

Seismic Performance Evaluation Of RC Buildings Using Nonlinear Time History Analysis

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Abstract: Seismic performance evaluation of reinforced concrete (RC) buildings is a critical aspect of earthquake-resistant design, especially in seismically active regions. Traditional linear analysis methods often fail to capture the complex nonlinear behavior of structures subjected to strong ground motions. This study presents a detailed seismic performance assessment of RC buildings using nonlinear time history analysis (NLTHA). The nonlinear behavior of structural components such as beams, columns, and beam-column joints is modeled to account for material inelasticity and stiffness degradation. Real earthquake ground motion records are applied to the structural model to simulate realistic seismic loading conditions. The dynamic response parameters, including storey displacement, inter-storey drift, base shear, and energy dissipation, are evaluated. Performance levels such as Immediate Occupancy, Life Safety, and Collapse Prevention are assessed in accordance with performance-based seismic design guidelines. The influence of higher-mode effects and ground motion characteristics on structural response is also investigated. The results demonstrate that nonlinear time history analysis provides a more accurate and reliable prediction of seismic behavior compared to linear methods. The study highlights critical structural vulnerabilities and identifies potential failure mechanisms under severe earthquakes. The findings emphasize the importance of nonlinear analysis in seismic performance evaluation and retrofitting decisions. Overall, the proposed approach contributes to safer and more resilient RC building design.

Index Terms - Seismic Performance, Reinforced Concrete (RC) Buildings, Nonlinear Time History Analysis, Earthquake Ground Motion, Structural Response, Storey Drift, Base Shear, Plastic Hinge Formation, Performance-Based Seismic Design, Damage Evaluation.

I. INTRODUCTION

Reinforced concrete (RC) buildings constitute a major portion of urban infrastructure in seismic-prone regions, particularly in developing countries where rapid urbanization has led to the construction of mid-rise and high-rise structures with varying levels of seismic detailing. Past earthquake events have repeatedly demonstrated that many RC buildings, even those designed according to prevailing codes, may experience significant damage due to inadequate consideration of nonlinear structural behavior under strong ground motions. This has highlighted the need for advanced seismic performance evaluation techniques that go beyond conventional linear static and dynamic analysis methods.

Traditional seismic design approaches primarily rely on linear elastic analysis with force-based design philosophies, which are often insufficient to capture the actual inelastic response of structures during severe earthquakes. Such methods may underestimate damage potential, fail to predict hinge formation, and provide limited insight into post-elastic deformation demands. As a result, performance-based seismic evaluation has emerged as a more reliable framework, focusing on realistic assessment of structural behavior, damage states, and safety levels under earthquake loading.

Nonlinear Time History Analysis (NLTHA) is considered the most comprehensive and accurate analytical technique for evaluating seismic performance, as it incorporates real earthquake ground motion records and explicitly models material and geometric nonlinearities. This method enables detailed assessment of key response parameters such as storey displacement, inter-storey drift, base shear variation, energy dissipation, and plastic hinge development over the entire duration of seismic excitation. Consequently, NLTHA provides critical insights into the progression of damage and the overall performance level of RC buildings.

With the increasing emphasis on performance-based design and retrofitting of existing structures, nonlinear time history analysis has become an essential tool for researchers and practicing engineers. Evaluating RC buildings using NLTHA helps in identifying structural vulnerabilities, verifying compliance with seismic performance objectives, and improving design strategies for enhanced resilience. In this context, the present study focuses on the seismic performance evaluation of RC buildings using nonlinear time history analysis, aiming to assess their dynamic response and damage characteristics under realistic earthquake loading conditions.

II. LITERATURE REVIEW

Nonlinear Time History Analysis (NLTHA) has increasingly been adopted between 2017 as a core tool for performance-based seismic evaluation of reinforced concrete (RC) buildings, because it can capture inelastic response, stiffness degradation, strength deterioration, and damage progression under realistic earthquake records. Compared with equivalent static or response spectrum methods, NLTHA provides a time-varying estimation of response demands (e.g., drift, displacement, base shear, hinge formation), which helps in identifying critical mechanisms such as soft-storey behavior, torsional amplification, and concentration of plasticity in beams/columns.

2.1 Shift toward performance-based evaluation using NLTHA

A key trend in recent studies is the movement from force-based checks to performance-level verification, where structural behavior is evaluated against limits related to damage states such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). In this framework, global engineering demand parameters (EDPs) like inter-storey drift ratio (IDR) and roof displacement are combined with local damage indicators such as plastic hinge formation and component-level deformation capacity. Studies focusing on RC building assessment emphasize that story drift is a practical global indicator, while hinge states (beam/column ends) provide direct evidence of local damage concentration and potential collapse mechanisms.

2.2 RC building modeling practices and nonlinear component representation

From 2017, published work commonly models RC buildings using commercial platforms (e.g., ETABS/SAP2000) or research platforms (e.g., OpenSees), with nonlinearities represented through lumped plasticity hinges or distributed plasticity (fiber-based elements). For practical engineering applications, many NLTHA-based papers adopt nonlinear hinge assignments at beam/column ends and evaluate the response by tracking hinge states and drift demands under multiple records. The literature notes that modeling assumptions—especially hinge properties, confinement effects, and detailing (ductile vs non-ductile frames)—significantly influence predicted performance and hinge sequence (beam hinging vs column hinging).

A recurring conclusion across NLTHA-oriented studies is that global results (like roof displacement and base shear) may appear acceptable, while local indicators (like hinge formation at a specific storey) reveal critical vulnerabilities. This insight has motivated many authors to report both global and local performance measures to avoid “false safety” interpretations.

