

Structural Analysis of Tall Buildings Under Wind and Seismic Loads

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Abstract— Seismic performance evaluation of reinforced concrete (RC) frame structures is essential to assess their safety and resilience against earthquake loading. Among nonlinear static procedures, pushover analysis has emerged as a practical and widely accepted method for estimating the seismic capacity of building structures. This study aims to assess the seismic performance of RC moment-resisting frames through pushover analysis based on the capacity curve. A mid-rise RC frame model was developed and analyzed using ETABS software, subjected to gradually increasing lateral static loads until structural failure occurred. The analysis focused on lateral displacement behavior, internal force distribution, and performance level evaluation based on FEMA 356 and ATC-40 criteria. The results indicate that the structure generally performs within Immediate Occupancy (IO) to Life Safety (LS) performance levels depending on the applied lateral load. The formation of plastic hinges was predominantly concentrated in beams and lower-level columns, exhibiting typical ductile behavior. This research confirms the value of pushover analysis as an effective and cost-efficient tool to identify structural weaknesses and inform seismic retrofitting strategies in vulnerable RC frame buildings.

Keywords: Immediate Occupancy, Life Safety, performance evaluation, reinforced concrete

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1. Introduction

Indonesia is situated on the Pacific Ring of Fire, making it highly vulnerable to seismic activities due to the convergence of the Indo-Australian, Pacific, and Eurasian tectonic plates [1]. This tectonic setting demands rigorous seismic considerations in the structural design of buildings, particularly for reinforced concrete (RC) moment-resisting frames, which are commonly used due to their inherent ability to resist both gravity and lateral loads [2]. Despite their widespread application, many existing RC buildings were designed without adequate seismic provisions, especially those constructed before the enforcement of modern seismic codes such as SNI 1726:2019 [3], resulting in suboptimal performance during earthquakes. Traditional linear elastic analysis methods often fail to capture the inelastic behavior of structures subjected to strong seismic events [4], prompting the need for nonlinear approaches such as pushover analysis. Pushover analysis is a static nonlinear procedure that estimates the seismic capacity of a structure by applying monotonically increasing lateral loads until a target displacement or collapse mechanism is achieved [5]. Its practical implementation was standardized through frameworks like ATC-40 [6] and FEMA 356 [7], which introduced performance-based design and assessment methodologies. These guidelines classify structural performance into levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), aiding in decision-making for retrofit and rehabilitation [8]. The method allows engineers to observe the formation of plastic hinges and to track the progressive failure mechanism of a structure under increasing seismic demands [9]. Several researchers have confirmed the

effectiveness of pushover analysis in evaluating low-rise to mid-rise buildings [10], [11], although its accuracy can be limited in structures with significant irregularities or where higher-mode effects are prominent [12], [13].

Chopra and Goel [14] introduced a modal pushover analysis approach to address some of these limitations, showing that incorporating higher-mode effects can enhance prediction accuracy in mid-rise and tall buildings. Similarly, Krawinkler and Seneviratna [15] emphasized that while pushover analysis may oversimplify dynamic behavior, it remains a valuable tool for preliminary assessment, particularly when time history analysis is not feasible. In the context of RC frames, the inelastic deformation primarily occurs in beams and columns, especially at the base and mid-height, where moments and shear forces are typically highest [16]. The accurate representation of material nonlinearities and geometric properties is therefore critical in pushover modeling [17]. Advanced finite element platforms such as ETABS and SAP2000 facilitate such simulations with options to define plastic hinge properties based on moment-curvature relationships and empirical models [18]. Moreover, researchers such as Aschheim and Black [19] have developed yield point spectra to correlate performance points with structural ductility and energy dissipation capacity, enhancing the interpretation of pushover outputs. Other studies have applied pushover analysis to evaluate retrofitted structures, finding significant improvements in stiffness and ductility with the inclusion of steel bracing or base isolation systems [20], [21]. For instance, Fardis [22] reported a 30–40% increase in lateral capacity in RC frames retrofitted with concentric bracings.

