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Comparative Study on Code-Based and Performance-Based Design Approach for Tall RC Building

by

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CERTIFICATE OF APPROVAL

Comparative Study on Code-Based and Performance-Based Design Approach for Tall RC Building

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(Mobeen Anwar)

Abstract

The seismic design of tall reinforced concrete buildings is traditionally governed by code-based design approaches, which ensure life safety through prescriptive, force-based methods. However, these approaches often fail to capture the complex nonlinear behavior, higher-mode effects, and localized inelastic demands that occur during strong earthquakes. This research presents a comprehensive comparative study of code-based and performance-based seismic design methodologies for a representative 35-story reinforced concrete dual-system building located in a seismically active region of Islamabad, Pakistan.

Initially, the building was designed using conventional code-based design procedures in accordance with ASCE 7-22, establishing a baseline for member sizing, material properties, and reinforcement detailing. The code-compliant model was then subjected to a performance-based assessment using nonlinear static pushover analysis as per ASCE 41-17. Plastic hinges were assigned to beams, columns, and shear walls to capture flexural and axial-moment behavior, and target displacements were calculated for Immediate Occupancy, Life Safety, and Collapse Prevention performance levels. Key engineering demand parameters, including inter-story drift ratios, roof displacements, plastic hinge formation, and base shear, were evaluated and compared between the two design approaches.

This study evaluates the seismic performance of a 35-story reinforced concrete dual system building by integrating code-based design (ASCE 7-22 and ACI 318-19) with performance-based nonlinear assessment using ETABS. The results indicate that the code-based design provides a conservative baseline, ensuring structural safety under design-level earthquakes. Performance-based assessment revealed that most structural members remained largely elastic even under maximum considered earthquake loads, with only a small percentage of beams near shear walls and lift cores reaching inelastic performance levels. The study highlights potential over-design in several members while identifying localized high-demand regions that could benefit from optimized reinforcement allocation. Overall, the dual system exhibited inherent redundancy and robustness, effectively distributing seismic demands and maintaining overall stability.

The results confirm that the code-based design satisfies all strength, drift, and stability requirements while exhibiting conservative behavior. Nonlinear pushover analysis indicates that most structural elements remain elastic under SLE, DBE, and MCE hazard levels, with limited inelastic action concentrated in beams near shear walls and core regions. The comparison between CBD and PBD highlights potential areas of over-design, suggesting opportunities for optimization without compromising seismic safety. Based on the findings of this research, a combined design approach is recommended for practicing structural engineers. Code-based design should continue to be used as the primary design framework to satisfy regulatory requirements, ensure constructability, and establish initial member sizes and reinforcement. Once a compliant code-based design is achieved, performance-based assessment should be employed as a verification and optimization tool rather than a replacement for conventional design. Future work should focus on reinforcement optimization and nonlinear time-history analysis using multiple ground motion records to further enhance seismic resilience and economic efficiency of tall RC dual system buildings.

Keywords: Seismic Design, Performance-Based Design (PBD), Code-Based Design (CBD), Reinforced Concrete (RC) Tall Buildings, Nonlinear Pushover Analysis

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Abbreviations

CBD	Code-Based Design
CBDA	Code-Based Design Approach
CBF	Concentrically Braced Frame
CP	Collapse Prevention
DDBD	Direct Displacement-Based Design
EQGM	Earthquake Ground Motion
FEMA	Federal Emergency Management Agency
IO	Immediate Occupancy
IS	Indian Standard
LS	Life Safety
P-B EQ-RD	Performance-Based Earthquake-Resistant Design
PBD	Performance-Based Design
PBDA	Performance-Based Design Approach
PBSD	Performance-Based Seismic Design
RC	Reinforced Concrete
YFS	Yield Frequency Spectra

Symbols

$\mathbf{Ct}$	Period coefficient
$\mathbf{R}$	Response modification factor
Ω	Overstrength factor
$\mathbf{Cd}$	Deflection amplification factor
$\mathbf{Ss}$	Spectral acceleration at short periods
$\mathbf{S1}$	Spectral acceleration at 1-second period
$\mathbf{SDS}$	Design spectral response acceleration at short periods
$\mathbf{SD1}$	Design spectral response acceleration at 1-second period
$\mathbf{T}$	Fundamental period of the structure
$\mathbf{Vb}$	Base shear
$\Delta_{\mathbf{target}}$	Target displacement for pushover analysis
$\Delta_{\mathbf{roof}}$	Roof displacement
θ	Plastic hinge rotation
$\mathbf{M}$	Bending moment
$\mathbf{P}$	Axial load
$\mathbf{I}$	Moment of inertia of a section
$\mathbf{E}$	Modulus of elasticity of concrete
f'_c	Compressive strength of concrete
f_y	Yield strength of steel
ρ	Reinforcement ratio
$\mathbf{h}$	Story height
$\mathbf{w}$	Story weight
δ	Inter-story drift

Chapter 1

Introduction

1.1 Background

The seismic design of structures has historically been governed by prescriptive building codes, which provide simplified, force-based procedures to ensure life safety. These Code-Based Design (CBD) approaches, such as Response Spectrum Analysis (RSA) outlined in standards like UBC 97 and ASCE 7, have formed the backbone of structural engineering practice for decades. These methods rely on linear elastic analysis modified by empirical behavior factors to account for ductility and energy dissipation, offering a straightforward and consistent framework for the design of conventional structures.

However, the rapid urbanization and architectural evolution in seismically active regions, particularly in developing countries like Pakistan, have led to a surge in the construction of tall and complex Reinforced Concrete (RC) buildings. For these structures, the limitations of traditional CBD become critically apparent. As evidenced by post-earthquake observations and advanced research, force-based methods often fail to fully capture the complex nonlinear behavior, sequence of component yielding and progressive damage mechanisms inherent in tall buildings under severe seismic loading. This can lead to a potential underestimation of displacements, story drifts and localized damage, resulting in structures that are "code-compliant" yet potentially vulnerable. In response to these limitations, Performance-Based Design (PBD) has emerged as a fundamental paradigm shift in earthquake engineering. Moving away from simplified force reduction, PBD frames the design process around achieving specific, predefined performance objectives such as Immediate Occupancy, Life Safety and Collapse Prevention for different levels of seismic intensity. Formalized by guidelines such as ASCE 41-17 and FEMA P-58, this methodology leverages advanced computational tools and nonlinear analysis techniques, including static pushover and dynamic time-history analysis, to provide a more transparent, reliable and quantitative understanding of a building's likely performance. This research aims to conduct a critical, direct comparison between these two design philosophies for a representative tall RC building, providing much-needed evidence to guide safer and more resilient design practices in regions experiencing rapid high-rise construction.

Research comparing code-based and performance-based design approaches has examined multiple structural systems including reinforced concrete moment frames, steel frames and concentrically braced frames across buildings ranging from 3 to 20 stories [1–3]. Studies consistently found that performance-based methods particularly Direct Displacement-Based Design (DDBD) and Performance-Based Plastic Design (PBPD) outperformed traditional Force-Based Design (FBD) in multiple dimensions [1, 4]. PBPD demonstrated dramatic improvement over baseline code-designed frames in seismic responses, while DDBD proved more economical than FBD for achieving the same performance level [1, 4].

Performance-based approaches achieved superior deformation distribution patterns, with DDBD producing uniform plastic deformation across building height compared to FBD's concentration in lower stories and showed excellent agreement between design predictions and detailed inelastic dynamic analyses [1, 5].

Critical findings include that both tension and compression members resist base shear in concentrically braced frames, contrary to Eurocode 8 assumptions and that FBD systematically requires larger structural sections [3]. Despite technical advantages, performance-based design faces significant implementation barriers, with lengthy and costly approval processes limiting adoption even though 75% of practitioners report cost savings [6]. The research reveals that optimal design approach depends on project context: performance-based design excels for structures requiring specific performance targets, innovative systems, or economic optimization, while code-based approaches remain efficient for conventional structures. Recent innovations include Value Based Design integrating life-cycle cost analysis, first-time applications to new structural systems and integration of fire performance considerations [3, 5]. Validation methods have matured from pushover analysis to rigorous nonlinear time history analysis with multiple ground motions, though systematic uncertainty quantification across design approaches remains underdeveloped [7, 8].

1.2 Research Motivation and Problem Statement

The proliferation of tall RC buildings in seismically active regions presents a formidable engineering challenge. While Code-Based Design is computationally efficient and deeply ingrained in practice, its reliance on simplified linear models may lead to structures that, though technically ”code-compliant,” exhibit unexpected and potentially catastrophic failure mechanisms during a major earthquake. This risk stems from unaccounted-for higher-mode effects, strength and stiffness irregularities, P-delta effects and complex nonlinear behavior that linear methods cannot accurately simulate.

Thus the Problem statement is as follows:

“The central problem is the uncertainty regarding the degree to which CBD conservatively or non-conservatively estimates true seismic demands in tall RC buildings compared to the more rigorous PBD framework. This gap in understanding can lead to an over-reliance on simplified assumptions, potentially compromising the resilience and safety of tall structures. Traditional structural engineering relies almost exclusively on Code-Based Design (CBD), which focuses on prescriptive regulatory compliance rather than simulating actual structural behavior. Recent earthquakes have demonstrated that this reliance often leaves fully code-compliant structures vulnerable to unexpected minor and major damage. Because conventional designers rarely implement Performance-Based Design (PBD) checks, they lack visibility into a structure’s true failure mechanisms and seismic deformation capacity."

Therefore, this research is motivated by the critical need to:

i. Quantify the discrepancies in seismic performance predictions, including inter-story drifts, floor accelerations and component damage, between CBD and PBD for a representative tall RC building.
ii. Identify specific structural vulnerabilities that a force-based CBD might overlook but are revealed through nonlinear PBD assessments.
iii. Promote the adoption of more advanced, reliable and transparent design methodologies by providing clear, evidence-based comparisons and practical guidelines for engineers and policymakers.

1.2.1 Research Questions

This study seeks to answer the following research questions:

i. How do seismic response predictions from code-based design differ from those obtained through performance-based assessment for a tall RC building?
ii. To what extent does CBD underestimate or overestimate critical engineering demand parameters such as inter-story drift and plastic hinge formation?
iii. What structural vulnerabilities are revealed through nonlinear pushover analysis that are not evident in linear CBD procedures?
iv. How can PBD be practically integrated into the seismic design workflow for tall RC buildings in seismic regions?

1.3 Overall Goal of the Research Program and Specific Aim of this MS Thesis

1.3.1 Overall Goal

The overall goal of this research is to perform a comparative study between two advanced seismic design methodologies, namely Code-Based Design (CBD) and

Performance-Based Design (PBD), to evaluate their effectiveness, accuracy and influence on the seismic behavior of tall reinforced concrete buildings.

1.3.2 Specific Aim of this MS Thesis

The specific aim of this MS thesis is to design a representative 35-story reinforced concrete dual-system building using a conventional force-based seismic design approach in accordance with ASCE 7-22 and to subsequently evaluate its seismic performance through a detailed performance-based assessment using nonlinear pushover analysis as per ASCE 41-17, with the objective of comparing key response parameters such as inter-story drift, plastic hinge development, floor accelerations and residual displacements and thereby establishing practical guidelines for integrating performance-based seismic design principles into the design of tall buildings in seismic regions.

1.4 Scope of Work and Study Limitations

The present research is centered on the seismic analysis, design and performance evaluation of a tall reinforced concrete building, represented by a 35-story structure employing a dual structural system consisting of moment-resisting frames and shear walls. A detailed three-dimensional analytical model of the building is developed using industry-standard finite element software (ETABS). Both linear dynamic analysis, in the form of Response Spectrum Analysis based on ASCE 7-22 and nonlinear static analysis using the pushover method in accordance with ASCE 41-17 are performed to investigate the global and local seismic response of the structure. The structural behavior is examined in terms of key response parameters such as inter-story drift ratios, plastic hinge formation patterns, floor accelerations and residual displacements, enabling a comprehensive comparison between code-based and performance-based seismic design approaches.

This study is subject to certain limitations that should be considered when interpreting the results. The investigation is restricted to a single building configuration to facilitate a detailed and controlled comparative assessment, although the adopted methodology is intended to be broadly applicable to similar tall building systems. Soil–structure interaction effects are neglected and all analytical models assume a fixed-base condition.

Furthermore, the assessment is limited to structural performance; non-structural components are not explicitly modeled and are instead evaluated indirectly through drift and acceleration demands. While these limitations constrain the scope of the study, they allow for a focused analysis that provides clear insights and establishes a foundation for future research incorporating more complex modeling considerations.

1.4.1 Rationale Behind Selected Limitations

The selected configuration of a 35-story dual system is highly representative of modern high-rise construction in seismically active developing regions, ensuring the findings have wide applicability. The fixed-base assumption is a common simplification that isolates the superstructure's behavior, providing a clearer comparison of the core CBD and PBD methodologies without the added complexity of soil-structure interaction. Focusing on a single configuration and the primary structural system ensures the research is controlled and feasible, delivering clear insights into the fundamental comparative question.

1.5 Brief Methodology

The methodology adopted in this research begins with the development of a detailed three-dimensional analytical model of a 35-story reinforced concrete dual-system building in ETABS. The structural members are first designed using a conventional code-based approach through Response Spectrum Analysis in accordance with ASCE 7-22. Based on this design, a nonlinear analytical model is then developed by defining appropriate plastic hinges in beams, columns and shear walls. Subsequently, nonlinear static pushover analysis is performed using multiple lateral load patterns to evaluate the inelastic seismic response of the structure. The results obtained from the code-based design (CBD) and performance-based design (PBD) analyses are systematically compared using key engineering demand parameters. Finally, the findings are interpreted to address the research questions and the conclusions are synthesized into the thesis along with practical guidelines for implementing performance-based seismic design in tall reinforced concrete buildings.

1.6 Research Novelty or Uniqueness

1.6.1 Research Novelty

The novelty of this research lies in its focused, in-depth comparative case study on a tall RC configuration that is emblematic of modern construction trends in seismically active developing regions. While previous comparative studies exist, this work distinguishes itself by conducting a direct, quantitative comparison of a wide range of engineering demand parameters from a single, code-compliant model subjected to the rigorous scrutiny of advanced PBD assessment tools.

1.6.2 Significance

The significance of this work is multi-faceted. For academia, it contributes a valuable, data-rich case study to the body of knowledge. For the engineering industry, the findings will offer crucial, evidence-based guidance on the benefits and implementation of PBD. For regulatory bodies, the results can inform future building code revisions by highlighting the potential shortcomings of current prescriptive methods.

1.6.3 Practical Implementation

The practical implementation of this research will be realized through the development of clear guidelines for engineers, outlining the steps, benefits and challenges of adopting a PBD framework for tall buildings, thereby facilitating its integration into professional practice. Additionally, the study provides a structured approach for incorporating nonlinear analysis procedures and acceptance criteria into routine practice, reducing the gap between research and real-world application. This will support engineers in making informed decisions regarding safety, cost-efficiency, and resilience, ultimately promoting wider adoption of PBD in both design offices and large-scale infrastructure projects.

1.6.4 National and Global Impact with Emphasis on Sustainable Development Goals Relevance

The research supports the objectives of the United Nations Sustainable Development Goals (SDGs), specifically SDG-9 (Industry, Innovation and Infrastructure) by promoting resilient and reliable infrastructure systems and SDG-11 (Sustainable Cities and Communities) by enhancing the safety and sustainability of urban developments in seismic regions. By advocating performance-based seismic design, the study contributes to long-term urban resilience, reduced disaster risk and sustainable development of high-rise buildings worldwide. Furthermore, the adoption of advanced seismic assessment methods encourages the integration of innovative engineering practices and materials, fostering safer construction standards and more efficient resource utilization. This alignment with sustainability principles not only mitigates earthquake-related losses but also supports the creation of resilient, adaptable and inclusive urban environments.

1.6.5 Research Challenges

The primary challenges encountered in this research are associated with the complexity of nonlinear seismic analysis. Developing accurate nonlinear models requires careful selection of material properties, plastic hinge definitions and acceptance criteria in accordance with ASCE 41-17. Numerical convergence issues during pushover analysis, particularly at advanced stages of structural degradation, also pose challenges in achieving stable and reliable solutions. Additionally, interpretation of performance limits and damage states demands sound engineering judgment to ensure meaningful comparison between code-based and performance-based results.

1.6.6 Ethical and Management Considerations Including Risk Management

This research is conducted in accordance with established principles of professional engineering ethics, with a strong emphasis on public safety, transparency and technical integrity.

