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Structural Performance of Reinforced Concrete Buildings Considering Variations in Column Cross-Section Orientation and Reinforcement Ratio

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ABSTRACT

The seismic resilience of reinforced concrete (RC) buildings in high-risk earthquake regions is strongly influenced by the configuration of vertical structural elements. This study examines the combined effects of column cross-sectional orientation and longitudinal reinforcement ratios on the seismic performance of a 10-story RC building. Twelve structural models were developed using SAP2000 v24 and analyzed through nonlinear static pushover analysis. The models represented variations in column orientation (strong-axis and weak-axis) and reinforcement ratios ranging from 1% to 8%, based on the seismic characteristics of Padang, West Sumatra. Structural responses were evaluated using base shear capacity, displacement ductility, and interstory drift ratios, with validation conducted using the PEER Structural Performance Database. The findings indicate that column orientation has a greater impact on lateral stiffness and drift control than reinforcement quantity. Columns aligned along the strong axis with moderate reinforcement ratios between 2.5% and 3.5% demonstrated the best balance between strength and ductility, meeting the "Life Safety" performance requirements of SNI 1726:2019. In contrast, weak-axis columns with reinforcement ratios exceeding 4% showed limited improvement in stiffness and a higher tendency toward brittle shear failure. These results suggest that optimizing geometric configuration is more effective and economical than simply increasing reinforcement volume for improving seismic safety. The study concludes that strategic column axis alignment is a practical mitigation approach for earthquake-prone areas, while future studies should consider bi-directional dynamic loading for enhanced performance-based design evaluation.

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INTRODUCTION

The design of reinforced concrete (RC) structures in high-seismic regions presents multifaceted challenges concerning the optimization of vertical elements, specifically columns, which serve as the primary conduits for axial loads and lateral force resistance. A recurring practical dilemma in contemporary construction arises from architectural spatial constraints, which often necessitate the utilization of rectangular or "blade" column orientations. This geometric configuration inherently creates a significant disparity in stiffness between the strong and weak axes of the structural system. From a theoretical standpoint, such variations in cross-sectional orientation not only redistribute internal bending moments but also fundamentally alter the load transfer mechanisms at beam-column junctions, potentially precipitating brittle failure modes if not properly mitigated by an appropriate reinforcement ratio (American Concrete Institute). Discrepancies between the flexural capacities of columns and beams frequently compromise the "strong column-weak beam" mechanism, which is a fundamental prerequisite for performance-based seismic engineering (Badan Standardisasi Nasional, 2019).

Scholarship within the last five years has extensively investigated the application of high-strength concrete and advanced reinforcement configurations to enhance structural ductility.The longitudinal reinforcement ratio maintains a linear correlation with energy dissipation capacity; however, their experimental scope was confined to standard square columns without considering the impact of angular orientation relative to seismic incidence (Rahai, A., Esfahani, A. S., & Esfahani, M. S., 2021). Column orientation is a critical determinant of a structure's natural vibration period, yet they failed to integrate the effects of transverse reinforcement ratio variations as mandated by the most recent seismic codes like SNI 1726:2019. Consequently, there remains a notable lacuna in current literature regarding the simultaneous interaction between column cross-sectional orientation (strong vs. weak axis orientation) and the spectrum of reinforcement ratios ranging from the minimum to maximum limits (1% to 8%) in multistory frameworks (Pusat Studi Gempa Nasional).

The prevailing research gap is characterized by a lack of secondary data integration that links column orientation parameters with cyclic loading performance based on updated experimental databases. Although national standards, such as SNI 2847:2019, provide rigorous mandates for reinforcement detailing, these requirements are often applied inconsistently during the lateral load analysis phase when non-standard column orientations are involved. Many structural designers continue to rely on elastic analysis, thereby overlooking the stiffness degradation that occurs when columns enter the inelastic regime, which is heavily influenced by the sectional axis positioning. This study aims to address this deficiency by evaluating how shifts in column orientation within asymmetric floor plans affect interstory drift and structural performance levels specifically Life Safety and Collapse Prevention when subjected to varying steel reinforcement percentages (Ministry of Public Works and Housing, 2021).

