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Comparative seismic performance of flat slabs using four design codes

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Abstract
This study evaluated the seismic performance of flat slab structures designed according to four international standards: SNI 2847-2019 (Indonesia), NZS 3101:2006 (New Zealand), IS 456-2000 (India), and JSCE 15-2007 (Japan). A five-story reinforced concrete building was modeled using ETABS for nonlinear pushover analysis, while MATLAB was utilized for calculating slab thickness, moment distribution, reinforcement design, and punching shear strength. Results unveiled that the JSCE 15-2007 code provided the stiffest system with minimal lateral displacement and the highest base shear capacity, whereas IS 456-2000 exhibited superior ductility and flexibility. SNI 2847-2019 and NZS 3101:2006 delivered balanced performance in terms of stiffness and material efficiency. The variation in slab thickness, reinforcement area, and natural period highlighted each code's design philosophy regarding seismic safety. These findings suggest that code selection should consider regional seismic risk, structural demands, and construction priorities to ensure optimal safety and efficiency. The study contributes to the harmonization of global flat slab design practices and offers practical recommendations for improving the seismic resilience of buildings.

Keywords:
Design codes;
Flat slab;
Pushover analysis;
Reinforced concrete;
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INTRODUCTION

Flat slab systems have been increasingly adopted in reinforced concrete buildings due to their architectural flexibility, efficient use of space, and ability to reduce floor-to-floor height. These systems enable direct load transfer from the slab to the supporting columns, eliminating the need for intermediate beams. It simplifies formwork, accelerates construction, and facilitates the integration of mechanical, electrical, and plumbing (MEP) services [1][2]. However, flat slabs typically exhibit low lateral stiffness and are prone to punching shear failure, making them less reliable in seismic regions [3].

Recent studies have examined various aspects of flat slab seismic behavior, consistently depicting that slab thickness, reinforcement detailing, and punching shear capacity govern the structural response under earthquake loading [4]. Muttoni et al. demonstrated that inadequate punching resistance contributes to brittle slab–column failures, while Isufi et al. highlighted the influence of flexural reinforcement distribution on deformation and collapse patterns. These findings highlight that the performance of flat slabs is highly susceptible to geometric properties and detailing assumptions.

Existing comparative studies also provide essential insights, although they remain limited in relevance to international code evaluation. Gong et al. compared flat slabs with reverse and conventional column caps and discovered significant differences in stiffness. Sawwalakhe and Pachpor, on the other hand, compared flat slabs and conventional slabs using ETABS and reported higher drift demands in flat slabs. More recent comparative analyses, such as those by Vargas et al. (on isolator systems), Laissy et al. (on slab systems), and Poudel and Gyawali (on grid slabs), do not isolate differences across international design codes, as they involve different slab systems or varying geometries, materials, and load assumptions.

A synthesis of previous research displays three consistent findings: (1) flat slabs generally exhibit larger lateral drifts than conventional slabs, (2) punching shear remains the most critical and common failure mode, and (3) stiffness varies widely depending on slab thickness rules, with stricter codes such as JSCE resulting in stiffer systems. Despite these results, no study established a unified analytical comparison of SNI, NZS, IS, and JSCE under identical modeling conditions. Consequently, the existing literature remains descriptive and fragmented, lacking the analytical basis required to evaluate how code-to-code differences translate into variations in seismic performance.

The central problem addressed in this study is the absence of a systematic, quantitative comparison of seismic performance outcomes, such as stiffness, base shear capacity, ductility, and drift behavior, resulting from the application of different international flat slab design codes. Differences in slab thickness limits, reinforcement requirements, moment distribution rules, and punching shear criteria across SNI, NZS, IS, and JSCE lead to substantial variations in structural stiffness, ductility, and failure mechanisms. These inconsistencies may result in overdesign (excessive material use and cost) or underdesign (insufficient seismic capacity). Furthermore, post-earthquake reports have documented excessive drift, punching failures, and even gravity-load collapse in flat slab buildings, emphasizing the need for a unified evaluation. However, no previous research has compared the four codes under identical geometry, material properties, loading conditions, and nonlinear analysis frameworks.

