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REVIEW OF NONLINEAR TIME HISTORY ANALYSIS IN PERFORMANCE-BASED DESIGN FOR MEDIUM- TO HIGH-RISE RC BUILDINGS

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ABSTRACT

Medium- to high-rise reinforced concrete (RC) buildings are highly vulnerable to earthquake forces due to their complex dynamic behavior and nonlinear response characteristics. Conventional force-based seismic design methods are often inadequate for accurately predicting structural performance during strong earthquakes, leading to the development of Performance-Based Seismic Design (PBSD) as a more reliable and objective-oriented approach. This review paper examines the role of Nonlinear Time History Analysis (NLTHA) in the PBSD of medium- to high-rise RC buildings. The study discusses the development of PBSD, international seismic guidelines, nonlinear modeling techniques, ground motion selection and scaling, material and geometric nonlinearities, performance assessment procedures, and recent research trends. It also reviews seismic performance studies on regular and irregular RC buildings, shear wall systems, dampers, and base isolation techniques.

The review highlights that NLTHA provides superior accuracy in predicting structural response, damage progression, plastic hinge formation, and collapse mechanisms compared to conventional seismic analysis methods. Although NLTHA requires significant computational effort and detailed modeling, it is considered one of the most effective tools for realistic seismic performance evaluation and for achieving safer, more resilient, and performance-oriented design of reinforced concrete buildings.

Keywords: Performance-Based Seismic Design (PBSD), Nonlinear Time History Analysis (NLTHA), Reinforced Concrete Buildings, Seismic Performance Evaluation, Earthquake Engineering.

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1. INTRODUCTION

Reinforced concrete (RC) buildings of medium to high rise constitute a major portion of urban infrastructure in seismic-prone regions across the world. Rapid urbanization, population growth, and scarcity of land have led to the construction of taller and more slender structures in metropolitan cities. Although these buildings are designed to withstand gravity and lateral loads, earthquakes continue to pose a significant threat to their structural safety and serviceability. During seismic events, medium- and high-rise RC buildings experience complex dynamic behavior due to factors such as increased height, irregular mass distribution, stiffness variation, torsional effects, and higher mode participation. Severe earthquakes occurring in recent decades have demonstrated that inadequate understanding of seismic response can result in excessive structural damage, collapse, economic losses, and human casualties. Consequently, ensuring the seismic resilience and performance of such structures has become a major objective in structural engineering research and practice.[1]

Traditionally, seismic design of RC buildings has been carried out using the conventional force-based design (FBD) approach. In this method, structures are designed primarily on the basis of elastic forces estimated from design response spectra and simplified code provisions.

Although force-based procedures are relatively simple and computationally efficient, they possess several limitations when applied to modern high-rise buildings subjected to strong ground motions. Conventional methods generally assume linear elastic structural behavior and use reduction factors to account indirectly for inelastic deformation capacity. However, actual structures subjected to severe earthquakes exhibit highly nonlinear behavior involving cracking of concrete, yielding of reinforcement, stiffness degradation, energy dissipation, and possible failure mechanisms. Force-based methods often fail to accurately predict damage distribution, deformation demands, and post-yield behavior, especially for irregular or tall buildings. As a result, structures designed using traditional approaches may satisfy code requirements while still experiencing unacceptable damage during strong seismic events.[2]

To overcome these shortcomings, the concept of Performance-Based Seismic Design (PBSD) has emerged as an advanced and more rational seismic design philosophy. PBSD focuses on achieving predefined performance objectives under different levels of earthquake intensity rather than merely satisfying force requirements.

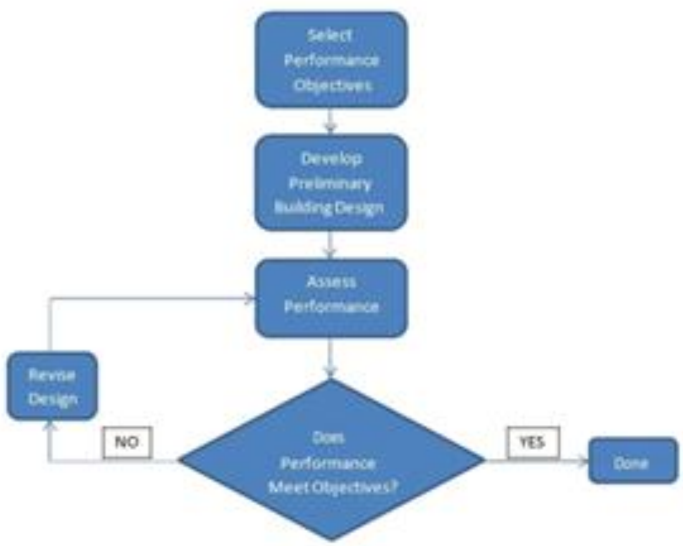

Figure 1. Performance – based design flow diagram

The fundamental aim of PBSD is to evaluate how a structure is expected to perform during and after an earthquake in terms of safety, functionality, reparability, and collapse prevention. Instead of relying solely on elastic force calculations, PBSD considers realistic structural behavior, including nonlinear response and damage progression.