All analytical procedures are based on recognized international standards and assumptions and limitations are clearly stated to avoid misinterpretation of results. From a risk management perspective, the study aims to identify potential seismic vulnerabilities in tall buildings and propose methodologies that reduce structural risk, thereby supporting safer design decisions and responsible engineering practice.

1.6.7 Research Deliverables, Sale and Marketing Potential

The key deliverables of this research include a validated three-dimensional analytical model of a tall RC building, comparative seismic performance results obtained from code-based and performance-based analyses and a structured guideline for integrating performance-based seismic design into professional practice. These outcomes have strong practical value and may be utilized by structural design consultants, academic institutions and regulatory bodies. The developed methodology and findings also have potential for adaptation into professional design manuals, training programs and consultancy services, enhancing their sale and marketing potential within the engineering industry.

1.7 Thesis Outline

This thesis is organized into six chapters, structured as follows:

i. Chapter 1 – Introduction: This chapter presents the background of seismic design for tall reinforced concrete buildings and discusses the evolution from conventional code-based design (CBD) toward performance-based design (PBD). It outlines the research motivation, problem statement, objectives, scope of work, adopted methodology and overall organization of the thesis.

ii. Chapter 2 – Literature Review: This chapter provides a comprehensive review of existing research related to seismic design methodologies for tall reinforced concrete buildings. It examines code-based design principles, performance-based assessment approaches, nonlinear analysis techniques and previous comparative studies. The chapter identifies knowledge gaps and establishes the justification for the present study.

iii. Chapter 3 – Methodology: This chapter describes the research methodology adopted in the study. It includes the selection and description of the 35-story reinforced concrete dual system building, modeling procedures in ETABS, material properties, structural design criteria, load definitions and analysis procedures for both linear (CBD) and nonlinear (PBD) evaluations.

iv. Chapter 4 – Results and Analysis: This chapter presents the outcomes of the code-based design and performance-based assessment. It includes model verification checks, drift and torsional evaluations, member design results, pushover analysis findings, hinge formation patterns and comparisons between predicted and actual inelastic behavior under different seismic hazard levels.

v. Chapter 5 – Guidelines for Practicing Designers: This chapter translates the analytical findings into practical recommendations for structural engineers. It highlights lessons learned from the comparison of CBD and PBD, discusses reinforcement optimization strategies and provides guidance for improving seismic efficiency and material economy in tall reinforced concrete dual system buildings.

vi. Chapter 6 – Conclusion and Future Work: This final chapter summarizes the key findings of the research, emphasizing the comparative performance of code-based and performance-based approaches. It outlines the main contributions of the study, discusses its limitations and proposes recommendations for future research aimed at enhancing seismic resilience and design efficiency. References are provided at the end of the thesis following Chapter 6.

Chapter 2

Literature Review

2.1 Background

Tall Reinforced Concrete (RC) buildings are critical components of urban infrastructure and are particularly vulnerable to seismic forces due to their height and complexity. Damage to such buildings during earthquakes can result in severe economic losses and loss of functionality; therefore, ensuring their adequate seismic performance is essential. Traditionally, these structures are designed using code-based design approaches that primarily target life safety. However, this approach does not explicitly address damage control or post-earthquake operability. To address these limitations, performance-based seismic design has been developed, which evaluates structural behavior under different seismic hazard levels. In this study, a tall RC dual-system building is analyzed using both code-based and performance-based approaches in ETABS to assess and compare their seismic performance.

2.2 Evolution of Seismic Design Philosophy

2.2.1 Early Seismic Design: Allowable Stress and Elastic Concepts

In the early stages of seismic engineering, structural design was primarily governed by the allowable stress design (ASD) philosophy. Within this framework, earthquake effects were represented using simplified equivalent static lateral forces, usually defined as a fixed percentage of the building's self-weight. The underlying assumption of ASD-based seismic design was that structures should remain predominantly elastic during earthquake excitation, with induced stresses limited to prescribed allowable values to prevent damage [9]. This approach offered simplicity and computational efficiency, which made it attractive during periods when analytical tools and computational resources were limited. However, it inadequately captured the dynamic and cyclic nature of seismic loading and did not account for variations in ground motion intensity, frequency content, or duration [10]. More critically, ASD neglected the role of inelastic deformation and energy dissipation, which are now recognized as fundamental mechanisms governing seismic performance. Consequently, structures designed using ASD often exhibited unpredictable damage patterns and insufficient safety margins under strong ground motions, leading to limited reliability and prompting the need for more rational and performance-oriented seismic design methodologies.

2.2.2 Transition to Strength-Based and Code-Based Design

Advancements in earthquake engineering research led to the recognition that designing structures to remain fully elastic during severe earthquakes was both impractical and uneconomical. This realization resulted in the adoption of strength-based design, which later evolved into modern Code-Based Design (CBD) frameworks. In CBD, elastic seismic forces obtained from response spectra are reduced using response modification factors to account for ductility, overstrength and redundancy [11].

Although CBD implicitly permits inelastic behavior, it does not explicitly evaluate damage, deformation, or post-earthquake functionality. The dominant and often sole performance objective remains life safety, achieved through compliance with prescriptive code provisions [12].

2.2.3 Lessons from Major Earthquakes and Limitations of Code-Based Design

Several devastating earthquakes highlighted the inherent limitations of force-based and prescriptive seismic design approaches. Buildings designed to an older seismic code do not become unsafe overnight, but they can be left with less reserve against the hazards that newer codes were written to address. Khose et al. (2010) found consistently treat this as a risk problem: older code provisions can be obsolete relative to current practice and existing buildings designed before modern seismic provisions tend to have higher collapse or damage probability under today's demand levels .

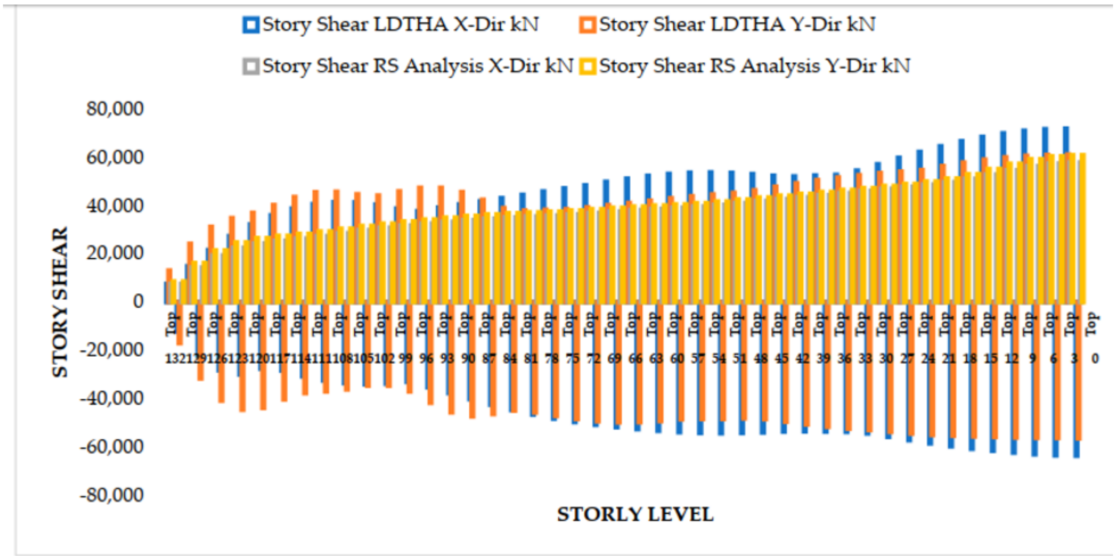


Figure 2.1: Different Base Shear Calculated for same building by different Methods [14]

The 1994 Northridge earthquake exposed brittle failures in steel moment-resisting frames that were designed in full accordance with seismic codes [15]. Similarly, the 1995 Kobe earthquake caused extensive damage to engineered buildings and infrastructure, emphasizing deficiencies in force-based assumptions and detailing practices [16]. The 1999 Chi-Chi earthquake further demonstrated that code-compliant structures could experience excessive damage and prolonged downtime, even when collapse was prevented [17].

These events collectively revealed that code compliance does not guarantee predictable or acceptable seismic performance, especially for complex and tall structures. Figure 2.1 illustrates the variation in base shear obtained for the same building when analyzed using different seismic design methods, highlighting the differences in force estimation between alternative analytical approaches. This discrepancy underscores the need for performance-based evaluation methods that can more accurately capture structural response and damage potential beyond simplified force-based estimations.

2.2.4 Challenges of Code-Based Design for Tall Reinforced Concrete Buildings

Tall reinforced concrete (RC) buildings exhibit highly complex seismic behavior that cannot be fully captured using simplified force-based procedures prescribed in conventional code-based design (CBD) frameworks. Due to their significant height and flexibility, these structures are strongly influenced by higher-mode effects, which alter force and deformation demands along the building height and often result in non-uniform damage distribution [18].

In addition, P–Δ effects, shown in Figure 2.2, arising from the interaction between gravity loads and lateral displacements, can significantly amplify seismic demands, particularly in the lower stories, increasing the risk of instability and progressive damage. Such second-order effects are either neglected or only approximately accounted for in most prescriptive CBD procedures [19].

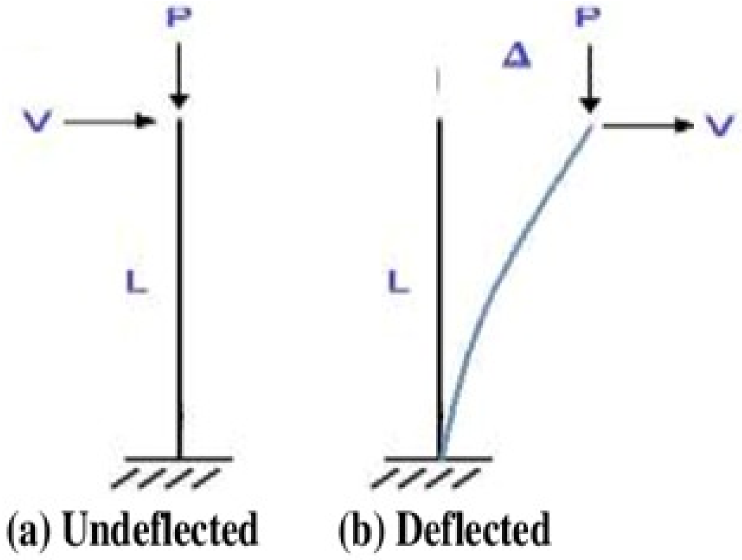


FIGURE 2.2: P–Δ effects, arising from the interaction between gravity loads and lateral displacements

Seismic design codes for reinforced concrete structures are continuously updated to incorporate advancements in research, observed earthquake performance and improved analytical procedures.

Despite these periodic revisions, code-based design remains primarily force-based and simplified in nature, particularly for tall and complex structural systems. Table 2.1 presents a summary of the evolution of major international design codes to highlight their progressive development and to contextualize the limitations of purely code-based approaches in high-rise RC buildings.

TABLE 2.1: Evolution of Major Seismic Design Codes

Code or Standard	**Edition Year**	**Remarks**
Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE)	2005	Introduction of modern load combinations
	2010	Improved seismic provisions
	2016	Enhanced risk categories and site factors
	2022	Latest edition
Building Code Requirements for Structural Concrete (ACI)	2008	Traditional strength design provisions
	2014	Major restructuring of code format
	2019	Latest edition used in this study
	2022	Reapproved 2019
International Building Code	2006	Early unified building code framework
	2009	Improved seismic design provisions
	2012	Enhanced coordination with ASCE 7
	2015	Updated seismic and wind load provisions
	2018	Refined risk categories and design criteria
	2021	References ASCE 7-16
	2024	Utilizes 2018 USGS National Hazard Models

The evolution of ASCE 7, ACI 318, ASCE 41 and International Building Code demonstrates a continuous effort to improve seismic safety provisions. However, despite these advancements, the fundamental approach in most design codes still relies on equivalent static forces and simplified response assumptions.

Furthermore, tall RC buildings often exhibit irregular stiffness and strength distribution due to architectural constraints, functional requirements and the use of dual structural systems involving moment-resisting frames and shear walls. These irregularities can lead to torsional response, localized damage concentration and unintended load redistribution during strong ground motions. The linear-elastic analysis methods commonly employed in CBD are inherently incapable of simulating the nonlinear material behavior, stiffness degradation and strength deterioration that govern the actual seismic response of reinforced concrete components under cyclic loading. Other than that, different procedures used in CBD show different demands using different procedures like shown in Figure 2.3.

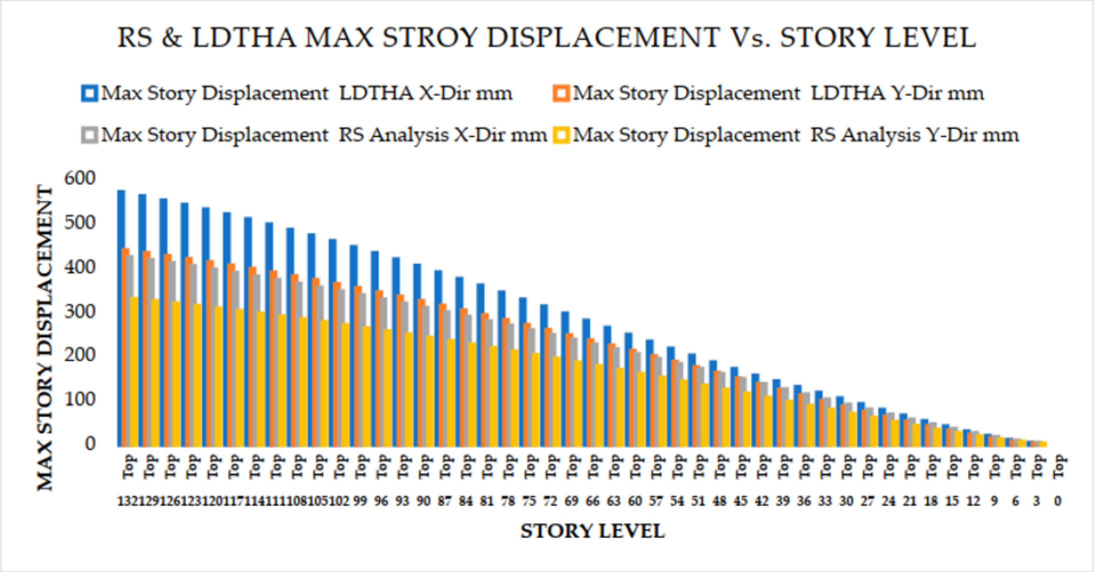


Figure 2.3: Increase in Story Displacement Due to Dynamic Analysis [14]

The linear-elastic analysis methods commonly employed in CBD are inherently incapable of simulating the nonlinear material behavior, stiffness degradation and strength deterioration that govern the actual seismic response of reinforced concrete components under cyclic loading [20]. Beyond structural safety, CBD is fundamentally limited by its exclusive focus on life-safety objectives, offering little to no insight into post-earthquake performance metrics such as repairability, downtime and economic losses. Code compliance does not explicitly ensure that damage remains within acceptable limits or that the building can be rapidly reoccupied following a major seismic event. For tall buildings that accommodate residential, commercial, or critical functions, prolonged downtime and extensive repair requirements can lead to severe economic and social consequences, even when collapse is avoided [21]. This limitation becomes particularly critical for high-rise structures, where nonlinear effects and damage accumulation significantly influence overall system performance during strong ground motions. Consequently, reliance solely on CBD may lead to designs that meet code requirements yet fail to achieve desired performance objectives related to functionality and resilience.

2.2.5 Emergence of Performance-Based Seismic Design

The evolution of seismic design philosophy from force-based approaches toward more realistic response-oriented methods has led to the emergence of Performance-Based Seismic Design (PBSD).

Table 2.2 summarizes the key underlying philosophies of different design concepts and highlights their fundamental differences.

TABLE 2.2: Key Philosophies Behind Different Design Concepts

Design Philosophy	**Primary Objective**	**Analysis Basis**	**Key Limitations**
Allowable Stress Design (ASD)	Elastic behavior	Static lateral force analysis	Ignores inelastic behavior and dynamic effects
Strength-Based Design	Strength adequacy	Reduced elastic force-based analysis	Structural damage is not explicitly controlled
Code-Based Design (CBD)	Life safety	Linear, force-based seismic analysis	No explicit prediction of performance levels
Performance-Based Design (PBSD)	Multi-level performance objectives	Displacement-based and nonlinear analysis	Higher modeling complexity and computational demand

To overcome the shortcomings of traditional seismic design, Performance-Based Seismic Design (PBSD) was developed as a comprehensive and rational framework. PBSD explicitly defines desired performance levels such as Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) and evaluates structural response under multiple seismic hazard intensities [22].

