

Region-Sensitive Seismic Optimization of RC Special Moment Frames in High-Seismic Indonesian Regions

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Abstract

This study evaluates the seismic performance of reinforced concrete special moment-resisting frames (RC-SMRFs) with varying longitudinal reinforcement ratios under high-seismic conditions in Indonesia. The objective is to determine the optimum reinforcement ratio that balances structural strength and ductility while considering regional tectonic variability in Palu, Padang, and Mataram. The study highlights the importance of region-sensitive reinforcement optimization in performance-based seismic design for Indonesian high-seismic zones. A nonlinear static pushover analysis was conducted using ETABS based on SNI 1726:2019, SNI 2847:2019, ASCE 41-17, and FEMA hinge performance criteria. An eight-story reinforced concrete office building was modeled under five longitudinal reinforcement ratio scenarios ranging from 1.0% to 3.0%. Seismic performance was evaluated through modal characteristics, base shear capacity, interstory drift, ductility response, and plastic hinge distribution under regional seismic hazard conditions. The results indicate that increasing reinforcement ratios improves initial stiffness and base shear capacity by reducing the structural fundamental period and enhancing lateral resistance. However, reinforcement effectiveness declines beyond moderate levels due to accelerated stiffness degradation and reduced deformation sustainability. Ratios above 2.5% produced concentrated plastic hinges and brittle response tendencies, particularly under near-fault pulse-dominated seismic conditions. The optimum reinforcement ratio was consistently identified within 2.0%–2.5%, providing stable post-yield behavior, controlled drift, adequate ductility, and desirable strong-column weak-beam mechanisms across all regions. Regional seismic characteristics significantly influenced nonlinear behavior, with Palu showing concentrated hinge localization, Padang prolonged displacement accumulation, and Mataram intermediate structural response.

KEYWORDS

reinforced concrete frame; seismic performance; longitudinal reinforcement ratio; nonlinear pushover analysis; Indonesian seismic design; ductility optimization; performance-based design.

Introduction

Indonesia is positioned within one of the most seismically active regions in the world due to the complex interaction among the Indo-Australian, Eurasian, Pacific, and Philippine Sea plates. This tectonic interaction produces highly variable seismic sources, including strike-slip faults, subduction interfaces, and back-arc thrust systems, generating distinct regional seismic demand characteristics that strongly influence structural response. Regional tectonic complexity in Indonesia, particularly in active fault systems such as the Seram–Buru and eastern Indonesian regions, ,

demonstrates how varying fault mechanisms alter spectral acceleration demand frequency content, and rupture directivity, thereby affecting the seismic performance of structural systems subjected to nonlinear deformation demands (Saputra et al., 2025).

The significance of this issue is amplified by the widespread use of reinforced concrete special moment resisting frames (RC-SMRFs) in Indonesian medium-rise construction. RC-SMRFs are widely recognized for their ductility, redundancy, and energy dissipation capability under severe seismic excitation. However, their actual seismic resilience depends heavily on reinforcement detailing, beam-column joint integrity, and compatibility between structural stiffness and regional seismic demand characteristics. In tectonically heterogeneous regions, structural systems designed using generalized spectral assumptions may exhibit performance deficiencies when subjected to fault-specific demands not explicitly represented in conventional code-based design procedures (Morante-Carballo et al., 2024).

One of the principal challenges in seismic structural design lies in the diversity of nonlinear response induced by different fault-source mechanisms. Near-fault strike-slip events commonly produce pulse-like velocity demands and abrupt displacement excursions that generate concentrated inelastic deformation and amplified joint distress. Conversely, subduction-generated ground motions often exhibit long-duration excitation with significant long-period energy content, increasing the likelihood of stiffness degradation, P-delta amplification, and progressive nonlinear deterioration in multi-story RC systems (Bai et al., 2018). Such differences indicate that structural response cannot be adequately represented using uniform hazard assumptions across geographically distinct seismic regions.

Despite this reality, most structural design practice remains based on generalized spectral representations that do not explicitly differentiate nonlinear demands arising from regional tectonic diversity. This creates uncertainty regarding whether reinforcement detailing prescribed under a unified design framework remains equally effective across varying fault environments. In particular, the relationship between longitudinal reinforcement ratio and structural seismic performance under region-specific fault excitation remains insufficiently quantified for Indonesian RC-SMRFs.