Different performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) are established to ensure that buildings meet desired safety and operational requirements under varying seismic hazards. This approach enables engineers to design structures that not only resist collapse but also limit economic losses and downtime after earthquakes.[3]

The present review paper aims to critically examine the role of Nonlinear Time History Analysis in the performance-based seismic design of medium- to high-rise reinforced concrete buildings. The study focuses on understanding how NLTHA contributes to accurate seismic performance evaluation and how it improves the reliability of PBSD methodologies compared to conventional design approaches. The review covers key aspects including nonlinear modeling techniques, seismic performance objectives, selection and scaling of ground motion records, analytical procedures, structural response parameters, code provisions, and recent research developments. Additionally, the paper discusses the advantages, limitations, and practical challenges associated with NLTHA implementation in seismic design practice. Through an extensive review of published literature, the study intends to provide valuable insights for researchers, practicing engineers, and academicians working in the field of earthquake engineering and performance-based structural design.[4]

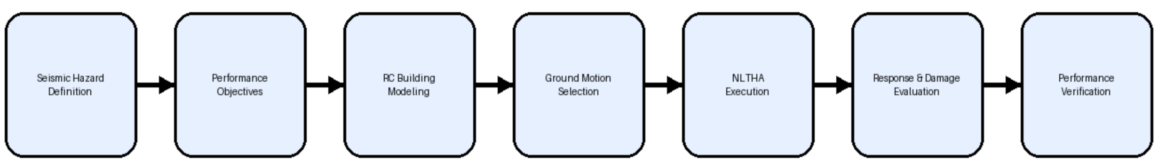

Figure 1. PBSD–NLTHA workflow for seismic performance evaluation of medium- to high-rise RC buildings.

Figure 1 illustrates the overall workflow adopted in Performance-Based Seismic Design (PBSD) using Nonlinear Time History Analysis (NLTHA). The process begins with seismic hazard definition and establishment of performance objectives, followed by structural modeling, ground motion selection, nonlinear dynamic analysis, and seismic response evaluation. The workflow highlights the sequential procedure used to assess the seismic performance and safety of reinforced concrete buildings under earthquake loading.

2. STATE OF DEVELOPMENT IN PERFORMANCE-BASED SEISMIC DESIGN

Performance-Based Seismic Design (PBSD) has evolved significantly over the past few decades as a response to the limitations of conventional seismic design procedures. Earlier seismic design philosophies primarily focused on preventing structural collapse during earthquakes through strength-based provisions. Traditional force-based design methods assumed that if a structure possessed sufficient lateral strength and ductility, it would perform satisfactorily under seismic loading. However, observations from major earthquakes revealed that many buildings designed according to existing codes still suffered severe structural and non-structural damage, resulting in substantial economic losses and functional disruption. These shortcomings highlighted the need for a more advanced design philosophy capable of predicting actual structural performance rather than merely satisfying minimum strength requirements.[5]

2.1. Conventional Seismic Design Approaches

Conventional seismic design approaches are primarily based on the force-based design (FBD) philosophy, in which structures are designed to resist lateral seismic forces calculated using elastic analysis procedures and codal response spectra. The fundamental assumption of this approach is that if a building possesses adequate strength, stiffness, and ductility, it can survive earthquake loading without collapse. Seismic codes traditionally estimate earthquake forces using simplified methods such as the equivalent static method or response spectrum analysis. Reduction factors, commonly known as response reduction or behavior factors, are introduced to account indirectly for the inelastic deformation capacity of structures during severe earthquakes. Although these methods are computationally efficient and simple to implement, they do not explicitly evaluate the actual damage or performance level of a structure under seismic loading.

One of the major limitations of conventional seismic design is that it mainly focuses on life safety and collapse prevention without accurately predicting structural damage, repairability, or post-earthquake functionality. These approaches generally assume linear elastic behavior and cannot fully capture the nonlinear response characteristics of reinforced concrete buildings subjected to strong ground motions. Medium- and high-rise buildings often exhibit complex dynamic behavior, including higher mode effects, torsional irregularities, stiffness degradation, and P-delta effects, which are difficult to represent using simplified force-based procedures.

Consequently, buildings designed according to conventional methods may satisfy codal strength requirements but still experience excessive damage during major earthquakes. These limitations created the need for more realistic and performance-oriented seismic design methodologies.[6]

2.2. Evolution of Performance-Based Design

Performance-Based Seismic Design (PBSD) evolved as an advanced alternative to traditional force-based seismic design approaches. The concept emerged from extensive research and post-earthquake observations showing that compliance with conventional design codes did not always guarantee acceptable structural performance. Researchers recognized that earthquake-resistant design should focus not only on structural strength but also on the expected level of damage, functionality, and safety after seismic events. This led to the development of performance-oriented methodologies that evaluate how a structure behaves under varying earthquake intensities.