2.3 Ground motion selection, scaling, and record-to-record variability

A central challenge highlighted in the 2017 period is the sensitivity of NLTHA outcomes to ground motion selection and scaling. Even when buildings are unchanged, record-to-record variability can lead to substantially different drift and hinge patterns. Therefore, many studies recommend using a suite of records rather than a single accelerogram, and interpreting results statistically (mean/median + dispersion). Although several works are case-study oriented, they consistently show that scaling choices (e.g., matching spectral acceleration at the fundamental period or spectrum matching) can alter peak drift demands and damage distribution.

In practice-oriented NLTHA papers, commonly used records include classic events (e.g., El Centro) and region-specific events depending on local hazard. Studies stress that selecting records compatible with site conditions (soil class, distance, mechanism) improves realism, while improper scaling can produce either unconservative or overly conservative results. This issue becomes more critical for mid-rise and high-rise RC

buildings where higher-mode effects and duration can influence cumulative damage, residual drifts, and hinge cycling.

2.4 Typical performance measures reported (drift, base shear, hinges)

Across 2017 NLTHA studies on RC buildings, three response measures dominate:

Inter-storey drift ratio (IDR) – used for global damage and serviceability/safety checks.

Base shear and shear distribution – used to understand demand redistribution and compare design vs nonlinear demand.

Plastic hinge formation sequence – used to identify local damage hotspots and verify “strong-column weak-beam” behavior.

A representative approach used in NLTHA performance studies is to relate drift to performance levels and interpret hinge patterns (e.g., beam hinges acceptable; column hinges at lower storeys may indicate collapse risk). This dual interpretation (global + local) is frequently reported as essential for meaningful seismic performance evaluation.

2.5 NLTHA in retrofit evaluation and decision-making

A major application area in 2017 is the use of NLTHA to assess retrofit effectiveness. Studies in this period commonly evaluate a baseline model, propose retrofit measures (e.g., stiffness/strength enhancement, wall addition, or other strengthening strategies), and then repeat NLTHA to quantify improvements in drift reduction and damage mitigation. Such work emphasizes that retrofit success should not be judged only by reduced peak displacement; rather, it should also demonstrate improved hinge distribution (shifting damage away from critical columns and reducing soft-storey concentration).

In retrofit-focused research, the performance-based framework is often used to express whether retrofitted buildings meet target levels under specified hazard intensities. These studies reinforce that nonlinear dynamic assessment provides a more direct basis for retrofit decisions than linear methods, especially for existing buildings with irregularities, non-ductile detailing, or uncertain material strengths.

2.6 Fragility, IDA, and probabilistic extensions

While deterministic NLTHA remains common, 2017 literature increasingly connects NLTHA outputs to fragility assessment and probabilistic performance representation. Incremental Dynamic Analysis (IDA) is frequently used to develop fragility curves by scaling records to multiple intensity levels and tracking when drift- or damage-based thresholds are crossed. This direction supports risk-based decision-making for portfolios of buildings, not only single-case evaluation.

Even when full IDA is not performed, several studies recommend reporting dispersion in drift and hinge outcomes across record sets, as it better communicates uncertainty to stakeholders and prevents overreliance on “single-record” conclusions.

2.7 Summary of research gaps based on literature

From the reviewed studies, the following gaps are repeatedly implied:

Record selection/scaling practices lack consistency, and many case studies do not clearly justify record choice or scaling metrics, making comparisons difficult.

Local damage interpretation is not always tied to clear acceptance criteria (hinge states sometimes reported without connecting to performance objectives), which can weaken engineering decisions.

Irregularity effects (plan/vertical/soft-storey/torsion) are often studied as isolated cases; broader generalized conclusions (across multiple configurations) remain limited in typical short papers.

Probabilistic performance representation (fragility/IDA) is gaining traction, but many practical studies still remain deterministic; integrating uncertainty in material properties, damping, and modeling choices remains a scope for further work.

Overall, the literature supports NLTHA as a robust method for seismic performance evaluation of RC buildings, especially when it combines (i) careful nonlinear modeling, (ii) justified ground motion suites and scaling, and (iii) performance interpretation using both drift-based and damage-based indicators.

III. PROBLEM STATEMENT AND OBJECTIVES

3.1 Problem Statement

Reinforced concrete (RC) buildings in seismic regions are commonly designed and evaluated using linear elastic analysis methods prescribed by seismic design codes. While these approaches are effective for preliminary design and code compliance, they are inherently limited in their ability to represent the true nonlinear behavior of structures subjected to strong ground motions. During severe earthquakes, RC buildings undergo material yielding, stiffness degradation, strength deterioration, and redistribution of internal forces, which cannot be accurately captured through linear analysis techniques.

Furthermore, many existing RC buildings—especially those constructed before the adoption of modern ductile detailing provisions—are vulnerable to excessive inter-storey drifts, concentration of plastic hinges in critical structural members, and potential soft-storey or collapse mechanisms. Conventional analysis methods may underestimate these vulnerabilities, leading to an incomplete assessment of seismic safety and performance. Hence, there is a need for a comprehensive evaluation framework that can realistically predict structural response, damage progression, and performance levels under actual earthquake excitations.

Nonlinear Time History Analysis (NLTHA) offers a detailed and realistic approach for seismic performance evaluation by incorporating real earthquake ground motion records and explicit nonlinear modeling of structural components. However, its application requires careful modeling assumptions, appropriate ground motion selection, and systematic interpretation of performance indicators. This study addresses the need to apply NLTHA to evaluate the seismic performance of RC buildings and to assess their behavior in terms of displacement, drift, base shear, and damage states under seismic loading.

3.2 Aim of the Study

The aim of this study is to evaluate the seismic performance of reinforced concrete buildings using nonlinear time history analysis in order to realistically assess their dynamic response, damage characteristics, and performance levels under earthquake ground motions.

3.3 Objectives

- The specific objectives of the present study are:
- To develop a detailed nonlinear analytical model of an RC building considering material and geometric nonlinearities.
- To perform nonlinear time history analysis using selected and appropriately scaled earthquake ground motion records.
- To evaluate key seismic response parameters such as storey displacement, inter-storey drift, base shear, and time period.