Several studies have proposed improvements in seismic performance assessment through advanced nonlinear modeling and hazard-informed design frameworks. Investigations on beam-column joint flexibility demonstrate that realistic nonlinear joint representation significantly alters predicted ductility and drift capacity, indicating that reinforcement effectiveness is inseparable from local deformation compatibility and joint rotational behavior (Gombosuren & Maki, 2022). Similarly, hazard-based design developments emphasize that updated regional seismic characterization improves structural reliability by producing design spectra calibrated to local tectonic environments rather than generalized assumptions (Woessner et al., 2015).

Regional hazard-informed approaches have also been reinforced through data-driven seismic discrimination methods capable of distinguishing tectonic from non-tectonic events with improved reliability, enabling more representative motion selection for nonlinear structural assessment (Liu et al., 2024). These advances support performance-based seismic evaluation approaches

capable of linking regional tectonic variability directly to nonlinear structural demand prediction.

Nevertheless, a significant research gap remains. Existing studies primarily focus on code evolution, comparative seismic design regulations, or building-height-dependent response characteristics. Very limited attention has been directed toward systematic evaluation of reinforcement optimization under fault-mechanism-specific seismic demands in Indonesian RC-SMRFs. This gap restricts the development of region-sensitive reinforcement recommendations capable of balancing structural strength enhancement and ductility preservation under realistic regional hazard conditions.

Therefore, this study investigates the comparative seismic response of reinforced concrete special moment resisting frames subjected to representative fault mechanisms from Palu, Padang, and Mataram, representing strike-slip near-fault, subduction interface, and back-arc thrust environments, respectively. The study evaluates how variations in longitudinal reinforcement ratio influence nonlinear structural performance through modal response, pushover capacity, drift behavior, ductility demand, overstrength development, and plastic hinge progression. The novelty of this work lies in integrating fault-mechanism-sensitive seismic characterization with reinforcement optimization analysis to establish region-specific detailing recommendations for Indonesian seismic structural design. The scope is limited to nonlinear static performance evaluation of an eight-story RC-SMRF building model under design spectra defined according to contemporary Indonesian seismic provisions.

Methods

Research Design Framework

This study employs a nonlinear static performance-based seismic assessment framework to evaluate the influence of regional fault mechanisms on the seismic behavior of reinforced concrete special moment resisting frames (RC-SMRFs). The analytical procedure integrates structural modeling, calibrated nonlinear hinge assignment, regional seismic hazard characterization, and comparative pushover analysis to quantify structural response sensitivity across representative Indonesian tectonic environments.

The methodology adopts a deterministic parametric approach in which structural response variations are evaluated through systematic modification of longitudinal reinforcement ratio under region-specific seismic spectra representing Palu, Padang, and Mataram. This framework enables direct assessment of how reinforcement detailing interacts with regional seismic demand characteristics to influence global structural performance.

Structural Prototype Modeling

An eight-story reinforced concrete office building was selected as the representative medium-rise RC-SMRF prototype due to its practical relevance within Indonesian urban construction and its suitability for capturing nonlinear lateral deformation mechanisms.

The structural model has a plan dimension of 30 m × 20 m with a regular grid arrangement of six bays in the longitudinal direction and four bays transversely, each spanning 5 m. Story height is fixed at 4 m, producing an overall structural height of 32 m.

Column dimensions decrease progressively from lower to upper stories to reflect realistic stiffness distribution and strong-column weak-beam requirements. Lower-story

columns measure 700 × 700 mm, intermediate columns 600 × 600 mm, and upper-story columns 500 × 500 mm. Beam cross-sections are maintained at 300 × 600 mm throughout all stories, while slab thickness varies between 120 and 150 mm.

Rigid diaphragm action is assumed at each floor level. The structural configuration satisfies regularity requirements and minimizes torsional irregularities, enabling direct evaluation of regional seismic demand effects without geometric complexity bias.

Material Constitutive Properties

Concrete compressive strength is varied within 25–35 MPa to reflect commonly used Indonesian structural concrete grades. Elastic modulus is calculated according to code provisions using:

$$E_c = 4700\sqrt{f_c'}$$

Longitudinal reinforcement yield strength is assigned as 400 MPa with elastic modulus of 200000 MPa. Steel behavior follows bilinear constitutive response with strain-hardening ratio between 0.01 and 0.015 to capture post-yield nonlinear hardening effects.

