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Engineering Assessment of Earthquake-Resistant Building Code Based on Seismic Load Responses

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Abstract. Earthquake-resistant building design is fundamentally aimed at safeguarding life safety while controlling structural damage and preserving post-earthquake functionality under uncertain seismic actions. Although contemporary seismic codes provide detailed procedures for estimating earthquake-induced loads, differences in seismic hazard representation, force distribution rules, and deformation assumptions can lead to considerable variation in predicted structural response. This study presents a comprehensive engineering assessment of earthquake-resistant building codes based on seismic load responses in reinforced concrete moment-resisting frame structures. An integrated analytical framework combining elastic seismic analysis and nonlinear static performance evaluation is adopted to examine global force demand, displacement behavior, stiffness degradation, and post-yield response. Particular attention is given to the interaction between force-based seismic demand indicators, such as base shear and story forces, and deformation-based performance measures, including interstory drift and performance point characteristics. By systematically evaluating structural response across elastic and inelastic stages, the study demonstrates that reliance on elastic force demand alone is insufficient for capturing true seismic performance. The results emphasize the importance of performance-oriented assessment in enhancing the reliability, consistency, and resilience of earthquake-resistant building design.

Keywords: disaster risk reduction, earthquake-resistant design, nonlinear static analysis, performance-based assessment, seismic load responses, structural resilience

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1. Introduction

Earthquakes continue to pose one of the most significant threats to the safety, functionality, and sustainability of the built environment, particularly in regions characterized by high seismic hazard and rapid urbanization. Unlike gravity or wind loads, seismic actions are inherently dynamic, cyclic, and highly uncertain, exhibiting complex time histories and frequency content that can induce severe structural demands [1]. These characteristics require design and assessment methodologies capable of capturing not only peak force demand but also cumulative damage and deformation accumulation.

Traditional earthquake-resistant design has largely relied on force-based methodologies, in which seismic effects are represented using equivalent static forces or elastic response spectra. While these approaches have contributed substantially to reducing collapse risk, extensive post-earthquake investigations have shown that buildings designed in accordance with force-based code provisions may still experience unacceptable levels of damage, excessive residual drift, or loss of functionality [2]. This discrepancy between code compliance and observed performance has motivated the evolution of performance-based seismic engineering, which explicitly incorporates deformation limits, damage states, and functionality objectives into the design and assessment process [3–5].

Reinforced concrete moment-resisting frame structures are among the most widely adopted structural systems in seismic regions due to their architectural flexibility, redundancy, and potential for ductile behavior. When appropriately detailed, these systems can dissipate significant amounts of seismic energy through controlled inelastic deformation [6]. However, their seismic response is governed by complex interactions among material nonlinearity, member stiffness, beam–column joint behavior, and load redistribution mechanisms. Prior experimental and analytical studies have demonstrated that relatively small variations in detailing quality, stiffness distribution, or load path continuity can significantly influence damage patterns and deformation demand [7–9].

Despite the common objective of life safety, seismic codes differ considerably in how seismic hazard is quantified and translated into design actions. Differences in response spectra, force reduction factors, vertical force distribution rules, and displacement limits can lead to markedly different estimates of base shear and interstory drift for identical structural configurations [10,11]. Comparative studies have further shown that these differences may result in inconsistent seismic performance levels across regions and design standards [12–15].

Recent advances in seismic assessment have expanded analytical frameworks to include near-fault ground motion effects, soil–structure interaction, probabilistic damage evaluation, and post-earthquake inspection outcomes [16–18]. At the same time, improvements in nonlinear analysis techniques have strengthened the relationship between analytical response indicators—such as drift ratios, ductility demand, and damage indices—and observed structural damage [19–21]. These developments highlight the necessity of integrated analytical approaches capable of bridging the gap between force-based design and actual seismic performance.

Within this context, the present study provides an engineering assessment of earthquake-resistant building codes based on seismic load responses in reinforced concrete frame structures. By integrating elastic seismic analysis with nonlinear static performance evaluation, the study aims to clarify how seismic loads are distributed, resisted, and dissipated, and how these processes collectively govern overall structural behavior and resilience [22–29].

2. Building Configuration and Geometry

The reference structure considered in this study is a mid-rise reinforced concrete moment-resisting frame building, representative of typical urban construction in seismically active regions. The building has a regular rectangular plan and is designed to minimize torsional irregularity while allowing clear evaluation of seismic load distribution and deformation behavior, as shown in Figure 1.

In plan, the building consists of three bays in the X-direction and two bays in the Y-direction. The typical span length in the X-direction is 6.0 m, while the span length in the Y-direction is 5.0 m, resulting in a total plan dimension of 18.0 m × 10.0 m. This bay arrangement reflects common practice for reinforced concrete office and residential buildings and allows for realistic stiffness distribution in both principal directions.