The evolution of PBSD was strongly influenced by advancements in structural dynamics, material modeling, and nonlinear analysis techniques. Initially, displacement-based concepts gained importance because structural damage was found to correlate more closely with deformation demands than with elastic force levels. Over time, nonlinear static pushover analysis and Nonlinear Time History Analysis (NLTHA) became key analytical tools for evaluating structural performance. PBSD introduced predefined performance objectives such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), enabling engineers to design structures according to expected operational requirements after earthquakes. The increasing availability of advanced computational tools and recorded earthquake data further accelerated the practical adoption of PBSD in structural engineering.[7]

Today, PBSD represents a major shift from prescriptive design methods toward objective-based engineering design. Modern PBSD frameworks consider not only structural collapse prevention but also economic losses, resilience, sustainability, and post-earthquake recovery. As a result, PBSD has become an essential approach for designing critical infrastructure and medium- to high-rise buildings in seismic regions.

2.3. International Guidelines and Codes

2.3.1. FEMA 356

Federal Emergency Management Agency published FEMA 356, titled *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*, to provide comprehensive procedures for evaluating and rehabilitating existing buildings under seismic loading. FEMA 356 introduced detailed guidelines for nonlinear static and nonlinear dynamic analysis procedures and established acceptance criteria for different structural components. The document emphasized performance objectives and provided engineers with methodologies to assess building performance at various seismic hazard levels. FEMA 356 became one of the foundational references for the practical implementation of PBSD.

2.3.2. FEMA 440

FEMA 440 was developed as an improvement over earlier nonlinear static analysis procedures presented in FEMA 356 and ATC-40. This guideline focused on enhancing the accuracy of displacement prediction methods used in pushover analysis. FEMA 440 introduced refined procedures for estimating seismic demands, particularly for structures exhibiting significant nonlinear behavior. It addressed limitations related to equivalent linearization and displacement modification techniques, thereby improving the reliability of performance evaluation methods within the PBSD framework.[8]

2.3.3. ASCE 41

American Society of Civil Engineers developed ASCE 41 as a standardized guideline for seismic evaluation and retrofit of existing buildings. ASCE 41 integrated and expanded concepts from FEMA 356 and related documents into a more comprehensive standard. It provides detailed acceptance criteria, modeling procedures, and performance objectives for different structural systems. The standard includes linear and nonlinear analysis methods and is widely used for assessing seismic vulnerability and rehabilitation of buildings. ASCE 41 is considered one of the most influential standards in modern performance-based seismic engineering practice.

2.3.4. Eurocode 8

European Committee for Standardization developed Eurocode 8 to provide seismic design provisions for structures within European countries. Eurocode 8 emphasizes ductility-based design, capacity design principles, and structural regularity to improve seismic performance. Although primarily based on force-based procedures, the code also incorporates several performance-oriented concepts and nonlinear analysis provisions. Eurocode 8 encourages the use of advanced analytical methods for important or irregular structures and provides guidance on seismic assessment and retrofitting. It has significantly influenced international seismic design practices and research related to PBSD.

2.3.5. ATC-40

Applied Technology Council published ATC-40 as one of the earliest guidelines focusing specifically on seismic evaluation and retrofit using performance-based concepts. The document introduced the Capacity Spectrum Method, which became widely used in nonlinear static pushover analysis. ATC-40 established procedures for evaluating structural performance levels based on displacement demands and capacity curves. The guideline played an important role in promoting the practical application of PBSD and nonlinear analysis methods in engineering practice.

2.3.6. IS 1893 and IS 13920

In India, seismic design provisions are primarily governed by Bureau of Indian Standards through IS 1893 and IS 13920. IS 1893 provides criteria for earthquake-resistant design of structures, including seismic zoning, design spectra, load combinations, and analysis procedures. IS 13920 specifies ductile detailing requirements for reinforced concrete structures to improve energy dissipation and seismic performance. Recent revisions of these codes have incorporated several modern seismic design concepts, including improved ductility provisions and dynamic analysis requirements for tall buildings. Although Indian codes are still largely force-based, there is increasing emphasis on adopting performance-based approaches and nonlinear analysis techniques for important and high-rise structures.[9]

2.4. Current State of PBSD Research

Current research in Performance-Based Seismic Design is primarily focused on improving the accuracy, reliability, and practical implementation of nonlinear seismic assessment methods. Researchers are extensively studying the nonlinear behavior of reinforced concrete buildings under different earthquake scenarios using advanced computational models and experimental investigations. Nonlinear Time History Analysis has become a central area of research because of its ability to simulate realistic structural response under actual ground motion records. Studies are being conducted to optimize ground motion selection procedures, improve material constitutive models, and reduce uncertainties associated with nonlinear analysis.