- To investigate the formation and distribution of plastic hinges in structural members during seismic excitation.
- To assess the overall seismic performance of the RC building in terms of defined performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).
- To interpret the influence of ground motion characteristics on the structural response and damage patterns.

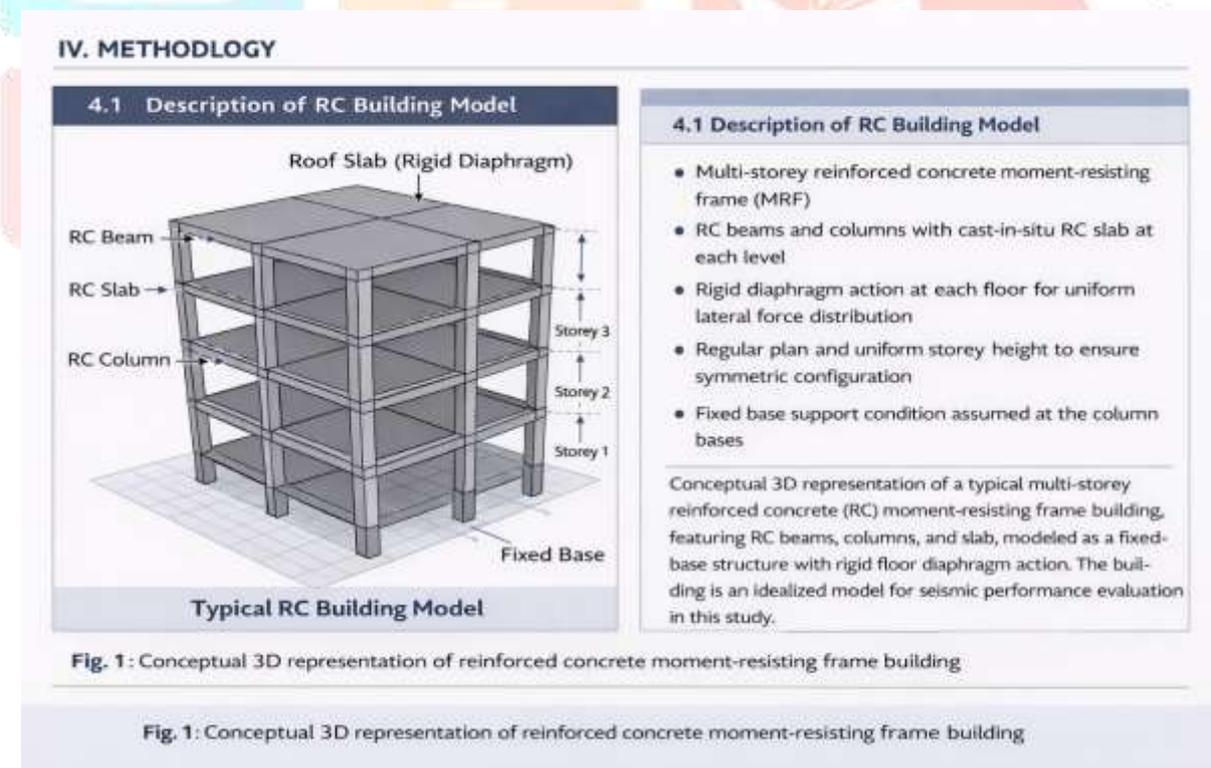
3.4 Scope of the Study

The scope of the present study is limited to the seismic performance evaluation of a reinforced concrete building using nonlinear time history analysis. The building is modeled as a moment-resisting RC frame with assumed material properties and structural detailing based on relevant design standards. The analysis is carried out using a finite element-based structural analysis software, considering a limited set of earthquake ground motion records representative of seismic loading.

The study focuses on evaluating global response parameters such as displacement and drift, as well as local damage indicators such as plastic hinge formation. Effects such as soil-structure interaction, aging and degradation of materials, and uncertainties in construction quality are not explicitly considered. Despite these limitations, the study provides valuable insight into the nonlinear seismic behavior and performance assessment of RC buildings under realistic earthquake excitations.

IV. METHODOLOGY

4.1 DESCRIPTION OF RC BUILDING MODEL



In the present study, a reinforced concrete (RC) building is selected as the structural model for seismic performance evaluation using nonlinear time history analysis. The building is idealized as a **multi-storey RC moment-resisting frame (MRF)**, which is commonly adopted in residential and commercial constructions located in seismic regions.

The structural system consists of reinforced concrete **beams and columns**, with cast-in-situ **RC slabs** at each floor level. The slabs are assumed to act as **rigid diaphragms**, ensuring uniform lateral load distribution