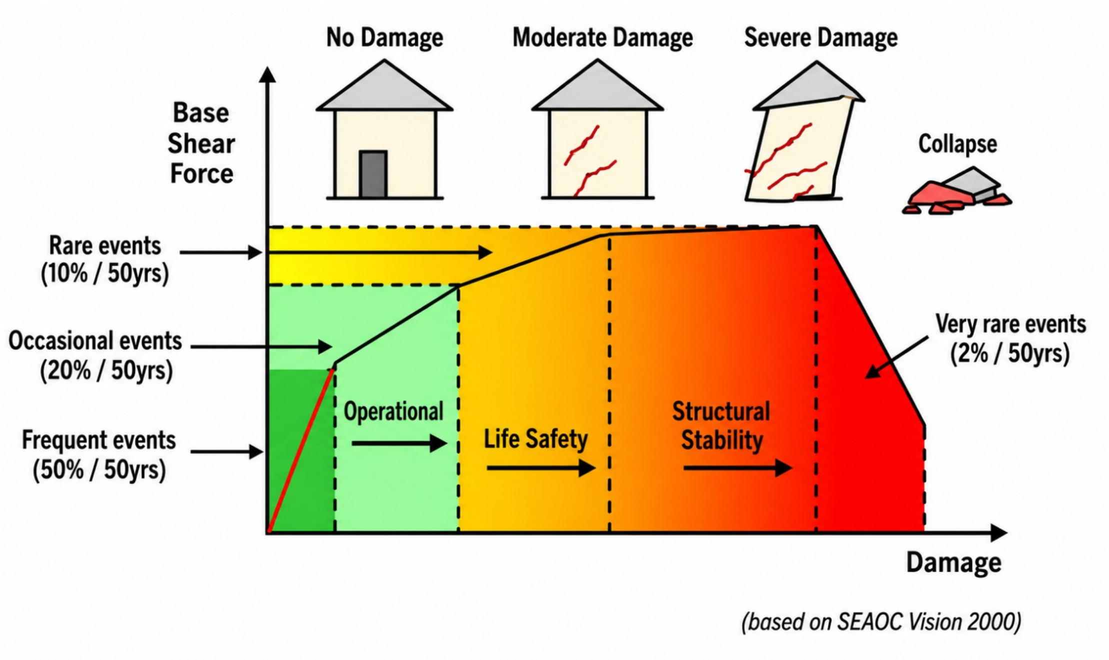


FIGURE 2.4: Performance-based Seismic Design explicitly defined desired performance levels

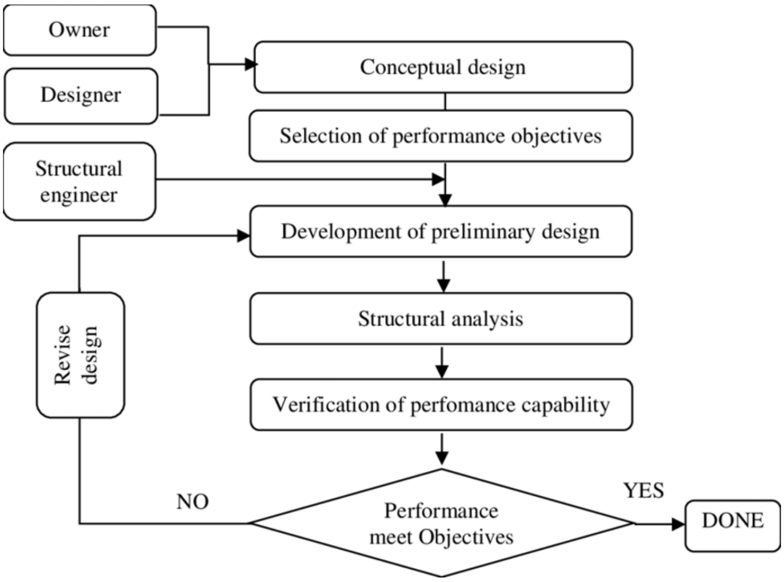


FIGURE 2.5: Conceptual flow chart of performance based seismic design philosophy

This approach emphasizes displacement, deformation and damage control, rather than forces alone and relies on nonlinear analysis techniques to realistically simulate structural behavior. PBSD thus represents a fundamental shift from prescriptive compliance to performance verification, making it particularly suitable for tall RC buildings. To better understand the implementation framework of PBSD, Figure 2.4 illustrates a conceptual flowchart outlining the step-by-step process of performance-based seismic design philosophy.

2.3 Current Practices in Structural Design Research and Professional Offices

Structural design practice today represents a balance between traditional prescriptive methods and emerging performance-oriented approaches. The choice of methodology largely depends on the type of structure, project complexity, seismic exposure and available resources. Research and professional practice show that while advanced tools and methodologies are available, most routine projects still rely on conventional procedures due to regulatory acceptance, cost constraints and simplicity of implementation.

2.3.1 Code-Based Design Practices

Code-Based Design (CBD) remains the predominant approach in structural engineering practice globally. CBD relies on prescriptive provisions that define minimum strength, stiffness and detailing requirements to achieve life-safety performance under predefined hazards. Most national and international codes, including seismic, wind and fire standards, continue to employ force-based methods supplemented with empirical safety and reduction factors [23]. CBD is widely applied to low- to mid-rise buildings and routine infrastructure projects due to its simplicity, regulatory acceptance and relatively low computational demand. Even in advanced systems, CBD often serves as the baseline design framework, with performance checks only as a supplementary step.

For instance, the Canadian Highway Bridge Design Code (CSA S6-14) represents a stringent code-based standard for bridges, emphasizing prescriptive compliance [17]. Similarly, most fire safety codes remain either fully prescriptive or adopt limited hybrid approaches [24]. As a result, CBD continues to govern everyday design practice, particularly in regions with limited computational resources or specialized expertise.

2.3.2 Performance-Based Design Practices

Performance-Based Design (PBD) is increasingly applied to tall buildings, long-span bridges and other high-value structures in seismically active regions such as the United States, Europe and Japan [17, 25]. Unlike CBD, PBD explicitly targets predefined performance objectives, including Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP), under specified hazard scenarios [26, 27]. Contemporary PBD frameworks include the FEMA or SAC program's probabilistic reliability-based procedures, displacement-based design using nonlinear time-history analysis and direct analysis methods for global performance evaluation [17, 25, 28].

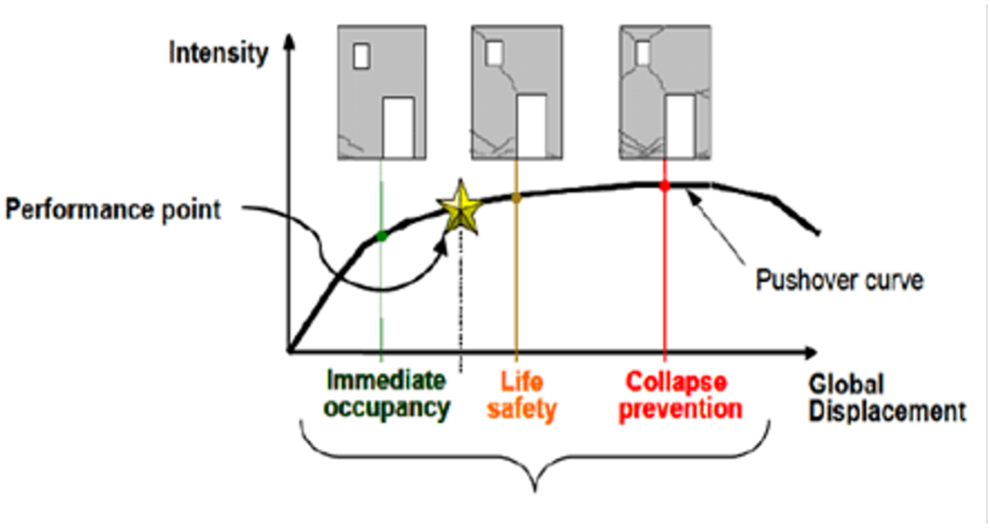


Figure 2.6: Performance points on Pushover Curve

This performance-based evaluation framework is further demonstrated in Figure 2.6, which presents the performance points on a pushover curve, indicating structural response progression from elastic to inelastic stages under increasing lateral demand. Modern PBD practice leverages nonlinear dynamic analysis, optimization algorithms such as evolutionary genetic algorithms and high-speed computational platforms to efficiently evaluate complex structural behavior [29]. Peer review and independent verification of PBD results are common quality assurance mechanisms in professional practice [17]. Although PBD offers a more realistic assessment of structural performance, its application is generally limited to complex, high-value projects where the benefits justify additional cost and effort [25, 27].

2.3.3 Challenges, Limitations and Transitional Practice Trends

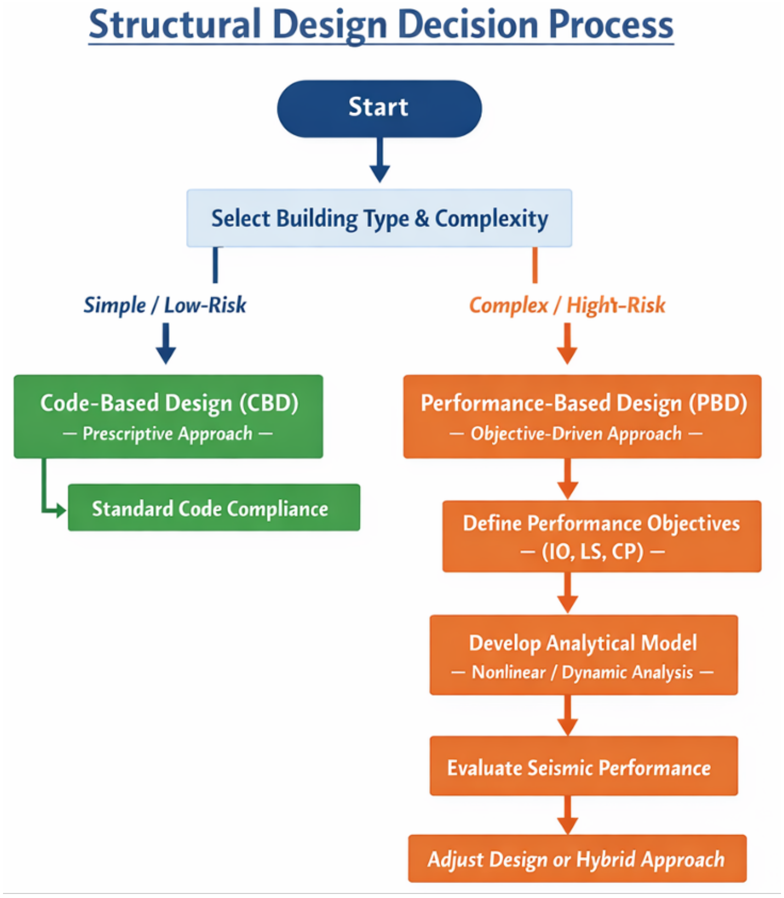


FIGURE 2.7: Conceptual flow chart of Selection of Design Procedure

Despite its potential, PBD adoption remains constrained by practical and theoretical challenges. Defining consistent damage states for structural components beyond primary elements (e.g., secondary beams or connections) is difficult, which complicates system-level performance evaluation [26, 30]. Evaluating global structural performance often requires iterative trial-and-error modeling, increasing computational effort and design time [31].

Another key limitation is the gap between analytical research and practical computational tools. Many advanced PBD methods lack extensive validation against observed structural performance during actual earthquakes, limiting confidence in predictions regarding residual load-carrying capacity and system-level behavior [22, 25].

As a result, current structural practice reflects a transitional state rather than a complete paradigm shift. Hybrid approaches that combine prescriptive code compliance with selective performance-based assessment have emerged as a stable solution [17, 32]. While PBD is justified for complex, high-risk, or high-value structures, simpler buildings continue to rely on conventional code-based procedures due to regulatory familiarity, reduced cost and lower computational requirements [26, 27]. In light of these challenges and the resulting reliance on hybrid design strategies, the selection of an appropriate design approach becomes a critical step in practice. This decision-making process is illustrated in Figure 2.7, which presents a conceptual flowchart for the selection of the design procedure.

2.4 Pros and cons of Considered Design Procedures

The seismic design procedures considered in this study primarily include Code-Based Design (CBD) and Performance-Based Design (PBD), which represent two complementary approaches widely used in modern earthquake-resistant design. Each approach has distinct advantages and limitations and their suitability depends on several factors such as project requirements, building height and complexity, functional importance, seismic risk and targeted performance objectives. CBD is generally preferred for routine design due to its simplicity, codified acceptance and ease of implementation, whereas PBD is increasingly adopted for tall, complex, or critical structures where a deeper understanding of inelastic behavior and damage control is required. By examining both methodologies within the same structural framework, this study aims to highlight their practical implications, strengths and limitations and to demonstrate how their combined application can lead to safer, more reliable and more efficient seismic design outcomes.

2.4.1 Pros and cons of Performance based design

The widespread adoption of Code-Based Design (CBD) as the foundational methodology in seismic engineering globally is a testament to its practical utility in establishing a baseline of life safety for the built environment. Its enduring appeal lies in its ability to translate complex structural dynamics into a set of standardized, prescriptive rules, thereby offering a clear and enforceable compliance path that is deeply embedded in regulatory frameworks, engineering education and professional practice. This approach has undoubtedly been successful in preventing catastrophic collapses in frequent, low-to-moderate seismic events, fostering a degree of uniformity and predictability in the design and construction of conventional buildings. However, the very prescriptiveness that constitutes its greatest strength also reveals its most significant limitations, particularly in an era defined by architectural ambition, rapid urbanization and a heightened understanding of seismic risk. As structures become taller, more irregular and functionally critical, the inherent simplifications of force-based design and the implicit, singular objective of life safety are increasingly exposed as inadequate. The following table provides a critical synthesis of the principal advantages and disadvantages of the CBD approach, systematically contrasting its operational benefits such as simplicity and a clear legal framework against its fundamental shortcomings, including a lack of explicit performance verification, its role as a barrier to innovation and its inadequacy in addressing the economic imperatives of post-earthquake functional recovery that define modern resilience. This comparison underscores the necessity for a paradigm shift towards more rational, performance-oriented methodologies for complex and essential infrastructure.

Performance-Based Seismic Design (PBSD) is widely regarded as the preferred framework for modern seismic assessment due to its powerful conceptual base and its ability to provide superior control over economic losses during earthquake events [22]. By moving beyond traditional stress-based methods, PBSD utilizes strain and deformation as more precise indicators of structural damage, allowing engineers to set specific performance targets that minimize repair costs and enhance overall seismic resilience [23].

This approach offers significant flexibility, particularly for complex structures like tall buildings, by employing tools such as yield frequency spectra (YFS) to fulfill multiple target objectives and optimize design solutions for cost-efficiency and safety [23, 33]. Furthermore, it promotes the development of more reliable seismic standards by integrating energy concepts and holistic methodologies that account for high overstrength and ductility [15]. Despite these advantages, the implementation of PBSD is challenged by significant randomness and uncertainties regarding seismic demand and structural capacity parameters [22, 34]. Critics point to a lack of standardization in interpretation and the inherent complexity of the required analyses, such as the need for detailed micro-zonation and the processing of various earthquake ground motion time histories [15, 34].

Additionally, current design codes often lack clarity regarding the damage states of non-column components like joints and foundations, which can complicate the prediction of residual load capacity and potential post-event operational interruptions [23]. Consequently, while PBSD offers a more tailored and effective design practice, it requires considerable additional effort and more sophisticated analytical tools compared to traditional methodologies [15, 22]. A summary of the key advantages and limitations of PBSD discussed above is presented in Table 2.3.