Despite extensive research on flat slab behavior, no existing study provides a unified, code-to-code comparison using identical structural models, consistent material assumptions, uniform loading conditions, and the same nonlinear pushover methodology. This lack of a standardized comparative framework represents a significant research gap that limits engineers' ability to understand how variations in international code provisions directly affect seismic performance.

The novelty of this study lies in offering the first unified modeling framework that directly compares the seismic performance of flat slab systems designed using SNI 2847:2019, NZS 3101:2006, IS 456:2000, and JSCE 15-2007 under identical structural, material, and loading conditions**.**

This study presents a comparative numerical analysis of flat slab systems designed in accordance with the four international standards. Slab section properties—including flexural capacity and punching shear resistance—were calculated using MATLAB scripts, while nonlinear pushover analysis was performed using ETABS to simulate structural behavior under lateral seismic loads. The primary objective is to assess the impact of each design code on the seismic performance of flat slab structures and to offer practical guidance for optimizing code selection and structural design in earthquake-prone regions [7, 8, 9, 10, 11].

METHOD

This study employed a comparative numerical analysis to assess the seismic performance of flat slab structures designed according to four international design standards: SNI 2847:2019, NZS 3101:2006, IS 456:2000, and JSCE 15:2007. These codes originate from Indonesia, New Zealand, India, and Japan, respectively, and represent a diverse range of seismic design philosophies and structural requirements.

A five-story reinforced concrete residential building employing a flat slab system was selected as the prototype model. The structural configuration features flat slabs directly supported by columns, eliminating the need for beams, a common approach in contemporary construction for open-plan layouts. The general geometry, including panel dimensions, story height, and column layout, is illustrated in Figure 1.

The structural analysis was conducted using ETABS 2018 software, incorporating both gravitational and lateral seismic loads in accordance with site-specific seismic zoning. Material properties, including concrete compressive strength and reinforcement yield strength, were kept consistent across all models to isolate the effect of design provisions [12][13].

For each code scenario, slab thickness, moment distribution, reinforcement area, and punching shear capacity were calculated using MATLAB based on the respective code provisions. The results were then implemented into ETABS models, where a nonlinear static pushover analysis was conducted to evaluate performance parameters, including base shear, roof displacement, inter-story drift ratio, and capacity curves. A three-dimensional representation of the modeled flat slab structure is illustrated in Figure 2.

Geometric and Material Parameters

The model represents a five-story reinforced concrete building with flat slab construction. Key geometric parameters include internal panel dimensions of 6 × 5 meters, story height of 3.5 meters, and column dimensions of 0.75 × 0.75 meters. The total building height is 17.5 meters. The concrete compressive strength is 25 MPa, and the yield strength of the reinforcement is 300 MPa. The applied loads consist of a live load of 7 kN/m² and a superimposed dead load of 5 kN/m².

Slab Thickness Estimation

The minimum slab thickness (tmin) was calculated using span-to-depth ratios specific to each design code. For example, SNI 2847:2019 recommends *Ln/33* for slabs without drop panels, while JSCE 15:2007 specifies a minimum of 150 mm for seismic safety. The general expression for calculating slab thickness is given in Equation (1), where *Ln* is the clear span length and the coefficient is code-specific. These calculations were implemented in MATLAB and validated through hand computation.

$$t_{min} = \frac{L_n}{\text{coefficient}} \tag{1}$$

Moment Distribution

Moment distribution between the column strip and the middle strip follows code-prescribed coefficients.