Material confinement effects are incorporated into hinge calibration using confinement-sensitive plastic rotation capacities. This approach reflects evidence that confinement significantly influences nonlinear strength degradation and displacement capacity under progressive seismic loading (Abd-Elhamed et al., 2023).

Reinforcement Ratio Parametric Variation

Five longitudinal reinforcement ratio scenarios are evaluated:

- R1 = 1.0%
- R2 = 1.5%
- R3 = 2.0%
- R4 = 2.5%
- R5 = 3.0%

These values satisfy code-prescribed reinforcement limits while covering practical under-reinforced to moderately over-reinforced structural conditions.

The selected range enables identification of transition behavior between ductility-dominant and stiffness-dominant response mechanisms.

Regional Seismic Hazard Definition

Three Indonesian seismic regions are selected to represent distinct tectonic fault mechanisms:

1. Palu represents strike-slip near-fault seismic excitation characterized by pulse-like demand amplification.
2. Padang represents subduction interface excitation with long-duration and moderate long-period spectral amplification.
3. Mataram represents back-arc thrust seismic demand with relatively moderate spectral intensity.

Design spectral parameters are defined according to contemporary Indonesian seismic provisions and include spectral acceleration coefficients, site amplification factors, and derived design spectra.

This regional hazard characterization reflects tectonic diversity shown to significantly alter structural demand patterns (Saputra et al., 2025).

Nonlinear Hinge Calibration Procedure

Nonlinear hinge properties are assigned using FEMA and ASCE performance-based seismic evaluation procedures as baseline references. However, default hinge properties are progressively refined to reflect actual member geometry, axial force state, reinforcement ratio, and confinement conditions.

Beam hinges are modeled using concentrated M3

rotational hinges placed at both member ends. Column hinges are modeled using coupled P-M2-M3 interaction hinges to capture axial-flexural interaction and stability degradation.

Hinge rotation capacities are calibrated according to member confinement level and reinforcement detailing to avoid misrepresentation associated with generic default hinge assignments (Behnamfar & Nezhad, 2022). This calibrated approach improves prediction fidelity of stiffness degradation, drift capacity, and collapse progression.

Pushover Analysis Configuration

Nonlinear static pushover analysis is performed using ETABS with geometric nonlinearity enabled through P-delta effects.

Two lateral loading distributions are considered:

1. Fundamental mode shape pattern
2. Uniform lateral force distribution

Target displacement is defined up to 6% roof drift with displacement increments ranging from 0.01 to 0.05 m. Incremental analysis proceeds until global instability or collapse prevention threshold is reached.

This multi-pattern strategy reduces sensitivity associated with single-mode approximation and improves reliability of nonlinear demand interpretation (Katsanos & Vamvatsikos, 2017).

Performance Evaluation Criteria

Structural performance is assessed using Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) criteria based on hinge-state progression and displacement demand.

Primary response indicators include:

- Fundamental period
- Base shear capacity
- Roof displacement
- Interstory drift ratio
- Ductility factor
- Overstrength factor
- Plastic hinge sequence

Comparative response trends are synthesized through regional sensitivity assessment to identify optimum reinforcement ratio under each fault mechanism.

Reliability and Modeling Sensitivity Control

Sensitivity checks are performed by varying hinge rotation properties and stiffness degradation assumptions to evaluate robustness of predicted response trends.

Particular attention is given to assumptions known to strongly affect nonlinear response, including hinge location, axial-flexural interaction, joint flexibility approximation, confinement representation, and P-delta amplification (Bai et al., 2018).

These checks improve methodological transparency and enhance reproducibility of seismic performance conclusions.

Result and Discussion

Modal Characteristics

The modal analysis demonstrates a consistent reduction in fundamental period as longitudinal reinforcement ratio increases from 1.0% to 3.0% across all seismic regions. This behavior reflects the expected increase in global lateral stiffness associated with enhanced member flexural rigidity.

For the Palu model, the reduction is more pronounced due to stronger near-fault stiffness demand concentration. Structures with lower reinforcement ratios exhibit elongated

effective vibration periods caused by progressive stiffness degradation under nonlinear displacement demand. Similar behavior is observed in Padang and Mataram, although period reduction is relatively smoother due to lower pulse concentration.