Vertically, the structure comprises six stories, with a uniform story height of 4.0 m, leading to a total building height of 24.0 m measured from the foundation level to the roof. The regular vertical configuration ensures that observed variations in seismic response are primarily attributed to seismic loading characteristics rather than geometric irregularities.

Columns are assumed to be continuous over the full height of the building, while beams are provided at every floor level in both horizontal directions, forming a fully moment-resisting frame system. Floor slabs are modeled as rigid diaphragms, enabling effective transfer of lateral forces to the vertical resisting elements. This configuration supports realistic simulation of global structural behavior, including interstory drift distribution, torsional response, and load redistribution under seismic excitation.

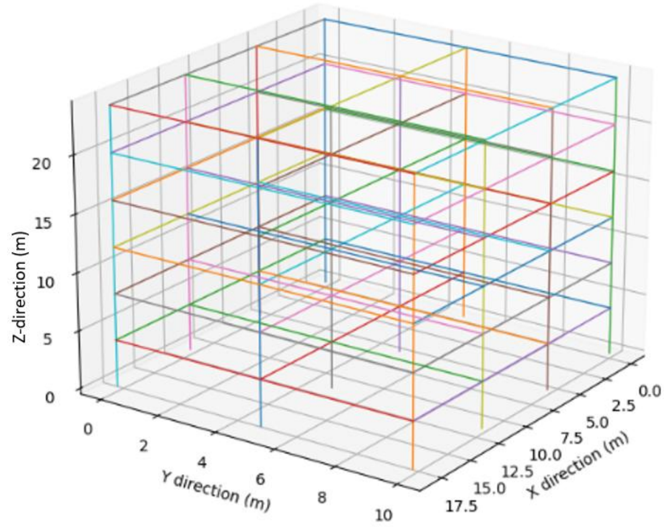


Figure 1. Three-dimensional finite-element model of the reinforced concrete moment-resisting frame building showing bay configuration in the X- and Y-directions and uniform story height

3. Research Methods

The research methodology is structured to deliver a comprehensive evaluation of seismic load responses by integrating elastic and nonlinear analytical procedures within a unified framework. This approach reflects contemporary seismic engineering practice, where conventional force-based design is increasingly complemented by deformation-based performance evaluation to achieve more reliable predictions of earthquake response [23].

The overall analytical workflow adopted in this study is illustrated in Figure 2, which outlines the sequential integration of seismic parameter definition, structural modeling, elastic analysis, and nonlinear performance evaluation. This structured approach ensures analytical consistency and supports transparent interpretation of results, in accordance with modern seismic assessment frameworks [23,24].

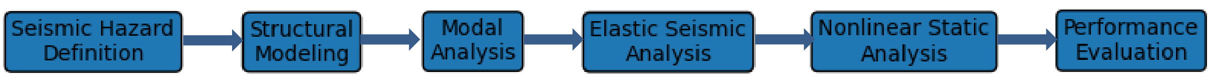


Figure 2. Analytical workflow adopted for seismic load evaluation and performance-based structural assessment

A ductile or special reinforced concrete moment-resisting frame building is selected as the reference structure, representative of typical mid-rise construction widely used in seismic regions [6,15]. The structural system is modeled using a three-dimensional finite-element approach that explicitly represents beams, columns, slabs, and their connectivity. The overall configuration and modeling strategy, shown in Figure 1, enable realistic simulation of stiffness distribution, torsional response, and load transfer mechanisms under seismic loading.

Material properties and cross-sectional dimensions are defined using standardized engineering assumptions consistent with previous comparative seismic studies [8,17]. Concrete and reinforcing steel are modeled to capture elastic stiffness, yielding behavior, and post-yield response. Gravity loads are applied uniformly, while boundary conditions are specified to represent realistic support behavior. Consistency in modeling assumptions across all analyses ensures that observed response differences are primarily attributable to seismic loading rather than numerical artifacts [9,10].

Dynamic characteristics of the structure are established through modal analysis. The natural periods, mode shapes, and modal mass participation ratios were obtained from this analysis. These dynamic properties provide insight into the dominant vibration modes governing seismic response and influence both force distribution and displacement demand [11,14].

Elastic seismic analysis is subsequently performed to evaluate equivalent static forces, base shear demand, and vertical force distribution. Although simplified, elastic analysis remains essential for understanding global force transfer mechanisms and identifying overall response trends [19,24]. To overcome the limitations of elastic analysis in representing inelastic behavior, nonlinear static (pushover) analysis is conducted. Incremental lateral loading is applied until significant inelastic deformation occurs, allowing assessment of stiffness degradation, plastic hinge development, and post-yield behavior [20,25].