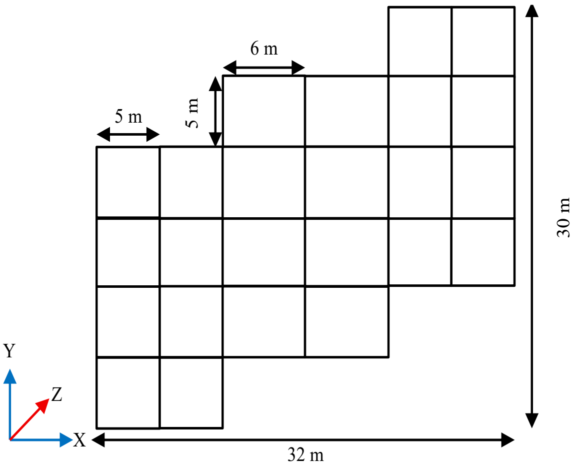


Figure 1. 5-Story Building Model

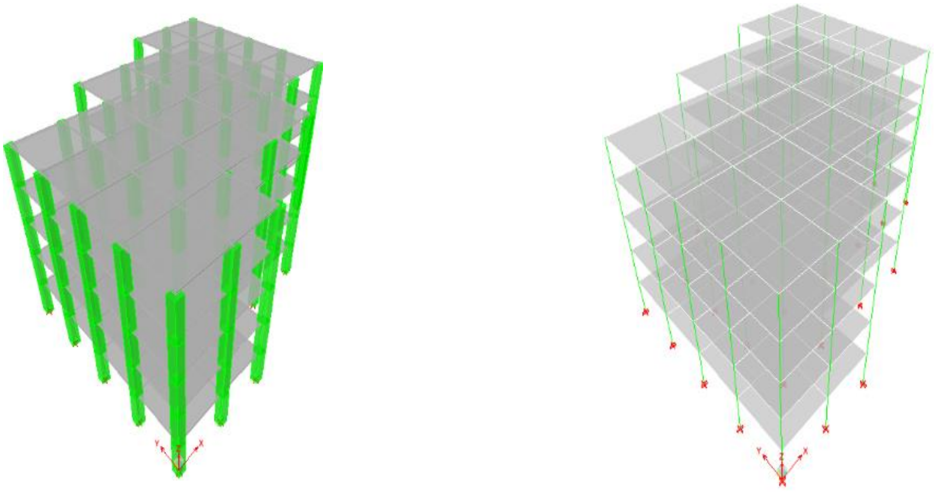


Figure 2. 5-Story Building Model

The total static factored moment (*Mo*) was calculated using Equation (2), where *w* denotes the total uniform load and *Ln* signifies the clear span. The moment was then distributed as 65% to the column strip and 35% to the middle strip for SNI and similar codes. JSCE 15:2007 adopts a 70/30 distribution [14][15].

$$M_o = \frac{wL^2{}_n}{8} \tag{2}$$

Reinforcement Design

The required area of reinforcement (*As*) was calculated using Equation (3), where *M* indicates the design moment, *ϕ* is the strength reduction factor, *d* implies the effective depth, and *fy* represents the yield strength of reinforcement steel. Equation (3) ensures compliance with each code's ductility and strength requirements [16][17].

$$A_s = \frac{M}{\phi \cdot \mathrm{d} \cdot \mathrm{fy}} \tag{3}$$

Punching Shear Evaluation

Punching shear strength at slab-column connections was evaluated based on Equation (4). In Equation (4), *fc′* represents the concrete compressive strength, *bo* denotes the critical perimeter around the column, and ddd signifies the effective depth. If the applied shear force (*Vu*) exceeds *Vc*, shear reinforcement must be provided. JSCE generally yields higher shear capacity due to greater slab thickness [18][19].

$$V_c = 0.17 \cdot \sqrt{fc' \cdot b_0 \cdot d} \tag{4}$$

Nonlinear Pushover Analysis

A nonlinear pushover analysis was performed in ETABS to evaluate the seismic response of the modeled flat slab structures. Material nonlinearity was defined for both concrete and reinforcing steel using the Mander model and bilinear kinematic hardening rule, respectively. A lateral load of 5000 kN was applied incrementally until significant strength degradation was observed. The structural response was assessed in terms of base shear, roof displacement, and inter-story drift ratios.

To ensure numerical accuracy, a mesh sensitivity analysis was conducted by varying the shell element size from 0.5 m to 1.0 m. The results revealed a variation of less than 3% in base shear capacity, confirming that the selected 0.75 m mesh size provided an optimal balance between computational efficiency and precision. Model reliability was further validated through comparison with previous studies [20][21], demonstrating consistent displacement patterns and capacity curve shapes under similar loading and boundary conditions.