Table 2.3: Summary of Performance-based Seismic Design Pros and Cons

Category	**Pros (Advantages)**	**Cons (Limitations)**	**References**
Economic	Loss-control, Cost-effective	High-effort	[22, 23]
Technical	Precise, Flexible, Holistic	Complex, Uncertain	[15, 35]
Operational	Resilient, Optimized	Non-standardized	[23, 34]
Structural	Ductility, Damage-control	Over-simplified	[15, 34]
Methodological	Iterative, Objective-based	Inadequate-codes	[22, 23]

2.4.2 Pros and cons of Code Based design

The Code-Based Design (CBD) approach represents the foundational and historically dominant methodology in structural engineering, providing a standardized framework for ensuring the safety and serviceability of structures, including Tall reinforced concrete (RC) buildings. Its philosophical basis is prescriptive compliance, where engineers adhere to a set of well-defined rules, simplified analytical procedures (such as the Equivalent Lateral Force method) and detailing requirements stipulated in national and international building codes. This methodology has been instrumental in establishing a consistent and legally defensible minimum standard of safety across the built environment, effectively preventing catastrophic failures under design-level events for a vast range of conventional structures. The merits of CBD are deeply rooted in its practicality, familiarity and the collective experience embedded within its provisions, which have been refined over decades based on observed performance and research.

Table 2.4: Summary of Code-Based Design

Category	**Pros (Advantages)**	**Cons (Limitations)**	**References**
Application	Simple, Straightforward	Prescriptive, Rigid	[25, 36]
Safety	Standardized, Uniform	Implicit, Minimal	[37, 38]
Innovation	Familiar, Proven	Restricted, Conservative	[25]
Analysis	Linear, Accessible	Inaccurate, Limited	[36, 37]
Legal	Defined, Defensible	Functionality-blind	[38]

However, the very characteristics that contribute to its widespread adoption also define its principal limitations, particularly when applied to the complex and high-stakes context of modern tall RC buildings. The simplified, force-based principles of CBD, while efficient, do not explicitly account for the inelastic behavior, higher-mode effects and unique dynamic responses of such structures. Furthermore, its implicit performance objective is almost exclusively focused on life safety, with little to no consideration for the economic implications of damage, repair costs, or functional downtime following a seismic event. To systematically deconstruct these characteristics, the following table provides a comprehensive overview of the key merits and limitations inherent to the Code-Based Design approach, setting the stage for a comparative analysis with its performance-based counterpart. A summary of the key advantages and limitations of CBD discussed above is presented in Table 2.4.

Code-Based Design (CBD) is primarily valued for its simplicity and ease of application, offering engineers straightforward, prescriptive rules and linear analysis methods, such as the Equivalent Lateral Force method, that do not require resource-intensive computations [36]. This approach promotes high levels of standardization and uniformity, ensuring a consistent minimum safety standard across the general building stock while providing a clear legal and liability framework for designers [37, 38]. Because it is deeply embedded in engineering practice and education, CBD provides a familiar and predictable path for project approvals and has an established track record of successfully preventing structural collapse in typical buildings [25].

However, the methodology faces significant criticism for its lack of explicit performance verification, as it focuses almost exclusively on the implicit goal of life safety without quantitatively predicting damage, repair costs, or downtime [36]. Its prescriptive nature can stifle innovation, often forcing designs to conform to rigid rules that may lead to conservative and economically inefficient solutions [25].

Furthermore, CBD is often inadequate for complex or irregular structures, as its simplified procedures may fail to capture intricate load paths and dynamic responses inherent in geometrically complex buildings [37]. Ultimately, because the primary objective is limited to preventing collapse, structures designed under this framework may still suffer from massive economic losses and social disruption due to a lack of post-earthquake functionality [38].

2.4.3 Comparative Analysis of Code-Based and Performance-Based Design Approaches

The preceding sections have independently detailed the philosophical underpinnings, merits and limitations of both the Code-Based Design Approach (CBDA) and the Performance-Based Design Approach (PBDA). To truly appreciate their implications for the design of tall RC buildings, a direct comparative analysis is essential.

This comparison reveals not merely a difference in methodology, but a fundamental divergence in objectives, analytical rigor and final outcomes. While conventional code-based design approaches (CBDA) emphasize compliance with prescriptive provisions to achieve the implicit objective of life safety, performance-based design approaches (PBDA) aim to explicitly evaluate a range of performance levels from serviceability to collapse prevention under defined seismic hazard scenarios. This fundamental distinction is reflected throughout the design process: CBDA generally relies on simplified linear-elastic analysis with reduced design forces, resulting in limited insight into actual structural performance under severe loading.

Table 2.5: Comparative Analysis of Code-Based and Performance-Based Design Approaches

Aspect	**CBD**	**PBD**	**Reference**
Design Outcome	The code-based design refers to a traditional method of seismic analysis and design that follows specific codes or standards for designing buildings to meet seismic demands, as opposed to the more modern and optimized performance-based design approach.	Quantifies a building's likely performance, including potential damage and economic losses. This allows for a more optimized, economical and robust design by focusing on controlling inelastic displacements and distributing damage more uniformly across the structure, providing a realistic understanding of seismic risk.	[38, 39]
Primary Focus	Force-Based Design	Direct Displacement-Based Design (DDBD)	[3]

In contrast, PBDA employs advanced nonlinear analysis to capture inelastic behavior, enabling a more realistic and often probabilistic assessment of structural damage, economic loss and functional downtime. The following synthesis consolidates findings from various studies to juxtapose these two paradigms across critical parameters, including their core philosophy, primary focus and the nature of their final design outcomes.

This comparison aims to move beyond a simple listing of features and instead highlight the trade-offs between computational efficiency and predictive accuracy, between standardized practice and tailored innovation and ultimately, between a design that is code-compliant and one that is performance-verified. The comparative aspects discussed above are systematically summarized in Table 2.5, which presents a detailed comparison of Code-Based and Performance-Based Design Approaches across key parameters.

2.5 Summary

This literature review examined the evolution of seismic design philosophy and its implications for tall reinforced concrete (RC) buildings, highlighting the transition from early allowable-stress and strength-based approaches to modern code-based design (CBD) and, ultimately, performance-based seismic design (PBSD). Lessons learned from major earthquakes such as Northridge (1994), Kobe (1995) and Chi-Chi (1999) demonstrated that code-compliant buildings could still suffer severe damage, extended downtime and significant economic and social consequences, even when collapse was prevented. The review identified key limitations of CBD for tall RC buildings, including inadequate consideration of higher-mode effects, P–Δ actions, stiffness irregularities and nonlinear material behavior, as well as its lack of explicit provisions for damage control, repairability and functional recovery. In response to these shortcomings, PBSD emerged as a rational and inevitable advancement, introducing explicit performance objectives Immediate Occupancy, Life Safety and Collapse Prevention and employing deformation-based criteria and nonlinear analysis to directly relate seismic demand to damage and functionality. Collectively, the reviewed studies establish PBSD not as an optional alternative but as a necessary framework for achieving safe, resilient and economically sustainable seismic performance in tall RC buildings.

Chapter 3

Research Methodology

3.1 Background

The seismic design of tall reinforced concrete buildings requires careful consideration of lateral load resistance, structural stiffness and overall stability to ensure satisfactory performance under earthquake loading. In current engineering practice, code based seismic design remains the most widely adopted approach due to its regulatory acceptance and practical applicability, with design procedures defined in modern standards such as ASCE 7 22.

For high rise buildings, particularly those exceeding thirty stories, lateral forces govern the design, making the selection of an efficient structural system critical. Dual structural systems consisting of reinforced concrete moment resisting frames in combination with shear walls are commonly used to achieve an optimal balance between strength, stiffness and ductility. Such systems provide effective control of story drifts and lateral displacements while ensuring adequate energy dissipation capacity.

Advanced structural analysis software plays a key role in implementing these design methodologies and ETABS is specifically developed for the analysis and design of multi-story buildings. Its three-dimensional modeling capabilities allow realistic representation of structural geometry, load paths and dynamic behavior. In this study, a thirty five story reinforced concrete building is selected and modeled in

ETABS using a dual system configuration, with architectural plans and a complete 3D analytical model incorporated to reflect practical code based design conditions.

3.2 Selection of Building

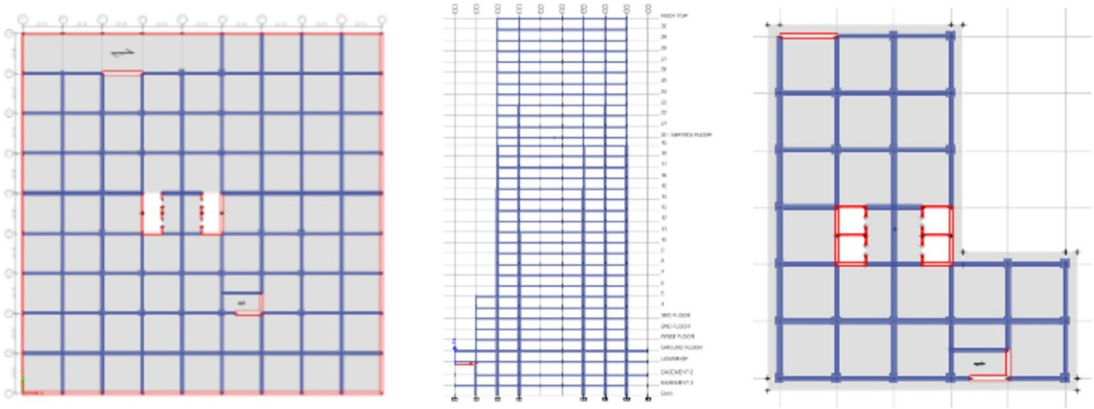
The selected building shown in Figure 3.1 is an actual project proposed for construction in a seismically active region of Islamabad. Therefore, the study reflects realistic design constraints, material properties and structural configurations encountered in professional practice.

The prototype structure considered in this study is a thirty five story reinforced concrete building designed as a mixed use facility with a dual structural system consisting of moment resisting frames and reinforced concrete shear walls. The total structural height of the building is 420 ft when including both above-ground and below-ground portions (i.e., 384 ft above ground level and 36 ft below ground level).

However, for lateral load analysis, only the height above ground level (384 ft) is considered, since wind and seismic forces are applied based on the exposed height of the structure above the ground surface. The basement portion is primarily embedded and restrained by surrounding soil and therefore does not contribute to the effective height used for wind and seismic force calculation in accordance with standard modeling practice.

The lower levels of the building comprise basement floors primarily used for parking, followed by commercial floors accommodating retail shops, while the upper stories are designated for residential apartments. One intermediate floor is allocated as a service floor to house mechanical and utility systems essential for building operation.

The total structural height of the building is three hundred eighty four feet measured from ground level and 36 feet below ground level. The building is located in Islamabad, Pakistan, which lies in a highly seismic prone region, thereby making seismic effects the governing design consideration further details about building are shown in Table 3.1 .



a) b) c)

Figure 3.1: Plan view of building developed in ETABS a) Basement Plan b) Elevation c) Roof Top Plan

Figure 3.2: 3D Architectural Model of Above Described Building

The selection of this building configuration reflects a realistic high rise urban development scenario and provides a representative case for evaluating code based seismic design and subsequent performance-based assessment of tall reinforced concrete dual system buildings.

Table 3.1: Description of Building Used in This Study

Parameter	**Description**
Building Type	Reinforced Concrete Dual System (Moment-Resisting Frames + Shear Walls)
Total Floors	35
Floor Height	12 ft (typical)
Roof Height	384 ft (total building height)
Floor System	Rigid concrete slabs with rigid diaphragm action
Lateral Load Resisting System	Moment-resisting frames and shear walls
Location	Islamabad, Pakistan
Usage	Mixed-use (assumed: parking, residential and commercial)

3.3 Structural Design Criteria

The structural design of the selected thirty-five-story reinforced concrete dual-system building was carried out in accordance with *ASCE 7-22* for minimum design loads and seismic provisions and *ACI 318-19* for reinforced concrete member design and detailing. The code-based design approach was adopted to ensure life safety under design-level earthquake loading.

Gravity loads, including dead loads (self-weight, finishes, partitions and service loads) and live loads corresponding to parking, commercial, residential and roof occupancy, were applied as per code requirements. Seismic forces were determined considering the high seismic hazard of Islamabad, Pakistan.

Since the building height exceeds thirty stories, dynamic analysis using the response spectrum method was performed in ETABS. The equivalent lateral force procedure was also used for preliminary evaluation and validation purposes. The dual structural system, consisting of special moment-resisting frames and shear walls, was proportioned to provide adequate strength, stiffness and ductility. The design ensured control of story drifts, lateral displacements, torsional irregularities and P–Δ instability effects.

Rigid diaphragm action was assigned at each floor level and cracked section stiffness modifiers were incorporated in accordance with ACI recommendations. The seismic mass was defined based on the dead load plus the appropriate portion of live load. Member design satisfied the strong column–weak beam requirements for moment frames. Axial load–moment interaction checks were performed for columns and shear walls were designed for combined axial, flexural and shear demands with special seismic detailing to ensure ductile performance under earthquake loading.

3.4 Development of Numerical Modeling

This study employs a numerical modeling and design framework to evaluate the seismic performance of the selected 35-story reinforced concrete dual-system building. The framework integrates code-based seismic design and performance-based assessment using a single, consistent modeling environment. The modeling approach facilitates both linear elastic and nonlinear inelastic analysis, allowing a systematic comparison between conventional force-based design and advanced performance-based evaluation.

The numerical framework is structured to capture global and local structural behavior, including inter-story drift, floor acceleration and plastic hinge development, while maintaining practical relevance to professional design practice. The modeling strategy also incorporates realistic material properties, boundary conditions and load combinations, ensuring that the simulated response closely reflects actual building behavior under seismic events. This approach enables accurate identification of critical structural components and potential failure mechanisms. Furthermore, the unified modeling environment ensures consistency in assumptions and parameters, thereby eliminating discrepancies that may arise from using separate models for different analyses.

3.4.1 Software Selection

For this research, ETABS is selected as the primary structural analysis and design software due to its user-friendly interface and widespread acceptance in professional engineering practice. ETABS is extensively used for the design and analysis of multi-story reinforced concrete buildings, particularly high-rise structures subjected to both gravity and seismic loads, such as the Burj Khalifa. The software provides a fully integrated environment for three-dimensional (3D) modeling, automatic load generation, structural analysis and code-compliant member design, making it highly suitable for implementing conventional code-based seismic design procedures.

Additionally, ETABS supports nonlinear analysis and includes built-in capabilities for performance-based seismic assessment, consistent with guidelines such as ASCE 41-17, allowing a seamless transition from code-based design to nonlinear evaluation within the same platform. Its comprehensive technical documentation further ensures that nonlinear modeling procedures are implemented accurately and consistently. These features collectively provide the accuracy, reliability and practical relevance required for the numerical modeling framework adopted in this study.

In addition to ETABS, several other structural analysis and design software packages enlisted in Table 3.2 are available and commonly used in seismic engineering practice. However, each has certain limitations when applied to tall reinforced concrete buildings and integrated code-based and performance-based seismic evaluation. SAP2000 is a general-purpose structural analysis program capable of linear and nonlinear analysis for a wide range of structures. While it offers strong flexibility and advanced nonlinear features, it is less specialized for high-rise building design. The modeling of large multi-story buildings is comparatively time-consuming and the absence of fully automated building-specific design workflows makes it less efficient for iterative code-based design of tall RC buildings. STAAD.Pro is widely used for conventional structural design and supports multiple international design codes. Its primary limitation lies in its relatively limited nonlinear modeling and performance-based design capabilities for reinforced concrete buildings. Modeling detailed plastic hinge behavior and performing pushover analysis in accordance with ASCE 41 requires significant manual intervention, reducing reliability and consistency for advanced seismic assessment.

MIDAS Gen provides advanced analysis capabilities, including nonlinear static and dynamic analysis and is suitable for complex structures. However, it has a steeper learning curve and less widespread adoption in local professional practice. Limited regional code calibration and smaller user support communities can also restrict its practical application in routine seismic design workflows.

Perform-3D is specifically developed for performance-based seismic design and offers highly detailed nonlinear modeling and damage evaluation. Despite its strong capabilities, it is not intended for conventional code-based design and requires a separate preliminary design platform. This separation limits its efficiency in workflows where both design and assessment need to be performed iteratively within a single environment.

The need to transfer models from another software increases modeling effort and the potential for inconsistencies, particularly for large buildings. OpenSees is a powerful open-source platform for advanced nonlinear and research-oriented seismic analysis. Its major limitation is the absence of a graphical user interface, requiring scripting-based model development. This makes it less practical for routine design office use and significantly increases modeling time and expertise requirements. Additionally, the steep learning curve can hinder its adoption among practicing engineers who require more user-friendly tools.