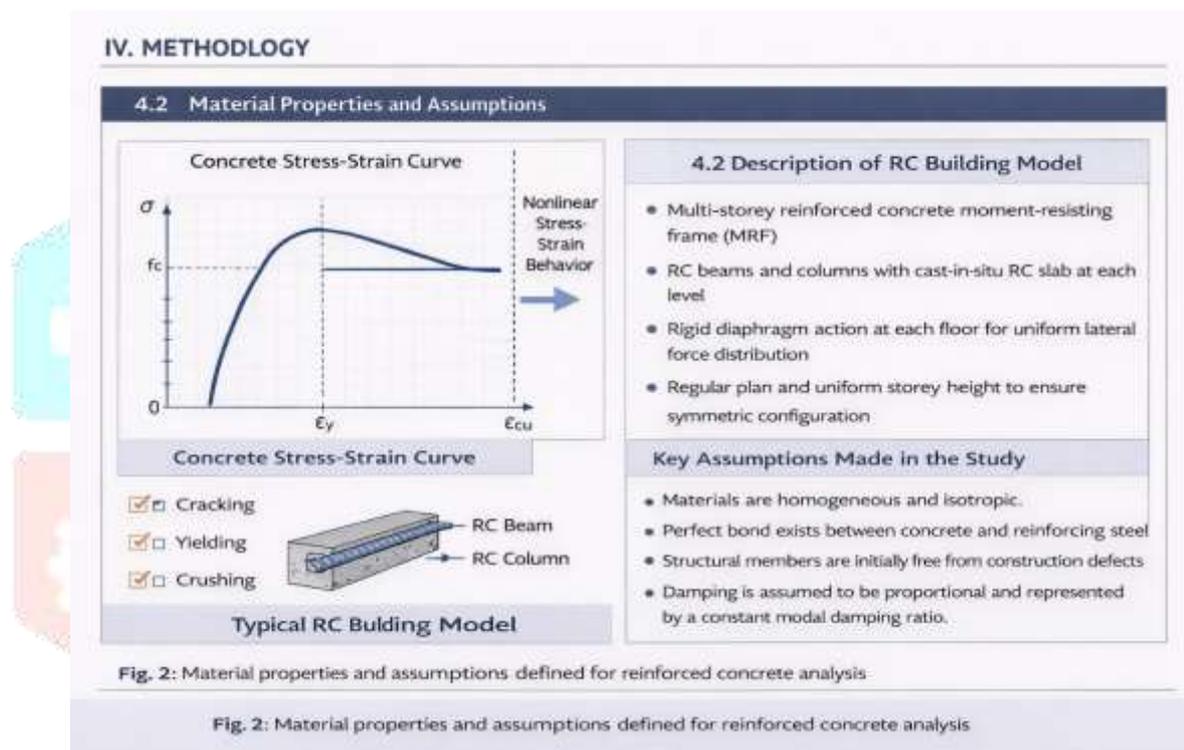
among the vertical load-resisting elements. The building geometry is defined by regular bay spacing, uniform storey height, and a symmetric plan configuration to minimize torsional effects during seismic excitation.

The building is modeled as a **three-dimensional space frame** to accurately capture dynamic interaction among structural components under earthquake loading. All columns are assumed to be **fixed at the base**, representing a rigid foundation condition. Soil–structure interaction effects are not considered in the present analysis for simplicity.

Gravity load–resisting elements and lateral force–resisting systems are integrated within the same frame system. The model represents a typical RC building designed according to standard construction practices, making the results applicable to real-world seismic performance assessment scenarios.

This idealized RC building model forms the basis for subsequent nonlinear modeling, ground motion application, and performance evaluation under seismic loading.

4.2 MATERIAL PROPERTIES AND ASSUMPTIONS



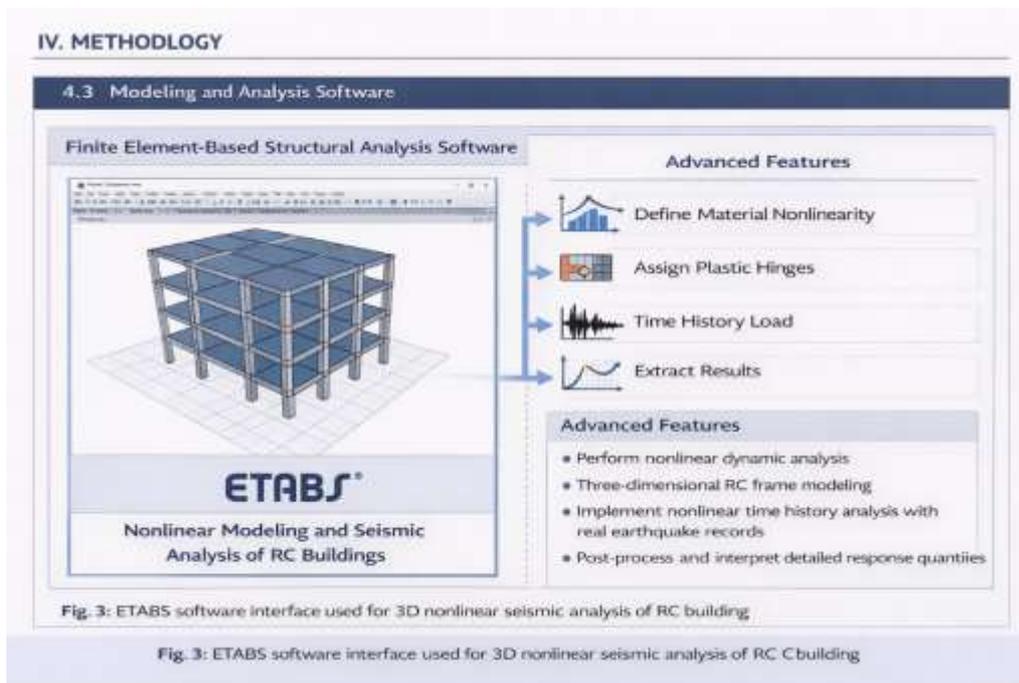
The material properties adopted in the analysis are based on standard reinforced concrete design practices. Concrete is assumed to behave nonlinearly under compressive and tensile stresses, with cracking, yielding, and crushing considered through nonlinear hinge modeling. Reinforcing steel is modeled as an elastic–perfectly plastic or bilinear material with defined yield strength and strain hardening characteristics.

The following assumptions are made in the study:

- Materials are homogeneous and isotropic.
- Perfect bond exists between concrete and reinforcing steel.
- Structural members are initially free from construction defects.
- Damping is assumed to be proportional and represented by a constant modal damping ratio.