The resulting force–displacement (pushover) curves enabled direct comparison of key performance indicators, including initial stiffness, yield point, ductility index, and ultimate capacity. These findings form the basis for interpreting the relative seismic performance of the four design codes under identical modeling conditions.

Summary of Research Methodology

The main stages of the methodology are summarized as follows:

1. Defining geometric dimensions, material properties, and loading conditions
2. Using (1) for all codes via MATLAB scripts
3. Determining total moment using (2) and applying code-specific ratios
4. Calculating the required steel area using (3)
5. Assessing shear strength with (4)
6. Conducting a nonlinear pushover analysis using ETABS

This structured approach enabled consistent evaluation of the seismic performance of flat slab systems across different international design standards.

To visualize the workflow, Figure 3 presents the overall research process. The diagram summarizes the sequential steps, beginning with the definition of input parameters, followed by computational design using MATLAB, structural modeling and nonlinear analysis in ETABS, and finally, the interpretation and comparison of results. This flow chart highlights the integrated framework applied to ensure that the computational and analytical stages remain coherent across all four design standards.

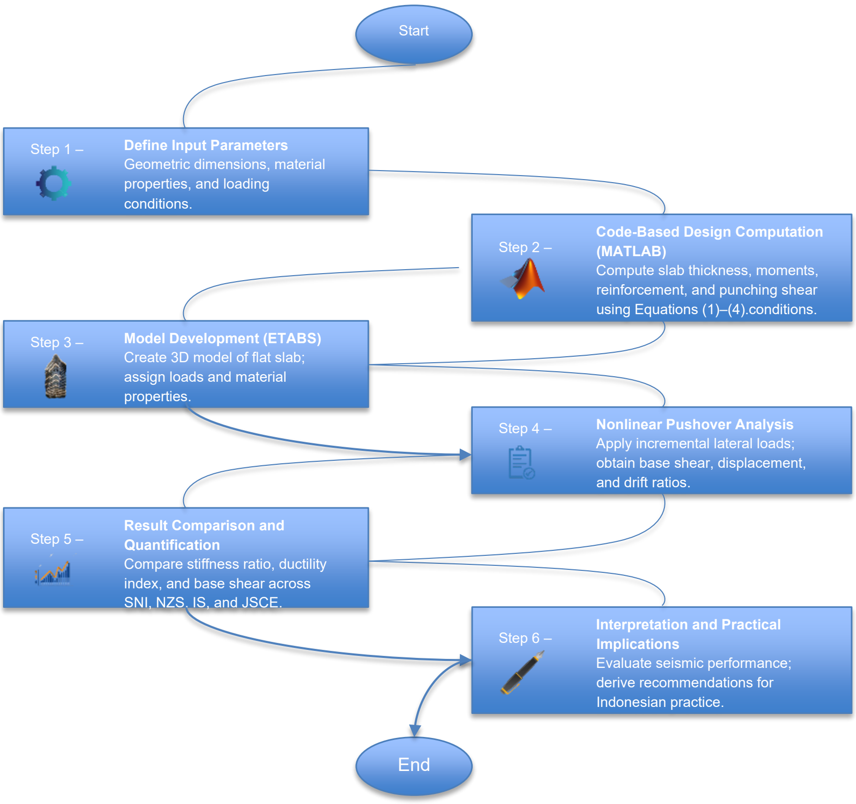


Figure 3. Research Flow Chart of the Study

RESULTS AND DISCUSSION

This section presents the analytical results and scientific discussions on the comparative seismic performance of flat slab structures designed using four different international standards: SNI 2847-2019 [22], NZS 3101:2006 [23], IS 456-2000 [24], and JSCE 15-2007 [25]. The findings are supported by simulation data, visual figures, and calculated values, focusing on slab thickness, moment distribution, reinforcement area, punching shear capacity, natural periods, and overall seismic behavior through pushover analysis.