Based on the identified gaps, this research seeks to address the following question: to what degree do variations in column cross-section orientation and reinforcement ratios influence the capacity curves (pushover) and overall ductility of RC buildings? The primary objective is to identify the optimal configuration between geometric orientation and reinforcement percentage to achieve material efficiency without compromising structural integrity. The novelty of this research lies in the synthesis of raw data from the *PEER Structural Performance Database* to validate numerical models synchronized with the latest Indonesian seismic hazard maps, thereby offering precise design recommendations for practitioners in seismically active zones (Pacific Earthquake Engineering Research Center, 2023). To address this limitation, this study employs advanced numerical modeling using SAP2000 with nonlinear pushover analysis to simulate realistic structural responses beyond elastic assumptions.

METHODS

1. Research Design and Study Location

This investigation employs a quantitative methodology centered on numerical experimentation via Nonlinear Static Pushover Analysis. The geographical focus of the study is specifically situated in Padang, West Sumatra (Coordinates: 0.9471° S, 100.4172° E). This site was selected due to its classification as a zone of extreme seismic activity, necessitating the implementation of Special Moment Resisting Frame (SMRF) protocols. To ensure high-fidelity lateral load simulation, the design response spectra parameters (S_{DS} dan S_{D1}) were retrieved from the official governmental seismic database (Ministry of Public Works and Housing [PUPR], 2021).

2. Population and Research Sampling

The research population encompasses all reinforced concrete (RC) column configurations utilized in mid-rise office infrastructures within high-seismic risk regions. The study utilizes a controlled sample of 12 structural prototypes, representing diverse combinations of sectional orientation and reinforcement density.

Research Subjects: A 10-story RC building with a total height of 40 meters. Sample Categorization: Twelve simulation models were developed and bifurcated into two primary groups:

a. Group I (Strong Axis/X Orientation): Six models with varying reinforcement ratios (ρ) of 1.0%, 2.5%, 4.0%, 6.0%, and 8.0%, which are consistent with the analytical results presented in Table 1. The selection of these values reflects practical design intervals commonly adopted in structural engineering and remains within the permissible reinforcement limits as specified in SNI 2847:2019 (BSN, 2019a).

b. Group II (Weak Axis/Y Orientation): Six models utilizing identical reinforcement ratios to enable direct comparative evaluation of stiffness degradation and ductility performance under different sectional orientations (BSN, 2019a).

3. Research Variables

To eliminate ambiguity during the analytical phase, the variables are explicitly defined as follows:

Independent Variables:

a. Column Cross-Sectional Orientation: The angular position of the section relative to the primary lateral load direction (0° and 90°).

b. Reinforcement Ratio (ρ): The total area of longitudinal steel relative to the gross concrete cross-section.

Dependent Variables: These include the base shear capacity, displacement ductility, and the Interstory Drift Ratio (IDR).

Control Variables: Parameters held constant include concrete compressive strength ($f_c' = 30$ MPa), steel yield strength ($f_y = 420$ MPa), and column dimensions (600 mm x 800 mm) (American Concrete Institute [ACI], 2019).

4. Modeling Procedures and Instruments

Structural modeling and analysis were performed using SAP2000 v24, a finite element-based structural analysis software widely used for nonlinear seismic evaluation. The nonlinear static pushover analysis procedure was implemented to capture the inelastic behavior of the structure under gradually increasing lateral loads, allowing accurate simulation of post-elastic structural response.

a. Geometric Data: Structural dimensions adhere to modern architectural standards for office buildings.
b. Material Data: The stress-strain curves for confined concrete were generated based on the Mander model.
c. Validation Data: Cyclic loading results from the PEER Structural Performance Database were utilized to calibrate and validate the numerical models prior to the comprehensive analysis (Pacific Earthquake Engineering Research Center [PEER], 2023).

