SSRG International Journal of Civil Engineering Volume 13 Issue 5, 358-367, May 2026
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I5P124

Original Article

Comparison of Nonlinear Methods in the Seismic Evaluation of Reinforced Concrete Frames and Their Applicability in the Construction of Fragility Curves

Víctor Hinostroza Maraví[1*], Deyvid Froilán Matamoros Paitán[1], Jean Fernando Pérez Montesinos[2]

[1]*Department of Civil Engineering, Universidad Continental, Huancayo, Junin.*
[2]*School of Civil Engineering, University of Idaho, Idaho, USA.*

[*]*Corresponding Author : 75476788@continental.edu.pe*

Received: 16 October 2025 Revised: 20 December 2025 Accepted: 30 April 2026 Published: 29 May 2026

Abstract *- Conventional seismic analysis based on elastic approaches presents limitations in realistically capturing structural response under severe events, which has driven the development of nonlinear methodologies that allow for a more accurate characterization of building performance. In this context, this study aims to make a systematic comparison between the nonlinear static and nonlinear dynamic analyses in reinforced concrete frames, with the goals of identifying any divergences in the prediction of parameter performances and then assessing their applicability as input data for methodologies oriented towards fragility. The ETABS software was used to model a four-story building, and nonlinearity was incorporated through the use of plastic hinges according to ASCE41-17 and NIST GCR 10-917-5, and the characterization of the materials followed the LATBSDC 2020 norm. The evaluation of the behavior was based on the overturning moment and the base shear, while also considering gravitational loads and a scaled record of real earthquakes. The results acquired from the evaluations indicated that the nonlinear dynamic analysis estimated that the base shear and overturning moment values are approximately 18% and 16% higher, respectively, than those obtained with nonlinear static analysis. These results highlight the great ability of nonlinear dynamic analysis to capture transient effects and global instability phenomena. These outcomes allow us to argue that both methods provide useful information for structural performance evaluation, with the dynamic analysis more suitable for probabilistic studies, while static analysis constitutes a simplified and less computationally demanding alternative in preliminary design stages. Considering the limitation, this study was restricted to the analysis of a regular two-dimensional frame and a single seismic record; therefore, an extension to three-dimensional and irregular models accompanied by multiple ground motions is recommended to strengthen the generalization of the results.*

Keywords *- Nonlinear static analysis, Nonlinear dynamic analysis, Reinforced concrete frames, Seismic performance evaluation, Capacity spectrum, Fragility assessment.*

1. Introduction

In the contemporary era, national governments are prioritizing initiatives aimed at enhancing the general welfare of their respective populations. A significant sector within this broader context pertains to the domain of construction, which is intricately linked to the development of contemporary infrastructure. However, this heightened exposure to sudden events, such as seismic occurrences, renders the construction sector increasingly vulnerable [1]. In 2007, in Pisco, Peru, a terrible earthquake occurred, and this natural disaster and its consequences accentuated not only the limitations of conventional seismic analysis methods but also the necessity for more rigorous evaluations. From this perspective, advanced methodologies have been developed that permit a more accurate estimation of the performance of structures under extreme events. These approaches are particularly relevant in the Peruvian context due to the fact that self-built dwellings in Huaycán, Lima, present collapse rates of up to 20.5% under severe seismic scenarios. This scenario confirms the consequences of non-compliance with seismic-resistant codes, as shown in Figure 1 [2, 3]. These findings strengthen the need for modern structural engineering to adopt approaches that realistically capture the nonlinear behavior of structures [4]. Additionally, seismic performance assessment has become a fundamental activity to ensure the structural safety of a building; this requires methods that go beyond traditional elastic approaches [5].

In this context, the nonlinear static analysis and nonlinear dynamic analysis stand out as the most promising analytical approaches that enable a prediction of structural response. The nonlinear static analysis has already been adopted in international standards and software; this approach offers a cost-effective procedure by modelling damage accumulation through a progressively increasing lateral loading [6]. However, its main weakness is the fact that it neglects the dynamic characteristics and the variability of earthquakes, which can result in a poor assessment of structural performance [7]. On the other hand, the nonlinear dynamic analysis method provides a more realistic assessment of the structure by applying a set of scaled seismic records, allowing a more comprehensive evaluation of the collapse probability as well as the development of fragility curves, with an increased computational effort [8, 9].

A critical review of the state of the art reveals an active debate on the suitability of both methods. Previous and different studies have compared both approaches in diagrid structures, finding that the static method provides conservative values of the response modification factor, while nonlinear dynamic analysis yields more realistic results [10]. Additionally, recent investigations have explored the applicability of pushover analysis in complex systems, such as tunnels and dams, focusing on its limitations with regard to the seismic variability [11].

Unlike the nonlinear static analysis, the nonlinear dynamic analysis has been well accepted and validated for a variety of structures, becoming an essential element of nonlinear analysis. The use of nonlinear dynamic analysis has been successfully applied in steel buildings, where it has led to a more comprehensive assessment of inelastic behaviour and deformation capacity [12-14], as well as other types of critical structures, such as bridges and dams, where the progressive collapse implies an extreme scenario. Nonlinear dynamic analysis, compared to simpler methods, provides a continuous representation of structural behaviour for a range of seismic intensities, allowing the identification of not only the ultimate strength, but also the sequence of stiffness and energy dissipation. Furthermore, recent studies highlight the effectiveness of this approach in assessing multiple-earthquake scenarios, where cumulative damage considerably reduces the residual capacity of structures [15, 16].

Another salient point pertains to the parameters that intervene in the seismic response, which are associated with uncertainty. These parameters can be classified as either random or epistemic. Moreover, the utilization of advanced analysis methods (see Table 1) enables the estimation of uncertainty variability, thereby facilitating the subsequent construction of the fragility curve [1].

