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Evaluation of Reinforced Concrete Structural Performance under Earthquake Loads Based on Nonlinear Analysis in Lombok

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Abstract: *Lombok is located in a highly seismic region of Indonesia, where reinforced concrete (RC) buildings dominate the urban built environment. However, the seismic performance of existing RC structures varies significantly depending on design practice, material quality, and structural configuration. This study evaluates the seismic performance of reinforced concrete buildings in Lombok using nonlinear structural analysis, with emphasis on nonlinear static pushover and nonlinear dynamic time history methods. The study adopts a comparative analytical approach by synthesizing findings from recent experimental, numerical, and field-based studies related to RC seismic performance in Indonesia and other seismic regions. Key performance indicators such as interstory drift, plastic hinge formation, displacement capacity, and performance levels (Immediate Occupancy, Life Safety, and Collapse Prevention) are examined. The analysis highlights that many existing RC structures in Lombok are vulnerable to moderate-to-strong earthquakes due to low material strength, inadequate detailing, and non-compliance with modern seismic codes. However, structures designed with proper ductility provisions and evaluated using performance-based methods show satisfactory behavior under seismic loads. The study concludes that nonlinear analysis is essential for realistic seismic performance evaluation and recommends systematic assessment and retrofitting of existing buildings in Lombok to enhance structural resilience and reduce seismic risk.*

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INTRODUCTION

Lombok Island is located within one of the most seismically active zones in Southeast Asia due to the interaction between the Indo-Australian Plate and the Eurasian Plate. This tectonic setting exposes the region to frequent moderate and strong earthquakes that pose significant risks to the built environment, particularly reinforced concrete buildings that dominate urban and semi-urban development. The 2018 Lombok earthquake sequence revealed extensive structural damage, including partial collapses and severe cracking, even in buildings that were not very old. These observations indicate that a substantial portion of existing reinforced concrete structures in Lombok does not perform adequately under seismic loading (Harris Pradono, 2018).

Field investigations after the Lombok earthquake demonstrated that many buildings began to suffer structural damage at relatively low intensity levels. Harris Pradono (2018) reported that several reinforced concrete mosque structures experienced initial damage at Modified Mercalli Intensity V, corresponding to peak ground accelerations between 0.039 g and 0.092 g. The early onset of damage was attributed primarily to low concrete compressive strength and insufficient reinforcement ratios. These findings highlight a critical structural vulnerability that cannot be captured accurately through

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elastic analysis alone and require nonlinear evaluation approaches that consider material and geometric nonlinearity.

Similar vulnerabilities have been observed in other seismically active regions of Indonesia. Arsyad et al. (2024) reported that reinforced concrete buildings in Mamuju exhibited poor seismic performance during the 2021 Mw 6.2 earthquake, particularly those designed using conventional force-based methods without adequate ductility detailing. These studies collectively suggest that a large portion of Indonesia's existing building stock may be structurally deficient when subjected to earthquake loads, particularly when evaluated against modern performance-based criteria.

To address this issue, performance-based seismic evaluation methods have been widely adopted in recent years. Nonlinear static pushover analysis has become a standard tool for assessing the seismic performance of reinforced concrete buildings. Studies by Sastra Wibawa et al. (2022), Afiah et al. (2023), Putri et al. (2022), and Pierre and Hidayat (2020) demonstrated that pushover analysis is effective in estimating displacement capacity, identifying plastic hinge formation, and classifying performance levels such as Immediate Occupancy, Life Safety, and Collapse Prevention. These studies generally found that structures designed and detailed in accordance with modern seismic provisions tend to achieve Immediate Occupancy or Damage Control performance levels.

However, nonlinear static analysis has limitations, particularly in representing higher mode effects, cyclic degradation, and the influence of near-fault ground motions. Nonlinear dynamic time history analysis provides a more realistic representation of structural response under earthquake excitation. Daniel and Sinaga (2020) showed that nonlinear time history analysis is particularly useful in evaluating retrofitted structures and assessing the effectiveness of strengthening techniques such as CFRP and base isolation. Waghmare and Kawade (2020) further emphasized that incremental dynamic analysis enables probabilistic assessment of structural collapse, which cannot be obtained from static procedures alone.

The influence of structural configuration and system type has also been extensively studied. Abd-Elhamed et al. (2023) demonstrated that floor slab systems significantly affect interstory drift and energy dissipation, especially in low- and mid-rise buildings. Zameeruddin and Sangle (2017) highlighted the importance of plastic hinge distribution in reinforced concrete frames to prevent undesirable soft-story mechanisms. These findings suggest that structural performance is not solely governed by material strength but also by structural layout and detailing.

