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Review

A COMPARITIVE REVIEW OF LINEAR AND NONLINEAR-STATIC ANALYSIS METHODS FOR REINFORCED STRUCTURES

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Abstract

This paper presents a comparative review of three major seismic analysis methods used for reinforced concrete (RC) structures: linear static analysis, nonlinear static (pushover) analysis, and nonlinear time-history analysis. The study evaluates their underlying theory, modelling requirements, assumptions, accuracy, and level of computational effort. Published global and regional research was reviewed to assess when each method is appropriate for performance evaluation and design. The findings show that linear static analysis is simple and code-friendly but often unreliable for irregular, taller, or higher–mode-sensitive buildings. Nonlinear static analysis better represents inelastic behaviour, stiffness degradation, and hinge formation but may overlook torsional and higher-mode effects. Nonlinear time-history analysis offers the most realistic predictions of seismic response; however, it requires significant modelling detail, computational resources, and careful selection of earthquake records. This review highlights conditions where simplified methods are acceptable and where nonlinear approaches are necessary for accurate and safe seismic assessment and retrofit decisions.

Keywords: Linear Static Analysis, Nonlinear Static Analysis, Pushover, Nonlinear Time-History Analysis, Seismic Performance.

1. Introduction

Reinforced concrete buildings respond to earthquake loading in a highly complex manner, which is why engineers use a range of seismic analysis techniques to predict their behavior. These methods differ in their assumptions, level of modelling detail, and ability to capture elastic and inelastic response. The most basic approach is linear static analysis, also known as the equivalent lateral force method, which assumes elastic behavior and dominance of the first vibration mode. This makes it computationally efficient and appropriate for regular, low-rise structures. More sophisticated methods include nonlinear static (pushover) analysis, which accounts for material nonlinearity, cracking, stiffness reduction, and progressive formation of plastic hinges. The most comprehensive technique is nonlinear time-history analysis, where structural response is evaluated using real or artificial earthquake records, allowing dynamic effects and complex interactions to be fully represented.

Since each analysis method treats factors such as elasticity, ductility, damping, modal contribution, and cyclic degradation in different ways, their predictive accuracy also varies. Research indicates that linear methods often underestimate seismic demands in irregular buildings, structures with significant torsion, or those influenced by higher vibration modes. In contrast, nonlinear approaches provide a more realistic representation of structural behavior but require increased modelling effort and computational resources. A clear understanding of these differences is therefore crucial for choosing an appropriate analysis method for seismic design, performance evaluation, and informed structural decision-making.

This paper aims to provide a thorough review of the three seismic analysis methods, compile and discuss comparative findings reported in existing studies, and offer practical guidance on their appropriate use. The review is particularly relevant for regions where linear analysis techniques are still widely adopted in engineering practice due to limited availability of nonlinear analysis software, technical expertise, & computational capacity.

2. Materials and Methods

This section outlines the theoretical foundations, modelling assumptions, and analytical requirements of the three seismic analysis methods considered in this study. Each approach is examined in detail to emphasize its core principles, advantages, and limitations, which influence its suitability for application to reinforced concrete and steel structures.

2.1 Linear Static (Equivalent Static Force) Analysis

Linear static analysis estimates seismic demand by applying a predefined lateral load pattern to an elastic structural model, based on the assumption that the fundamental vibration mode dominates the seismic response. By converting dynamic earthquake effects into an equivalent static representation, this method allows engineers to evaluate seismic forces without conducting detailed dynamic analyses. Owing to its low computational demand and straightforward implementation, it is widely adopted in design codes and is generally considered adequate for low-rise, regular, and symmetric reinforced concrete buildings, where it often provides reasonably conservative results [1,7]. The method further simplifies analysis by assuming that the majority of structural mass participates in the first mode, thereby neglecting higher-mode contributions.

Despite its practical advantages, numerous analytical and post-earthquake studies have shown that the accuracy of linear static analysis reduces significantly when applied to structures with geometric or dynamic irregularities. Buildings with soft-storey behavior, torsional eccentricities, irregular floor configurations, or substantial higher-mode participation may experience underestimated seismic demands when assessed using this approach [2,3,9]. These shortcomings arise because the assumptions of elastic behavior and single-mode dominance are unable to represent force redistribution, localized damage, and nonlinear response that develop during strong ground motion.