In this way, nonlinear dynamic analysis is a key approach for the prediction of collapse and the seismic vulnerability, through the provision of information useful for code revision and the enhancement of structural resilience. However, it still lacks direct comparison with nonlinear static analysis, especially in medium-rise reinforced concrete frames, as they are one of the most common types of seismic-resistant systems around the world. Most recent research has prioritized innovative structures, leaving conventional systems underexplored, thereby highlighting the need for systematic comparisons under uniform performance criteria, considering key variables such as drifts, energy dissipation, and collapse capacity [17].

In this context, the overall aim of this research is to perform a systematic and quantitative assessment of the differences between nonlinear static and nonlinear dynamic analysis of a four-story reinforced concrete frame, modeled in ETABS [18]. The study seeks to detect and measure the differences in the prediction of maximum displacements, plastic hinge formation, and overall capacity curves, as well as examining its suitability to contribute to the preparation of fragility curves.

Fig. 1 Self-constructed housing in urban settlements

Table 1. The table of study presents methodologies that have been advanced

Reference	Structure type	Nonlinear Methodology	Contribution
[19]	20-story reinforced concrete building	IDA (Incremental Dynamic Analysis)	It establishes the IDA as the standard method for determining frailty curves.
[20]	Buildings of 2 to 15 levels made of concrete with regular and irregular configurations	SPO (Pushover) vs. NDHA	It concludes that this SPO method underestimates the demand curve in mid-rise buildings.

[21]	Existing concrete structuresarmado	Cloud Analysis & Fragility Curves	It focuses on the uncertainty variable of Bayesian frames and materials of existing buildings.
[22]	General reinforced concrete structure	Dynamic analysis	They propose advanced methods to analyze the probability of collapse resulting from dynamic instability.

2. Materials and Methods

To perform the systematic comparison of the analysis approaches, a four-story reinforced concrete frame was modeled to represent the medium-rise buildings in Peru [23]. The simulation was carried out in the ETABS software [18], where the material nonlinearity was incorporated through plastic hinges defined according to the ASCE 41-17 standard [24]. The geometry, materials, and analysis procedures employed are detailed below. Moreover, the 2D model functions as a reference point for the analysis of this study. This is due to the fact that the nonlinear static methodology is dominated by the first mode of vibration, which represents the lateral behavior of the structure. However, in reality, the torsional behavior exists for 3D models, yet the contribution of its participating mass is relatively low.

The analysis was primarily framed to evaluate the overall strength and rollover stability, as these are the fundamental indicators for processing the nonlinear analysis [16].

2.1. Structural Model Configuration

2.1.1. Geometry and Structural Configuration

The analysis case corresponds to a four-story reinforced concrete frame, designed with a regular configuration in elevation. The geometry includes stories with a height of 3.0 m and a clear span of 5.0 m between columns, parameters commonly used in urban residential buildings [23]. Figure 2 shows the structural configuration along with the dimensions of beams and columns that characterize the model.

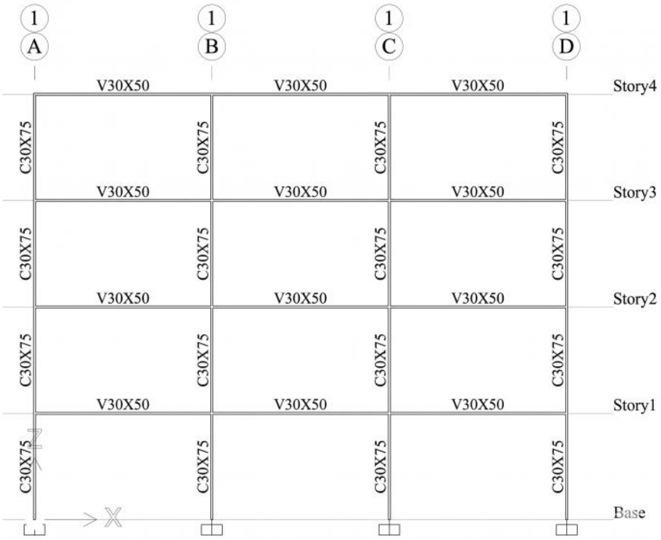


Fig. 2 Structural configuration of the frame and section dimensions

2.1.2. Material Characterization

The materials of the structural model correspond to concrete and reinforcing steel, characterized according to the guidelines of LATBSDC 2020 [25], which establishes the use of expected strengths for seismic performance analyses. The concrete was characterized with a compressive strength of f'c = 28 MPa, while the reinforcing steel was modeled with a yield strength of fy = 420 MPa. Table 2 summarizes the factors used for the calculation of expected strengths in both materials.

Table 2. Specified and Expected Strengths of Concrete and Steel According to LATBSDC 2020

Material	Property	Strength	Factor	Expected Strength
Concrete	f'c (Compression)	28 MPa	1.3	36.4 MPa
Steel	fy (Yield)	420 MPa	-	490 MPa
Steel	Fu (Ultimate)	630 MPa	-	742 MPa

2.1.3. Gravity and Seismic Loads

Representative gravity loads of an urban residential building were considered, applying on the beams a dead load of 3.00 tonf/m and a live load of 1.20 tonf/m, defined according to Technical Standard E.020 [26]. These values allow an adequate representation of the self-weight of the structural elements, as well as the effects of architectural finishes, partitions, and the expected occupancy [23]. In this way, the structural model is subjected to realistic service conditions that serve as the basis for the subsequent evaluation of its response to seismic demands.