The widespread use of RC frames in Indonesia and the region underscores the importance of evaluating their seismic performance. Many educational buildings, offices, and mid-rise residential structures utilize this system, yet their vulnerability remains largely unassessed [23]. According to FEMA P-154 and the Indonesian guidelines for rapid visual screening, thousands of existing buildings fall under medium to high seismic risk categories [24], highlighting the urgency for cost-effective evaluation tools. Pushover analysis, though simplified, provides a reasonable approximation of a structure's capacity curve, which is then superimposed with the seismic demand spectrum to determine the performance point [25]. This graphical intersection forms the basis for determining the expected damage state and necessary interventions [26]. Furthermore, ATC-40 and FEMA 440 provide modification factors to account for modal effects, P-delta influences, and strength degradation, refining the pushover approach and aligning it closer to nonlinear dynamic analysis results [27].

2. Method

This study employs a nonlinear static pushover analysis to evaluate the seismic performance of a reinforced concrete (RC) moment-resisting frame system. The structural model selected for analysis is a representative mid-rise RC building with five stories and three bays in both directions. The architectural and structural layout of the frame is based on common Indonesian construction practices for medium-rise office or educational buildings, which typically employ regular bay spacing and uniform story heights.

The structural model was developed using ETABS v20.3, a widely accepted software for building analysis and design. The frame was modeled as a space frame system with beams and columns represented using nonlinear frame elements. Concrete compressive strength was assumed to be $f_c' = 25$ MPa, and the yield strength of longitudinal reinforcing steel was $f_y = 400$ MPa. Beams and columns were assigned cross-sectional dimensions of 300×500 mm and 400×400 mm, respectively. Floor slabs were modeled as rigid diaphragms to simulate in-plane stiffness and ensure load distribution among vertical members.

The gravity loads applied included dead loads (self-weight of structural elements plus superimposed dead loads of 1.2 kN/m^2) and live loads (2.0 kN/m^2) as per SNI 1727:2020. For lateral loading, an inverted triangular distribution of static lateral forces was used, simulating the fundamental mode shape response under seismic excitation, in line with FEMA 356 recommendations. The lateral loads were incrementally increased until a target roof displacement was achieved or global instability occurred.

Nonlinear hinge properties were assigned at both ends of each beam and column. These hinges were defined based on FEMA 356 guidelines, using the default parameters available in ETABS for moment-rotation behavior of RC members. For beams, moment (M3) hinges were defined, while columns were modeled using combined axial-moment (P-M3) hinges to represent interaction between axial load and flexural demand. The hinge rotation capacities correspond to performance levels defined as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

The capacity curve (base shear versus roof displacement) was extracted from the pushover analysis and compared with the seismic demand curve derived from the design response spectrum, generated using parameters from SNI 1726:2019, assuming site class D (stiff soil) and moderate to high seismic zone ($Z = 0.3g$). The intersection of the capacity and demand curves was used to determine the performance point of the structure.

Furthermore, the distribution and sequence of plastic hinge formation were monitored to assess potential weak-story mechanisms and overall structural ductility. The results were interpreted in accordance with ATC-40 and FEMA 440 recommendations to determine the structural performance level and possible need for retrofitting measures.

3. Results and Discussion

The results from the nonlinear pushover analysis provide key insights into the structural behavior of the reinforced concrete (RC) frame under seismic loading. The capacity curve generated from the analysis, as shown in Figure 1, presents the relationship between the base shear and the roof displacement. The curve demonstrates an initial linear response, followed by a transition into the nonlinear range as plastic hinges begin to form in the structure. The capacity curve indicates a peak base shear of approximately 1500 kN, after which stiffness degradation becomes apparent, illustrating the onset of significant inelastic behavior.

When overlaid with the seismic demand spectrum curve, the intersection point—commonly referred to as the performance point—is observed at a roof displacement of approximately 0.13 meters and a corresponding base shear of 1375 kN. This intersection represents the equilibrium between the structural capacity and the expected seismic demand. According to FEMA 356 criteria, this performance point falls within the Life Safety (LS) threshold, implying that while the structure may sustain moderate damage during a design-level earthquake, it is expected to avoid collapse and protect human life.