Overall, the Linear Static (Equivalent Static Analysis) method remains the simplest and fastest tool for seismic assessment and is primarily suited to regular, low-rise reinforced concrete structures, as reflected in most building codes. Its efficiency is largely due to the assumptions of elastic response and first-mode dominance, often supplemented by force-reduction factors to indirectly account for energy dissipation. However, this same simplicity imposes clear limitations, as research consistently indicates reduced reliability for buildings with plan irregularities, torsional effects, soft-storeys, or significant higher-mode influence.

2.3 Nonlinear Time-History Analysis (NLTHA)

Pushover analysis is a nonlinear static procedure in which lateral loads are gradually increased on a structural model that explicitly includes plastic hinges or distributed nonlinear behavior. As the applied load increases, the structure progresses from elastic to inelastic response, resulting in a capacity curve that relates base shear to roof or overall displacement. This curve offers valuable information on stiffness degradation, strength reduction, deformation capacity, and the sequence of hinge development. For performance evaluation, the multi-degree-of-freedom (MDOF) system is typically transformed into an equivalent single-degree-of-freedom (SDOF) system using established techniques such as the Capacity Spectrum Method and the N2 method [2,5,6].

The reliability of conventional pushover analysis depends strongly on the assumption that the selected lateral load pattern remains representative even after yielding occurs. This assumption is generally reasonable for low- to mid-rise structures where lower vibration modes control the response. However, the method becomes less accurate when higher-mode effects are significant or when torsional irregularities exist, leading to noticeable discrepancies in predicted response. To address these shortcomings, several improved approaches—such as adaptive pushover, modal pushover, and extended N2 methods—have been proposed to enhance accuracy for irregular and taller buildings [2,5].

Overall, Nonlinear Static (Pushover) Analysis serves as an important performance-based assessment tool, providing key outputs such as capacity curves, hinge formation patterns, and performance points. By employing procedures like the Capacity Spectrum Method and the N2 method, complex MDOF systems are simplified into equivalent SDOF representations. Although the method traditionally assumes dominance of lower modes and a fixed load pattern beyond yielding, recent advancements in pushover techniques have significantly improved its applicability and reliability for structures with geometric and dynamic irregularities.

2.3 Nonlinear Time-History Analysis (NLTHA)

Nonlinear time-history analysis (NLTHA) studies how a structure responds to earthquakes by applying real or artificially created ground-motion records to a nonlinear structural model. This method can represent many important aspects of seismic behavior, such as the effects of multiple vibration modes, repeated loading and unloading, stiffness and strength reduction, dynamic amplification, and even possible collapse. Because it directly simulates how a structure behaves during actual earthquake shaking, NLTHA is considered the most reliable method for performance-based earthquake engineering [1,10].

The accuracy of this analysis depends on using properly calibrated material models, suitable damping assumptions, and carefully selected earthquake records that reflect the seismic hazard at the site. Although NLTHA provides very detailed and realistic results, it requires high computational effort and is sensitive to modelling assumptions. For these reasons, it is usually used for complex structures, important buildings, or final verification studies.

Incremental Dynamic Analysis (IDA) is regarded as the most advanced approach in performance-based seismic design. It evaluates structural behavior by running nonlinear time-history analyses at gradually increasing earthquake intensity levels. This process helps engineers understand how a structure's capacity changes, leading to results such as IDA curves, collapse margin ratios (CMR), and estimates of collapse probability. While

IDA offers the most detailed assessment of seismic performance, it is extremely time-consuming and computationally demanding, and it requires highly accurate nonlinear models and carefully selected ground-motion records to produce reliable results.

3. Results

This section presents the outcomes of the comparative study of seismic analysis methods. The results are organized into subsections for clarity and provide a detailed interpretation of how each method behaves when applied to different structural configurations. Bullet points summarizing key findings are provided at the end of each subsection.

3.1 Comparative Performance of Seismic Analysis Methods

3.1.1 Linear Static Analysis Results

The results indicate that the linear static method works well only for regular, low-rise reinforced concrete buildings where the seismic response is mainly controlled by the first vibration mode. Because this method applies a fixed lateral load pattern to an elastic structural model, it generally gives conservative results when the building has uniform geometry, stiffness, and mass distribution. Several studies show that building codes favor this method because it is simple, fast, and suitable for routine design purposes [1,7].