Compared to these alternatives, ETABS provides a balanced combination of building-specific modeling efficiency, direct support for both code-based and performance-based design, integrated RC design modules and strong industry acceptance. These advantages make ETABS particularly suitable for the objectives of this research, which require a consistent and practical framework for evaluating and comparing CBD and PBD approaches for tall reinforced concrete dual-system buildings. Furthermore, its integrated workflow reduces the likelihood of modeling errors and improves overall productivity in complex structural analyses. It also ensures consistency between design assumptions and analysis results, making the overall evaluation more reliable.

TABLE 3.2: Comparison of Commonly Used Structural Analysis Software for Seismic Design of Tall RC Buildings

Software	**Primary Application**	**Key Strengths**	**Major Limitations in This Study**
ETABS	High-rise building analysis and design	Building-oriented modeling environment; integrated CBD and PBD capabilities; direct implementation of ASCE 7 and ASCE 41 provisions; automated RC design; strong industry acceptance	Limited flexibility for highly customized research-level material constitutive models
SAP2000	General structural analysis	Advanced nonlinear analysis capabilities; flexible modeling for complex structural systems	Less efficient workflow for tall-building-specific modeling; limited automated building design features
STAAD.Pro	Conventional structural design	Supports multiple international design codes; relatively simple modeling interface	Limited nonlinear and performance-based design capabilities; manual hinge modeling required
MIDAS Gen	Advanced analysis of complex structures	Strong nonlinear analysis tools and advanced modeling options	Steep learning curve; comparatively limited local industry adoption
Perform-3D	Performance-based seismic design	Highly detailed nonlinear modeling and advanced damage assessment features	Not suitable for conventional code-based design; requires separate preliminary design software
OpenSees	Research-oriented seismic analysis	Highly advanced nonlinear modeling capabilities; open-source flexibility for research applications	No graphical user interface; steep learning curve; not practical for routine commercial design workflows

3.4.2 Finite Element Modeling

The 35-story building is modeled in ETABS as a three-dimensional finite element structure, including beams, columns, shear walls, slabs and diaphragms. Structural members are defined according to their geometric and material properties, while the dual system of moment-resisting frames and shear walls is explicitly represented to capture both lateral stiffness and ductile behavior.

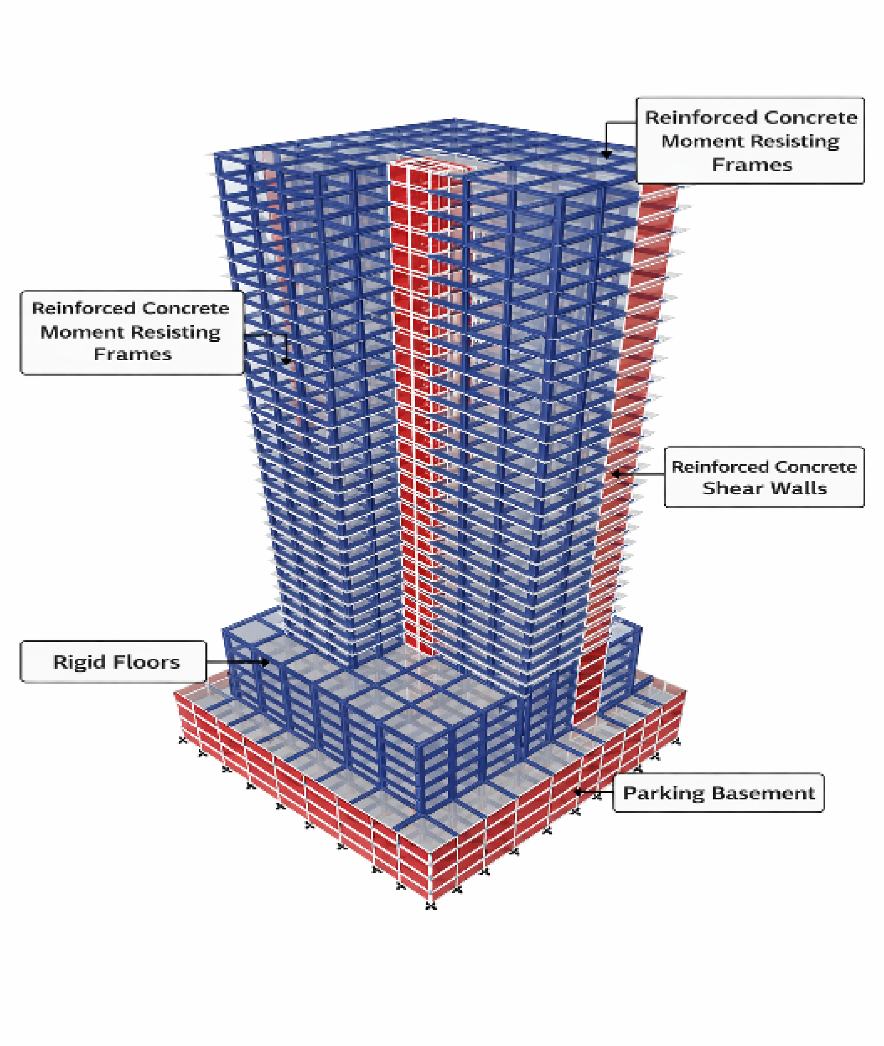


Figure 3.3: 3D ETABS model of the 35-story RC dual system building with moment frames, shear walls, rigid diaphragms and basement parking

Slabs are modeled as rigid diaphragms to ensure proper lateral load distribution to vertical elements. Plastic hinges are assigned at critical locations of beams, columns and shear walls for the nonlinear pushover analysis to simulate inelastic behavior under seismic loading.

Gravity loads, lateral seismic forces and boundary conditions are applied according to ASCE 7-22 and site-specific seismic hazard levels. The finite element model shown in Figure 3.3 provides a robust platform to evaluate both code-based and performance-based design responses, ensuring a consistent and detailed assessment of global and local structural performance.

3.5 Analysis and Design Procedures

3.5.1 Phase I: Code-Based Design

In the first phase of modeling, a code-based design approach was adopted using ETABS. The building elements were designed with concrete strengths of 6,000 psi and 4,500 psi, with material properties defined in accordance with ACI 318-19, Section 19.2.2.1, for columns, shear walls, beams and slabs. The key modeling parameters and assumptions adopted in this study are summarized in Table 3.3. To accurately capture the structural behavior, cracked section modifiers were applied to the concrete elements based on the guidelines provided in the ETABS manual and as specified in ACI Table Table 6.6.3.1.1. This approach ensured that the stiffness and strength reductions due to cracking were realistically represented in the model.

Table 3.3: Key Parameters and Assumptions for Code-Based ETABS Modeling of the 35-Story RC Dual System Building

Parameter	**Description**	**Reference**
Concrete Strength	6,000 psi (high-strength elements); 4,500 psi (normal-strength elements)	ACI 318-19, Sec. 19.2.2.1
Structural Elements	Columns, shear walls, beams and slabs	ACI 318-19, Sec. 19.2.2.1
Material Properties	Defined in accordance with ACI 318-19 provisions	ACI 318-19, Sec. 19.2.2.1
Cracked Section Modifiers	Applied to represent stiffness and strength reduction due to concrete cracking	ETABS Manual; ACI Table 6.6.3.1.1
Purpose	Realistic representation of cracked concrete stiffness and strength in nonlinear structural modeling	ETABS Manual; ACI 318-19

All the important parameters required for seismic load application on our structure are enlisted in Table 3.4. The seismic importance factor was taken as $I_e = 1.0$ in accordance with ASCE 7, based on the computed values of S_{DS} and S_{D1}. The seismic design category (SDC) was determined as Category D from ASCE 7 Table 11.6-1 and the period coefficient C_T was taken as 0.02 according to Table 12.8-2.

The building employs a dual lateral force-resisting system, which is permitted within this seismic design category. For the given building height, ASCE 7 Table 12.2-1 provided the response modification factor $R = 7$, the overstrength factor $\Omega_0 = 2.5$ and the deflection amplification factor $C_d = 5.5$.

Basic load combinations, including the vertical seismic component, were applied according to ASCE 7 Table 4.3-1, with minimum live loading considered.

TABLE 3.4: Seismic Design Parameters for Code-Based Design Using ASCE 7-22

Parameter	**Value or Description**	**Reference**
Spectral Accelerations	S_s and S_1 obtained from BCP 21	BCP 21
Seismic Importance Factor	1.0	ASCE 7-22
Seismic Design Category (SDC)	D	ASCE 7-22, Table 11.6-1
Period Coefficient C_t	0.02	ASCE 7-22, Table 12.8-2
Lateral Force-Resisting System	Dual system (SMRF + shear walls)	ASCE 7-22
Response Modification Factor R	7.0	ASCE 7-22, Table 12.2-1
Overstrength Factor Ω_0	2.5	ASCE 7-22, Table 12.2-1
Deflection Amplification Factor C_d	5.5	ASCE 7-22, Table 12.2-1
Load Combinations	Basic combinations including vertical seismic component and minimum live load	ASCE 7-22, Table 4.3-1

3.5.2 Phase II: Performance-Based Assessment

This assessment focuses on evaluating the nonlinear behavior of the structure under increasing lateral loads to capture its inelastic response characteristics. The results obtained are used to determine whether the existing design satisfies the target performance levels defined in ASCE 41-17.

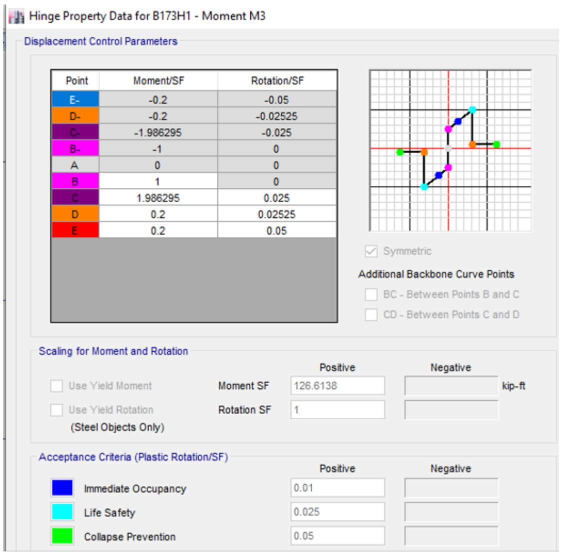
3.5.2.1 Development of the Nonlinear Model

In the second phase, performance-based design (PBD) was conducted using nonlinear analysis in accordance with the ETABS manual. The final design results from the code-based design (CBD) phase were used as input for PBD, making the preliminary CBD design effectively a subset of the PBD process. For PBD, actual concrete and steel sizes were defined in ETABS section properties, which were later used for plastic hinge modeling. Initially, the actual member sizes and reinforcement were specified, after which the auto-hinge option was employed to assign different hinges shown in Table 3.5 beams, with M3 hinges used for flexural behavior. ETABS references Table 10.7 ASCE 41-17 to calculate the Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) performance levels. Similarly, P-M2M3 hinges were assigned to columns and PM3 hinges to shear walls, with acceptance criteria evaluated using Tables 10-8 and 10-9. of ASCE 41-17 This step is critical in PBD, as it establishes the nonlinear hinge properties that control the inelastic response of the structure.

Table 3.5: Summary of Hinge Types, Assigned Elements and ASCE 41-17 Reference Tables

Structural Element	**Hinge Type**	**Purpose or Behavior**	**ASCE 41-17 Reference**
Beams	M3	Flexural hinge representing nonlinear moment–rotation behavior for inelastic response	Table 10.7
Columns	P–M2–M3	Axial–flexural interaction hinge capturing combined axial load and biaxial bending effects	Table 10-8
Shear Walls	PM3	Axial–flexural hinge for nonlinear wall behavior under combined axial load and bending	Table 10-9

For the M3 hinges shown in Figure 3.4 , section properties were defined with multiple points along the backbone curve, including ABCD for moment rotation curve and other nonlinear segments. These curves correspond to the Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) performance levels, allowing ETABS to capture the progressive inelastic behavior of the beams under increasing lateral demand. This detailed definition ensures that the plastic hinge response accurately reflects the structural performance at each target performance level.



Hinge Property Data for B173H1 - Moment M3

Displacement Control Parameters

Point	Moment/SF	Rotation/SF
E-	-0.2	-0.05
D-	-0.2	-0.02525
C-	-1.986295	-0.025
B-	-1	0
A	0	0
B	1	0
C	1.986295	0.025
D	0.2	0.02525
E	0.2	0.05

☑ Symmetric

Additional Backbone Curve Points

☐ BC - Between Points B and C

☐ CD - Between Points C and D

Scaling for Moment and Rotation

		Positive	Negative	
☐ Use Yield Moment	Moment SF	126.6138		kip-ft
☐ Use Yield Rotation (Steel Objects Only)	Rotation SF	1		

Acceptance Criteria (Plastic Rotation/SF)

	Positive	Negative
🟦 Immediate Occupancy	0.01	
🟦 Life Safety	0.025	
🟩 Collapse Prevention	0.05	

FIGURE 3.4: Defination of M3 plastic Hinge

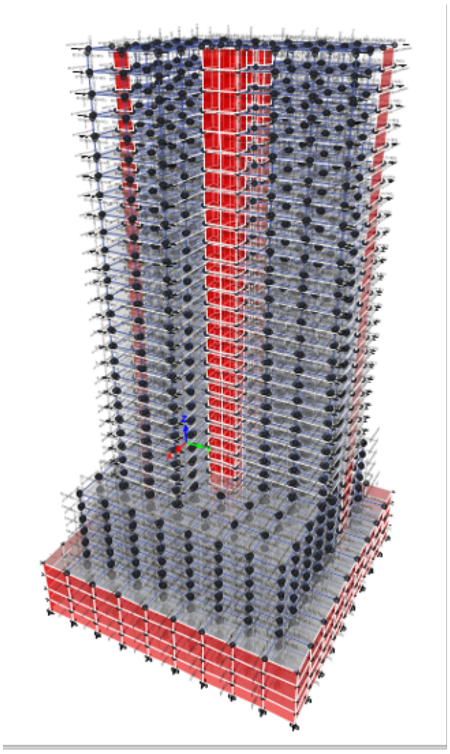


FIGURE 3.5: Assigned M3 plastic Hinge to Beams

All the above perameters are calculate from below table of ASCE 41-17 same like that well explained tables for all other structural components are availabe in ASCE 41-17 guideline.

3.5.2.2 Nonlinear Static Procedure - Pushover Analysis

For the seismic performance assessment of the proposed 35-story reinforced concrete dual system building, pushover analysis was selected as the primary nonlinear static analysis method. Pushover analysis provides a simplified yet effective means of evaluating the inelastic behavior of structures under gradually increasing lateral loads until a target displacement is reached. The target displacement represents the expected maximum displacement at the roof level under the design seismic event and serves as a benchmark for evaluating structural performance. In this study, the target displacement was calculated according to ASCE 41-17, Equation 7-22, which accounts for the building's fundamental period, seismic demand and nonlinear response characteristics. Following the guidelines from ASCE 41-17, the calculated target displacement allows the identification of potential plastic hinge formations, the evaluation of inter-story drift demands and the verification of whether structural elements meet the performance objectives for different performance levels, such as Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). This approach ensures that the pushover analysis is consistent with contemporary performance-based seismic design standards and provides a reliable framework for assessing the building's inelastic seismic response. The target displacement Δ_t can be calculated using the following equation:

$$\Delta_t = C_0 C_1 C_2 C_3 \, S_a(T_e) \, \frac{T_e^2}{4\pi^2} \, g \tag{3.1}$$

Where:

i. Δ_t = Target displacement of the structure

ii. C_0 = Modification factor relating spectral displacement to likely roof displacement

iii. C_1 = Factor accounting for maximum inelastic displacement

iv. C_2 = Factor representing the effect of the hysteresis shape

v. C_3 = Factor considering the P–Δ (secondary moment) effect

vi. $S_a(T_e)$ = Spectral acceleration at the effective fundamental period in the direction considered

vii. T_e = Effective fundamental period of the structure

viii. g = Acceleration due to gravity

3.6 Parameters to be Explained

To thoroughly evaluate the seismic performance of the 35-story reinforced concrete dual system building, it is essential to clearly define, describe and understand the key structural and seismic parameters that govern its behavior under earthquake loading. These parameters play a fundamental role in both code-based design (CBD) and performance-based design (PBD) approaches, serving as the foundation for accurate modeling, analysis and assessment of the building's response to seismic forces. In the CBD framework, parameters such as natural periods, base shear, story drift limits, torsional irregularities, member sizes and material properties directly influence the lateral load calculations, structural stability and compliance with prescriptive code requirements. In contrast, PBD parameters, including target displacements, plastic hinge formation, inter-story drift ratios, residual deformations and floor accelerations, allow for a more realistic evaluation of inelastic behavior, localized damage potential and overall system redundancy under varying earthquake intensity levels. Understanding these parameters not only enables engineers to assess the building's performance accurately but also provides a meaningful comparison between the conservative assumptions inherent in CBD and the more detailed, behavior-driven insights offered by PBD. By systematically defining and explaining these parameters, designers can make informed decisions regarding structural detailing, reinforcement allocation and overall seismic resilience, ultimately enhancing safety, serviceability and economic efficiency in tall building design. Soil Structure interaction is not studied because A parametric PBSD study of steel moment frames found that neglecting SSI matters most on softer soils; on stiffer soils, the response stayed close to fixed-base value [40]. The authors report that stiffer soils cause only minor deviations in base shear and drift metrics, which directly supports the idea that SSI may have a limited effect on global response under stiff-soil conditions.