Another important area of PBSD research involves the development of resilience-based design methodologies. Modern researchers are increasingly considering factors such as repair costs, downtime, environmental impact, and post-earthquake functionality in addition to structural safety. The integration of probabilistic approaches, fragility analysis, machine learning techniques, and artificial intelligence into seismic performance evaluation is also gaining significant attention. Researchers are working toward developing simplified yet accurate performance assessment procedures that can be efficiently used in professional engineering practice.[10]

In the context of medium- and high-rise reinforced concrete buildings, current studies emphasize the influence of vertical irregularities, soft stories, torsional effects, soil-structure interaction, and higher mode participation on seismic performance. The use of advanced damping devices, base isolation systems, and innovative construction materials is also being explored to improve seismic resilience. Despite significant advancements, challenges such as computational complexity, modeling uncertainty, and lack of uniform global standards continue to influence PBSD implementation. Nevertheless, ongoing research is continuously enhancing the effectiveness of PBSD as a reliable framework for earthquake-resistant structural design.

3. NONLINEAR TIME HISTORY ANALYSIS IN SEISMIC EVALUATION

3.1. Fundamentals of NLTHA

Nonlinear Time History Analysis (NLTHA) is one of the most advanced and realistic methods used for seismic evaluation of structures.

It involves analyzing the response of a structural system under earthquake excitation by applying ground motion records directly to a mathematical model of the structure. Unlike linear static or response spectrum methods, NLTHA captures the complete nonlinear behavior of buildings during earthquake loading, including cracking, yielding, stiffness degradation, and collapse mechanisms. Because earthquake loading varies continuously with time, NLTHA evaluates structural response at every small time interval throughout the duration of the earthquake. This makes it highly effective for Performance-Based Seismic Design (PBSD) of medium- and high-rise reinforced concrete buildings.[11]

3.1.1. Dynamic Equilibrium Equation

The foundation of NLTHA lies in the dynamic equilibrium equation, which represents the balance between inertial forces, damping forces, restoring forces, and externally applied earthquake forces. The equation is expressed as:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = P(t)$$

where *M* represents the mass matrix, *C* is the damping matrix, *K* is the stiffness matrix, *u(t)* is displacement, *ũ(t)* is velocity, *ü(t)* is acceleration, and *P(t)* is the time-dependent external earthquake force. In nonlinear analysis, stiffness is not constant and changes continuously as the structure undergoes cracking, yielding, and damage. Therefore, the equilibrium equation must be solved repeatedly at every time step throughout the analysis. This equation forms the basis for predicting how structures respond dynamically during seismic excitation.

3.1.2. Time-Step Integration

Since earthquake loading changes continuously with time, NLTHA divides the total duration of the earthquake into a series of very small time intervals known as time steps. Numerical integration techniques such as the Newmark-beta method, Wilson-theta method, and Hilber-Hughes-Taylor method are commonly used to solve the dynamic equilibrium equation at each time step. These methods calculate displacement, velocity, and acceleration responses incrementally throughout the earthquake duration. The selection of appropriate time-step size is extremely important because smaller time intervals improve accuracy but increase computational effort. Time-step integration enables engineers to capture rapid changes in structural behavior and identify critical response stages during seismic excitation.

3.1.3. Nonlinear Structural Response

The most significant feature of NLTHA is its ability to represent nonlinear structural response realistically. During strong earthquakes, reinforced concrete buildings do not behave elastically; instead, they undergo material and geometric nonlinearities. Concrete cracking, reinforcement yielding, stiffness reduction, energy dissipation, and plastic hinge formation occur progressively as seismic intensity increases. NLTHA captures these nonlinear phenomena directly within the analysis process. This allows engineers to evaluate actual damage patterns, deformation demands, inter-story drift, and collapse potential more accurately than conventional linear methods. As a result, NLTHA is considered essential for realistic seismic performance assessment of complex and tall RC structures.[12]

3.2. Ground Motion Selection and Scaling

Ground motion selection is a critical component of NLTHA because the accuracy of seismic response prediction depends heavily on the characteristics of the earthquake records used in the analysis. Since earthquake ground motions vary in amplitude, frequency content, duration, and energy release, appropriate selection and scaling of records are necessary to ensure realistic seismic assessment. In PBSD, multiple ground motion records are generally used to capture variability in earthquake behavior and reduce uncertainty in structural response prediction.

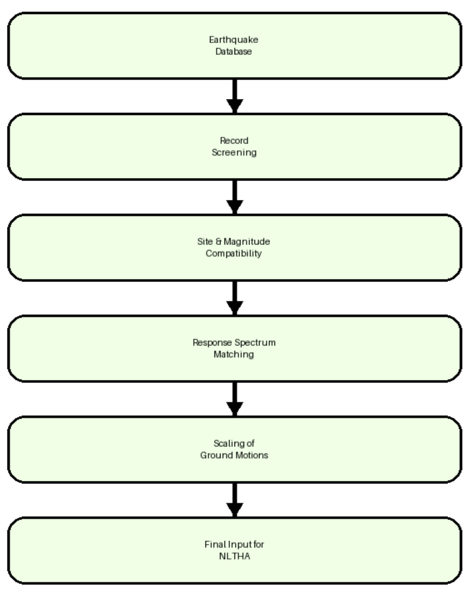

Figure 2. Procedure for ground motion record selection and scaling in nonlinear time history analysis.