Minimum Slab Thickness Requirements

The thickness of a flat slab significantly affected its structural performance, especially in seismic zones. The analysis unveiled notable differences among the four standards. JSCE 15-2007 prescribes a thickest slab of 190 mm, emphasizing seismic safety. In contrast, IS 456-2000 requires a slab thickness of 163 mm, prioritizing durability. SNI 2847-2019 sets 151 mm, balancing safety and material efficiency. NZS 3101:2006 permits the thinnest slab at 149 mm, with a focus on resource optimization. These variations align with each standard's philosophy and regional seismic demands. Thicker slabs enhanced deflection control and punching shear resistance, but boosted construction costs. This finding is consistent with previous studies indicating that material properties and section dimensions significantly influence structural performance [26].

Figure 4 displays a comparison of minimum slab thickness. A linear relationship was observed between slab thickness (x) and reinforcement area (y), as modeled by the equation $y = 13.1x + 130.5$ ($R^2 = 0.8029$). This regression analysis revealed that slab thickness significantly impacted the required reinforcement [27].

Moment Distribution Analysis

Negative and positive moment values varied significantly across standards. JSCE 15-2007 produced the highest negative (74.14 kNm) and positive moments (32.02 kNm), due to greater slab stiffness. SNI 2847-2019, NZS 3101:2006, and IS 456-2000 provided lower moment values consistent with their thinner slabs. Figure 5 illustrates these differences, indicating higher stiffness and moment capacity under JSCE, which enhanced seismic resistance at the expense of material usage [28].