The results confirm that reinforcement ratio significantly controls modal stiffness evolution. However, period reduction becomes marginal beyond 2.5%, indicating stiffness saturation and potential over-reinforced behavior. This aligns with prior studies suggesting that excessive reinforcement increases initial stiffness but does not proportionally improve nonlinear performance sustainability.

The observed trend indicates that reinforcement optimization should balance stiffness enhancement with deformation adaptability to avoid excessive rigidity-induced brittle response.

Base Shear Capacity

Ultimate base shear capacity increases progressively with reinforcement ratio for all regional models. The increase is most substantial between 1.0% and 2.0%, after which the growth rate declines.

Palu exhibits the highest base shear demand due to concentrated near-fault pulse excitation, requiring greater force redistribution through frame members. Padang shows moderately elevated strength demand associated with long-duration subduction excitation, while Mataram produces comparatively lower force demand.

At reinforcement ratios above 2.5%, additional strength gain becomes inefficient. Although nominal lateral resistance increases, post-yield degradation initiates earlier due to concentrated plastic demand at beam-column interfaces.

This indicates diminishing returns beyond moderate reinforcement levels and supports the hypothesis that excessive longitudinal reinforcement may produce inefficient strength accumulation when confinement detailing is unchanged.

The pushover curves demonstrate that R3 and R4 provide the most balanced strength-growth trajectory, sustaining post-yield resistance more effectively than R5.

Drift Performance

Interstory drift ratios decrease significantly as reinforcement increases from R1 to R4. This reflects enhanced stiffness and delayed crack propagation.

Palu consistently produces the largest drift demand, particularly at upper-story levels where pulse amplification intensifies displacement concentration. Drift concentrations approach Life Safety thresholds for R1 and R2 models.

Padang exhibits sustained drift accumulation due to long-period energy transfer, resulting in broader displacement distribution across multiple stories. Mataram demonstrates the most stable drift profile with reduced peak concentration.

At R5, drift reduction becomes negligible despite additional reinforcement. In several cases, local stiffness irregularity induces concentrated hinge rotations that offset drift-control benefits.

This confirms that reinforcement beyond the optimum range produces limited displacement-control improvement and may compromise structural ductility reserve.

Ductility Performance

Ductility factors increase from R1 through R4, reaching maximum values within the 2.0–2.5% reinforcement range.

This trend indicates improved plastic deformation

sustainability due to balanced strength and rotational capacity.

For R5, ductility declines in all regional models. The decline is most severe in Palu due to abrupt pulse-driven nonlinear demand exceeding localized rotational capacity.

Padang demonstrates moderate ductility reduction due to prolonged cyclic accumulation, while Mataram shows relatively minor degradation.

The results indicate that excessive reinforcement increases stiffness sufficiently to suppress beneficial distributed yielding, causing brittle localization at critical hinges.

These observations strongly support the proposed optimum reinforcement range and validate previous literature linking over-reinforcement to reduced deformation sustainability (Gombosuren & Maki, 2022).

Plastic Hinge Distribution

Plastic hinge progression patterns reveal clear differences among reinforcement scenarios.

R1 exhibits early hinge initiation concentrated at lower-story beam-column joints, particularly under Palu excitation. This indicates insufficient stiffness and rapid inelastic demand localization.

R2 and R3 produce distributed hinge formation consistent with desirable strong-column weak-beam behavior. Hinges develop progressively at beam ends before column degradation initiates, reflecting efficient energy dissipation. R4 maintains similar distributed behavior while delaying collapse-prevention exceedance.

R5 exhibits concentrated hinge localization with abrupt stiffness loss once yielding begins. Although initial yielding is delayed, collapse progression accelerates rapidly after plastic demand initiation.

Near-fault Palu excitation intensifies hinge clustering compared with Padang and Mataram, confirming that seismic source type strongly affects nonlinear damage distribution.

The results demonstrate that reinforcement optimization directly governs hinge progression stability and collapse resistance.

Comparative Regional Performance Assessment

Among all regional cases, Palu generates the most critical nonlinear response due to pulse-dominated strike-slip demand.

Padang produces extended ductility demand caused by long-duration subduction excitation.

Mataram demonstrates the most stable structural performance with moderate drift and distributed hinge formation.

Across all regions, reinforcement ratio between 2.0% and 2.5% consistently achieves the best strength–ductility balance.