Figure 2 presents the systematic process used for selecting and scaling earthquake ground motion records for NLTHA. The procedure includes database collection, record screening, compatibility checking with seismic hazard conditions, response spectrum matching, and scaling according to target seismic demand. Proper selection and scaling of ground motions are essential for obtaining realistic seismic response predictions in PBSD studies.

3.2.1. Real Earthquake Records

Real earthquake records are obtained from actual seismic events recorded by strong motion instruments during past earthquakes. These records provide realistic representation of ground shaking characteristics, including peak acceleration, frequency content, duration, and pulse effects. Examples include records from earthquakes such as Northridge, Kobe, El Centro, and Bhuj earthquakes. Real records are widely preferred because they reflect actual seismic behavior observed in nature. However, selecting appropriate records requires consideration of factors such as seismic source characteristics, soil conditions, magnitude, fault mechanism, and distance from the epicenter. Proper selection ensures compatibility between the chosen records and the seismic hazard conditions of the study area.[13]

3.2.2. Artificial Ground Motions

Artificial ground motions are synthetically generated acceleration records developed to match specific target response spectra or seismic parameters. These records are often used when sufficient real earthquake data are unavailable for a particular seismic region or hazard condition. Artificial motions provide flexibility in controlling frequency content and intensity levels according to design requirements. Although they may not fully reproduce the complexity of real earthquakes, they are useful for parametric studies and code-based seismic assessments. Researchers often combine artificial and recorded ground motions to improve reliability of structural response evaluation.

3.2.3. Spectrum Matching

Spectrum matching is a process used to modify selected ground motion records so that their response spectra closely match the target design spectrum specified by seismic codes or hazard analysis. Since individual earthquake records may differ significantly from required design spectra, spectrum matching ensures consistency between seismic demand and codal requirements.

This process improves the reliability of NLTHA results by ensuring that the selected records represent the expected seismic intensity level for the structure under investigation. Spectrum matching can be performed using time-domain or frequency-domain adjustment techniques while preserving important characteristics of the original record.

3.2.4. Scaling Procedures

Scaling procedures are applied to adjust the amplitude of earthquake records before using them in analysis. Ground motions are scaled so that their response spectra become compatible with the target seismic design spectrum within a specified period range. Scaling may be performed using peak ground acceleration (PGA), spectral acceleration, or other seismic intensity measures. Proper scaling ensures that the earthquake records represent the intended seismic hazard level without excessively altering their natural characteristics. In PBSD studies, multiple scaled records are analyzed, and average structural responses are generally considered for performance evaluation.

3.2.5. Material and Geometric Nonlinearity

Nonlinear behavior in reinforced concrete buildings arises mainly from material and geometric nonlinearities during strong earthquake loading. Accurate representation of these nonlinear effects is essential for realistic seismic performance assessment using NLTHA.

3.3. Modeling Techniques for RC Buildings

Accurate modeling of reinforced concrete buildings is essential for reliable NLTHA results. Different modeling approaches are used depending on the required level of accuracy, computational resources, and complexity of the structure.

3.3.1. Lumped Plasticity Models

Lumped plasticity models assume that nonlinear behavior is concentrated at specific locations within structural members, typically near beam-column joints where plastic hinges are expected to form. The remaining portions of the members are assumed to behave elastically. This modeling approach is computationally efficient and widely used in practical engineering applications. Lumped plasticity models are particularly suitable for large-scale structural analysis where reduced computational demand is important.[14]

3.3.2. Distributed Plasticity Models

Distributed plasticity models represent nonlinear behavior continuously along the entire length of structural members rather than concentrating it at discrete hinge locations. These models provide more accurate simulation of gradual stiffness degradation, yielding spread, and strain distribution within members. Although computationally more demanding than lumped plasticity models, distributed plasticity approaches are highly effective for detailed seismic performance assessment of complex structures.

3.3.3. Fiber Models

Fiber models are among the most advanced modeling techniques used in NLTHA. In this approach, structural cross-sections are divided into numerous small fibers representing concrete and reinforcing steel materials individually. The stress-strain response of each fiber is calculated separately during analysis, allowing highly accurate simulation of material nonlinearity, cracking, confinement effects, and reinforcement yielding. Fiber models are capable of capturing complex interaction between axial force and bending moments, making them highly suitable for detailed seismic evaluation of RC buildings.

3.4. Plastic Hinge Formation and Damage Mechanisms

Plastic hinge formation is a key indicator of nonlinear behavior and energy dissipation in reinforced concrete structures subjected to seismic loading. During strong earthquakes, localized inelastic deformations develop at critical regions of beams, columns, and walls, leading to the formation of plastic hinges. The sequence and distribution of hinge formation provide valuable information regarding structural performance and collapse potential.