4. Result and Discussion

The results and discussion obtained from the analysis can be elaborated and discussed in the following subsections.

4.1. Seismic Design Parameters and Dynamic Characteristics

The seismic design parameters adopted in this study establish the foundation for estimating earthquake-induced demand. Table 1 presents the seismic importance factor (I_e), response modification factor (R), and related parameters used in the analysis. These parameters reflect assumptions of acceptable ductility and energy dissipation capacity embedded within earthquake-resistant design philosophies [7,8]. Higher I_e and design spectral acceleration (S_{DS} and S_{D1}) lead to increased force demand, while larger R factor imply greater reliance on inelastic deformation as in ductile or special RC moment-resisting frames.

Table 1. Seismic design parameters and response modification factors adopted in the analysis

Parameter	Symbol	Value	Description
Seismic importance factor	I_e	1.0	Ordinary occupancy building
Response modification factor	R	8.0	Ductile RC moment-resisting frame
Site classification	—	Medium soil	Based on average shear wave velocity
Fundamental period coefficient	C_t	0.0466	Code-based empirical coefficient
Design spectral acceleration (short period)	S_{DS}	0.75 g	Elastic response spectrum
Design spectral acceleration (1.0 s)	S_{D1}	0.35 g	Long-period response control

Dynamic characteristics obtained from modal analysis indicate that the structural response is dominated by lower vibration modes. As summarized in Table 2, the fundamental mode contributes the majority of modal mass participation, while higher modes primarily influence localized response effects. This behavior is consistent with observations from previous analytical investigations of reinforced concrete moment-resisting frames [11,15], supporting the applicability of equivalent static procedures for preliminary force estimation [16].

4.2. Vertical Distribution of Seismic Forces

The distribution of equivalent static earthquake forces along the building height reveals a progressive increase in force demand toward upper stories. This trend, which can be observed directly in the story-level force values summarized in Table 3, reflects the combined influence of floor mass, modal participation, and dynamic amplification effects. Similar vertical force distributions have been reported in numerous comparative studies of regular building configurations [10,19].

Table 2. Modal properties and mass participation ratios obtained from structural dynamic analysis

Mode No.	Natural Period (s)	Direction	Mass Participation Ratio (%)
1	1.42	X-direction	68.3
2	1.35	Y-direction	65.7
3	0.48	Torsional	14.2
4	0.31	X-direction	6.1
5	0.29	Y-direction	5.4

Table 3. Story-level equivalent static seismic forces resulting from elastic seismic analysis

Story Level	Elevation (m)	X-Direction Seismic Force (kN)	Y-Direction Seismic Force (kN)
Roof	24.0	420	398
5	20.0	385	360
4	16.0	335	318
3	12.0	270	255
2	8.0	195	180
1	4.0	115	105

Directional variation in force demand is also evident. When lateral forces are applied in orthogonal directions, differences arise due to variations in stiffness distribution and dynamic characteristics. These effects are clearly illustrated in the comparative force profiles shown in Figure 3, emphasizing the necessity of evaluating seismic response in both principal directions to avoid underestimation of demand [9,21].

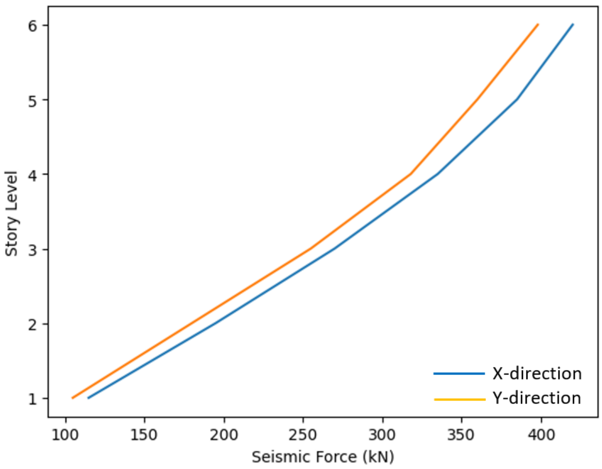


Figure 3. Vertical distribution of equivalent static seismic forces along the building height in orthogonal loading directions

4.3. Structural Modeling and Global Response Representation

Realistic representation of global structural behavior is achieved through the three-dimensional model shown in Figure 1. By explicitly modeling member connectivity and stiffness distribution, the analysis captures torsional effects, interstory deformation patterns, and load redistribution mechanisms that cannot be adequately represented using simplified two-dimensional models [22,24].