Despite the growing body of research on nonlinear seismic analysis of reinforced concrete buildings in Indonesia, most studies focus on regions such as Palu, Balikpapan, Lampung, and Mamuju (Afiah et al., 2023; Putri et al., 2022; Mustofa et al., 2024; Arsyad et al., 2024). There is limited systematic analysis that specifically addresses the seismic performance of reinforced concrete buildings in Lombok using nonlinear performance-based approaches. This represents a significant knowledge gap given Lombok's high seismic hazard and demonstrated structural vulnerability.

Therefore, this study aims to evaluate the seismic performance of reinforced concrete structures in Lombok using nonlinear analysis methods and to synthesize existing empirical and numerical evidence to identify dominant vulnerability patterns, performance trends, and implications for seismic risk mitigation. The contribution of this study lies in its integrative evaluation of nonlinear analysis results within the Lombok context and its support for evidence-based policy on structural assessment and retrofitting.

RESEARCH METHOD

This study adopted a qualitative–comparative analytical design based on a systematic synthesis of published empirical and numerical studies related to the seismic performance evaluation of reinforced concrete structures. This approach was selected to obtain a comprehensive understanding of structural behavior under earthquake loading without conducting new experiments, additional simulations, or independent numerical modeling beyond the findings already reported in the literature.

The object of analysis was the seismic performance of reinforced concrete buildings, with a contextual focus on Lombok as a region with high seismic hazard. The analysis emphasized structural vulnerability patterns, performance levels, and mitigation implications derived from previously conducted nonlinear evaluations.

Data Sources and Selection Criteria

The data were obtained from peer-reviewed journal articles, conference proceedings, and academic publications listed exclusively in the reference section of this article. All selected sources reported validated field observations, nonlinear static pushover analyses, nonlinear dynamic time history analyses, or performance-based seismic evaluations of reinforced concrete structures.

- The inclusion criteria were defined as follows:
- The study focuses on reinforced concrete structures.
- The study applies nonlinear static or nonlinear dynamic analysis.
- The study reports measurable seismic performance indicators.
- The study is relevant to Indonesian seismic conditions or regions with comparable seismic characteristics.

Studies that were purely conceptual, did not report structural performance results, or were not directly related to nonlinear seismic evaluation were excluded from the analysis.

Performance Evaluation Framework

The analytical framework was based on seismic performance indicators commonly applied in earthquake engineering practice. These indicators include interstory drift ratio, global displacement capacity, plastic hinge formation and distribution, and overall structural performance levels. Performance levels were classified according to Immediate Occupancy, Life Safety, and Collapse Prevention criteria as defined in ATC-40, FEMA 356, FEMA 440, ASCE 41-17, and SNI 1726:2019.

All performance indicators were extracted directly from the reported results of each reviewed study and used for comparison without normalization, modification, or reinterpretation of the original data.

Analysis Procedure

The analysis was conducted through three main stages. The first stage involved data extraction, including identification of study location, building typology, applied nonlinear analysis method, and reported seismic performance outcomes. The second stage consisted of finding classification, where results were grouped according to analysis type, namely nonlinear static pushover analysis, nonlinear dynamic time history analysis, and combined approaches. The third stage was comparative analysis, aimed at identifying consistent performance trends, shared vulnerability characteristics, and variations in structural response associated with material quality, reinforcement detailing, and structural system configuration.

The analysis was performed using a descriptive–analytical approach, emphasizing consistency across studies and their relevance to the seismic behavior of reinforced concrete buildings in Lombok.

Validity and Analytical Consistency

To maintain scientific validity, this study did not introduce new assumptions, additional parameters, or interpretations beyond those explicitly reported in the source studies. All analytical conclusions were derived directly from the available empirical and numerical evidence. This approach ensures traceability, logical coherence, and consistency with the original data.

Through this methodology, the study provides a systematic and objective evaluation of reinforced concrete seismic performance and establishes a reliable basis for subsequent discussion and conclusions regarding structural assessment and retrofitting needs in earthquake-prone regions such as Lombok.

RESULTS AND DISCUSSION

This section presents a structured synthesis of the empirical and analytical findings reported in the reviewed studies and discusses their implications for the seismic performance of reinforced concrete buildings in Lombok. The results are organized according to observed performance levels, analysis methods, structural vulnerability patterns, and implications for seismic risk mitigation.

Summary of Empirical and Analytical Findings

Table 1 summarizes the core findings from the reviewed studies, focusing on location, analysis approach, and reported seismic performance.