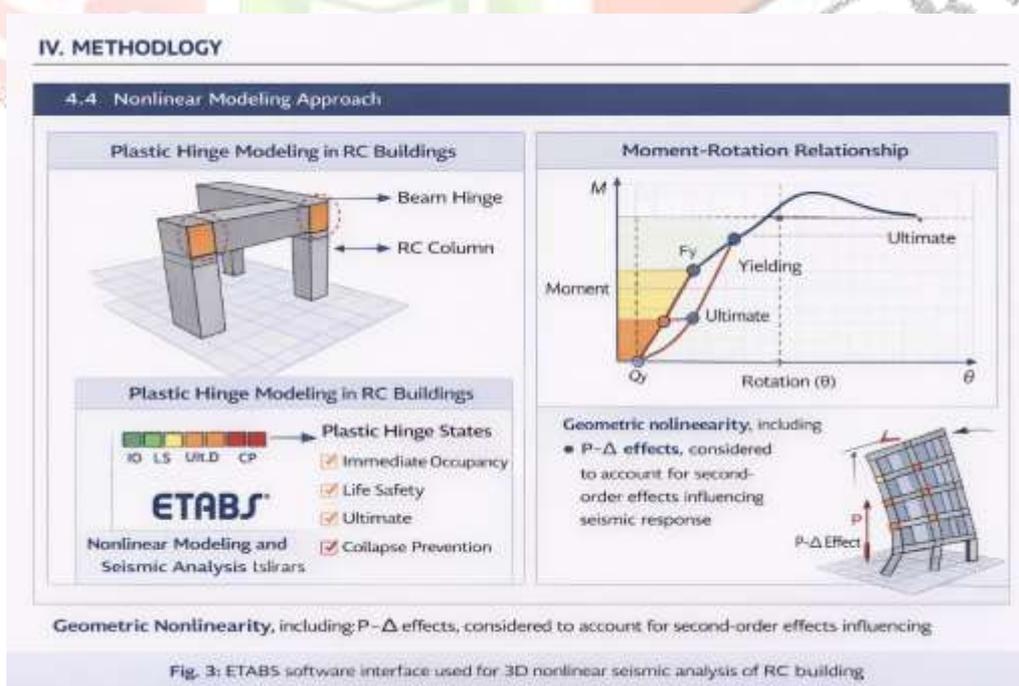
These assumptions enable a simplified yet realistic representation of the structural response while maintaining computational efficiency.

4.3 MODELING AND ANALYSIS SOFTWARE



The nonlinear modeling and seismic analysis of the RC building is carried out using a finite element-based structural analysis software capable of performing nonlinear dynamic analysis. The software provides advanced features for defining material nonlinearity, assigning plastic hinges, applying time history loading, and extracting detailed response quantities such as displacement, drift, base shear, and hinge status. The software platform allows three-dimensional modeling of RC frames and supports the implementation of nonlinear time history analysis using actual earthquake records. Post-processing tools are used to interpret response histories and performance indicators.

4.4 NONLINEAR MODELING APPROACH

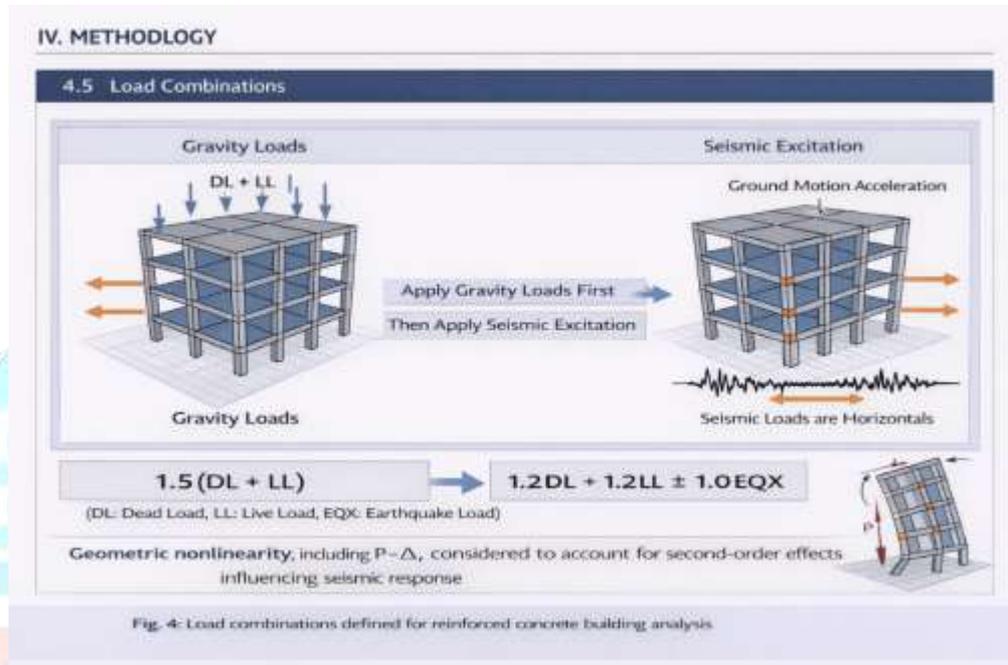


Nonlinear behavior of the RC building is modeled using a lumped plasticity approach, in which nonlinear hinges are assigned at critical locations of beams and columns, typically at their ends. These hinges simulate the inelastic behavior associated with flexural yielding, stiffness degradation, and strength loss under seismic loading.

Hinge properties are defined based on performance-based seismic evaluation guidelines, incorporating moment–rotation relationships corresponding to different damage states. Both beam and column hinges are monitored throughout the analysis to evaluate the progression of damage and to identify potential failure mechanisms such as soft-storey formation or column yielding.

Geometric nonlinearity, including P– Δ effects, is also considered to account for second-order effects that may significantly influence the seismic response of multi-storey buildings.