4.4. Base Shear Demand and Directional Effects

Base shear demand serves as a fundamental indicator of seismic load response. Table 4 summarizes the total base shear values obtained from elastic seismic analysis, revealing noticeable variation depending on seismic load assumptions [8,17]. Higher base shear values generally correspond to more conservative force-based design approaches, whereas lower values imply greater reliance on ductile energy dissipation.

Table 4. Comparison of total base shear demand under different seismic loading conditions

Loading Direction	Base Shear (kN)	Base Shear Ratio
X-direction	1,720	1.00
Y-direction	1,616	0.94
Average	1,668	—

Directional differences in base shear are also observed. These differences, illustrated in Figure 4, reflect variations in lateral stiffness and dynamic characteristics between principal directions. Similar directional sensitivity has been reported in comparative studies of reinforced concrete frame systems [16,18], underscoring the importance of balanced stiffness distribution in earthquake-resistant design.

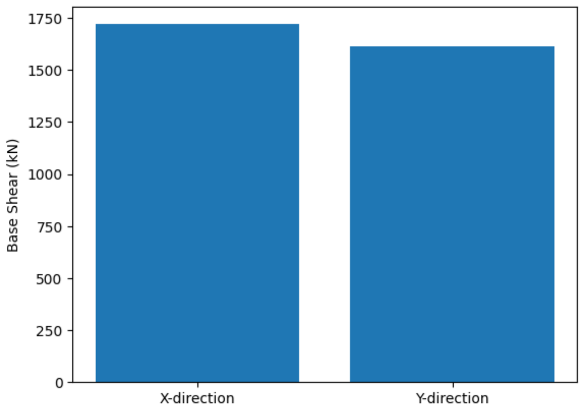


Figure 4. Comparison of total base shear demand under different seismic loading conditions

4.5. Interstory Drift and Deformation Demand

Interstory drift is among the most critical deformation-based indicators of seismic performance due to its strong correlation with both structural and nonstructural damage. Maximum drift ratios obtained from elastic and nonlinear analyses are illustrated in Figure 5, revealing nonuniform drift distribution along the building height and clear concentrations of critical interstory drift. Drift concentration at specific story levels indicates potential zones of damage accumulation [14,20]. Such deformation patterns are consistent with previous studies on damage localization in reinforced concrete frame structures and underscore the limitations of assessing seismic performance solely on the basis of force demand [6,25]. The X-direction corresponds to the longer plan dimension (18.0 m), comprising three bays, which results in greater lateral flexibility, higher drift demand, and a more critical deformation response. Consequently, this direction is particularly suitable for illustrating drift concentration and associated damage potential.

4.6. Nonlinear Capacity and Performance Evaluation

Nonlinear static analysis provides insight into the progressive evolution of structural response from elastic behavior to inelastic deformation. Key nonlinear performance parameters, including yield displacement, ultimate displacement, and ductility ratios, are summarized in Table 5. These parameters quantify deformation capacity and energy dissipation potential [20,26].

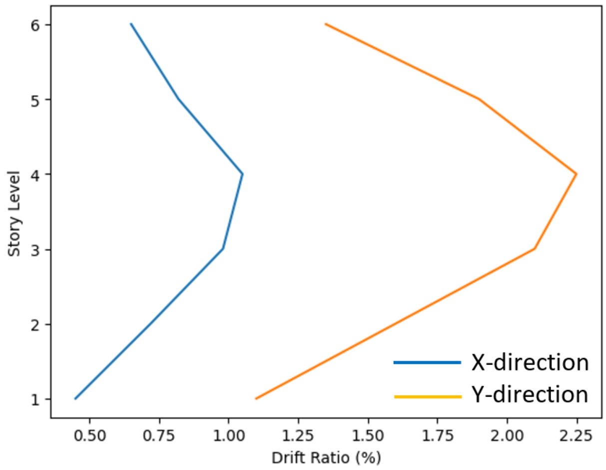
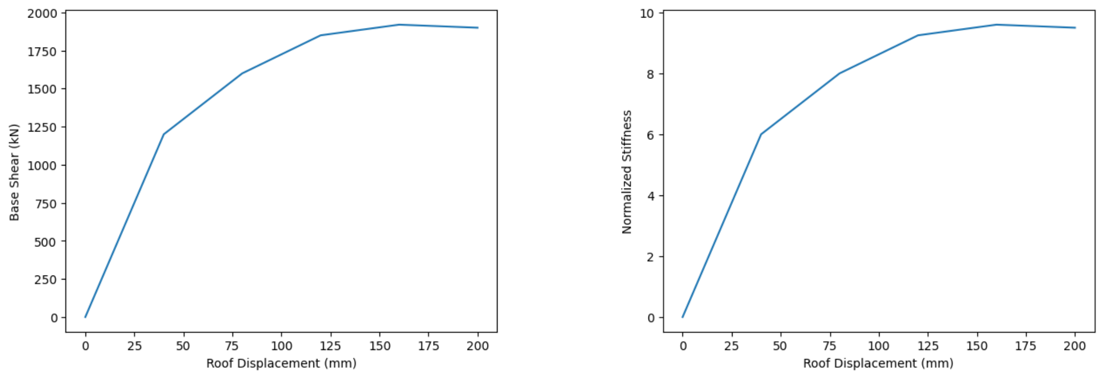