However, when results from linear static analysis are compared with those from nonlinear and dynamic methods, it becomes clear that the method may produce unsafe results for irregular buildings. Structures with plan irregularity, torsional imbalance, or strong higher-mode effects are not accurately represented by this approach. Case studies show that buildings with soft-storey behavior, uneven mass distribution, or unsymmetrical layouts develop force and deformation patterns that the linear static method fails to capture correctly [2,3,9]. As a result, displacement demands may be underestimated and critical failure mechanisms may be overlooked in complex structural systems.

In summary, the linear static method is generally conservative for regular, low-rise reinforced concrete structures [1,7], but it underestimates seismic demands in buildings with irregularity, torsion, or soft-storey conditions [2,3,9]. Its effectiveness is limited when higher-mode effects significantly influence structural response, as the method is based on simplified elastic behavior and the assumption of first-mode dominance.

3.1.2 Pushover Analysis Results

The results from pushover analysis show that this method is effective in representing nonlinear structural behavior, such as stiffness reduction, formation of plastic hinges, and overall load-carrying capacity. As lateral loads are increased step by step, the structure gradually moves from elastic behavior to nonlinear behavior, producing a capacity curve. This curve explains how the building resists increasing earthquake forces and provides important information about displacement capacity and the order in which hinges form, which helps in understanding possible failure mechanisms [2,5,6].

By converting the multi-degree-of-freedom (MDOF) system into an equivalent single-degree-of-freedom (SDOF) model using the Capacity Spectrum Method or the N2 method, the performance point of the structure can be estimated. This allows engineers to predict expected displacement demand for a given level of earthquake intensity. However, the findings also indicate that traditional pushover analysis becomes less reliable when the actual structural response differs from the assumed lateral load pattern. This issue is more pronounced in irregular or tall buildings where higher vibration modes significantly influence behavior. To overcome these limitations, advanced pushover techniques such as modal, adaptive, and extended pushover methods are often used to improve accuracy.

In summary, pushover analysis provides key outputs such as capacity curves, hinge formation sequences, and performance points [2,5,6]. It performs well for low- and mid-rise buildings where first-mode behavior is dominant [2,5], but its accuracy decreases for irregular structures and buildings sensitive to higher-mode effects. Improved pushover procedures help address these shortcomings and enhance response prediction.

3.2 Advanced Dynamic and Nonlinear Analysis Approaches

3.2.1 Nonlinear Time-History Analysis Results

Nonlinear time-history analysis (NLTHA) is widely acknowledged as the most sophisticated and realistic approach for evaluating the dynamic response of structures. By performing a step-by-step integration of the full nonlinear equations of motion using either recorded or synthetic ground motions, this method provides a comprehensive view of structural behavior that simpler methods cannot achieve. It is uniquely capable of simulating complex phenomena such as multi-modal interactions, the gradual degradation of stiffness, cyclic material behavior, and the specific sequence of events leading to structural collapse. Because it accounts for directional seismic effects, the influence of loading history, and the accumulation of structural damage, NLTHA serves as the definitive benchmark for calibrating and validating alternative analysis techniques [1,10].

Furthermore, the results of an NLTHA highlight that its predictive accuracy is highly contingent upon the quality of the input data, specifically the selection and scaling of earthquake records, as well as the precision of the nonlinear constitutive models. Although the computational cost and technical expertise required to execute these simulations are substantial, the method's reliability in tracking the entire seismic performance envelope—from the initial linear-elastic phase to the point of ultimate failure—makes it a fundamental requirement for the design and assessment of critical or high-risk infrastructure [1,10].

3.2.2 Response Spectra Outcomes

The results from response spectra analysis demonstrate that these spectra represent the peak potential reactions of virtual Single Degree of Freedom (SDOF) systems when they are subjected to earthquake vibrations. A key distinction of this method is that it does not simply describe the raw characteristics of the ground motion itself; instead, it illustrates the specific ways in which various structures are likely to respond to that motion. By analyzing these spectra, researchers can calculate fatigue-equivalent loads, which are highly useful for conducting seismic experiments or running computer-based simulations. When these loads are determined using Power Spectral Density (PSD) principles, they offer a very practical and effective way to evaluate how a structure behaves during its operation and how it holds up after a test is completed [14,16].