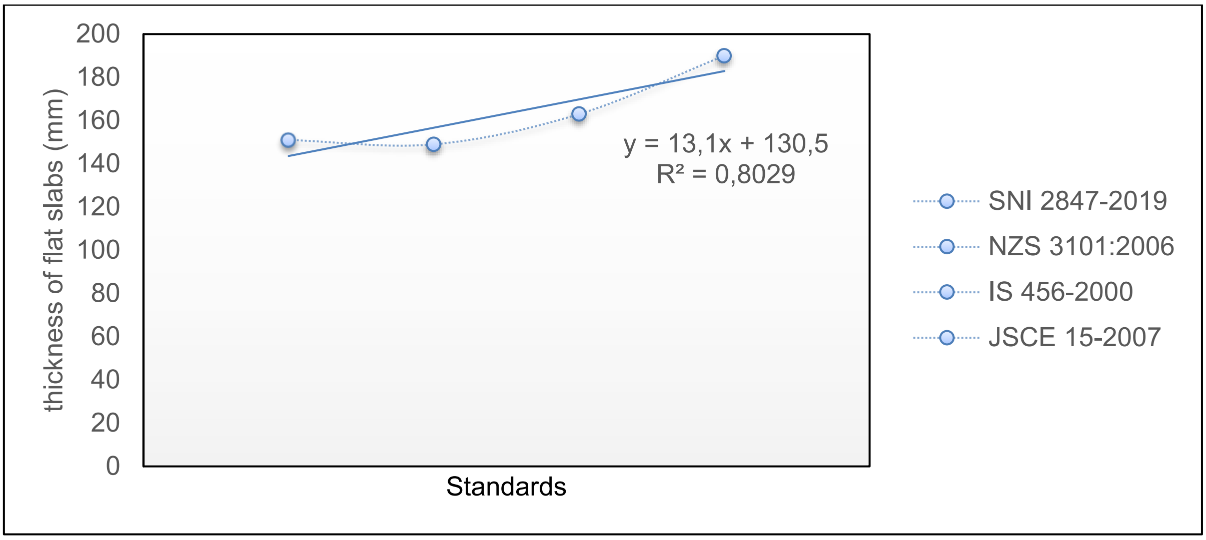


Figure 4. Minimum Flat Slab Thickness Comparison Based on Design Codes

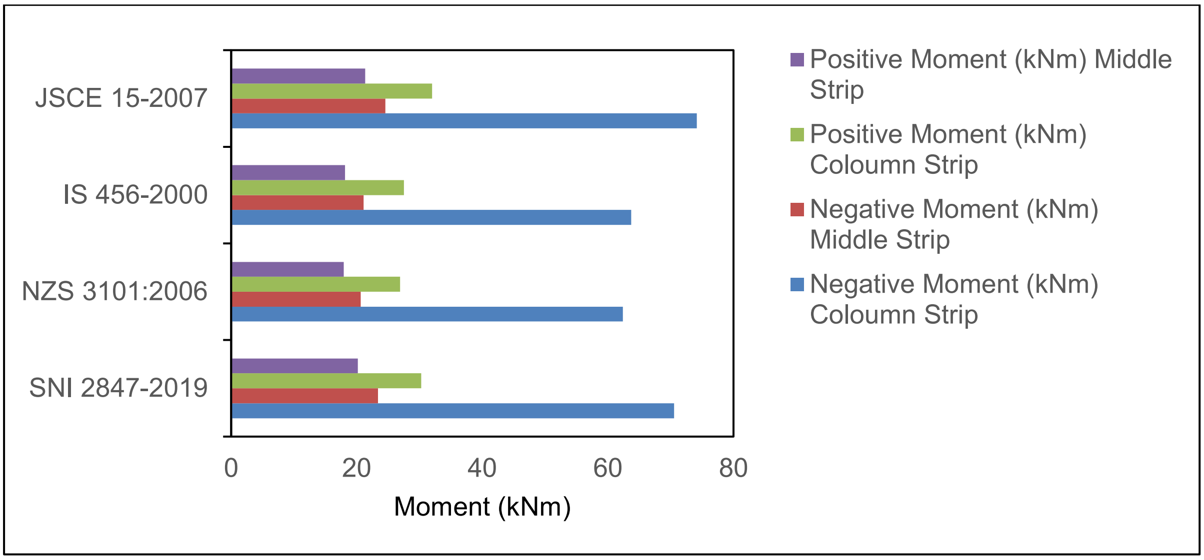


Figure 5. Comparison of Positive and Negative Moments in Flat Slab Systems

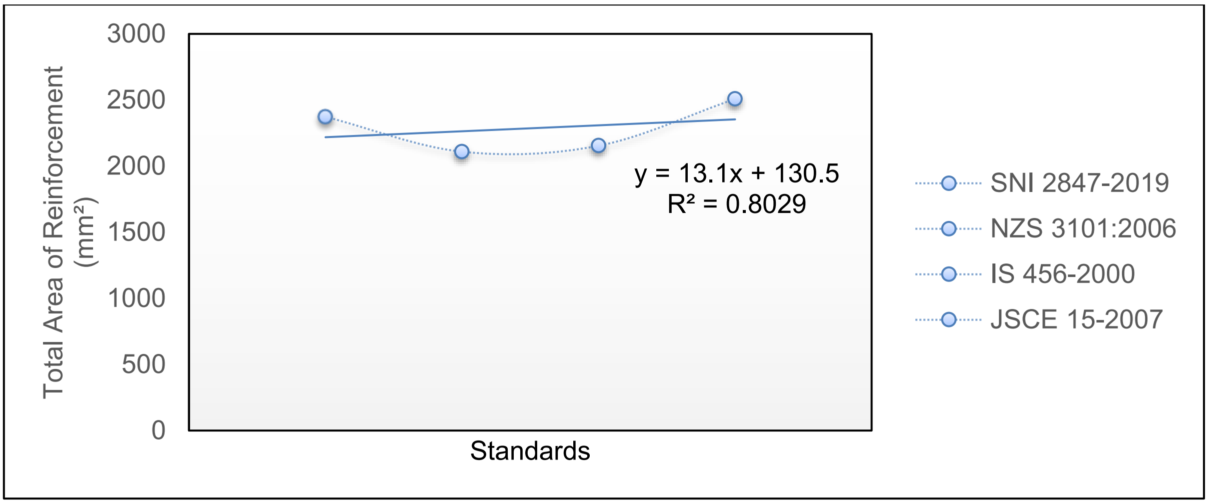


Figure 6. Total Reinforcement Area for Flat Slabs According to Each Standard

Total Reinforcement Area

The total area of required reinforcement reflects each standard's safety margin. JSCE 15-2007 requires 2508 mm², SNI 2847-2019 needs 2373 mm², IS 456-2000 demands 2154 mm², and NZS 3101:2006 utilizes 2109 mm². Figure 6 confirms the linear correlation with slab thickness. Greater reinforcement corresponded to higher flexural demand and moment resistance. These differences also impacted cost and constructability [29].