The seismic action was defined according to Technical Standard E.030 [27], adopting a seismic zone factor Z of 0.45, corresponding to Zone 4, a soil profile of type S1, and a seismic reduction factor R of 8, characteristic of ductile frame systems.

It is important to note that this R value was applied only in the design phase for the sizing of the reinforcing steel, without affecting the nonlinear analyses carried out subsequently.

2.1.4. Design Criteria

The structural model in this paper was developed following the guidelines established in Standard E.060 [28] and Standard E.030 [27], and it was also complemented with international criteria. For the design of the beams and columns, it was performed while also considering the load combinations that are established in the Peruvian standards, ensuring that the structure met the minimum requirements for strength, stiffness, and global stability.

Priority was given to achieving a ductile and predictable collapse mechanism, applying the strong-column–weak-beam principle, so that plastic hinges are concentrated in the beams, and the integrity of the columns is preserved [28]. Additionally, the continuity in the transfer of gravity and seismic loads was verified, which guaranteed that the structural behavior is compatible with the expected performance objectives in medium-rise buildings.

Figure 3 exhibits the reinforcement details in beams and columns, illustrating the configuration adopted in the structural model, and this served as the basis for its subsequent evaluation through nonlinear analyses.

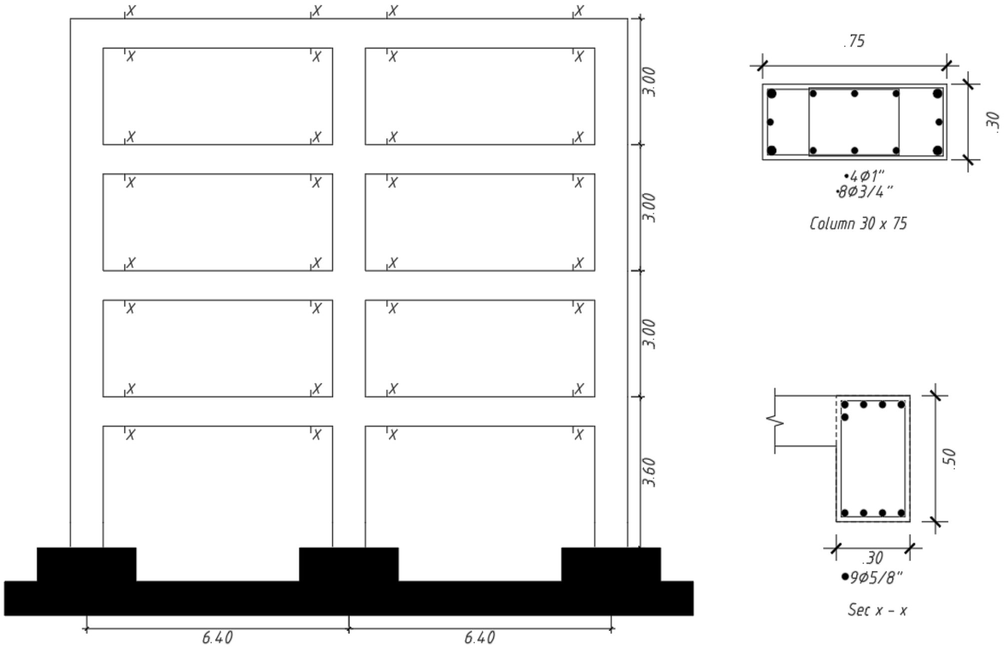


Fig. 3 Reinforcement Configuration adopted in the reinforced concrete frame

2.2. Modeling of Nonlinear Behavior

The inelastic representation of the structure was carried out through the incorporation of plastic hinges in beams and columns, located at the ends of the elements where the highest deformation demands are concentrated. Their definition was based on the criteria of ASCE 41-17 [24] and the recommendations of NIST GCR 10-917-5 [29], establishing limit rotations associated with different states of structural performance. These parameters allow a clear identification of the transition from initial damage to the collapse condition, in accordance with international performance assessment approaches.

The concrete was modeled using the Mander constitutive model, which incorporates the effects of lateral confinement and progressive strength degradation, allowing a more realistic representation of behavior in the inelastic range [29]. Figure 4 shows the stress-strain curve used, where the difference between confined and unconfined concrete can be observed, as well as the post-peak degradation.

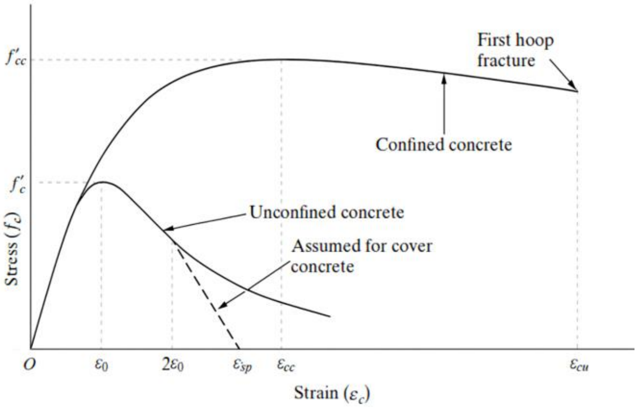


Fig. 4 Mander constitutive model for confined and unconfined concrete

The constitutive model of the reinforcing steel was taken from Park's model, which defines bilinear behavior with kinematic hardening, dividing the behavior into elastic, yielding, and post-yielding stages [30]. This model permits not only capturing the energy dissipation under cyclic loads, but also simulating the effects of strain hardening in advanced stages more accurately. Figure 5 reveals the stress-strain diagram adopted for the reinforcing steel. In this diagram, the initial elastic portion, the yield strength, and the post-yield hardening phase are clearly differentiated. This scheme, combined with the expected yield and ultimate strengths defined in LATBSDC 2020 [25], certifies a realistic representation of the material's inelastic performance.