3.6.1 Code-Based Design Parameters

Table 3.6: ASCE 7-22 Checks for Vertical and Horizontal Irregularities

Irregularity Type	**Description**	**ASCE 7-22 Limit or Check**	**Impact**
Vertical – Soft or Weak Story	Lateral stiffness less than 70% of the story above	Section 12.3.3.1	Concentrated inter-story drift and increased collapse risk
Vertical – Mass Irregularity	Story mass greater than 150% of the adjacent story	Section 12.3.3.2	Uneven seismic force distribution
Vertical – Geometric Irregularity	Sudden change in building height or presence of setbacks	Section 12.3.3.3	Increased drift and stress concentration
Vertical – In-Plane Discontinuity	Offset or missing vertical lateral load-resisting elements	Section 12.3.3.4	Disrupted load transfer mechanism
Horizontal – Torsional Irregularity	Maximum story drift exceeds 1.2 times the average drift	Section 12.3.4.1	Additional torsion-induced seismic demands
Horizontal – Re-entrant Corners	L- or U-shaped plan with more than 15% re-entrant area	Section 12.3.4.2	Stress concentration and torsional effects
Horizontal – Diaphragm Discontinuity	Large diaphragm openings or abrupt stiffness changes	Section 12.3.4.3	Uneven distribution of lateral forces
Horizontal – Out-of-Plane Offsets	Misalignment of vertical lateral load-resisting elements	Section 12.3.4.4	Drift incompatibility between structural components

In the code-based design (CBD) approach, parameters focus on ensuring structural safety and compliance with prescriptive code limits. Fundamental parameters include the building's natural period, which affects the dynamic response and spectral acceleration and base shear, which determines the lateral forces to be resisted by vertical structural elements. Other key parameters include story drift ratios and torsional irregularities limits of each are shown in Table 3.6, which ensure lateral deformations and torsional effects are within acceptable limits, thereby maintaining stability and serviceability. Member sizes and reinforcement ratios are also primary design parameters; columns, beams and shear walls are proportioned based on expected axial and bending demands, with reinforcement carefully distributed to satisfy both strength and ductility requirements. Material properties, such as concrete compressive strength and steel yield strength, form an additional critical parameter set influencing member stiffness, strength and deformation capacity. Overall, CBD parameters provide a conservative baseline for structural design, ensuring life-safety under seismic loads and adherence to code-defined limits. However, they do not explicitly capture actual inelastic behavior or local damage mechanisms that may occur under severe seismic events.

3.6.2 Performance-Based Design Parameters

The performance-based design (PBD) approach defines parameters that quantify the realistic response of a building under seismic events. Central to this approach is the target displacement, which represents the expected roof movement while accounting for inelastic deformations, hysteresis behavior and P–Δ effects.

Table 3.7: Common Hinge Types in ETABS or ASCE 41-17

Structural Element	**Hinge Type**	**Behavior Mode**	**Reference**
Beam	M3	Flexural hinge representing pure bending behavior	Table 10.7, ASCE 41-17
Column	P–M2 pr M3	Combined axial load and biaxial flexural moment interaction hinge	Table 10.8, ASCE 41-17
Shear Wall	PM3	Axial–flexural hinge capturing wall bending and axial force interaction	Table 10.9, ASCE 41-17
Beam–Column Joint	P–M2J or P–M3J	Combined flexure, shear and moment transfer behavior at joint region	Table 10.10, ASCE 41-17

Plastic hinge formation in beams, columns and shear walls is another key parameter, reflecting the sequence and extent of yielding under seismic demand. These hinges are used to evaluate performance levels such as Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP), providing insight into both global and local structural performance. Additional PBD parameters include inter-story drift ratios, residual drifts and floor accelerations, which indicate potential non-structural damage and occupant safety considerations. By assessing the building's response through these parameters, PBD provides a more detailed understanding of inelastic behavior, localized vulnerabilities and system redundancy, which cannot be fully captured by CBD alone.

In Performance-Based Design (PBD) for reinforced concrete buildings, plastic hinges hinges shown in Table 3.7 are a key concept used to model inelastic behavior of beams, columns and walls under seismic loading. ASCE 41-17 provides detailed guidance on hinge types, properties and checks to assess structural performance at different seismic performance levels (Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP)). Here's a detailed explanation:

3.7 Summary

Chapter 3 presents the methodology for evaluating the seismic performance of a 35-story reinforced concrete dual system building. The study uses a dual system of moment-resisting frames and shear walls, representing a realistic mixed-use high-rise in a high seismic zone. ETABS is employed for three-dimensional finite element modeling, capturing both global and local structural behavior and enabling code-based (CBD) and performance-based (PBD) design evaluations. The methodology is divided into two phases. Phase I (CBD) establishes baseline member sizes, material properties and seismic parameters according to ASCE 7-22. Phase II (PBD) uses nonlinear static pushover analysis following ASCE 41-17 to assess target displacements, plastic hinge formation and performance levels including Immediate Occupancy, Life Safety and Collapse Prevention, providing insight into actual inelastic behavior. Key parameters are defined for each approach. CBD parameters include natural period, base shear, story drift and member reinforcement ratios, ensuring code compliance and safety. PBD parameters include target displacement, hinge behavior, inter-story drift and floor accelerations, offering a detailed view of realistic structural response and system redundancy. The methodology integrates CBD and PBD within a consistent modeling framework, providing a robust basis for assessing seismic performance and informing efficient design and reinforcement strategies.

Chapter 4

Results and Analysis

4.1 Background

In this study, the code-based design (CBD) of the 35-story reinforced concrete dual system building was first completed using ETABS to establish baseline member sizes, material properties and overall structural configuration according to standard seismic provisions. Subsequently, a performance-based assessment (PBD) was conducted on the same model to capture the building's actual inelastic behavior under seismic loading.

This phase allows for the evaluation of how accurately the CBD predicts the strength, stiffness and deformation capacity of structural members and the overall system. By comparing the outcomes of CBD and PBD, the analysis provides insight into potential discrepancies between design assumptions and realistic structural performance, highlighting areas where members may be under- or over-designed and informing strategies to enhance seismic resilience.

4.2 Code Based Design

4.2.1 Finite Element Analysis

The first step in the code-based design process involved the creation of a comprehensive three-dimensional model of the 35-story reinforced concrete dual system building using ETABS. The modeling process accurately represented the structural geometry, including beams, columns, shear walls, slabs and rigid diaphragms, while incorporating the dual lateral force-resisting system of moment-resisting frames and shear walls. Gravity loads corresponding to dead and live loads, as well as lateral seismic loads based on ASCE 7-22 provisions, were applied to simulate realistic service and design conditions.

4.2.2 Critical Checks in Code-Based Design

Once the loads were assigned, a series of critical checks were conducted to identify and address potential irregularities in the building configuration. Vertical irregularities, including setbacks, soft stories and abrupt changes in stiffness between floors, were carefully reviewed, as these features can significantly influence inter-story drift, amplify seismic demand and induce localized stress concentrations. Horizontal irregularities, such as torsional eccentricities and asymmetries in plan layout, were also examined, as they may result in uneven distribution of lateral forces and unexpected torsional response under seismic excitation. To mitigate these effects, modifications were made to the dual system layout, including adjustments to the placement and stiffness of shear walls and moment frames, ensuring that both global stability and lateral load distribution were maintained within acceptable limits.

Following the definition of seismic loading parameters and preliminary structural modeling, the global seismic response of the structure was evaluated to establish the governing lateral force demand. This included the determination of equivalent static seismic forces and the resulting base shear, which form the basis of the code-based seismic design framework. The input and computed seismic parameters and corresponding base shear for the model are presented in Table 4.1. The seismic parameters in the X and Y directions are identical as they are defined based on code provisions and depend primarily on-site characteristics, seismic hazard level and overall structural system, which remain the same in both directions. Since the seismic mass of the building is also same, the applied seismic load is similar in both directions. However, the resulting structural response may vary depending on the stiffness, geometry and configuration of the building in each principal direction.

However, the resulting structural response may vary depending on the stiffness, geometry and configuration of the building in each principal direction as shown in Figure 4.1.

TABLE 4.1: Seismic Design Parameters for EQX and EQY Directions

Parameter	**EQX**	**EQY**
C_t	$0.02,\ x = 0.75$	$0.02,\ x = 0.75$
Response Modification Factor, R	7	7
Overstrength Factor, Ω_0	2.5	2.5
Deflection Amplification Factor, C_d	5.5	5.5
Mapped Spectral Acceleration, S_s	1.302	1.302
Mapped Spectral Acceleration, S_1	0.381	0.381
Site Class	D	D
Design Spectral Acceleration, S_{DS}	0.868	0.868
Design Spectral Acceleration, S_{D1}	0.487426	0.487426
Period Used (sec)	2.598	2.598
Weight Used (kip)	195616.739	195616.739
Base Shear (kip)	7470.994	7470.994

A preliminary comparison of base shear obtained from wind and seismic loading was carried out to identify the governing lateral load case for the structure. The results are summarized in Table 4.2.

Table 4.2: Compariso of Base Shear due to Wind and Seismic Loads

Load Case	**Base Shear (X-Dir)**	**Base Shear (Y-Dir)**
Wind Load	2120 kips	1874 kips
Seismic Load	7470 kips	7470 kips

According to ASCE 7-05, structures in regions exposed to both wind and earthquakes are designed separately for each hazard, with the governing design based on the more critical load case. This approach assumes consistent risk levels across single- and multi-hazard regions [41]. It is evident that the base shear due to seismic loading exceeds that from wind loading, confirming that seismic effects govern the design. Therefore, wind loading was not considered critical within the scope of this study.

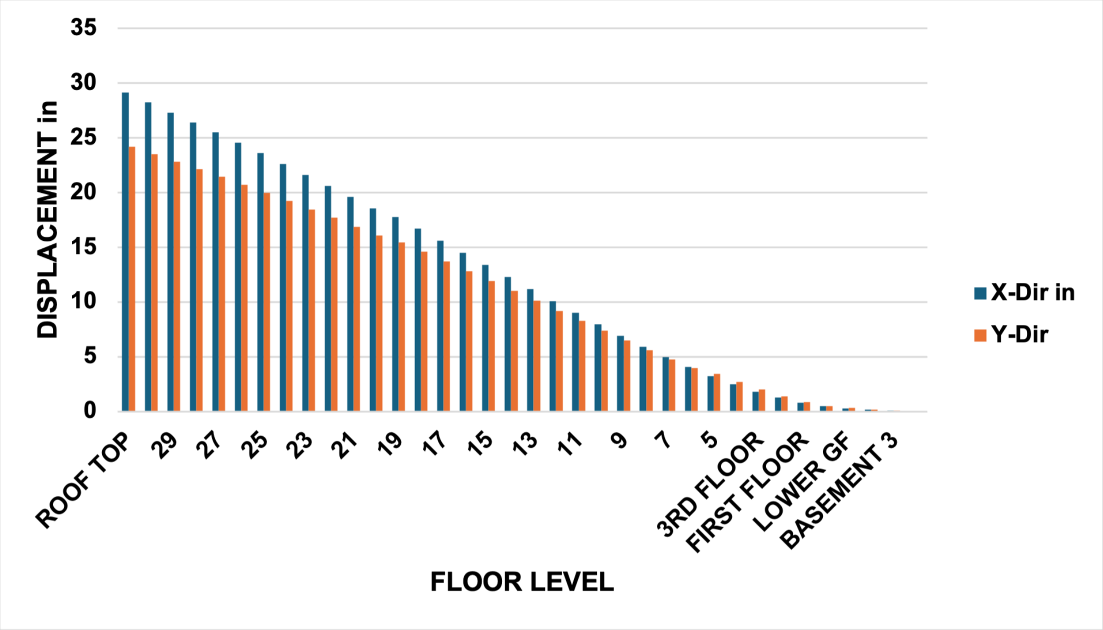


Figure 4.1: Maximum Story displacement against seismic forces

In addition to geometric and load considerations, serviceability parameters such as story drift limits shown in Table 4.2 and inter-story displacement shown in Table 4.1 criteria were checked to confirm compliance with code-based requirements. These verifications ensured that the structure would not experience excessive lateral deformation, which could compromise non-structural elements and occupant comfort, while also validating the adequacy of member stiffness under seismic loading.

By systematically addressing these aspects, the model development phase established a robust and realistic baseline for the code-based seismic design, providing the foundation for subsequent member sizing, reinforcement detailing and performance-based assessment. Although the absolute roof displacement appears large, it corresponds to a drift ratio well within code-prescribed limits, confirming acceptable lateral deformation behavior for a tall structure.

TABLE 4.3: Key Parameters Checks in Code Based Design

Aspect	**Result**
Time Period X and Y	5.00 s and 5.67 s
Maximum Torsion (Eqx and Eqy)	1.12 and 1.18 $<$ 1.2 and OK
Maximum Drift Ratio X and Y	0.0027 and 0.0021 $<$ 0.0036 and OK
Base Shear	7470 kips

TABLE 4.4: Seismic Parameters and Base Shear

Parameter	**Eqx**	**Eqy**
Ct (ft)	0.02 ft, 0.75	0.02 ft, 0.75
Response Modification Factor R	7	7
Overstrength Factor Ω_0	2.5	2.5
Deflection Amplification Factor C_d	5.5	5.5
Short-Period Spectral Acceleration S_s	1.302	1.302
1-Second Period Spectral Acceleration S_1	0.381	0.381
Site Class	D	D
Design Spectral Acceleration (SDS)	0.868	0.868
Design 1-Second Period Spectral Acceleration (SD1)	0.487426	0.487426
Period Used (sec)	2.598	2.598
Weight Used (kip)	195,616.739	195,616.739
Base Shear (kip)	7470.994	7470.994

4.2.3 Member Design and Reinforcement

Table 4.5: Moment Frame Preferences – ACI 318-19 Parameters

Parameter	**Value**
Multi-Response Design	Envelopes – All
Number of Interaction Curves	24
Number of Interaction Points	11
Minimum Eccentricity	Yes
Design for BCCR	Yes
Seismic Design Category	D
Seismic System Ω_0	1
Seismic System ρ	1
Seismic System S_{ds}	1
Consider ICC_ESR2017	No
Φ (Tension)	0.9
Φ (Compression Tied)	0.65
Φ (Compression Spiral)	0.75
Φ (Shear and Torsion)	0.85
Φ (Shear Seismic)	0.6
Φ (Shear Joint)	0.85
Pattern Live Load Factor	0.75
D/C Ratio Limit	1.0

Following the verification of the building's overall structural behavior in the 3D ETABS model, the next step focused on the detailed design of structural members, including beams, columns and slabs using ACI 318-19 Parameter shown in Table 4.5 and Table .The objective was to optimize member sizes and reinforcement ratios to achieve a balance between structural safety, material economy and practical constructability. Columns were designed to carry both axial and bending demands while maintaining adequate ductility and strength.

To account for the variation in axial load along the building height, column cross-sections were progressively reduced from the lower floors to the upper stories. This tapering strategy not only reflects the decreasing axial load demands but also improves material efficiency and reduces unnecessary weight, which is particularly critical in high-rise construction. A minimum reinforcement ratio of 1% was adopted in accordance with code requirements to establish a conservative baseline design. However, it is acknowledged that, for practical and economical column design, reinforcement ratios typically range between 1.5% and 2.5%, which may reduce member dimensions and improve overall efficiency.