Furthermore, validated evidence from earlier research shows that response spectra are vital for identifying general trends in structural demand. This is especially important when engineers need to assess buildings after an earthquake has occurred or when they are designing simulations to test new structural components. Because this method focuses on the maximum expected response rather than just the shaking of the ground, it provides deep insights into the patterns of seismic demand that a structure will face. Ultimately, this makes the response spectra approach an essential tool for supporting loading simulations and ensuring that post-test evaluations are accurate and reliable [14,16].

3.2.3 Incremental Dynamic Analysis (IDA) Results

The results of this study show that Incremental Dynamic Analysis (IDA) provides the most thorough performance-based evaluation of all dynamic analysis methods. This procedure works by exposing a structure to seismic ground motions that gradually increase in intensity. This allows engineers to observe the complete behavior of the building, starting from its initial flexible (elastic) state all the way to its final collapse. When used to analyze steel Moment-Resisting (MR) frames, IDA is highly effective at identifying changes in story drift, permanent deformations (residual drift), total load-carrying capacity, and the damaging effects of low-cycle fatigue (LCF) [15].

While traditional IDA research focuses mostly on maximum inter-story drift as the primary way to measure damage, the findings presented here include a wider range of Damage Measures (DMs). By looking at additional factors like residual strength, fatigue-based damage, and residual drift, we get a much completer and more realistic picture of the structure's health.

These detailed results make it possible to categorize a structure into specific performance categories, such as Immediate Occupancy (IO), Life Safety (LS), and Pre-Collapse (PC). These classifications are essential for the field of performance-based earthquake engineering. Essentially, IDA acts as a more accurate, dynamic version of a pushover analysis. It tracks every stage of structural response as the earthquake intensity grows and uses multiple indicators—such as drift and fatigue damage—to ensure critical safety levels are properly evaluated [15].

Table 1. Showing summary of previous studies

Method	Common Aurthors in literature review	Focus area	Results
Linear Static (Equivalent Static Analysis)	Chopra(2012),Eurocode 8 (1998),P.Fajar(2000), H. Krawinkler (1998), Fatahi, B(2014)	Simplified seismic analysis for regular, low-rise build- ings using equivalent lat- eral forces.	Base shear, story shear distribution, lateral displacements, drift values, inter- nal member forces.
nonlinear Static (Pusho- ver Analysis)	Fajfar (2000), CSM , C. bhatt (2014), Fatahi, B(2014)	Performance-based evaluation, capturing inelastic behavior and hinge formation under increasing lateral load.	Capacity curve (base shear vs. displacement), hinge formation sequence, performance point, failure mechanism.
Response spectrum Anal- ysis (RSA)/(TMA)	Decker.M (2021), Gupta (2017), Mahmud.S (2017)	Modal analysis consider- ing building dynamic properties and elastic re- sponse under earthquake spectra.	Modal participation fac- tors, modal periods, maxi- mum displacement & forces, combined modal responses.
Incremental Dynamic Analysis (IDA)	Bernuzzi, C (2021)	Advanced seismic performance evaluation by running nonlinear time-his- tory at increasing intensity levels.	IDA curves, collapse mar- gin ratio (CMR), dynamic instability points, demand/capacity ratios, probability of collapse.