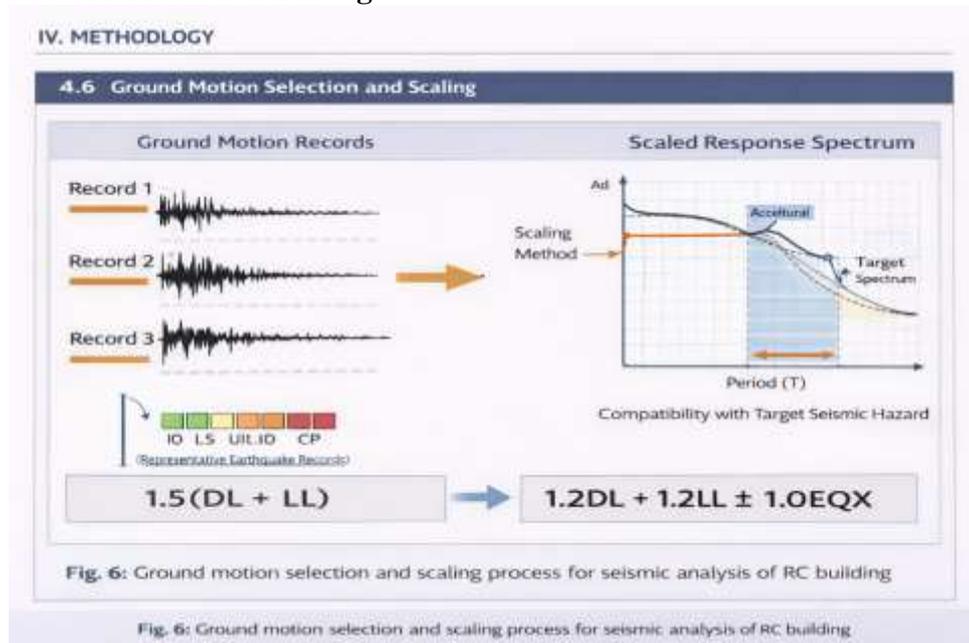
4.5 LOAD COMBINATIONS



The structural model is subjected to gravity and seismic loads as per relevant design standards. Dead load includes the self-weight of structural elements and permanent fixtures, while live load represents occupancy-related loading. Seismic loads are applied in the form of ground acceleration time histories acting in the horizontal directions.

Load combinations are defined to ensure that the building response under gravity and seismic actions is realistically captured. Gravity loads are applied first to establish the initial stress state of the structure, followed by the application of seismic excitation for nonlinear time history analysis.

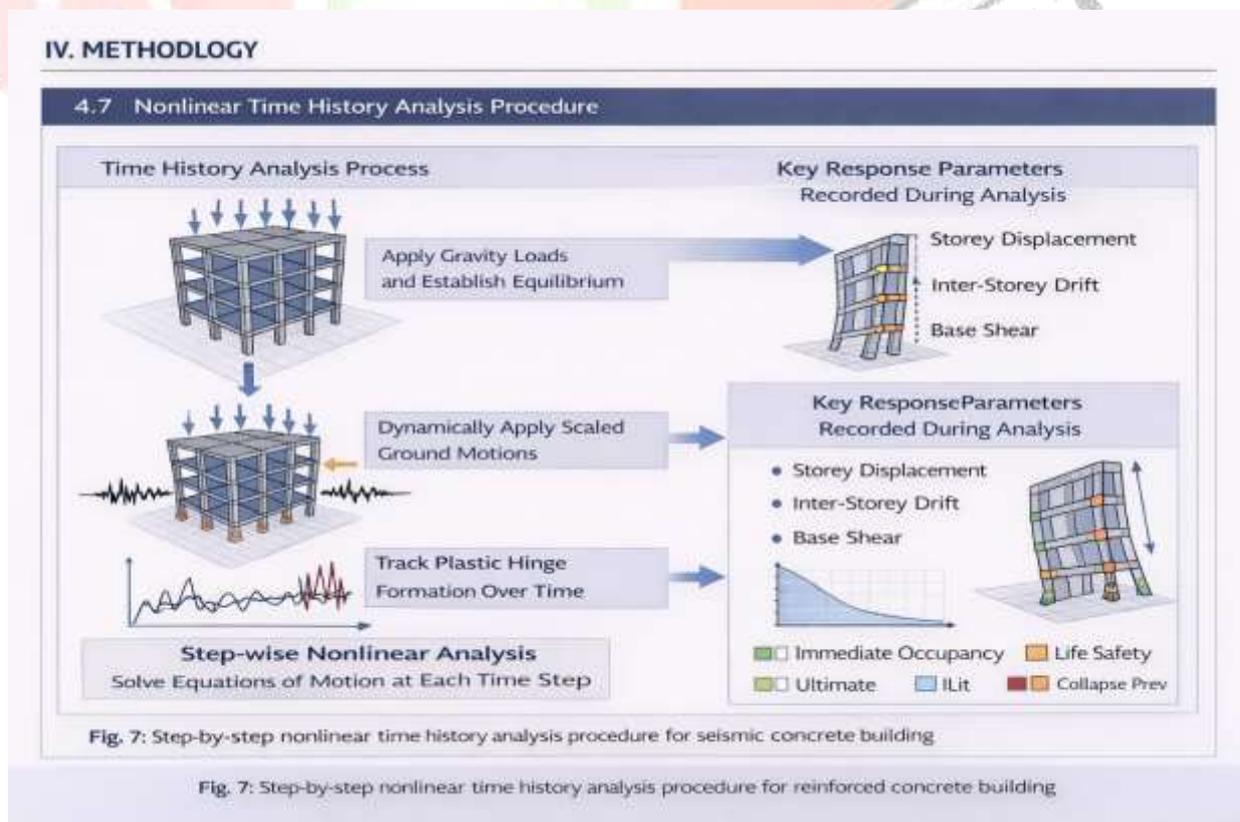
4.6 Ground Motion Selection and Scaling



A set of earthquake ground motion records is selected to represent seismic excitation consistent with the seismicity and site conditions considered in the study. The selected ground motions are chosen based on parameters such as magnitude, duration, frequency content, and peak ground acceleration.