3.4.1. Hinge States

Plastic hinges pass through different performance states as deformation demand increases. These states generally include elastic behavior, yielding, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). At the IO level, structural damage is minimal and the building remains functional. At the LS level, significant damage occurs but collapse is prevented, allowing occupants to evacuate safely. At the CP level, the structure experiences severe damage and is close to collapse. Monitoring hinge states during NLTHA helps engineers evaluate whether the structure satisfies desired performance objectives.

3.4.2. Failure Modes

Reinforced concrete buildings may experience different failure modes depending on structural configuration, detailing, and seismic demand. Common failure modes include flexural failure, shear failure, axial compression failure, joint failure, and soft-story collapse. Ductile flexural failure is generally preferred because it allows significant energy dissipation before collapse. Brittle failure modes such as shear failure are highly undesirable because they occur suddenly with limited warning. NLTHA helps identify critical failure mechanisms and evaluate the adequacy of structural detailing.

3.4.3. Collapse Mechanisms

Collapse mechanisms refer to the progressive sequence of failures that eventually lead to structural instability or total collapse during severe earthquakes. In medium- and high-rise buildings, collapse mechanisms may involve soft-story formation, excessive torsional response, column failure, or global instability caused by P–Delta effects. Understanding collapse mechanisms is essential for designing earthquake-resistant structures and preventing catastrophic failure. NLTHA provides detailed insight into the development of collapse patterns and enables engineers to improve structural performance through better design and detailing strategies.

4. PERFORMANCE ASSESSMENT PROCEDURES

4.1. Performance Objectives and Limit States

Performance assessment procedures in Performance-Based Seismic Design (PBSD) are used to evaluate whether a structure can achieve desired safety and functionality levels during earthquakes. These procedures define specific performance objectives corresponding to different seismic hazard levels and expected structural conditions after an earthquake. The primary performance levels commonly adopted in seismic engineering are Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

4.1.1. Immediate Occupancy (IO)

Immediate Occupancy represents the highest performance level in which the structure experiences very minor damage during an earthquake. Structural components remain largely elastic, and the building retains most of its strength and stiffness. Non-structural damage is limited, allowing occupants to continue using the building safely after the earthquake with minimal repairs. This performance level is generally required for essential facilities such as hospitals and emergency response buildings.

4.1.2. Life Safety (LS)

Life Safety is an intermediate performance level where significant structural and non-structural damage may occur, but the probability of collapse remains low. Structural elements undergo inelastic deformation and plastic hinge formation, yet sufficient strength and stability are maintained to protect occupants from serious injury or death. Although the building may require extensive repairs, it continues to provide safe evacuation during and after the earthquake.

4.1.3. Collapse Prevention (CP)

Collapse Prevention is the minimum acceptable performance level intended to prevent total structural collapse under severe earthquake loading. At this stage, the structure experiences extensive damage, large permanent deformations, and substantial loss of stiffness and strength. However, enough residual capacity remains to avoid catastrophic failure. Buildings at the CP level are generally considered unsafe for further occupancy and may require demolition after the earthquake.

4.2. Incremental Dynamic Analysis (IDA)

Incremental Dynamic Analysis (IDA) is an advanced seismic assessment procedure used to evaluate structural behavior under progressively increasing earthquake intensity levels. In IDA, a structure is subjected to multiple scaled ground motion records, and its response is monitored until collapse or instability occurs. This method provides detailed insight into structural performance, damage progression, and collapse capacity.

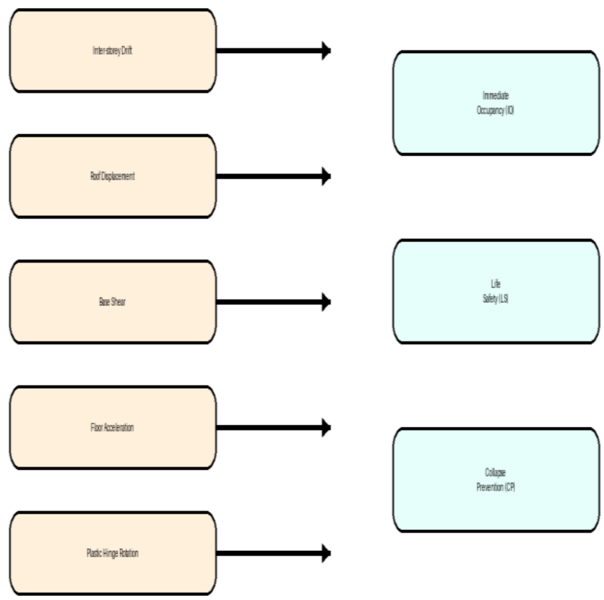

Figure 3. Relationship between NLTHA response parameters and seismic performance levels.

Figure 3 shows the important engineering demand parameters evaluated during NLTHA, including inter-storey drift, roof displacement, base shear, floor acceleration, and plastic hinge rotation. These response quantities are used to assess structural performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The figure demonstrates how nonlinear seismic response is linked with predefined PBSD performance objectives.

4.2.1. Fragility Curves

Fragility curves are probabilistic relationships that represent the likelihood of a structure reaching or exceeding a specific damage state under varying earthquake intensities. These curves are developed using IDA results and are widely used in seismic risk assessment and performance evaluation.