This finding confirms that while regional fault mechanism modifies structural demand severity, optimum reinforcement remains within a narrow efficiency window suitable for region-sensitive seismic detailing recommendations.

The present study demonstrates that reinforcement ratio significantly affects the nonlinear seismic response of reinforced concrete special moment-resisting frames (RC-SMRFs), yet its effectiveness is strongly moderated by regional fault mechanisms and corresponding seismic demand characteristics. The findings indicate that longitudinal reinforcement cannot be considered an isolated strength-enhancement parameter, because nonlinear structural performance depends on how regional ground-motion characteristics interact with stiffness distribution, plastic hinge progression, and energy dissipation pathways.

This confirms that reinforcement effectiveness is fundamentally a source-sensitive response parameter rather than a purely sectional property.

The influence of regional fault mechanisms was clearly reflected in the nonlinear response trends observed for Palu, Padang, and Mataram. Structures subjected to near-fault pulse-dominated demands, represented by Palu, experienced concentrated plastic hinge development and rapid stiffness degradation at lower displacement levels. This agrees with previous investigations demonstrating that pulse-type excitations localize inelastic demand and reduce the effectiveness of reinforcement enhancement unless confinement detailing is sufficient to sustain distributed yielding (Abass & Jarallah, 2021; Bai et al., 2018; Eslami & Ronagh, 2012). In contrast, Padang's subduction-controlled long-period spectra produced broader displacement accumulation and prolonged inelastic cycling, enabling reinforcement to contribute more effectively to energy dissipation, although increased P-Delta sensitivity was evident at high drift levels. These findings support observations by Behnamfar & Nezhad (2022) and Hussain et al., (2024), who emphasized that regional seismic-source characteristics strongly control hinge migration patterns and deformation sustainability.

The observed strength-ductility trade-off highlights the physical limitations of increasing reinforcement ratio beyond an optimum range. As reinforcement increased from 1.0% to 2.5%, lateral strength and stiffness improved substantially, reflected by shorter periods and increased base shear resistance. However, beyond 2.5%, marginal strength gains diminished while ductility decreased due to earlier confinement degradation and concentrated hinge rotations. This confirms that excessive reinforcement may shift failure mechanisms toward brittle behavior when transverse reinforcement detailing is not proportionally enhanced. Similar conclusions were reported by Dicleli & Durucan, (2013) and Abd-Elhamed et al. (2023), who demonstrated that strength enhancement without corresponding confinement improvement reduces rotational capacity and accelerates post-yield degradation.

The optimum reinforcement ratio consistently emerged between 2.0% and 2.5% across all regional scenarios. Within this interval, frames achieved balanced nonlinear performance characterized by sufficient flexural resistance, stable post-yield stiffness degradation, distributed hinge development, and acceptable drift control within Life Safety performance objectives. This optimum reflects a balance between sectional stiffness and deformation capacity, enabling plastic redistribution without triggering premature joint distress. Gombosuren & Maki (2022) similarly observed that ductility maximization occurs when reinforcement supports stable hinge propagation while preserving joint flexibility and confinement integrity.

Plastic hinge distribution further validated this optimum condition. Frames with low reinforcement ratios exhibited premature beam hinging and localized drift concentration, increasing soft-story vulnerability. Conversely, highly reinforced models showed delayed yielding followed by abrupt hinge concentration near column bases, suggesting reduced deformation redistribution capacity. The intermediate reinforcement models produced the most desirable strong-column weak-beam mechanism, with gradual hinge progression from beam ends toward distributed plastic zones. This pattern aligns with established performance-based seismic design principles requiring ductile hierarchy and controlled energy dissipation pathways (Ragab et al., 2021; Rezavandi & Fu, 2016).

These findings have direct implications for Indonesian

seismic design practice. Current design workflows commonly adopt generalized FEMA default hinge properties and uniform hazard assumptions, which may not adequately reflect regional tectonic diversity. The results suggest that reinforcement optimization should be region-sensitive, incorporating local fault characteristics, source-dependent spectral demands, and calibrated nonlinear hinge properties. Such calibration should explicitly include confinement effects, axial-flexural interaction, and bidirectional loading sensitivity, consistent with recommendations from Perceka, (2025) and Zareian & Kanvinde, (2013). Integrating these refinements into Indonesian performance-based seismic design practice would improve reliability and reduce the risk of unconservative detailing assumptions.

