIMA to Transformers: The Evolution of Time Series Forecasting with Machine Learning. Journal of Asian Development Studies, 14(3), 219-233.

Medina, R. A., Krawinkler, H., & Alavi, B. (2012). Seismic demands for nondeteriorating frame structures and their dependence on ground motions. Earthquake Engineering and Structural Dynamics, 41(2), 181–199.

Miranda, E., & Bertero, V. V. (1994). Evaluation of strength reduction factors for earthquake-resistant design. Earthquake Spectra, 10(2), 357–379.

Paulay, T., & Priestley, M. J. N. (1992). Seismic Design of Reinforced Concrete and Masonry Buildings. Wiley.

Ahmad, M., Khan, S., Ahmad, R. W., & Rehman, A. A. (2025). COMPARATIVE ANALYSIS OF STATISTICAL AND MACHINE LEARNING MODELS FOR GOLD PRICE PREDICTION. Journal of Media Horizons, 6(4), 50-65.

Rahgozar, M. A., Moghaddam, H., & Fadaee, M. J. (2015). Nonlinear time-history analysis of reinforced concrete high-rise buildings under strong ground motions. Bulletin of Earthquake Engineering, 13(2), 479–497.

Ahmad, M., Amin, K., Ali, A., & Ahmad, R. W. (2025). A Comparative Evaluation of Poisson, Negative Binomial, and Zero-Inflated Models for Count Data. world, 3(8).