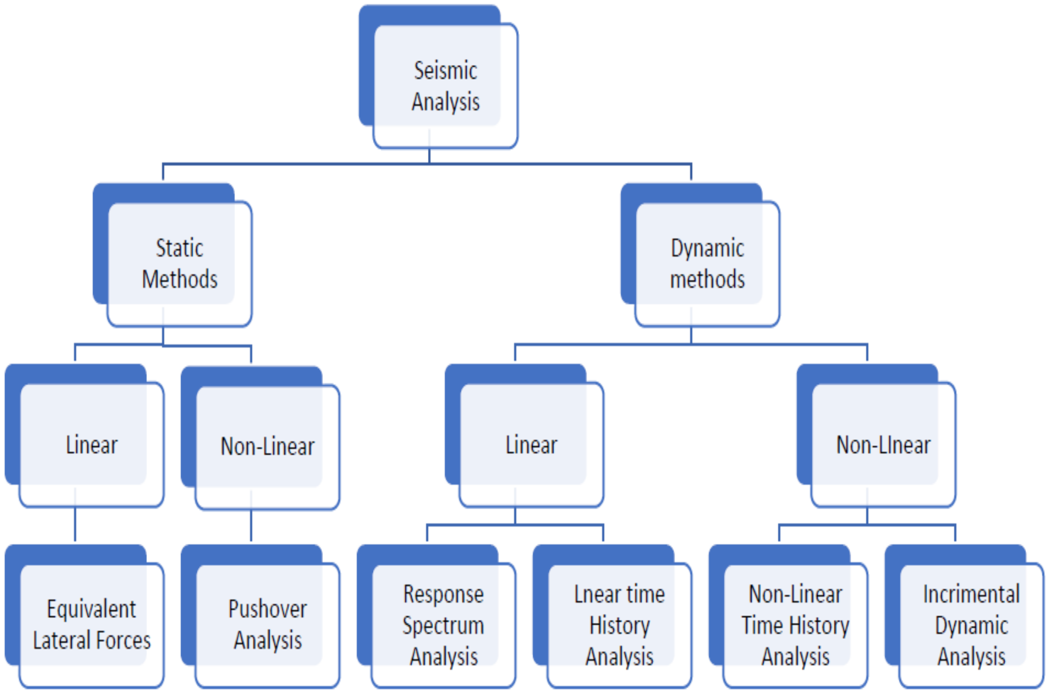

Figure 1. Flowchart outlining the major Static and Dynamic methods used in Seismic Analysis of structures [8].

The flowchart in Figure 1 provides a clear overview of the different ways engineers analyze how buildings handle earthquakes, categorizing them into static and dynamic methods. Static methods are the most basic and include linear techniques, like the equivalent lateral force method, and nonlinear techniques, such as pushover analysis [8]. On the other hand, dynamic methods are more advanced because they account for how a building's movement changes over time. These include response spectrum analysis, linear time history, and the most complex options like nonlinear time history or incremental dynamic analysis (IDA). By following the flowchart, one can see how these methods progress from simple calculations to highly detailed simulations that more accurately reflect real-world seismic behavior.

In addition to the flowchart, Table 1 provides a helpful summary of the major research and key authors associated with these different seismic analysis techniques. The table organizes the methods into four main groups: linear static analysis, nonlinear static (pushover) analysis, response spectrum analysis, and incremental dynamic analysis. For each group, it lists important studies and explains the primary goals of that method such as estimating simple forces, assessing performance, or evaluating how a building might collapse.

The table also highlights the different types of data each method produces. For example, simpler linear methods typically give results for base shear and story drift. In contrast, more advanced dynamic methods provide much more detailed information, such as how structural hinges form, how different vibration modes interact, and the safety margins before a total collapse occurs. This comparison makes it easier to understand which method is best suited for different types of engineering challenges.