Despite these contributions, several limitations should be acknowledged. First, the nonlinear static pushover methodology cannot fully capture cyclic degradation and cumulative damage effects associated with repeated strong-motion pulses. Second, FEMA default backbone assumptions may underestimate local joint degradation in highly confined nonlinear states. Third, higher-mode contributions and bidirectional excitation effects were approximated rather than explicitly simulated through nonlinear time-history analysis. These limitations are consistent with concerns raised by El-Mahdy et al., (2023) and Dicleli & Durucan (2013), who emphasized the importance of region-specific NLTHA validation.

Future research should therefore extend this work using nonlinear time-history analysis with regionally selected Indonesian ground-motion suites representing strike-slip, subduction, and crustal scenarios. Additional calibration of hinge properties using local material datasets and experimental beam-column joint behavior would further improve predictive reliability. Such efforts would strengthen Indonesia's transition toward fully performance-based seismic design frameworks capable of explicitly accounting for regional tectonic variability.

Overall, this study establishes that reinforcement optimization in Indonesian RC-SMRFs must be interpreted through a regional seismic lens. The reinforcement ratio of 2.0–2.5% provides the most effective balance between strength and ductility across high-seismic Indonesian regions, offering a practical and scientifically defensible benchmark for future seismic design guidance.

Conclusion

This study investigated the seismic performance of reinforced concrete special moment-resisting frames (RC-SMRFs) subjected to variations in longitudinal reinforcement ratio under high-seismic Indonesian regional conditions represented by Palu, Padang, and Mataram. Through nonlinear pushover analysis calibrated using SNI 1726:2019, SNI 2847:2019, ASCE 41-17, and FEMA-based hinge modeling, the research evaluated the interaction between reinforcement ratio, regional seismic source characteristics, structural strength, ductility, drift response, and plastic hinge development.

The results demonstrate that reinforcement ratio significantly influences global nonlinear response. Increasing longitudinal reinforcement improves lateral stiffness and base shear capacity, reflected by shorter fundamental periods and enhanced resistance against seismic demand. However, these gains are not linearly sustained beyond moderate reinforcement levels. Reinforcement ratios exceeding 2.5% showed diminishing

structural efficiency due to reduced deformation capacity, accelerated stiffness degradation, and concentrated hinge formation that increased brittle response tendencies.

The analysis consistently identified an optimum reinforcement ratio range between 2.0% and 2.5%, where the structural system achieved the most balanced seismic performance across all regional hazard scenarios. Within this range, frames exhibited stable post-yield response, controlled interstory drift, adequate ductility, and desirable strong-column weak-beam plastic hinge mechanisms that satisfied Life Safety and Collapse Prevention performance objectives.

Regional seismic characteristics were shown to strongly influence reinforcement effectiveness. Near-fault pulse-dominated conditions, represented by Palu, accelerated localized hinge formation and stiffness degradation, requiring higher confinement sensitivity to maintain ductile response. In contrast, subduction-dominated spectral conditions, represented by Padang, imposed prolonged displacement demands that emphasized deformation sustainability and P-Delta stability. Mataram demonstrated intermediate behavior, confirming that tectonic source variation fundamentally alters the reinforcement-performance relationship.

The principal scientific contribution of this study is the establishment of a region-sensitive reinforcement

optimization framework for Indonesian RC-SMRF design. Unlike conventional approaches that adopt generalized reinforcement prescriptions, the present findings demonstrate that reinforcement effectiveness must be evaluated relative to local seismic source characteristics and nonlinear deformation demands. This provides a practical benchmark for integrating regional hazard-informed reinforcement calibration into Indonesian performance-based seismic design practice.

From a practical engineering perspective, the study recommends that Indonesian designers adopt longitudinal reinforcement ratios within the 2.0–2.5% range for medium-rise RC-SMRFs in high-seismic zones, accompanied by rigorous confinement detailing and calibrated nonlinear performance verification. This range offers the most effective balance between strength enhancement and ductility preservation while reducing the risk of over-reinforced brittle failure mechanisms.

Future research should extend this work through nonlinear time-history analysis using region-specific Indonesian ground-motion suites, bidirectional excitation modeling, and experimental validation of local beam-column joint behavior. Such investigations will further refine performance-based reinforcement design recommendations and support the continued advancement of resilient seismic structural design frameworks in Indonesia.

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