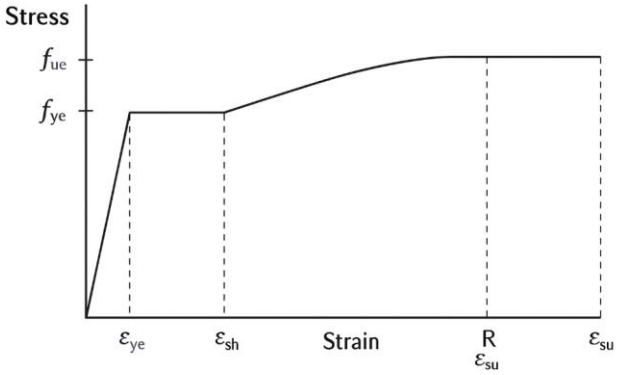


Fig. 5 Park Constitutive model for reinforcing steel

2.3. Nonlinear Analysis Procedure

The procedure for the structural evaluation was based on the application of two widely known methodologies: nonlinear static analysis and nonlinear dynamic analysis. These two approaches allow executing the characterization of the inelastic response of the reinforced concrete frame, and they also allow establishing a systematic comparison between the techniques for assessing the seismic performance. In comparison, current research using simplified expressions based on nonlinear static analysis [31], Nonlinear dynamic analysis is not employed as a reference parameter, due to the acceptance of current regulations.

The calibration of the model was executed in two stages. Initially, the elasticity state was characterized by the assessment of the vibrational periods. In this instance, the estimated period is approximately 0.1 seconds for lower levels [32]. This phenomenon is concomitant with the configuration of the vibration modes and the effective mass participation. Conversely, the nonlinear response exhibited adherence to the protocol established for plastic rotulas, as delineated in the NIST GCR 10-917-5 standard. The protocol stipulates the establishment of thresholds in accordance with the degradation, force, and rigidity of the structural element under consideration.

For the analysis model, the Newton-Raphson numerical convergence was followed with an error tolerance of 10-4 in the displacements to ensure better stability. The damping employed was Rayleigh, and the integration steps utilized were 0.001 s to ensure the stability of the Newmark model at constant average acceleration.

2.3.1. Nonlinear Static Analysis

Regarding the nonlinear static analysis, this process consists of applying an incremental lateral load pattern until reaching a predefined maximum drift or the global collapse condition. For the purposes of this study, the distribution of seismic forces was established based on the first predominant vibration mode, which allows a reasonable approximation of the overall dynamic response of the structure. During the procedure, interstory displacements, formation and propagation of plastic hinges, and the increase of base shear were recorded. The parameters related to the limit rotation that were used in the definition of hinges complied with the guidelines of ASCE 41-17 [24] and NIST GCR 10-917-5 [29], ensuring consistency with international assessment criteria.

2.3.2. No Linear Dynamic Analysis

The nonlinear dynamic analysis was carried out using a seismic record obtained from CISMID [33], selected for its representativeness regarding the characteristic seismicity of the central coast of Peru. This record corresponds to an event with intermediate magnitude and propagation conditions compatible with the S1 soil profile established in Technical Standard E.030 [27], which ensures the consistency of the analysis with the local geotechnical context. It has been acknowledged that the seismic record in question imposes constraints on the capture of random deviation. Nevertheless, it enables the optimization of computational cost without the interference of transient states and global instability for the specific case under analysis.

Prior to its application, the accelerogram was processed and scaled to ensure that its response spectrum was compatible with the target spectrum of the Peruvian code. Figure 6 shows the Lima 1966 seismic record, obtained from CISMID [33], from which the scaling procedure and its application to the structural model were carried out, while Figure 7 shows the response spectrum derived from this record, compared with the target spectrum used in the analysis.

2.4. Evaluation of the FRACAS Methodology

The FRACAS methodology constitutes a procedure based on the modified capacity spectrum method, designed for constructing fragility curves from the interaction between structural capacity and inelastic seismic demand [34]. Although fragility curves are not developed in the present study, the compatibility of the results obtained from the nonlinear analyses with the inputs required by FRACAS is analyzed in order to assess its applicability in future research aimed at the probabilistic estimation of seismic performance. Consequently, a reference value, or benchmark, was obtained that facilitates comparison with more simplified models (Pushover) and the quantification of systematic uncertainty.

The data necessary for the implementation of FRACAS include the capacity curve in ADRS format, obtained from the pushover analysis; the Maximum Interstory Displacements

(MIDR), considered as the Structural Demand Parameter (EDP) and extracted from the nonlinear dynamic analysis; and the inelastic response spectra calculated from the scaled seismic record. These inputs allow defining the structural performance points that serve as the basis for the subsequent derivation of fragility functions. The analysis focuses on two main things: the demand curve related to uncertainty about the structure's mechanical and physical properties, and the capacity spectrum related to random uncertainty, which is the definition of seismic phenomena [16].

The comparative analysis focuses on determining the extent to which discrepancies in displacements, plasticization mechanisms, and overall capacity affect the reliability of the inputs that feed the FRACAS methodology.

Figure 8 schematically summarizes the procedure, showing the sequence from obtaining the capacity curve to preparing the parameters that are subsequently used in the generation of fragility curves.