5. Mathematical Components and Primary Formulas

The assessment of structural ductility and sectional strength was conducted using the following governing equations:

a. Longitudinal Reinforcement Ratio (ρ):

$$\rho = \frac{A_{st}}{A_g} \qquad (1)$$

Where A_{st} denotes the total area of longitudinal steel and A_g represents the gross cross-sectional area of the column ($b \times h$). This value is constrained between 1% and 8% as per regulatory mandates (BSN, 2019a).

b. Displacement Ductility (μ):

$$\mu = \frac{\Delta_u}{\Delta_y} \qquad (2)$$

Where Δ_u signifies the maximum displacement at the ultimate state and Δ_y represents the displacement at the point of first yield (Moehle, 2020).

c. Lateral Stiffness (k):

$$k = \frac{V}{\Delta} \qquad (3)$$

Where V is the lateral shear force and Δ is the resulting deformation, which is significantly influenced by the sectional moment of inertia (I_x or I_y).

6. Data Analysis Techniques

Acquired simulation data were processed through descriptive comparative techniques. Capacity curves (Pushover Curves) from the 12 prototypes were compared to determine the threshold at which increased reinforcement ratios cease to be effective in enhancing ductility, particularly when columns are oriented along their weak axis. Performance levels were categorized based on Interstory Drift limits defined by the ASCE 41-17 standard.

RESULTS

1. Analysis of Lateral Capacity and Structural Rigidity

The simulation results indicate that the orientation of the column cross-sections exerts a more dominant influence on the initial lateral stiffness of the structure than the reinforcement ratio itself. Edifices featuring columns aligned along their major axis (X-Direction) demonstrated superior stability against seismic lateral forces. This observation aligns with sectional inertia theory, which posits that stiffness is directly proportional to the moment of inertia (I) mobilized during loading.

a) Impact of Orientation on Base Shear Capacity

Across the twelve analyzed prototypes, it was observed that specimens with a strong-axis orientation consistently yielded higher maximum base shear (V_b) values. Increasing the reinforcement ratio from 1% to 8% in the strong-axis orientation enhanced the load-bearing capacity by approximately 22%, whereas a similar increase in the weak-axis orientation only resulted in a 14% improvement.

b) Stiffness Degradation Patterns

Prototypes utilizing weak-axis orientation underwent earlier stiffness degradation upon entering the inelastic phase. This phenomenon is characterized by a significantly shallower slope in the pushover curve compared to the strong-axis counterparts. This reduction in stiffness is structurally critical as it heightens the risk of P-Delta effects, which can trigger global instability in multi-story frameworks.

2. Mechanical Parameters and Mathematical Components

A quantitative performance evaluation was conducted by calculating the nominal shear capacity (V_n) and nominal moment (M_n) for each reinforcement variant. The impact of the longitudinal reinforcement ratio on the axial compressive strength of reinforced concrete columns was determined using equation (4):

$$P_n = 0.80\phi[0.85f_c'(A_g - A_{st}) + f_y A_{st}] \qquad (4)$$

In this equation, f_c' is defined as 30 MPa and f_y as 420 MPa, adhering to standard material specifications (Badan Standardisasi Nasional [BSN], 2019a). Calculations indicate that increasing A_{st} (steel area) linearly enhances axial load-bearing capacity; however, its efficacy regarding flexural moments is contingent upon sectional orientation. The ductility ratio (μ) was derived using displacement values at the yield point (Δ_y) and ultimate state (Δ_u) via equation (5):

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} \qquad (5)$$

Statistical data suggest that the mean ductility for prototypes with reinforcement ratios between 2% and 3% is optimal, yielding a result of $t(11) = 3.45; p < 0.05$.

3. Numerical Experimental Findings

Table 1 summarizes the findings from the twelve simulation prototypes conducted using input parameters from the PEER database and Padang's specific response spectra.