Punching Shear Capacity

The safety against punching shear was confirmed for all standards using MATLAB analysis. JSCE 15-2007 provided the highest capacity due to its larger effective depth. Table 1 summarizes the results, confirming that all standards ensured safe design. Differences in punching shear capacity reflected varying philosophies on safety and economic considerations [30].

Natural Periods of Vibration

Natural periods were computed for Mode 1 and Mode 2. JSCE 15-2007 produced the shortest periods (0.6188 s and 0.5950 s), indicating higher lateral stiffness and reduced deformation potential under dynamic loads. Conversely, IS 456-2000 yielded the most extended periods (0.9373 s and 0.9223 s), reflecting greater structural flexibility and increased potential for energy dissipation through deformation. SNI 2847:2019 and NZS 3101:2006 generated intermediate values, suggesting a balanced approach between stiffness and ductility. These trends are illustrated in Figure 7 and Figure 8 [31][32].

The natural period is a critical dynamic property in seismic design because it directly influences the magnitude of acceleration demand based on the response spectrum. Shorter periods correlate with stiffer structures that typically experience higher seismic forces, while longer periods are associated with more flexible structures that may exhibit larger drifts. The observed differences across codes highlight variations in design philosophy—JSCE prioritizes rigidity and strength, whereas IS 456 emphasizes ductility.

Understanding these differences allows engineers to align code selection with performance objectives. In high-seismic regions, shorter periods (as in JSCE) may be preferable to limit displacement, while more extended periods (as in IS 456) may reduce force demands but require enhanced ductility provisions.