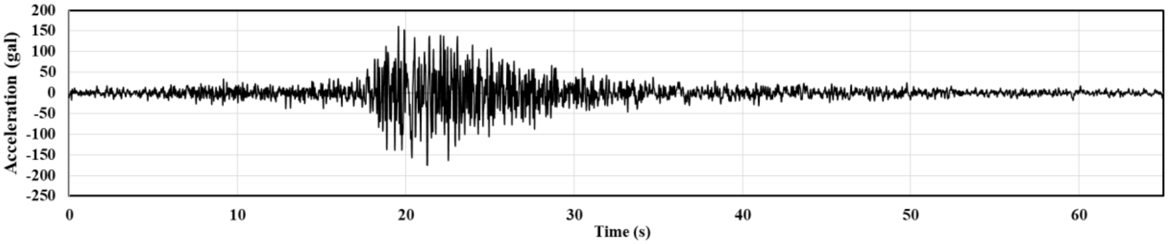


Fig. 6 Seismic Record Selected from CISMID

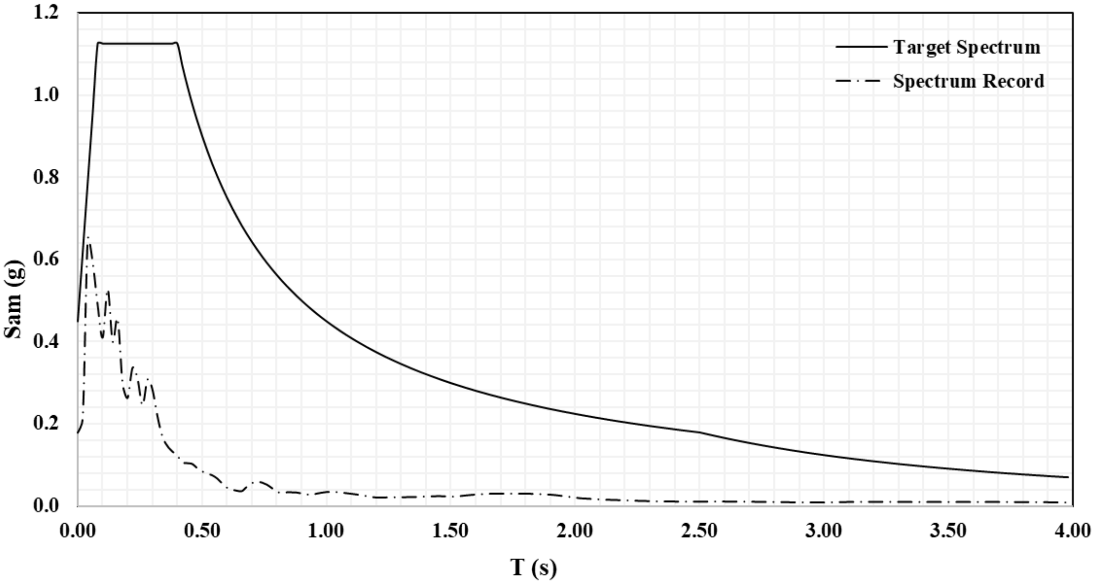
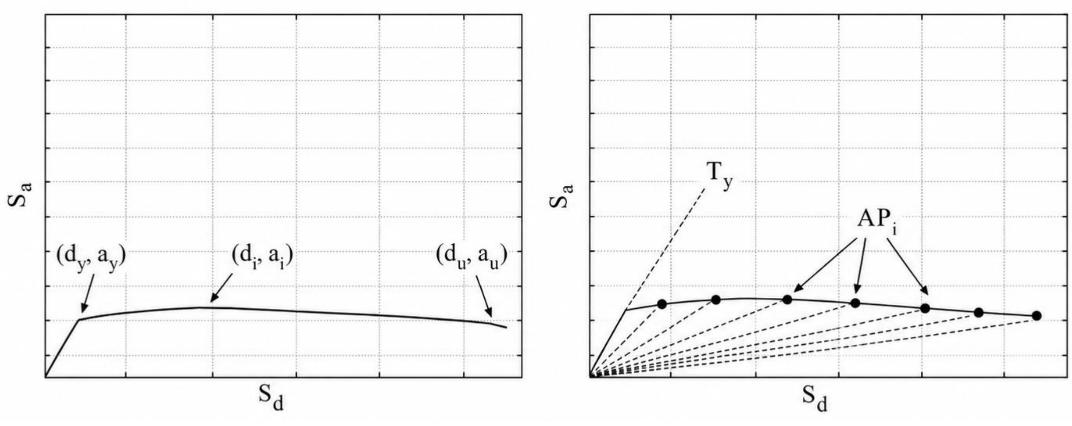
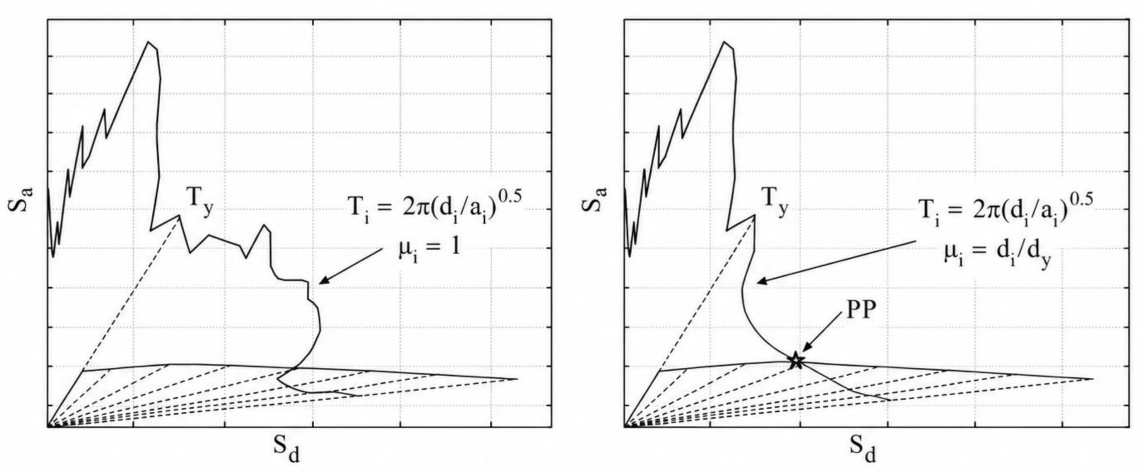