4.2.2. Collapse Capacity

Collapse capacity refers to the maximum seismic intensity that a structure can withstand before experiencing global instability or collapse. IDA helps determine collapse capacity by gradually increasing earthquake intensity and observing the point at which structural failure occurs.

4.2.3. Performance Evaluation Under Multiple Intensity Levels

One of the major advantages of IDA is its ability to assess structural performance under different seismic hazard levels. By analyzing responses under multiple earthquake intensities, engineers can evaluate deformation demands, damage progression, and collapse risk more comprehensively. This approach improves reliability of PBSD and helps ensure safer seismic design of reinforced concrete buildings.

5. REVIEW OF RECENT STUDIES ON MEDIUM- TO HIGH-RISE RC BUILDINGS

5.1. Regular RC Buildings

Many researchers have studied regular reinforced concrete (RC) buildings using Nonlinear Time History Analysis (NLTHA) under the Performance-Based Seismic Design (PBSD) framework. Regular buildings have uniform mass and stiffness distribution, resulting in better seismic performance and lower torsional effects. Software such as ETABS, SAP2000, and OpenSees are commonly used with earthquake records like El Centro, Kobe, and Northridge. Studies showed that regular buildings generally perform better than irregular structures, although higher mode effects and P–Delta effects become important in high-rise buildings.

5.2. Vertically Irregular Buildings

Vertically irregular buildings, including setback and soft-story structures, have been widely investigated because irregularities significantly affect seismic behavior. Researchers mainly used ETABS and SAP2000 with FEMA- and ASCE-based nonlinear hinge models. Findings indicated that vertically irregular buildings experience larger inter-storey drifts, concentrated plastic hinges, and greater collapse vulnerability. However, many studies were limited by simplified modeling assumptions and lack of soil-structure interaction consideration.

5.3. Torsionally Irregular Buildings

Torsional irregularity causes rotational response due to eccentricity between the center of mass and center of rigidity. Studies using ETABS and OpenSees reported that torsionally irregular buildings experience larger edge displacements and uneven damage distribution. Researchers concluded that torsional irregularity increases seismic demand and collapse risk in high-rise buildings. Limited three-dimensional modeling and experimental validation remain major research gaps.

5.4. Shear Wall and Dual Structural Systems

Studies on shear wall and dual structural systems showed that the inclusion of shear walls significantly improves seismic resistance by reducing inter-storey drift and lateral displacement. Researchers commonly performed NLTHA using ETABS and SAP2000 with real earthquake records. Dual systems demonstrated better stiffness, stability, and energy dissipation compared to bare frame structures. However, improper wall placement may lead to stiffness irregularities and stress concentration.

5.5. Buildings with Dampers and Base Isolation

Recent studies focused on seismic protection systems such as fluid viscous dampers, friction dampers, and base isolators. Using NLTHA in ETABS, SAP2000, and OpenSees, researchers found that these systems effectively reduce base shear, floor acceleration, inter-storey drift, and structural damage. Base-isolated buildings showed improved seismic performance and energy dissipation. Nevertheless, higher cost, maintenance, and modeling complexity remain important limitations.

Table 1: Comparison Table of Recent Studies on Medium- to High-Rise RC Buildings

Author	Year	Building Type	Analysis Method	Major Findings
V. R. Deoda and S. Adhikary[15]	*2022*	5-storey monolithic and precast RC buildings	NLTHA using SAP2000	Monolithic RC building showed lower roof displacement than precast RC building; site-specific spectra significantly affected structural response.
Bed Prakash Gupta[16]	*2025*	10-storey vertically irregular RC building with dampers	Time history analysis using SAP2000	Fluid viscous dampers significantly reduced roof displacement and plastic hinge formation in irregular buildings.
Amin Tahmasebi and Mostafa Rahimi[17]	*2021*	Multi-storey steel and high-rise frame structures	Nonlinear static and dynamic analysis	FEMA 356 criteria were effective for low- and mid-rise buildings but less reliable for small high-rise structures.
J. Guadalupe Monjardin-Quevedo et al.[18]	*2022*	RC and steel buildings under multi-level earthquakes	Probabilistic PBSD assessment using NLTHA	Multi-level seismic assessment improved reliability of performance prediction and fragility evaluation.
Mrudula Madhukumar et al.[19]	*2022*	Low-, medium-, and high-rise RC buildings with base isolation	NLTHA with lead rubber bearing systems	Base isolation significantly reduced seismic response, displacement demand, and structural damage.
Andrew Sen et al. [20]	*2023*	Existing RC buildings	ASCE 41 nonlinear dynamic procedures	ASCE/SEI 41 procedures showed reasonable agreement with observed empirical damage patterns.

Figure 5 compares the relative seismic response of various reinforced concrete building configurations, including regular buildings, vertically irregular structures, torsionally irregular systems, shear wall systems, and base-isolated buildings. The comparison highlights how structural irregularities increase seismic demand, while shear walls and base isolation systems significantly improve seismic performance and reduce structural response during earthquakes.