Table 1. Summary of Key Findings from Reviewed Studies

Study	Location	Analysis Type	Key Performance Outcome
Harris Pradono (2018)	Lombok	Field observation	Damage initiated at low intensity due to low concrete strength
Sastra Wibawa et al. (2022)	Lombok	Pushover	Solid infill walls improved Immediate Occupancy performance
Afiah et al. (2023)	Palu	Pushover	Building achieved Immediate Occupancy
Putri et al. (2022)	Balikpapan	Pushover	Structure satisfied SNI 1726:2019 requirements
Mustofa et al. (2024)	Lampung	Pushover	Building exhibited stable nonlinear behavior
Arsyad et al. (2024)	Mamuju	Field and numerical	Conventional designs showed poor seismic performance
Daniel and Sinaga (2020)	General	Time history	Retrofitting improved structural response
Sulthan and Seki (2023)	Indonesia	Fragility analysis	Base isolation reduced collapse probability

The reviewed evidence indicates a clear contrast between buildings designed with modern seismic provisions and those constructed without adequate detailing. Structures evaluated using nonlinear pushover analysis and designed according to current standards generally achieved

Immediate Occupancy or Damage Control performance levels (Afiah et al., 2023; Putri et al., 2022; Pierre & Hidayat, 2020). In contrast, field observations in Lombok and Mamuju showed that many existing buildings suffered damage at relatively low seismic intensities due to low material quality and inadequate reinforcement (Harris Pradono, 2018; Arsyad et al., 2024).

Performance Trends Identified Through Nonlinear Static Analysis

Nonlinear static pushover analysis consistently revealed that buildings with adequate ductility detailing exhibit stable post-yield behavior and controlled displacement demand. Studies by Sastra Wibawa et al. (2022) and Afiah et al. (2023) demonstrated that pushover curves typically showed gradual stiffness degradation and distributed plastic hinge formation, which corresponded to Immediate Occupancy or Damage Control performance levels.

However, pushover analysis also identified vulnerabilities in older structures. Buildings with low concrete compressive strength and insufficient transverse reinforcement showed early hinge formation and rapid stiffness degradation (Harris Pradono, 2018). These characteristics indicate a higher likelihood of brittle failure mechanisms and reduced displacement capacity.

The results suggest that pushover analysis is effective for identifying global performance levels and potential failure mechanisms, but its reliability depends on accurate representation of material properties and detailing practices.

Insights from Nonlinear Dynamic Analysis

Nonlinear dynamic time history analysis provided deeper insight into structural behavior under realistic earthquake excitations. Daniel and Sinaga (2020) and Moniri (2017) demonstrated that near-fault and pulse-type ground motions significantly increase displacement and rotation demands, often exceeding those predicted by static methods.

These findings imply that pushover analysis may underestimate seismic demand in regions influenced by near-fault earthquakes, such as parts of Indonesia. The dynamic response characteristics highlight the importance of considering record-to-record variability and higher mode effects, particularly for mid-rise and irregular structures.

Structural Configuration and System Effects

Structural configuration was found to be a major factor governing seismic response. Abd-Elhamed et al. (2023) reported that flat slab systems tend to exhibit higher interstory drift and lower energy dissipation compared to frame systems. Zameeruddin and Sangle (2017) emphasized that proper distribution of plastic hinges along beams rather than columns is essential to avoid soft-story collapse mechanisms.

These findings indicate that structural performance is not solely dependent on material strength but is strongly influenced by system-level design choices and detailing practices.

Implications for Lombok's Building Stock

When the synthesized findings are interpreted in the context of Lombok, a consistent pattern emerges. Field observations indicate low material quality and inadequate detailing in many existing buildings (Harris Pradono, 2018), while analytical studies show that such deficiencies significantly reduce seismic performance (Arsyad et al., 2024).

Conversely, buildings evaluated using performance-based approaches and strengthened through retrofitting or base isolation demonstrate substantially improved seismic resilience (Daniel & Sinaga, 2020; Sulthan & Seki, 2023). This supports the argument that systematic nonlinear assessment and targeted retrofitting can effectively reduce seismic risk in Lombok.

Synthesis

The results collectively demonstrate that nonlinear analysis provides essential insight into seismic vulnerability that cannot be captured through linear methods alone. The consistent evidence across studies supports the conclusion that Lombok's reinforced concrete building stock contains a significant proportion of vulnerable structures that require assessment and strengthening. Performance-based evaluation using nonlinear methods offers a reliable framework for prioritizing intervention and improving seismic resilience.

CONCLUSION

This study demonstrates that nonlinear analysis provides essential insight into the seismic performance of reinforced concrete buildings in Lombok. Field evidence and analytical studies indicate that many existing structures are vulnerable due to low material quality, inadequate reinforcement detailing, and non-compliance with modern seismic codes. These deficiencies result in early damage initiation and reduced structural reliability under moderate to strong earthquakes.

Conversely, buildings evaluated and designed using performance-based approaches generally exhibit satisfactory seismic behavior and achieve Immediate Occupancy or Damage Control performance levels. Nonlinear static pushover analysis is effective for identifying global performance levels, while nonlinear dynamic analysis captures higher mode effects and near-fault ground motion impacts that static methods cannot represent.

The findings support the urgent need for systematic nonlinear assessment of existing buildings in Lombok and the implementation of retrofitting strategies for structurally deficient buildings. Such measures are essential to enhance seismic resilience, reduce potential losses, and support sustainable development in earthquake-prone regions.

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