Fig. 7 Response spectrum of the Lima 1966 seismic record compared to the target spectrum



(a) Capacity Curve Idealization

(b) Discretization into Post-Yield Periods



(c) Elastic response Spectrum **(d) Inelastic response spectrum and performance point**

Fig. 8 FRACAS Procedure scheme for obtaining inputs for fragility curves [34]

2.5. Seismic Performance Evaluation Metrics

The evaluation of structural performance was carried out using a set of quantitative metrics that allow characterizing the building's capacity and establishing comparisons between nonlinear static analysis and nonlinear dynamic analysis. These metrics include global and local response parameters, selected according to the criteria of ASCE 41-17 [24], NIST GCR 10-917-5 [29], and LATBSDC 2020 [25], in order to ensure a comprehensive and consistent evaluation of seismic behavior.

2.5.1. Base Shear

The base shear constitutes a measure of the overall lateral resistance capacity of the structure. Its analysis allows obtaining the distinctive force-displacement relationship, while also identifying the maximum capacity and evaluating subsequent degradation. This is a key parameter for comparing the capacity obtained from the pushover with the demand from the dynamic analyses.

2.5.2. Overturning Moment

The overturning moment was employed with the purpose of analyzing the effects of global instability generated by seismic actions. This index permits the identification of the magnitude of destabilizing forces and their relationship with the resisting capacity, providing key insights.

3. Results

3.1. Base Shear

The base shear relationships from the nonlinear analyses can be seen in Figure 9. The maximum value for the nonlinear dynamic analysis was 113.98 tonf, and for the nonlinear static analysis was 96.59 tonf.

This represents an increase of about 18% in the dynamic method over the static method, suggesting a greater global strength in the dynamic method when the accelerogram is considered.

In both analyses, past the maximum load, the curve was descending, which indicates loss of stiffness and gradual deterioration of the strength. The results obtained allow us to initially compare both approaches, which is relevant for the application of other methods, such as FRACAS, for the development of fragility curves.

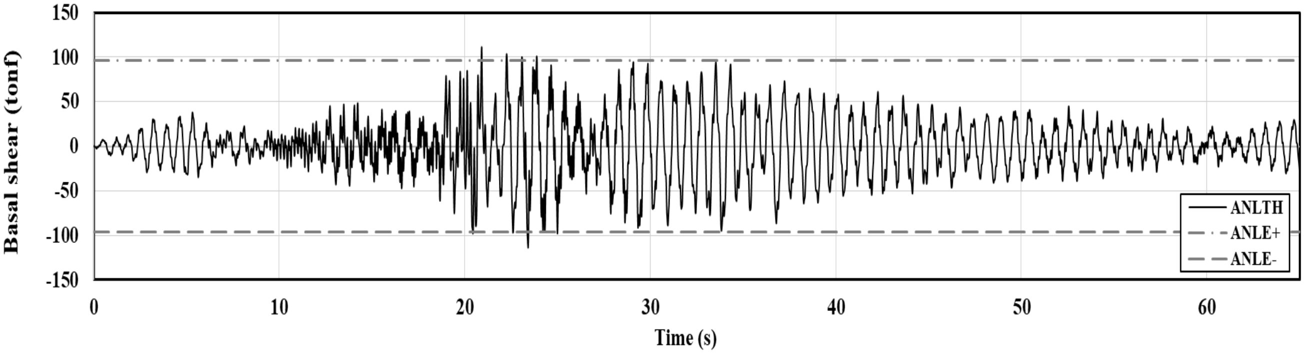


Fig. 9 Base shear–displacement curve obtained from nonlinear analyses

3.2. Overturning Moment

Figure 10 shows the variation of the overturning moment. The results of the nonlinear dynamic analysis were 901.61 tonf-m of maximum moment, while the nonlinear static analysis yielded 777.10 tonf-m, which is a difference of 16% between the two methods. The growth of the moment in the first instantaneous response was similar, but the second part (after the maximum) showed greater destabilising actions in the dynamic analysis. This observed behaviour highlights the need to assess metrics related to the global instability when comparing the nonlinear analysis methods, as the results are direct inputs for seismic fragility assessment procedures.

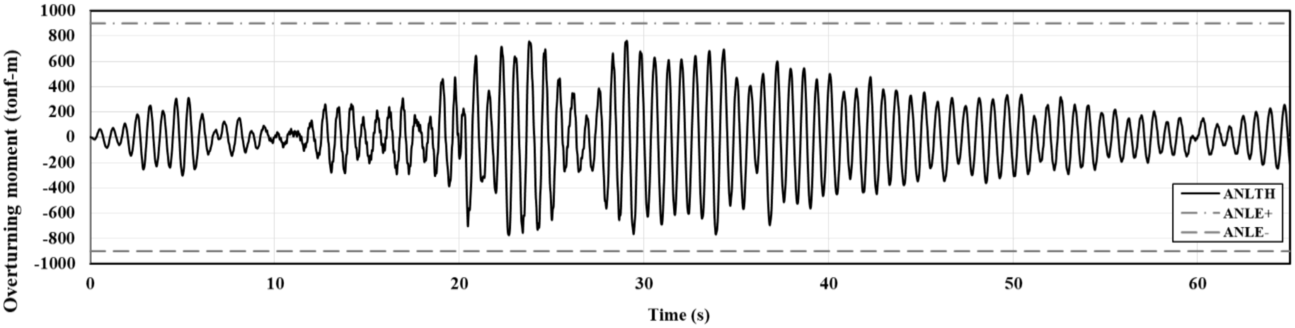


Fig. 10 Variation of the overturning moment in nonlinear analyses

4. Discussion

The study reveals that the nonlinear dynamic analysis is able to estimate a larger capacity than the one estimated by the nonlinear static analysis. This difference demonstrates that the dynamic nature of seismic action and the record dependence make the seismic response more stringent, as presented in recent studies; this ultimately reflects the conservative aspects of static analysis for different seismic records [9, 10]. The importance of the study lies in the groundwork it lays for probabilistic methods, such as cloud analysis and risk assessment [21], among others.