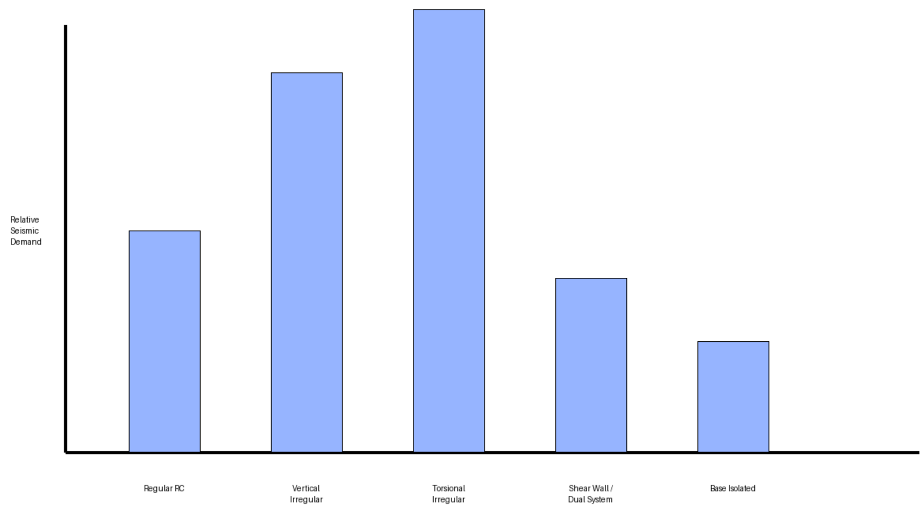

Figure 4. Comparative seismic response characteristics of different RC building configurations.

6. COMPARATIVE REVIEW OF SEISMIC ANALYSIS METHODS

6.1. Linear Static Analysis

Linear Static Analysis is the simplest seismic analysis method in which earthquake forces are applied as equivalent static lateral loads. It is easy to perform and requires less computational effort. However, this method cannot capture dynamic effects, nonlinear behavior, or higher mode response, making it unsuitable for complex and high-rise buildings.

6.2. Response Spectrum Analysis

Response Spectrum Analysis considers the dynamic characteristics of structures such as natural periods and mode shapes. It provides better accuracy than linear static analysis for multi-storey buildings. However, the method assumes linear elastic behavior and cannot directly represent material nonlinearity or collapse mechanisms during severe earthquakes.

6.3. Nonlinear Static (Pushover) Analysis

Nonlinear Static or Pushover Analysis estimates the seismic capacity of structures by applying gradually increasing lateral loads until failure occurs. It helps identify plastic hinge formation and performance levels. Although useful for low- and medium-rise buildings, it has limitations in representing higher mode effects and complex dynamic behavior in high-rise structures.

6.4. Nonlinear Time History Analysis

Nonlinear Time History Analysis (NLTHA) is the most advanced seismic analysis method because it captures actual nonlinear structural response under real earthquake ground motions. It accurately predicts displacement, damage progression, plastic hinge formation, and collapse behavior. However, NLTHA requires significant computational effort, detailed modeling, and large analysis time.

6.5. Comparative Discussion

Among all seismic analysis methods, Linear Static Analysis requires the least computational effort but provides the lowest accuracy. Response Spectrum Analysis improves dynamic response prediction but still assumes elastic behavior. Pushover Analysis offers better insight into structural capacity and nonlinear behavior but is less reliable for tall buildings with higher mode effects. NLTHA provides the highest accuracy and is most suitable for medium- and high-rise buildings, although it is computationally expensive and complex to perform.

7. CONCLUSION

The review highlights that Performance-Based Seismic Design (PBSD) has emerged as a more reliable and advanced approach compared to conventional force-based seismic design methods for medium- to high-rise reinforced concrete buildings. Traditional seismic analysis methods such as linear static and response spectrum analysis are useful for preliminary assessment but are limited in capturing the actual nonlinear behavior of structures during strong earthquakes. Among the available analytical procedures, Nonlinear Time History Analysis (NLTHA) is identified as the most accurate and comprehensive method for evaluating seismic performance because it can realistically simulate cracking, yielding, stiffness degradation, plastic hinge formation, and collapse mechanisms under earthquake loading. The literature review further shows that structural irregularities, torsional effects, and higher mode responses significantly influence seismic behavior and must be carefully considered in performance evaluation. Studies also demonstrate that shear walls, dual systems, dampers, and base isolation techniques considerably improve the seismic performance and resilience of RC buildings. Despite its advantages, NLTHA involves high computational demand, complex modeling procedures, and uncertainties related to ground motion selection and material behavior.

Nevertheless, ongoing advancements in computational tools, seismic guidelines, and nonlinear modeling techniques are continuously improving the effectiveness of PBSD. Therefore, NLTHA-based PBSD can be considered an essential and reliable framework for achieving safer, more resilient, and performance-oriented seismic design of medium- to high-rise reinforced concrete buildings.

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