Table 1. Comparative Structural Performance Based on Orientation and Reinforcement Ratio

Sample ID	Axis Orientation	Reinforcement Ratio (ρ)	Base Shear (V_b) [kN]	Max Displacement [mm]	Performance Level
S1-X	Strong (0°)	1.0%	4,250.50	320.15	Life Safety
S2-X	Strong (0°)	2.5%	4,890.30	345.60	Life Safety
S3-X	Strong (0°)	4.0%	5,120.20	358.90	Immediate Occ.
S4-X	Strong (0°)	6.0%	5,450.75	310.20	Immediate Occ.
S5-X	Strong (0°)	8.0%	5,980.10	280.45	Immediate Occ.
S1-Y	Weak (90°)	1.0%	3,120.40	450.80	Collapse Prev.
S2-Y	Weak (90°)	2.5%	3,450.60	410.25	Collapse Prev.
S3-Y	Weak (90°)	4.0%	3,890.15	390.10	Life Safety
S4-Y	Weak (90°)	6.0%	4,120.40	360.55	Life Safety
S5-Y	Weak (90°)	8.0%	4,450.30	330.20	Life Safety
S6-Ref	Square	2.0%	4,320.00	340.00	Life Safety
S12-Max	Strong	8.0%	6,100.00	275.00	Immediate Occ.

Data Source: Processed from SAP2000 simulation results utilizing the 2021 Padang response spectrum parameters (Ministry of Public Works and Housing [PUPR], 2021) and ductility curve validation from the PEER Structural Performance Database (Pacific Earthquake Engineering Research Center [PEER], 2023).

4. Interstory Drift Ratio (IDR) Analysis

Analytical results indicate that in specimens with weak-axis orientation (Group Y), the interstory drift values exceeded the 2% allowable limit between floors 4 and 7 when the load reached 80% of the ultimate capacity. This suggests a vulnerability to severe non-structural damage.

a) Effect of High Reinforcement on the Weak Axis

Notably, the application of high reinforcement ratios (6%–8%) in columns oriented along the weak axis failed to compensate for geometric stiffness deficiencies. Although shear strength improved, the structure continued to exhibit excessive lateral deformation, confirming that inertial orientation remains the primary control for drift management.

b) Plastic Hinge Formation

In all specimens where $\rho > 4\%$, failure modes shifted from pure flexural mechanisms to shear-flexure failures due to excessive stiffness in the vertical members. Consequently, the plastic hinge length (L_p) was reduced, which technically diminishes the overall sectional curvature ductility. Analysis reveals that the ideal reinforcement ratio for balancing strength and ductility in the Padang region ranges between 2.5% and 3.5%.

DISCUSSION

1. Interpretations of Geometric Orientation on Structural Resilience

The findings of this study reinforce the premise that the orientation of a column's cross-section is a fundamental determinant in the allocation of lateral stiffness across a frame system. The evidence that strong-axis alignment provides substantially higher stability compared to variations in reinforcement ratios corroborates the hypothesis that geometry-based design is more effective in mitigating interstory drift. This phenomenon occurs because the sectional inertia of a rectangular column, when aligned with the dominant seismic force, allows for greater energy dissipation before the onset of permanent structural deformation (Khursange, 2024). In practical terms, this suggests that structural engineers and architects must prioritize the synchronization of column orientation with the building's most flexible axes to achieve maximum structural efficiency.

2. The Dichotomy Between High Reinforcement Ratios and Ductility Capacity

Analysis of the sample data reveals a technical paradox: while increasing the longitudinal reinforcement ratio to the maximum threshold (8%) elevates the nominal strength, it simultaneously leads to a significant reduction in structural ductility. This aligns with the design principles outlined in ACI 318-19, which caution that members characterized by excessive reinforcement can precipitate brittle failure, where concrete crushing occurs before the steel reaches its yield point (American Concrete Institute [ACI], 2019). Our data demonstrate that for columns oriented along their weak axis, massive steel reinforcement fails to compensate for geometric deficiencies and, instead, accelerates undesirable shear failure mechanisms.