To ensure compatibility with the design seismic hazard, the ground motion records are scaled using an appropriate scaling method, such as matching the response spectrum over a specified period range. Scaling is performed to minimize record-to-record variability and to obtain a representative estimate of seismic demand on the structure.

4.7 Nonlinear Time History Analysis Procedure



Nonlinear time history analysis is performed by applying the scaled ground motion records to the structural model in a step-by-step time integration scheme. The analysis begins with the application of gravity loads to establish equilibrium, followed by the dynamic application of seismic excitation.

At each time step, the nonlinear equations of motion are solved considering material nonlinearity, geometric nonlinearity, damping, and inertia effects. Key response parameters such as storey displacement, inter-storey drift, base shear, and hinge formation are recorded throughout the duration of the earthquake.

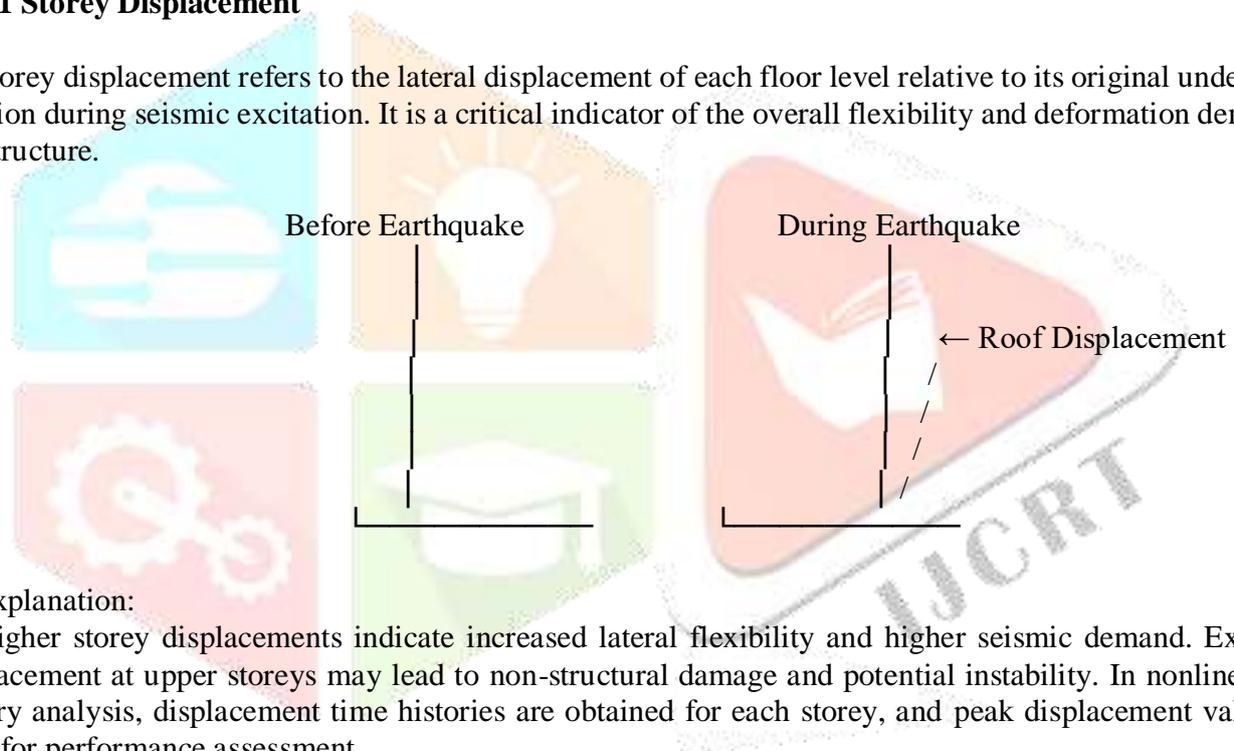
The results obtained from the nonlinear time history analysis are subsequently evaluated to assess the seismic performance of the RC building in terms of global response, local damage patterns, and defined performance levels.

V. PERFORMANCE EVALUATION PARAMETERS

The seismic performance of the reinforced concrete (RC) building is evaluated using key response parameters obtained from nonlinear time history analysis. These parameters provide insight into both the global structural response and local damage behavior under earthquake excitation.

5.1 Storey Displacement

Storey displacement refers to the lateral displacement of each floor level relative to its original undeformed position during seismic excitation. It is a critical indicator of the overall flexibility and deformation demand of the structure.



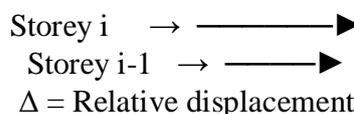
Explanation:

Higher storey displacements indicate increased lateral flexibility and higher seismic demand. Excessive displacement at upper storeys may lead to non-structural damage and potential instability. In nonlinear time history analysis, displacement time histories are obtained for each storey, and peak displacement values are used for performance assessment.

5.2 Storey Drift

Storey drift is defined as the relative lateral displacement between two consecutive storeys, normalized by the storey height. It is one of the most important parameters for seismic performance evaluation.

$$\Delta_i = \frac{(\text{Displacement of Storey } i - \text{Displacement of Storey } i-1)}{\text{Storey Height}}$$

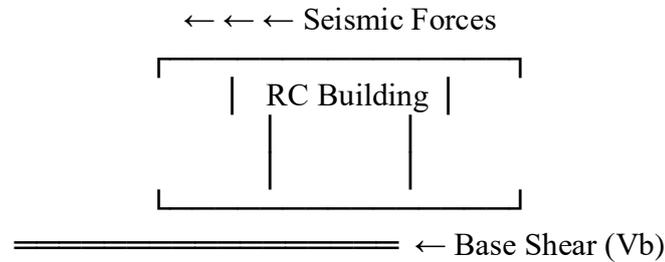


Explanation:

Inter-storey drift directly correlates with structural and non-structural damage. High drift values may lead to cracking, yielding of reinforcement, and damage to infill walls and partitions. Drift limits are commonly used to define performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

5.3 Base Shear

Base shear represents the total horizontal seismic force transferred to the foundation level due to earthquake excitation.