Table 4.6: Shear Wall Preferences – ACI 318-19 Parameters

Parameter	**Value**
Multi-Response Design	Step-by-Step – All
Rebar Material	A615 Gr60
Rebar Shear Material	A615 Gr60
Seismic System ρ	1
Seismic System S_{ds}	0.5
Importance Factor	1
System C_d	4.5
Φ (Tension)	0.9
Φ (Compression)	0.65
Φ (Shear and Torsion)	0.75
Φ (Shear Seismic)	0.85
Pmax Factor	0.6
Number of Interaction Curves	24
Number of Interaction Points	11
Edge Design PT-Max	0.06
Edge Design PC-Max	0.04
Section Design IP-Max	0.04
Section Design IP-Min	0.0025
D/C Ratio Limit	0.95

The reinforcement detailing also accounted for constructability considerations, including standard bar sizes, spacing and anchorage lengths, to facilitate practical and safe on-site implementation. This iterative design process ensured that all members satisfied strength and serviceability criteria defined by ASCE 7-22 and ACI 318-19 while maintaining a conservative approach to accommodate uncertainties in loading and material properties.

By integrating these considerations, the final member design provides a robust baseline for performance-based assessment, allowing subsequent nonlinear analyses to evaluate the building's actual inelastic response and performance levels under seismic events.

Table 4.7: Final Frame Sections and Reinforcement

Name	**Material**	**Shape**	**Top Steel**	**Bottom Steel**
B1 – 18×25 – 4.5 ksi	4500 psi	Concrete Rectangular	4#6	4#6
B2 – 18×25 – 5 ksi	4500 psi	Concrete Rectangular	5#6	4#6
B3 – 18×25 – 5 ksi	4500 psi	Concrete Rectangular	4#8	4#6
B4 – 18×25 – 5 ksi	4500 psi	Concrete Rectangular	4#8	6#6
B5 – 18×25 – 4.5 ksi	4500 psi	Concrete Rectangular	5#8	3#8
B6 – 18×25 – 4.5 ksi	4500 psi	Concrete Rectangular	5#8	3#8
B7 – 18×25 – 4.5 ksi	4500 psi	Concrete Rectangular	5#8	4#8
C – 18×24 – 6 ksi	6000 psi	Concrete Rectangular	1.50%	–
C – 24×24 – 6 ksi	6000 psi	Concrete Rectangular	1.50%	–
C – 30×30 – 6 ksi	6000 psi	Concrete Rectangular	1%	–
C – 36×36 – 6 ksi	6000 psi	Concrete Rectangular	1%	–
C – 42×42 – 6 ksi	6000 psi	Concrete Rectangular	1%	–
C – 48×48 – 6 ksi	6000 psi	Concrete Rectangular	1%	–

For beams and slabs, reinforcement ratios were carefully adjusted based on calculated bending moments, shear forces and deflection requirements shown in Table 4.7 . Generally, steel ratios were targeted within a 1–2% range of the gross section area, with attention given to locations of potential stress concentrations, such as mid-spans and beam-column joints.

The distribution of top and bottom reinforcement was optimized to resist both positive and negative bending moments, ensuring adequate flexural capacity and energy dissipation under seismic loading. Shear reinforcement was provided as per code requirements to prevent brittle failure, particularly near supports and around openings.

4.3 Performance Based Design

After completing the code-based design, the building model was analyzed using performance-based assessment to evaluate its actual behavior under seismic loads. Target displacements were calculated for three earthquake intensity levels: Service Level Earthquake (SLE), Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE). Plastic hinges were assigned to beams, columns and shear walls to capture flexural and axial-moment behavior and their status was recorded at each target displacement to assess performance relative to Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) levels.

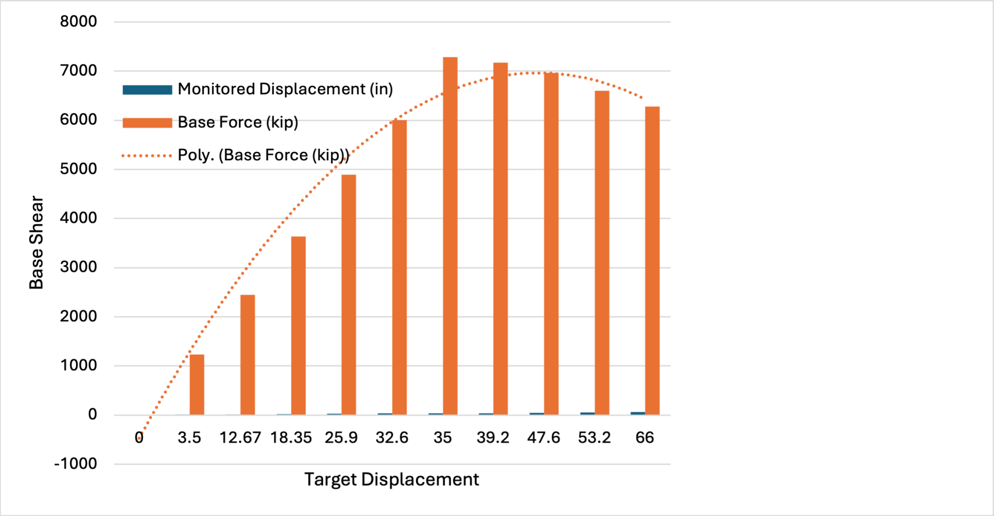


FIGURE 4.2: Base Shear versus Monitored Displacement Pushover Analysis

The results in Table 4.8 show a clear nonlinear response with progressive stiffness degradation. The base shear increases with displacement up to a peak value of about 7280 kip at 30 inches, indicating the onset of significant inelastic behavior and initial plastic hinge formation. Beyond this point, base shear decreases with further displacement, reaching 6280 kip at 50 inches, which reflects post-yield strength degradation and reduced lateral resistance. A same type of trend can be visualized in Figure 4.2.

Table 4.8: Base Shear versus Monitored Displacement with Plastic Hinge Performance Levels

Step	**Monitored Displacement (in)**	**Base Force (kip)**	**Immediate Occupancy (IO)**	**Life Safety (LS)**	**Collapse Prevention (CP)**	**Beyond CP**	**Total**
0	0.0	0.0	0	0	0	0	7997
1	5.0	1235	0	0	0	0	7997
2	10.0	2450	0	0	0	0	7997
3	15.0	3635	0	0	0	0	7997
4	20.0	4890	0	0	0	0	7997
5	25.0	6000	0	0	0	0	7997
6	30.0	7280	2056	0	0	0	7997
7	35.0	7170	3926	59	0	0	7997
8	40.0	6960	4138	225	59	0	7997
9	45.0	6600	4967	351	110	0	7997
10	50.0	6280	5896	455	203	0	7997

The plastic hinge pattern confirms this behavior, with the response transitioning from mainly Immediate Occupancy (IO) at lower displacements to increasing Life Safety (LS) and Collapse Prevention (CP) levels at higher displacements. Overall, the results highlight progressive damage accumulation and strength degradation that can only be captured through performance-based analysis.

4.3.1 Hinge Result at Different Levels for Performance Check

Results shown on Figure 4.3 indicate that at the SLE level, only a small percentage of beam hinges, approximately 10 percent, reached the IO performance level, while the majority remained elastic, showing that the code-based design is conservative at service-level loads.

At the DBE level, about 44 percent of beam hinges reached the LS level, indicating the onset of significant inelastic behavior in a portion of the structure, whereas the remaining members did not yield. Even at the MCE level, only a few beams located near shear walls and lift cores reached the CP level, demonstrating that the overall structure remains largely elastic and exhibits substantial over-design.

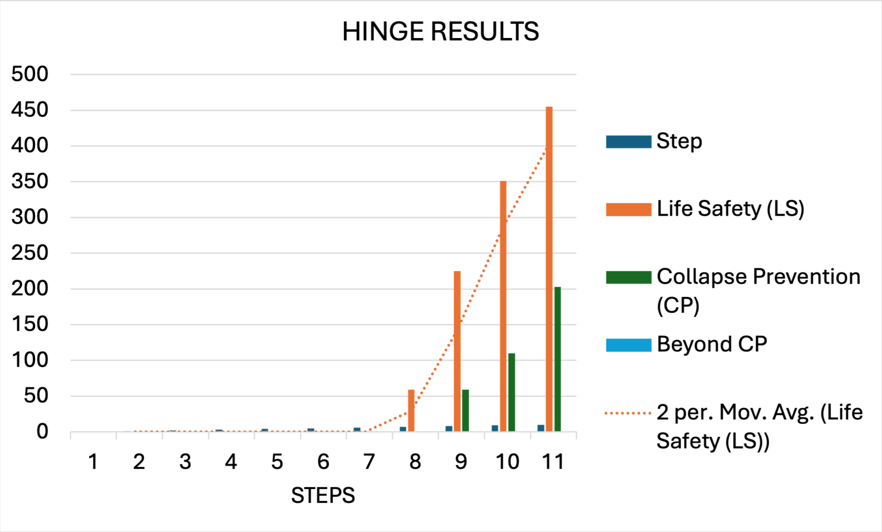


FIGURE 4.3: Hinge condition at different steps at Pushover Curve

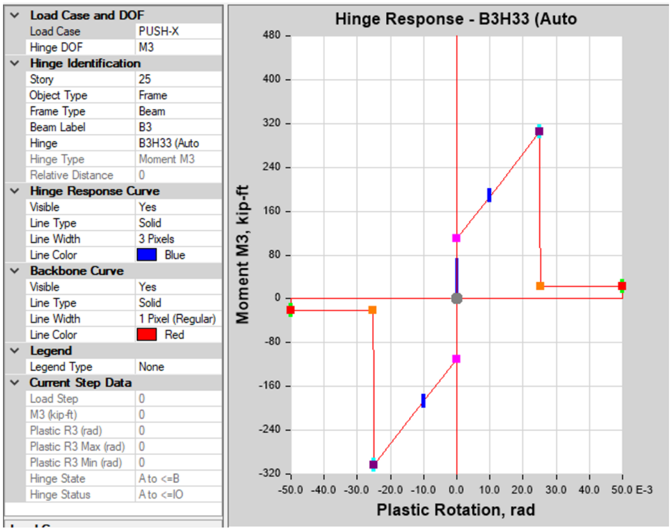

Load Case and DOF	
Load Case	PUSH-X
Hinge DOF	M3
Hinge Identification	
Story	25
Object Type	Frame
Frame Type	Beam
Beam Label	B3
Hinge	B3H33 (Auto
Hinge Type	Moment M3
Relative Distance	0
Hinge Response Curve	
Visible	Yes
Line Type	Solid
Line Width	3 Pixels
Line Color	🟦 Blue
Backbone Curve	
Visible	Yes
Line Type	Solid
Line Width	1 Pixel (Regular)
Line Color	🟥 Red
Legend	
Legend Type	None
Current Step Data	
Load Step	0
M3 (kip-ft)	0
Plastic R3 (rad)	0
Plastic R3 Max (rad)	0
Plastic R3 Min (rad)	0
Hinge State	A to <=B
Hinge Status	A to <=IO

FIGURE 4.4: Beams 24 hinge not even reaching IO level

Figure 4.5, Figure 4.6 and Table 4.10 revealed that some beams with lower reinforcement ratios from the code-based design experienced higher demand in nonlinear analysis. These members displayed greater hinge rotations and localized yielding, indicating that code-based reinforcement allocation may not always match the actual inelastic demand. Overall, the comparison between code-based predictions and performance-based outcomes highlights the redundancy and safety inherent in the dual system while suggesting that reinforcement and section optimization could improve material efficiency without compromising structural safety.

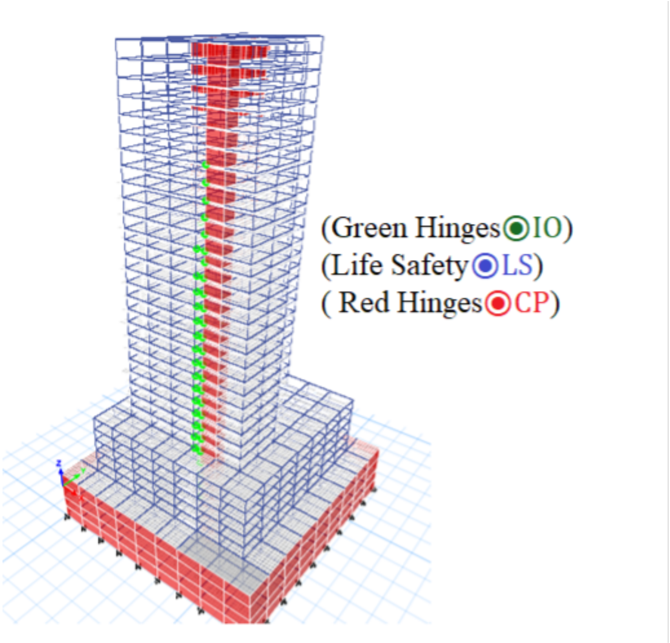


FIGURE 4.5: Beams (Green Hinges) Reaching IO Level at Initial Steps

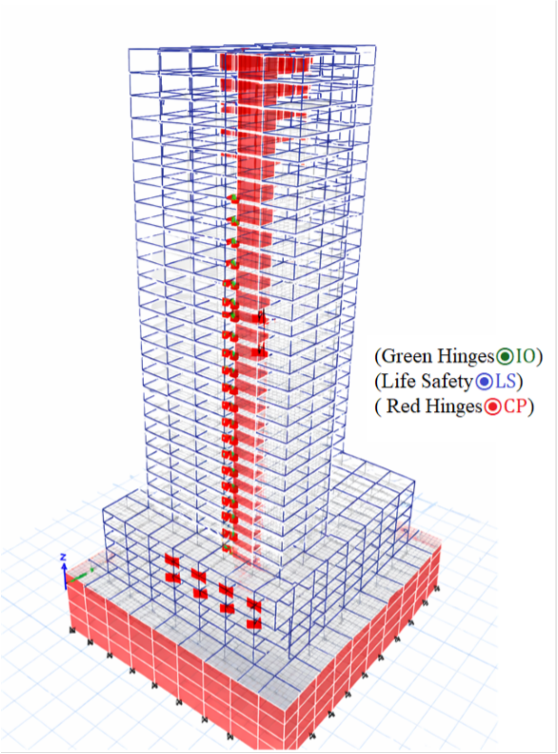


FIGURE 4.6: Beams (Red Hinges) Reaching CP Level at DBE

Table 4.9: Beam Plastic Hinge Status at Different Seismic Levels

Seismic Level	**Performance Level**	**Percentage of Beam Hinges Reached**	**Observations**
SLE	IO	10%	Most beams remained elastic
DBE	LS	44%	Significant inelastic behavior in some beams
MCE	CP	Few beams near shear walls and lift cores	Majority of beams remained below yielding

Table 4.10: Observed High-Demand Beams in Nonlinear Analysis

Member ID or Location	**Code-Based Reinforcement**	**Observed Demand**	**Performance Level Reached**	**Notes**
Beam B12 near lift core	Low	High	LS or CP	Localized yielding observed
Beam B25 near shear wall	Moderate	High	LS	Hinges rotated more than predicted
Beam B7 mid-span	Low	Moderate	IO	Slight yielding observed

These tables provide a clear visual comparison of how the building members performed under increasing seismic demand, highlighting the differences between code-based predictions and actual nonlinear behavior.

4.4 Comparison Between Code-Based Design and Performance-Based Assessment

This section presents a direct comparison between the Code-Based Design (CBD) results and the Performance-Based Design (PBD) outcomes to evaluate differences in predicted versus actual structural behavior.

The objective is to assess whether the CBD assumptions regarding stiffness, strength and deformation capacity align with the nonlinear response obtained from pushover analysis.