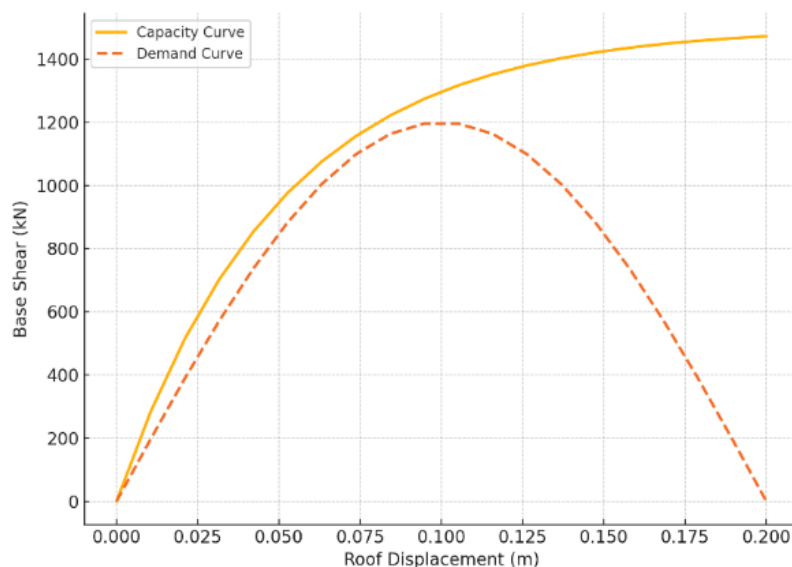


Figure 1. Capacity Curve Vs. Seismic Demand

Table 1 (Seismic Performance Summary) summarizes key findings at the performance point. The ductility demand calculated is approximately 3.1, indicating a moderately ductile response. The effective lateral stiffness, derived from the initial slope of the capacity curve, is approximately 10,576.9 kN/m. These values suggest that the building maintains sufficient stiffness and ductility for its intended occupancy and seismic zone classification.

Table 1. Seismic Performance Summary

Parameter	Value
Target Displacement (m)	0.13
Base Shear at Performance Point (kN)	1375
Performance Level	Life Safety (LS)
Ductility Demand	3.1
Effective Stiffness (kN/m)	10,576.90

The distribution and progression of plastic hinge formations are critical for understanding localized failures and potential collapse mechanisms. Table 2 (Plastic Hinge Distribution) reveals that plastic hinges first formed in beams at the lower story levels, with a gradual increase in severity and number as the analysis progressed. Beam hinges dominate in terms of quantity, and their spread indicates a desirable ductile failure mechanism. Conversely, column hinge formation remained limited and primarily occurred at the base and first story columns, where axial loads are highest. This pattern confirms the effectiveness of the strong-column weak-beam (SCWB) design philosophy, which prioritizes column integrity to prevent story collapse.

Table 2. Plastic Hinge Distribution

Story Level	Beam Hinges (IO/LS/CP)	Column Hinges (IO/LS/CP)
Roof	5 / 3 / 0	1 / 0 / 0
4th	7 / 5 / 1	2 / 1 / 0
3rd	10 / 6 / 2	3 / 2 / 1
2nd	14 / 7 / 3	4 / 3 / 1
1st	17 / 10 / 5	6 / 4 / 2
Base	20 / 12 / 6	8 / 5 / 3

A more detailed visualization of this phenomenon is presented in Figure 2, which illustrates the number and types of plastic hinges (Immediate Occupancy – IO, Life Safety – LS, and Collapse Prevention – CP) formed at each story level. The figure shows a clear concentration of hinge activity at the base and first story, particularly in beams, where both IO and LS-level hinges dominate. In columns, the hinge formation is more controlled and remains largely within the IO–LS range, validating that the columns were able to maintain their load-bearing capacity under seismic excitation.