The larger value of the overturning moment calculated in the dynamic analysis indicates that this method realistically accounts for the effects of global instability, which has been highlighted in other research on steel and reinforced concrete structures [11-13]. It shows that the static analysis, when it is applied using an idealized load distribution, underestimates the destabilizing forces.

The practical consequences of these findings are that, despite the dynamic analysis being a better approach to describe seismic behavior, the static analysis can be applied because of its simpler approach and reduced computational effort. This approach can be applied in the preliminary phases of design or in cases where multiple models have to be analysed, with the appropriate considerations based on the limitations observed in the present study. However, to obtain these deterministic values, it is necessary to use sophisticated analysis methods, such as nonlinear dynamic analysis, which allows the determination of a reference point that, in turn, represents the fragility curves with a very small bias compared to the simplified approaches [16].

Finally, the consistency of the parameters obtained with the inputs required for approaches such as FRACAS enables the extension of the results towards probabilistic seismic fragility methods. However, the availability of only a regular two-dimensional frame and one accelerogram hinders the generalisation of the results, and future studies on three-dimensional structures with different irregularities and multiple earthquakes should be conducted, as suggested in recent research [14, 15].

5. Conclusion

This research provided a direct comparison between the nonlinear static and dynamic analyses in a medium-rise reinforced concrete frame, with greater global demands and capacities in the latter approach, with an increase of 16-18% in the metrics of interest. The comparison, in terms of base shear and overturning moment, enabled the analysis of both methods with clearly defined and measurable criteria, achieving the goal of identifying significant differences for performance-based design.

The most relevant contribution of this study is that it offers a framework to perform a comparison between nonlinear analysis methods, and this is valuable for design and independent verification. The dynamic analysis performed in this paper is identified as a benchmark for response calibration and limit-state assessment, and in this respect, the nonlinear static analysis is proven as a simpler and less time-consuming method for preselection and screening of design solutions since the differences with respect to the dynamic analysis are within a certain ratio acceptable in projects. This advice leads to the optimisation of resources, minimisation of uncertainty, and better decision-making in early design phases.

In addition, the results presented are also suitable for probabilistic performance schemes, which allow the use of these results as input for vulnerability analyses that are not the core of this work.

The novelty of this research lies in the fact that the analysis carried out in this manuscript is limited to a regular two-dimensional frame and one accelerogram. Thus, it is recommended to extend the scope to three-dimensional models with plan and elevation irregularities and sets of representative records, to strengthen the generalization of the findings, evaluate sensitivity to motion variability, and explore adjustment factors that systematically link the estimated demands by the static method with those obtained from the dynamic method. This continuity will enhance the practical applicability of the comparative approach in projects of new performance-oriented buildings, and the quantification of output variables, including interstory drifts, internal stresses, and ductility, is imperative for a comprehensive understanding of the subject matter.