Figure 5. Distribution of maximum interstory drift ratios along the building height under seismic loading

Table 5. Nonlinear performance parameters derived from pushover analysis

Parameter	X-direction	Y-direction
Yield displacement (mm)	42	39
Ultimate displacement (mm)	185	170
Yield base shear (kN)	1,480	1,390
Ultimate base shear (kN)	1,920	1,810
Displacement ductility	4.4	4.3

Capacity curves obtained from pushover analysis illustrate stiffness degradation and post-yield behavior, as shown in Figure 6. Differences in nonlinear response characteristics between the two principal directions reflect variations in structural stiffness and load distribution and are consistent with trends reported in deformation-based seismic performance assessment studies [18,27]. The pushover curve is used to represent the global force–displacement response in the governing direction. As the X-direction exhibits higher base shear demand and larger displacement capacity, it is appropriate to present the primary capacity curve in this direction. Moreover, since stiffness degradation is a post-yield phenomenon, it should be evaluated and illustrated in the same direction as the pushover analysis to ensure analytical consistency and clarity.



(a) Capacity curve (b) Stiffness degradation

Figure 6. Pushover capacity curve and stiffness degradation of the structure in the X-direction

4.7. Performance Points and Seismic Resilience

Performance points derived from capacity–demand relationships provide a comprehensive measure of expected seismic response under design-level excitation. The calculated performance point parameters are summarized in Table 6, representing the intersection between structural capacity and seismic demand [15,26].

Table 6. Structural performance point characteristics and corresponding displacement demands

Performance Indicator	X-direction	Y-direction
Performance point displacement (mm)	110	102
Effective period (s)	1.85	1.78
Effective damping (%)	14.5	13.8
Performance level	Life Safety	Life Safety

The graphical determination of performance points, as illustrated in Figure 7, highlights the interaction among strength, ductility, and displacement capacity. These results reinforce findings from recent studies indicating that seismic resilience is governed not only by peak strength but also by post-yield stability and effective deformation control [18,27–29]. Performance point evaluation must be based on the same capacity curve employed in the nonlinear analysis. Accordingly, since the pushover analysis is conducted in the X-direction, the corresponding performance point is also determined for this direction to ensure analytical consistency.

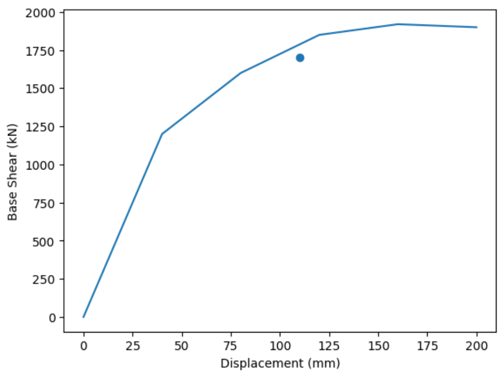


Figure 7. Determination of structural performance point based on the intersection of capacity and seismic demand curves

5. Result and Discussion

This study has presented an extensive engineering assessment of earthquake-resistant building codes based on seismic load responses in reinforced concrete moment-resisting frame structures. Through the combined use of elastic seismic analysis and nonlinear static performance evaluation, the study has provided detailed insight into force demand, deformation behavior, stiffness degradation, and post-yield response.

The results demonstrate that seismic load responses are strongly influenced by assumptions embedded within earthquake-resistant design codes regarding hazard representation, force distribution, and ductility. While elastic analysis remains valuable for understanding global force demand, it does not adequately capture deformation capacity or damage progression. Nonlinear performance evaluation is therefore essential for achieving a realistic understanding of earthquake-resistant behavior.

Overall, the findings highlight the importance of adopting performance-oriented assessment frameworks that balance strength-based design with deformation-based evaluation. Such integrated approaches are critical for improving seismic resilience, enhancing damage control, and supporting the continued development of reliable and consistent earthquake-resistant building design practices.

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