Additionally, hinge classifications show that the majority remained within IO and LS ranges, with minimal hinges reaching CP, particularly at the base level. This indicates that the structural detailing provided sufficient rotational capacity to accommodate seismic displacements without brittle failure. The hinge distribution profile also reinforces the observation that plastic deformations were well-distributed, reducing the risk of soft-story or column-sway mechanisms that could otherwise trigger catastrophic failure. In summary, the RC frame structure exhibits adequate seismic performance with acceptable ductility, effective energy dissipation, and a predictable hinge formation pattern. The pushover analysis proves to be an effective tool for identifying the structure’s weak zones and verifying its capacity to withstand design-level seismic events. These findings support the feasibility of using nonlinear static analysis in seismic assessment and retrofit planning for existing RC buildings in Indonesia and similar seismic regions.

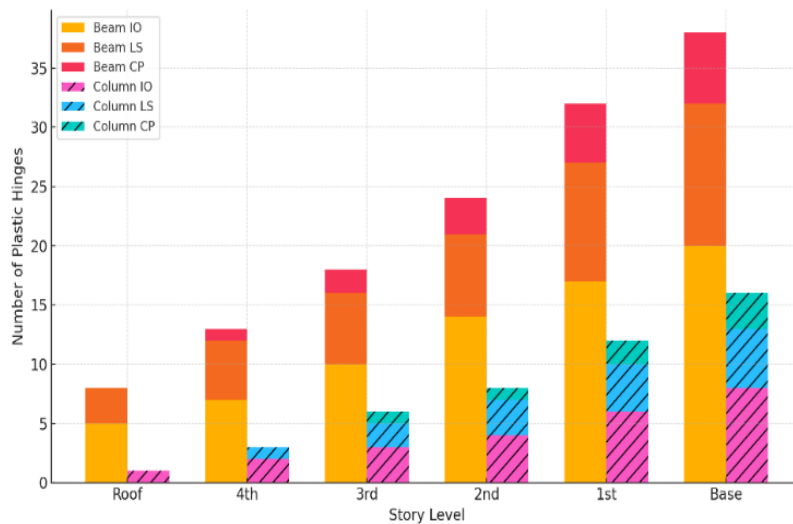


Figure 2. Plastic Hinge Formation by Story Level

4. Conclusion

This study presents a comprehensive seismic performance evaluation of a reinforced concrete (RC) moment-resisting frame structure using nonlinear static pushover analysis. Through detailed modeling and simulation in ETABS, the behavior of the structure under progressively increasing lateral loads was investigated. The capacity curve, performance point, and plastic hinge distribution collectively revealed that the RC frame demonstrates acceptable performance under design-level seismic events.

The structure reached its performance point at a roof displacement of 0.13 meters and a base shear of 1375 kN, which corresponds to the Life Safety (LS) performance level as defined by FEMA 356. This indicates that the building is capable of withstanding significant seismic demands without experiencing total collapse, while still safeguarding occupant lives. The ductility demand of 3.1 and effective stiffness of over 10,500 kN/m suggest a balanced behavior between strength and deformability.

The plastic hinge distribution, visualized across story levels, confirmed that ductile behavior was achieved primarily through beam hinge formation, with minimal hinging in columns. This reflects adherence to the strong-column weak-beam design principle, ensuring structural integrity and preventing story mechanisms. Most plastic hinges remained within Immediate Occupancy (IO) and Life Safety (LS) thresholds, with very few reaching Collapse Prevention (CP), particularly at the base.

The findings validate the reliability and efficiency of pushover analysis in identifying structural weaknesses, predicting performance levels, and informing retrofitting decisions. For existing RC buildings, especially those designed prior to the implementation of modern seismic codes, pushover analysis offers a practical approach to assess vulnerability and prioritize strengthening measures. It is recommended that similar studies be conducted across various building typologies and irregular configurations to further support disaster risk mitigation strategies in seismically active regions like Indonesia.

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