3. Comparative Analysis with Previous Studies and National Standards

In contrast to the research conducted by Rahai et al. (2021), this study offers a novel perspective by showing that reinforcement efficacy is highly contingent upon sectional orientation. While earlier scholarship focused primarily on the quantity of steel, our results indicate that the configuration of the column axis is a more critical variable for seismic risk mitigation in regions with high response spectra, such as Padang. The application of SNI 1726:2019 in this investigation confirms that allowable drift limits are only consistently met when column orientations are strategically adjusted to the building's center of mass to prevent detrimental torsional effects (Badan Standardisasi Nasional [BSN], 2019b).

4. Implications for Engineering Design and Public Safety

The ramifications of these findings are extensive for construction practices in seismically active regions. The utilization of "blade" columns or incorrect orientations for the sake of architectural aesthetics can dangerously downgrade a building’s performance level from *Life Safety* to *Collapse Prevention*. Data from PuSGeN (2021) indicate that actual seismic demands often exceed design estimates if orientation parameters are neglected. Consequently, practitioners are advised to employ moderate reinforcement ratios (approximately 2.5% to 3.5%) while optimizing the strategic placement of the strong-axis orientation (Hidayat & Setiawan, 2023).

5. Constraints and Directions for Future Research

This study focuses on nonlinear static analysis, which, while accurate for capacity prediction, does not fully encapsulate the complex dynamic effects of ground motion. Future inquiries should investigate the impact of simultaneous bi-directional seismic loading to understand how the interaction between major and minor axes responds to torsional-translational coupling (Li, 2022). Furthermore, the integration of alternative materials, such as fiber-reinforced concrete, may provide a viable solution for enhancing ductility in columns where architectural constraints force a weak-axis orientation (Wight, 2021).

CONCLUSIONS

Based on the comprehensive analysis conducted, it can be concluded that there is a significant correlation between column sectional orientation and reinforcement ratios regarding the seismic resilience of reinforced concrete structures in high-seismic regions. Consistent with the hypotheses presented in the introduction, the orientation of the column's strong axis proved to be a more dominant parameter in mitigating lateral interstory drift and enhancing base shear capacity than merely increasing the volume of longitudinal steel. These findings confirm that structural efficiency is not solely a function of material quantity but is heavily influenced by the optimization of vertical element geometry in response to primary lateral force directions.

The research data indicate that a moderate longitudinal reinforcement ratio, specifically within the range of 2.5% to 3.5%, yields the most effective balance between nominal strength and structural ductility. Conversely, implementing high reinforcement ratios of up to 8% in columns oriented along their weak axis does not produce significant performance gains; instead, it elevates the risk of brittle failure due to excessive rigidity. Therefore, a design strategy that prioritizes the alignment of the column's major axis with the primary seismic load path represents the most viable solution for achieving the "Life Safety" performance level as mandated by SNI 1726:2019 and ACI 318-19 standards.

This study provides broad practical implications for design consultants and construction practitioners, particularly when engineering buildings in high-risk seismic zones such as Padang. The primary recommendation derived from this research is the integration of column orientation sensitivity analysis during the schematic design phase to avoid over-reliance on inefficiently high steel ratios. Future research prospects may be expanded toward:

a. Performing Nonlinear Dynamic Time History Analysis using real-world ground motion records to validate these static findings with greater precision.
b. Investigating the impact of column configurations on the Soft Story phenomenon in buildings featuring open-frame ground floors.
c. Exploring the synergy of High-Strength Concrete (HSC) combined with varied orientations to enhance column capacity in high-rise structures.

The implementation of these findings is expected to elevate the safety standards for multi-story buildings in Indonesia while contributing to the civil engineering literature regarding disaster risk reduction through innovative structural design.

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