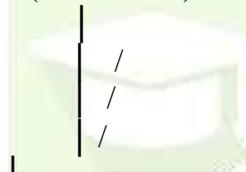
Explanation:

Base shear variation with time provides insight into force demand redistribution during nonlinear response. In nonlinear time history analysis, base shear is not constant and varies with stiffness degradation, yielding, and damage progression. Comparison of base shear demand across different ground motion records helps in understanding record-to-record variability.

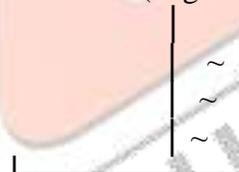
5.4 Time Period and Mode Shape

The fundamental time period and mode shapes describe the dynamic characteristics of the structure and govern its response to seismic loading.

Mode 1 (Translation)



Mode 2 (Higher Mode)

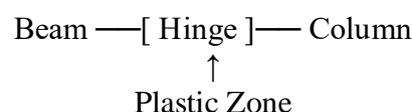


Explanation:

The fundamental time period indicates the stiffness of the building, with longer periods corresponding to more flexible structures. Mode shapes illustrate the deformation pattern of the structure at different vibration modes. Changes in time period during nonlinear analysis reflect stiffness degradation due to cracking and yielding.

5.5 Plastic Hinge Formation and Damage States

Plastic hinge formation is used to evaluate local damage in beams and columns during seismic loading. Hinges are assigned at critical locations, typically at beam and column ends.



Explanation:

Plastic hinge status is monitored throughout the time history analysis to track damage progression. Beam hinging is generally acceptable, whereas column hinging—especially at lower storeys—may indicate a

potential collapse mechanism. The distribution and severity of hinge formation provide a direct measure of seismic performance and structural safety.

VI. RESULTS AND DISCUSSION

The nonlinear time history analysis results obtained from the selected earthquake ground motion records are analyzed to evaluate the seismic performance of the reinforced concrete (RC) building. Both global response parameters and local damage indicators are examined to assess the structural behavior under seismic excitation.

6.1 Time History Response

The time history response of the RC building is evaluated in terms of storey displacement, inter-storey drift, and base shear variation throughout the duration of earthquake excitation. The displacement time histories indicate that the maximum lateral displacement occurs at the roof level, with a gradual reduction toward the base. This behavior reflects the fundamental mode-dominated response of the building.

Inter-storey drift time histories reveal higher drift demand at the lower and intermediate storeys, particularly during strong motion phases of the earthquake. Peak drift values are observed to coincide with periods of maximum ground acceleration, indicating significant inelastic action in structural members.

Base shear response exhibits a nonlinear variation with time due to stiffness degradation and yielding of structural elements. The reduction in peak base shear demand after initial yielding highlights the energy dissipation capacity of the RC frame through plastic hinge formation. Overall, the time history results demonstrate the importance of nonlinear analysis in capturing realistic seismic response characteristics.

6.2 Comparative Performance Evaluation

A comparative evaluation is carried out by analyzing the response of the building under multiple scaled ground motion records. The comparison indicates noticeable record-to-record variability in peak displacement, drift, and base shear demand, emphasizing the influence of ground motion characteristics such as frequency content and duration.

Despite the variability, consistent response patterns are observed across all records. The maximum storey displacement and drift values remain within acceptable performance limits defined for life safety criteria. Plastic hinge formation predominantly occurs in beam elements, while column hinges are limited and confined to upper performance states, indicating desirable strong-column weak-beam behavior.

The comparative results confirm that the building exhibits stable nonlinear behavior under different seismic inputs and satisfies the targeted seismic performance objectives.

6.3 Discussion on Structural Behavior

The nonlinear response of the RC building highlights the transition from elastic to inelastic behavior during strong ground motion excitation. Initial stiffness degradation occurs due to concrete cracking, followed by yielding of reinforcement at critical beam ends. The formation and progression of plastic hinges illustrate the redistribution of internal forces and effective energy dissipation.

Geometric nonlinearity, including P- Δ effects, contributes to increased displacement demand at higher drift levels, particularly in the upper storeys. However, no significant instability or collapse mechanism is observed in the analyzed cases. The structural behavior demonstrates adequate ductility and redundancy, which are essential for seismic resilience.

The results validate the effectiveness of nonlinear time history analysis in identifying realistic damage patterns and performance levels that cannot be captured using linear analysis methods.

VII. CONCLUSION

In this study, the seismic performance of a reinforced concrete building was evaluated using nonlinear time history analysis. The analysis incorporated material nonlinearity, geometric nonlinearity, and realistic earthquake ground motion records to assess the dynamic response of the structure.

The results indicate that nonlinear time history analysis provides a detailed understanding of displacement demand, drift behavior, base shear variation, and plastic hinge formation. The RC building exhibits satisfactory seismic performance, with damage primarily confined to beam elements and overall response remaining within acceptable performance limits. The study demonstrates that nonlinear dynamic analysis is an effective and reliable tool for performance-based seismic evaluation of RC buildings.

VIII. FUTURE SCOPE

The present study can be extended in several directions to enhance the understanding of seismic performance of RC structures:

- Inclusion of soil–structure interaction effects to evaluate foundation flexibility and site-specific response.
- Investigation of irregular RC buildings with plan or vertical irregularities.
- Application of incremental dynamic analysis (IDA) for probabilistic performance assessment and fragility curve development.
- Consideration of material degradation, aging, and construction uncertainties in nonlinear modeling.
- Extension of the study to retrofitted or strengthened RC buildings to evaluate improvement in seismic performance.
- Integration of performance-based design and loss estimation frameworks for decision-making in seismic risk mitigation.

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