References

[1] Pratyush Kumar, and Avik Samanta, “Seismic Fragility Assessment of Existing Reinforced Concrete Buildings in Patna, India,” *Structures*, vol. 27, pp. 54-69, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[2] Christos G. Lachanas, and Dimitrios Vamvatsikos, “Rocking Incremental Dynamic Analysis,” *Earthquake Engineering & Structural Dynamics*, vol. 51, no. 3, pp. 688-703, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[3] Francisco Bañuelos-Garcia et al., “Dynamic Capacity Curve and its Application to the Seismic Evaluation of Structures,” *Earthquakes and Structures*, vol. 28, no. 1, pp. 75-87, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] Cesar Arriola Prieto, “Evaluation of the Seismic Resilience of Self-Built Buildings using Nonlinear Analysis and Incremental Dynamic Analysis,” *Journal of Scientific and Technological Research Work*, vol. 5, no. 2, pp. 13-23, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] A. Seyedkazemi, and F. Rahimzadeh Rofooei, “Comparison of Static Pushover Analysis and IDA-Based Probabilistic Methods for Assessing the Seismic Performance Factors of Diagrid Structures,” *Scientia Iranica*, vol. 28, no. 1, pp. 124-137, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[6] Mohsen Soltani, Rouhollah Amirabadi, and Mahdi Sharifi, “Comparison of IDA and Multicomponent IDA-Based Fragility Analysis,” *Research Square*, pp. 1-29, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[7] Mahmoud Miari, and Robert Jankowski, “Incremental Dynamic Analysis and Fragility Assessment of Buildings Founded on Different Soil Types Experiencing Structural Pounding during Earthquakes,” *Engineering Structures*, vol. 252, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[8] A. Kaveh, S.M. Javadi, and R. Mahdipour Moghanni, “Optimization-Based Record Selection Approach to Incremental Dynamic Analysis and Estimation of Fragility Curves,” *Scientia Iranica. Transaction A, Civil Engineering*, vol. 28, no. 2, pp. 700-708, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[9] Khadije Mahmoodi et al., “Seismic Performance Assessment Of A Cemented Material Dam Using Incremental Dynamic Analysis,” *Structures*, vol. 29, pp. 1187-1198, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[10] Yaghub Minaei et al., “Incremental Dynamic Analysis of Mid-Rise Buildings with Buckling Restrained Brace Frame System under Pulse-Like Near-Fault Ground Motions,” *Journal of Rehabilitation in Civil Engineering*, vol. 13, no. 4, pp. 47-66, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[11] Yan Zou et al., “Performance-Based Seismic Assessment Of Shield Tunnels By Incorporating A Nonlinear Pseudostatic Analysis Approach for the Soil-Tunnel Interaction,” *Tunnelling and Underground Space Technology*, vol. 114, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[12] Abed Rigi et al., “Study of the Seismic Behavior of Rigid and Semi-Rigid Steel Moment-Resisting Frames,” *Journal of Constructional Steel Research*, vol. 186, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[13] Shuling Hu et al., “Performance-Based Design of Self-Centering Energy-Absorbing Dual Rocking Core System,” *Journal of Constructional Steel Research*, vol. 181, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[14] De-Cheng Feng et al., “Investigation of 3D Effects on Dynamic Progressive Collapse Resistance of RC Structures Considering Slabs and Infill Walls,” *Journal of Building Engineering*, vol. 54, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[15] Andrea Nettis et al., “Cloud Capacity Spectrum Method: Accounting for Record-to-Record Variability in Fragility Analysis using Nonlinear Static Procedures,” *Soil Dynamics and Earthquake Engineering*, vol. 150, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[16] Navid Rahgozar, and M. Shahria Alam, “Seismic Collapse Assessment of Hybrid Self-Centering Piston-Based Braced Frames Equipped with SMA Bars and Friction Springs,” *Journal of Constructional Steel Research*, vol. 208, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[17] Yutao Pang, and Xiaowei Wang, “Enhanced Endurance-Time-Method (EETM) for Efficient Seismic Fragility, Risk and Resilience Assessment of Structures,” *Soil Dynamics and Earthquake Engineering*, vol. 147, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[18] ETABS, Csiespana. [Online]. Available: http://www.csiespana.com/software/5/etabs

[19] Dimitrios Vamvatsikos, and C. Allin Cornell, “Incremental Dynamic Analysis,” *Engineering & Structural Dynamics*, vol. 31, no. 3, pp. 491-514, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[20] Sinan Akkar, and Asli Metin, "Assessment of Improved Nonlinear Static Procedures in FEMA-440," *Journal of Structural Engineering*, vol. 133, no. 9, pp. 1237-1246, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[21] Fatemeh Jalayer, Ufuk Hancilar, and Nurullah Açıkgöz, "Data-Driven Seismic Fragility Modelling using Bayesian Inference," *Research Square*, pp. 1-41, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[22] Farzin Zareian, and Helmut Krawinkler, "Assessment of Probability of Collapse and Design for Collapse Safety," *Earthquake Engineering & Structural Dynamics*, vol. 36, no. 13, pp. 1901-1914, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[23] Carlos Joao Saldaña Becerra, "*Structural Design of A Five-Story Reinforced Concrete Multi-Family Building in the Santiago De Surco District*," Thesis, Pontifical Catholic University of Peru, pp. 1-162, 2024. [Google Scholar] [Publisher Link]

[24] *Seismic Evaluation and Retrofit of Existing Buildings (41-17)*, American Society of Civil Engineers, pp. 1-550, 2017. [Google Scholar] [Publisher Link]

[25] Los Angeles Tall Buildings Structural Design Council — 2020 Los Angeles Tall Buildings Conference. 2020. [Online]. Available: https://www.latallbuildings.org/2020-conference

[26] Standard E.020 Loads, National Building Regulations, 2020. [Online]. Available: https://drive.google.com/file/u/1/d/15atg-9w0OEXjR5C1m6IXUFihwYeUh1aN/view?usp=sharing&usp=embed_facebook

[27] Standard E.030 Seismic-resistant Design, National Building Regulations, 2020. [Online]. Available: https://drive.google.com/file/d/1W14N6JldWPN8wUZSqWZnUphg6C559bi-/view

[28] Standard E.060 Reinforced Concrete, National Building Regulations, 2020. [Online]. Available: https://drive.google.com/file/u/1/d/19EYUVMgwvm6rDs47GV374avco2ylU5Kz/view?usp=sharing&usp=embed_facebook

[29] Properties of Materials in Reinforced Concrete Sections, Mander, [Online]. Available: https://es.slideshare.net/juanjosepaganmartinez/modelo-de-mander

[30] Properties of Materials in Reinforced Concrete Sections. Scribd. [Online]. Available: https://es.scribd.com/doc/243416282/MODELO-KENT-Y-PARK-Y-MODIFICADO-pdf

[31] Michael N. Fardis, Alexandra Papailia, and Georgios Tsionis, "Seismic Fragility of RC Framed and Wall-Frame Buildings Designed to the EN-Eurocodes," *Bulletin of Earthquake Engineering*, vol. 10, pp. 1767-1793, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[32] H. Crowley, and R. Pinho, "Period-Height Relationship for Existing European Reinforced Concrete Buildings," *Journal of Earthquake Engineering*, vol. 8, pp. 93-119, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[33] CISMID, 2025. [Online]. Available: https://www.cismid.uni.edu.pe/

[34] Tiziana Rossetto et al., "FRACAS: A Capacity Spectrum Approach for Seismic Fragility Assessment including Record-to-Record Variability," *Engineering Structures*, vol. 125, pp. 337-348, 2016. [CrossRef] [Google Scholar] [Publisher Link]