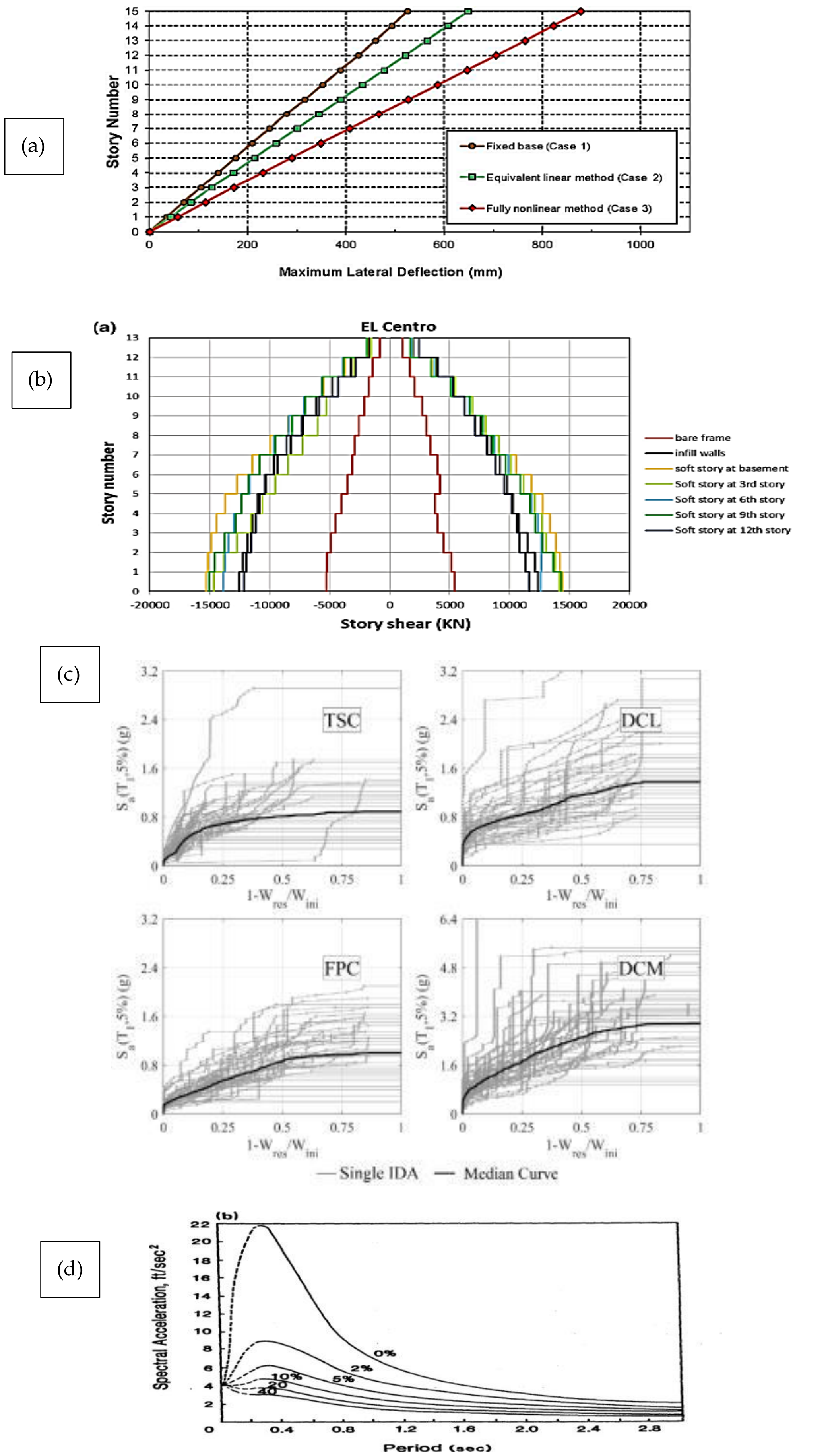

Figure 2. presents the visual data highlighting the varying levels of precision and 301 structural behavior captured by different seismic analysis techniques.

In Figure 2(a), the comparison of a 15-story building's lateral deflection shows that as height increases, the results of fixed-base and linear methods diverge significantly from the fully nonlinear approach, with the latter providing the most realistic assessment of structural flexibility [18]. This complexity is further detailed in Figure 2(b), where nonlinear time-history analysis of a 13-story building reveals how infill walls and soft-story placements cause dynamic force redistribution and stiffness degradation during the El Centro earthquake [10]. Additionally, the Incremental Dynamic Analysis (IDA) curves in Figure 2(c) and the spectral acceleration data in Figure 2(d) demonstrate the progression of various steel frame configurations toward failure, using both individual ground-motion data and median trends to track the loss of load-carrying capacity as seismic intensity grows [15,16].

Table 2. Absolute maximum inter story drifts for a 4-story building, comparing Nonlinear Time History (benchmark) and Push over analysis results under various seismic ground motions (Station 1 to Station 9) for each story[3]

	Method	S1	S2	S3	S4	S5	S6	S7	S8	S9
1	THA	0.009	0.010	0.009	0.018	0.017	0.007	0.017	0.010	0.007
	PA	0.010	0.010	0.008	0.011	0.010	0.005	0.008	0.006	0.009
2	THA	0.014	0.017	0.014	0.023	0.021	0.009	0.023	0.014	0.016
	PA	0.014	0.017	0.014	0.020	0.019	0.008	0.021	0.013	0.015
3	THA	0.014	0.017	0.013	0.022	0.019	0.007	0.021	0.013	0.015
	PA	0.013	0.017	0.013	0.019	0.020	0.007	0.021	0.012	0.015
4	THA	0.012	0.016	0.008	0.022	0.016	0.006	0.012	0.007	0.012
	PA	0.009	0.013	0.009	0.019	0.016	0.005	0.018	0.009	0.012

4. Discussion

A comparison of these techniques confirms that linear static analysis is only reliable for simple, regular reinforced concrete structures where the first mode of vibration is dominant. For buildings with irregularities—such as setbacks, soft stories, or a tendency to twist (torsion)—this simple method often yields inaccurate results that could lead to unsafe designs. In contrast, nonlinear static (pushover) analysis provides a useful middle ground, offering deeper insight into material failure, hinge formation, and overall structural capacity without requiring extreme computing power. However, its effectiveness is limited when a building's response is influenced by higher vibration modes.