4.4.1 Global Structural Response Comparison

Table 4.11: Global Response Comparison (Code-Based Design vs Performance-Based Design)

Parameter	**Code-Based Design (CBD)**	**Performance-Based Design (PBD)**	**Observation**
Maximum Drift Ratio	0.0027 (X), 0.0021 (Y)	Yielding begins after ∼30 in displacement	Drift within limits; conservative stiffness
Design Base Shear	7470 kips	Peak ≈ 7280 kips	Good correlation
Structural Behavior	Elastic with safety factors	Gradual inelastic hinge formation	Ductile response confirmed
Torsion Ratio	< 1.2 (OK)	No significant torsional amplification	Stable lateral distribution

At the global level, CBD ensured compliance with drift limits, torsional irregularity limits and base shear requirements. The maximum drift ratios (0.0027 in X and 0.0021 in Y) were well below the allowable limit of 0.0036, indicating adequate stiffness. However, nonlinear pushover results showed that significant inelastic action did not occur until higher displacement levels (beyond 30 inches), suggesting that the building possesses additional reserve strength beyond code minimum requirements. The design base shear obtained from ASCE 7-22 was 7470 kips, while the pushover curve showed a peak base shear of approximately 7280 kips before softening behavior initiated. The close agreement between these values confirms consistency in strength estimation; however, the nonlinear response demonstrates gradual stiffness degradation rather than sudden failure, reflecting ductile system behavior. The comparative global response is summarized in Table 4.11 .

4.4.2 Member-Level Behavior Comparison

While CBD proportioned members to satisfy strength demands with demand-to-capacity (D/C) ratios less than unity, nonlinear analysis revealed that many members did not reach significant inelastic states even at higher seismic intensity levels. Only selected beams near shear walls and lift cores exhibited LS or CP performance levels. . The comparison in Table 4.12 indicates that CBD ensures safety but may not accurately predict where inelastic demand will concentrate.

Members with lower reinforcement ratios showed higher nonlinear rotations, suggesting that force-based design does not always reflect true deformation demand distribution.

This observation highlights the conservative nature of code-based design, where member sizing often exceeds the demands imposed by expected seismic loads. Consequently, the structure demonstrates inherent reserve strength and ductility, which can be effectively captured through performance-based assessment, providing a more realistic evaluation of safety margins and potential damage distribution.

Table 4.12: Member Performance Comparison

Aspect	**CBD Prediction**	**PBD Observation**	**Interpretation**
Beam Behavior	Designed to resist factored forces	Majority remained elastic	Possible over-design
Column Performance	Strong column–weak beam satisfied	Columns largely elastic	Adequate hierarchy maintained
Shear Wall Demand	Designed for combined axial-flexure	Minimal CP-level hinges	High redundancy
Low-Reinforced Beams	Within code limits	Higher hinge rotations	Localized demand underestimated

The comparison indicates that CBD ensures safety but may not accurately predict where inelastic demand will concentrate. Members with lower reinforcement ratios showed higher nonlinear rotations, suggesting that force-based design does not always reflect true deformation demand distribution.

4.4.3 Hinge Distribution Comparison

From nonlinear analysis:

i. At SLE, approximately 10% of beam hinges reached IO level.

ii. At DBE, about 44% reached LS.

iii. At MCE, only a few reached CP.

Table 4.13 confirms that CBD satisfies life safety objectives with significant reserve capacity. However, hinge concentration near core regions suggests stiffness interaction effects between shear walls and moment frames that are not explicitly captured in conventional force-based design.

Table 4.13: Performance Level Distribution

Seismic Level	**CBD Intended Objective**	**Observed PBD Performance**	**Conclusion**
SLE	Elastic behavior	Mostly elastic	Conservative
DBE	Life Safety	Partial LS in beams	Acceptable
MCE	Collapse Prevention	Very few CP hinges	High safety margin

4.4.4 Strength and Efficiency Evaluation

The comparison highlights three key observations:

i. Strength Adequacy**:** CBD accurately predicted overall strength capacity.

ii. Stiffness Conservatism**:** Drift limits ensured higher stiffness than strictly required for collapse prevention.

iii. Material Optimization Potential**:** Many members remained elastic at MCE, indicating opportunity for reinforcement optimization.

To better illustrate the behavioral contrast, the pushover curve demonstrates nonlinear stiffness degradation beyond 30 inches displacement, while CBD assumes linear elastic response up to factored force limits. This difference explains why CBD may lead to conservative reinforcement allocation.

4.4.5 Overall Comparative Assessment

The integration of CBD and PBD results demonstrate that:

i. The dual system provides high redundancy and ductility.

ii. Code-based provisions ensure compliance and safety but may not reflect realistic inelastic demand distribution.

iii. Performance-based evaluation offers deeper insight into hinge mechanisms and deformation capacity.

iv. Combining both approaches results in safer yet more economical seismic design strategies.

The comparative analysis confirms that while code-based design establishes a reliable and regulation-compliant foundation, performance-based assessment reveals the true inelastic behavior and reserve capacity of the structure. The dual system exhibits strong seismic resilience, but targeted optimization of beam reinforcement particularly in regions away from critical core zones could enhance material efficiency without compromising safety.

4.5 Summary

The results of this study demonstrate that the code-based design provides a safe and conservative baseline for the 35-story reinforced concrete dual system building, ensuring compliance with seismic provisions and overall structural stability. The subsequent performance-based assessment revealed that, under service, design basis and maximum considered earthquake levels, most structural members remained largely elastic, with only a small portion of beams and selected areas near shear walls or lift cores reaching inelastic performance levels. The comparison highlights that code-based reinforcement and section sizing often exceed the actual inelastic demands predicted in nonlinear analysis, indicating potential over-design in several members. At the same time, some lightly reinforced beams exhibited higher-than-expected hinge rotations, showing localized vulnerabilities. Overall, the study confirms the inherent safety and redundancy of the dual system while illustrating that performance-based insights can guide more efficient reinforcement allocation and section optimization, enhancing material economy without compromising seismic resilience. This study demonstrates that conventional code-based design does not explicitly reveal the distribution of inelastic demand and higher-mode effects in tall dual-system buildings, whereas the performance-based approach provides critical insight into localized demand concentrations and reserve capacity, enabling more rational and optimized reinforcement design.

Chapter 5

Guidelines for Practicing Designers

5.1 Background

Seismic design practice for tall reinforced concrete buildings has traditionally relied on code-based design procedures due to their simplicity, standardization and regulatory acceptance. Modern seismic codes, such as ASCE 7, provide minimum strength and drift requirements intended to ensure life safety under design-level earthquakes. However, these procedures are primarily force-based and do not explicitly quantify structural performance, damage distribution, or post-earthquake functionality.

With increasing building heights, architectural complexity and seismic demand in urban regions, there is growing recognition within the engineering community that performance-based design offers a more rational framework for evaluating actual structural behavior.

Performance-based assessment allows designers to directly relate seismic demand to structural damage states, deformation limits and operational objectives. This chapter translates the findings of the present study into practical guidance for designers, focusing on how code-based design and performance-based assessment can be used together effectively in professional practice.

5.2 Outcomes of Current Research from an Industry Point of View

From an industry perspective, the outcomes of this research confirm that code-based seismic design provides a safe and conservative baseline for tall reinforced concrete dual system buildings. When designed in accordance with current seismic provisions, such structures generally exhibit significant reserve strength and deformation capacity beyond code-required limits.

This inherent conservatism is particularly evident in dual systems, where moment-resisting frames and shear walls provide redundancy and multiple load paths. The study demonstrates that a performance-based design approach provides enhanced insight into the actual behavior of such structures by identifying regions of concentrated inelastic demand and evaluating the available reserve capacity. This allows for a more realistic assessment of structural performance beyond global parameters such as base shear and inter-story drift.

At the same time, the study highlights that code-based procedures may not accurately reflect the true distribution of inelastic demand within the structure. Certain members, particularly beams located near shear walls, cores, or stiffness discontinuities, may experience higher nonlinear demands than anticipated, while other members remain largely elastic even under severe shaking.

From an industry standpoint, this implies that reliance solely on force-based design can lead to uneven material utilization, localized over-design and, in some cases, inefficient reinforcement detailing.

Performance-based assessment offers valuable insight into these behaviors by identifying critical components, expected hinge formations and deformation demands at different hazard levels. For practicing engineers, such information can improve confidence in seismic performance, support value engineering decisions and enhance communication with stakeholders regarding expected damage and functionality. Performance-based assessment also helps bridge the gap between analytical design assumptions and real seismic behavior by explicitly quantifying damage states and acceptance criteria.

5.3 Proposed Line of Action for Designers

Based on the findings of this research, a combined design approach is recommended for practicing structural engineers. Code-based design should continue to be used as the primary design framework to satisfy regulatory requirements, ensure constructability and establish initial member sizes and reinforcement. Once a compliant code-based design is achieved, performance-based assessment should be employed as a verification and optimization tool rather than a replacement for conventional design.

Based on the findings of this research, a combined design approach is recommended for practicing structural engineers. Code-based design should continue to be used as the primary design framework to satisfy regulatory requirements, ensure constructability and establish initial member sizes and reinforcement. Once a compliant code-based design is achieved, performance-based assessment should be employed as a verification and optimization tool rather than a replacement for conventional design.

Based on the findings of this study, designers should incorporate performance-based evaluation alongside conventional code-based procedures, particularly for tall dual-system buildings where higher-mode effects are significant. Designers are encouraged to use nonlinear static or dynamic analyses to evaluate deformation demands, plastic hinge development and overall system behavior under multiple seismic hazard levels. Particular attention should be given to members with lower reinforcement ratios, regions near shear walls and cores and stories with stiffness or strength irregularities.

Where excessive reserve capacity is observed, selective refinement of member sizes or reinforcement may be considered to improve material efficiency, provided that serviceability and robustness are maintained. In professional practice, performance-based insights can also be used to define explicit performance objectives, such as immediate occupancy for service-level earthquakes or controlled damage for design-level events. This approach allows engineers to deliver designs that are not only code-compliant but also better aligned with client expectations, resilience goals and long-term building performance. Although the presented design chart appears similar to conventional workflows, its key distinction lies in the integration of code-based design (CBD) with performance-based design (PBD) within an iterative framework. Unlike traditional CBD, which generally follows a linear, non-iterative process based on prescribed forces, the proposed approach incorporates repeated evaluation and refinement through nonlinear performance assessment. This enables identification of demand concentrations, inelastic behavior and potential overdesign, leading to a more optimized and performance-oriented structural solution. . In this context, PBDA is most readily accepted when it is used to validate critical or high-rise structures, support optimization of reinforcement, or justify design decisions in complex projects, rather than as a complete substitute for prescriptive code procedures. For practicing engineers, such information can improve confidence in seismic performance, support value engineering decisions and enhance communication with stakeholders regarding expected damage and functionality.

5.4 Summary

This chapter presented practical guidelines for applying the outcomes of the present research to real-world structural design practice. The study confirms that code-based seismic design remains an effective and reliable foundation for tall reinforced concrete buildings, particularly those employing dual structural systems. However, it also demonstrates that performance-based assessment provides essential insight into actual structural behavior, damage distribution and deformation capacity that cannot be captured through force-based methods alone.

For practicing designers, the integration of code-based design with targeted performance-based evaluation offers a balanced and efficient approach. Such a framework enhances seismic reliability, improves material utilization and supports informed engineering judgment, ultimately leading to safer, more resilient and more economical tall building designs in seismic regions.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The primary aim of this research was to evaluate the seismic performance of a 35-story reinforced concrete dual system building by integrating code-based and performance-based design approaches using ETABS software. In many practical scenarios, conventional code-based design is widely adopted, but it may not fully capture the actual inelastic behavior of tall buildings. This study provides a detailed comparison between code-based design predictions and nonlinear performance-based assessment, with the following conclusions:

i. The code-based design (CBD) approach, implemented using ASCE 7-22 and ACI 318-19 provisions, successfully provided a safe and stable structural configuration for the 35-story reinforced concrete dual system building, satisfying all strength, drift (0.027 in elastic), torsion ($1.18_{\text{max}} < 1.2$) and stability requirements.

ii. Performance-based design (PBD) assessment demonstrated that 65% structural members remained elastic under SLE, DBE and even 20% structural members at MCE levels, confirming the conservative nature and inherent redundancy of the dual moment frame shear wall system.

iii. Nonlinear pushover analysis revealed that only 1% of beams, primarily near shear walls and lift cores, reached Life Safety (LS) or Collapse Prevention (CP) performance levels, while most elements did not experience critical inelastic demand.

iv. Comparison between CBD and PBD results indicated areas of over-design in several members, suggesting that reinforcement and section optimization could improve material efficiency without compromising seismic safety.

v. Overall, the integration of performance-based evaluation with conventional code-based design enhances understanding of actual structural behavior, supports more rational reinforcement distribution and provides a pathway toward achieving both seismic resilience and economic efficiency in tall reinforced concrete buildings.

6.2 Future Work

This study serves as a preliminary step towards a more comprehensive understanding of seismic behavior in high-rise reinforced concrete dual system buildings. Future research directions include:

i. Exploration of performance-based optimization of reinforcement and member sizes to achieve a balance between safety and material economy.

ii. Nonlinear dynamic analysis under multiple ground motion records to complement pushover results and provide a more realistic evaluation of seismic response.

iii. Exploration of performance-based Wind design and influence of soil Structure Interaction on PBD.

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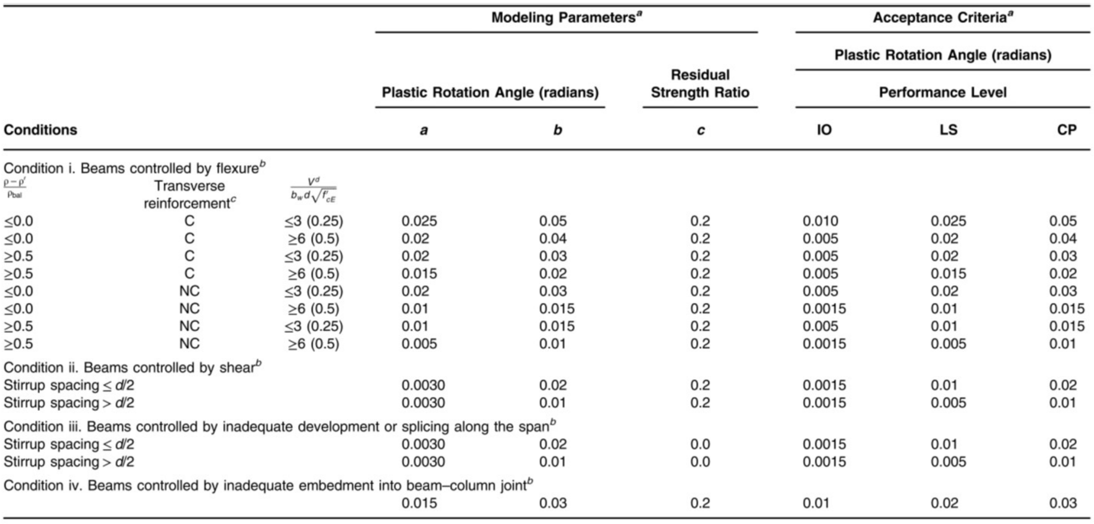
Appendix A



			Modeling Parameters^a			Acceptance Criteria^a		
			Plastic Rotation Angle (radians)		Residual Strength Ratio	Plastic Rotation Angle (radians) Performance Level		
Conditions			***a***	***b***	***c***	**IO**	**LS**	**CP**
Condition i. Beams controlled by flexure^b								
$\frac{\rho - \rho'}{\rho_{bal}}$	Transverse reinforcement^c	$\frac{V^d}{b_w d \sqrt{f'_{cE}}}$						
≤0.0	C	≤3 (0.25)	0.025	0.05	0.2	0.010	0.025	0.05
≤0.0	C	≥6 (0.5)	0.02	0.04	0.2	0.005	0.02	0.04
≥0.5	C	≤3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≥0.5	C	≥6 (0.5)	0.015	0.02	0.2	0.005	0.015	0.02
≤0.0	NC	≤3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≤0.0	NC	≥6 (0.5)	0.01	0.015	0.2	0.0015	0.01	0.015
≥0.5	NC	≤3 (0.25)	0.01	0.015	0.2	0.005	0.01	0.015
≥0.5	NC	≥6 (0.5)	0.005	0.01	0.2	0.0015	0.005	0.01
Condition ii. Beams controlled by shear^b								
Stirrup spacing ≤ $d/2$			0.0030	0.02	0.2	0.0015	0.01	0.02
Stirrup spacing > $d/2$			0.0030	0.01	0.2	0.0015	0.005	0.01
Condition iii. Beams controlled by inadequate development or splicing along the span^b								
Stirrup spacing ≤ $d/2$			0.0030	0.02	0.0	0.0015	0.01	0.02
Stirrup spacing > $d/2$			0.0030	0.01	0.0	0.0015	0.005	0.01
Condition iv. Beams controlled by inadequate embedment into beam–column joint^b								
			0.015	0.03	0.2	0.01	0.02	0.03

Figure 1: Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedure for RC Beam [42]