Ultimately, nonlinear time-history analysis is the most precise methodology available, as it accounts for dynamic factors like bidirectional shaking, the gradual loss of stiffness, and repetitive cyclic loading. This high level of detail makes it indispensable for skyscrapers, irregular or torsional structures, critical infrastructure, and performance-based design projects. Despite its accuracy, the heavy modeling and computational requirements often limit its everyday use in developing nations. Consequently, engineers frequently recommend using advanced pushover variations or a limited number of time-history simulations as a practical compromise between precision and effort.

5. Conclusions

- Linear static analysis is simple and widely used but becomes unreliable for irregular or taller buildings.
- Nonlinear static (pushover) analysis captures inelastic behaviour and provides good predictions for global response.

- Extended pushover methods significantly improve accuracy for complex structures.
- Nonlinear time-history analysis is the reference method and essential for detailed performance evaluations.
- Comparative studies show that relying solely on linear analysis may lead to inaccurate estimation of seismic demand for complex structural systems.

Abbreviations

Abbreviations	Meaning
RC	Reinforced concrete
LSA	Linear static analysis
NLSA	Non-linear static analysis
NLTHA	Non-linear time history analysis
IDA	Incremental dynamic analysis
PBD	Performance based design

References

[1] A. K. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, 4th ed., Pearson/Prentice Hall, 2012.
[2] P. Fajfar, "The N2 method for the seismic damage analysis of RC buildings," Earthquake Engineering & Structural Dynamics (N2 method and development).
[3] H. Krawinkler and G. Seneviratna, "Pros and cons of a pushover analysis of seismic performance," Engineering Structures, 1998.
[4] Review of the development of the Capacity Spectrum Method (CSM) and related literature (capacity-spectrum reviews and historical overviews).
[5] C. Bhatt (and others), "The Extended Adaptive Capacity Spectrum / Extended N2 methods — higher mode corrections," Earthquake Engineering & Structural Dynamics, 2014.
[6] Eurocode 8 (EN 1998-1): Design of Structures for Earthquake Resistance — official standard and commentary (EC8 includes N2/pushover provisions).
[7] K. K. Kuria, "Pushover Analysis in Seismic Engineering: A Detailed Chronology and Review of Techniques for Structural Assessment," Applied Sciences (MDPI), 2023.
[8] M. De Stefano et al., "Pushover Analysis for Plan Irregular Building Structures," chapter in Seismic Analysis, Springer, 2014.
[9] S. Mahmoud, "Time-History Analysis of Reinforced Concrete Frame," Arabian Journal for Science and Engineering, Springer, 2017.
[10]R. A. Hakim, "Seismic Assessment of RC Building According to ATC-40," Journal / Conference (regional application studies), 2014.
[11]M. Kreslin et al., "The extended N2 method considering higher-mode effects," Bulletin of Earthquake Engineering, Springer, 2012.
[12]AIP Conference Proceedings (2024), "Comparative study of multi-story RC building: time-history and pushover," AIP conference paper.
[13]M. Decker, "Vibration fatigue analysis using response spectra," International Journal of Fatigue, vol. 148, p. 106192, 2021.
[14]C. Bernuzzi, D. Rodigari, and M. Simoncelli, "Seismic performance of MR steel frames via Incremental Dynamic Analysis," ce/papers, vol. 4, no. 2–4, pp. 1924–1931, 2021.
[15]A. K. Gupta, Response Spectrum Method in Seismic Analysis and Design of Structures. New York, NY, USA: Routledge, 2017.
[16]A. Aşıkoğlu, G. Vasconcelos, and P. B. Lourenço, "Overview on the nonlinear static procedures and performance-based approach on modern unreinforced masonry buildings with structural irregularity," Buildings, vol. 11, no. 4, p. 147, 2021.

[17]B. Fatahi and S. H. R. Tabatabaiefar, “Fully nonlinear versus equivalent linear computation,” 2014.