Pushover Analysis

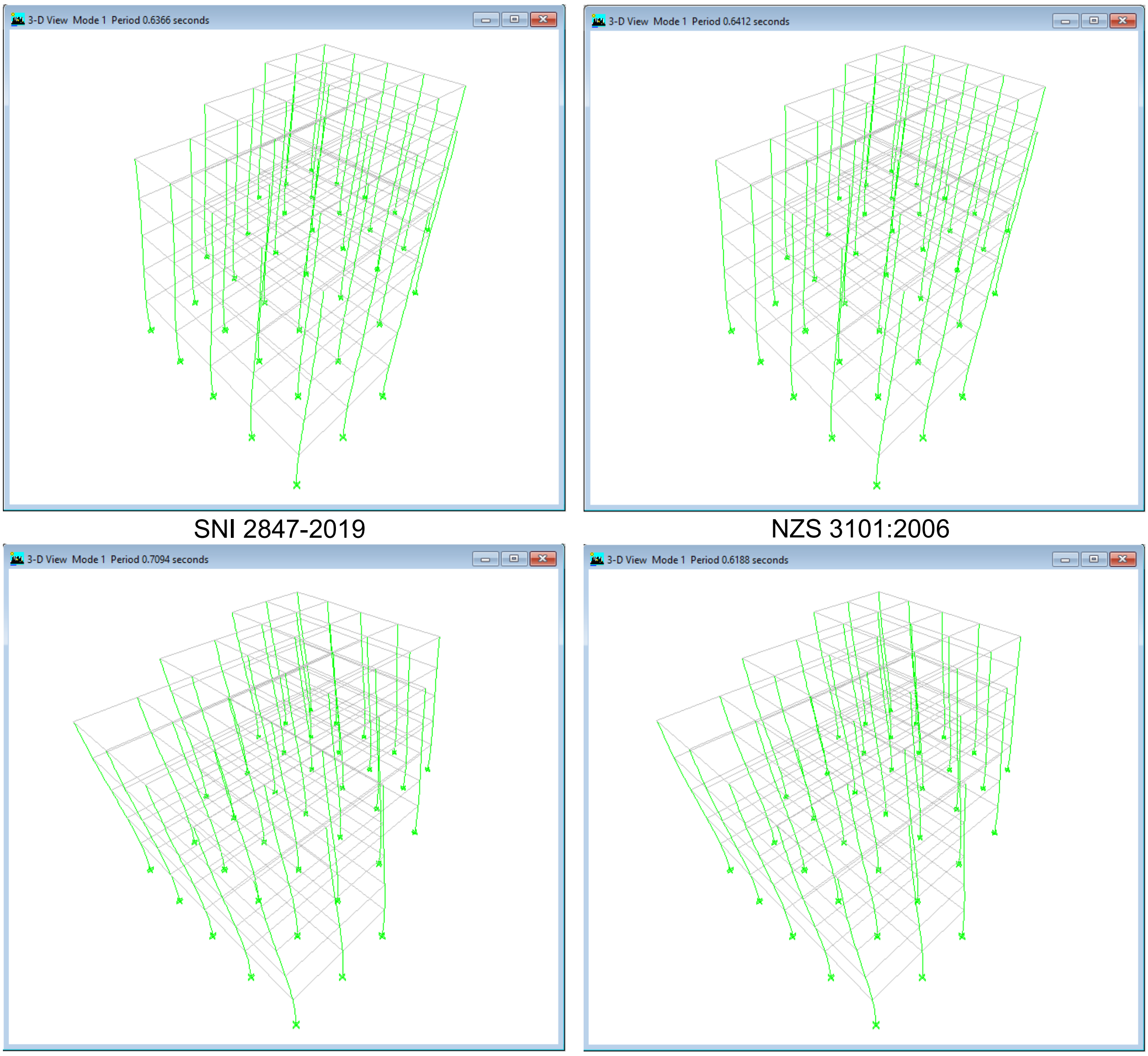
Pushover analysis has offered valuable insights into the nonlinear behavior and ultimate strength of structural systems subjected to lateral seismic loads. The generated pushover curves revealed that JSCE 15-2007 delivered the highest base shear capacity, approximately 1,240 kN, and the lowest corresponding roof displacement, about 48 mm, indicating superior lateral stiffness and strength. This observation aligns with previous research, such as Ayuddin and Bindhu [33], who demonstrated that nonlinear analysis methods are effective in evaluating seismic performance of reinforced concrete structures.

In contrast, IS 456-2000 exhibited the highest displacement capacity, approximately 72 mm, and the most extensive deformation, indicating enhanced ductility but reduced lateral load resistance. SNI 2847:2019 and NZS 3101:2006 depicted intermediate behavior, combining moderate base shear values ranging from 1,050 to 1,120 kN and roof displacements between 55 and 60 mm, which reflect a balanced performance between stiffness and ductility.

To further clarify these differences, Table 2 summarizes the key quantitative parameters, base shear, roof displacement, stiffness ratio, and ductility index, for each design code. The stiffness ratio is defined as the initial slope of the pushover curve, while the ductility index represents the ratio between ultimate and yield displacements.

Table 1. Summary of Design Parameters and Punching Shear Safety

	Thickness of Flat Slab (mm)	**Negative Moment (kNm)**		**Positive Moment (kNm)**		**Total Area of Reinforcement (mm^2)**	**Punching Shear**
		Column Strip	**Middle Strip**	**Column Strip**	**Middle Strip**		
SNI 2847-2019	151	70.52	23.40	30.27	20.18	2373	Safe
NZS 3101:2006	149	62.38	20.63	26.92	17.95	2109	Safe
IS 456-2000	163	63.73	21.09	27.50	18.14	2154	Safe
JSCE 15-2007	190	74.15	24.55	32.02	21.34	2508	Safe



SNI 2847-2019 NZS 3101:2006

IS 456-2000 JSCE 15-2007

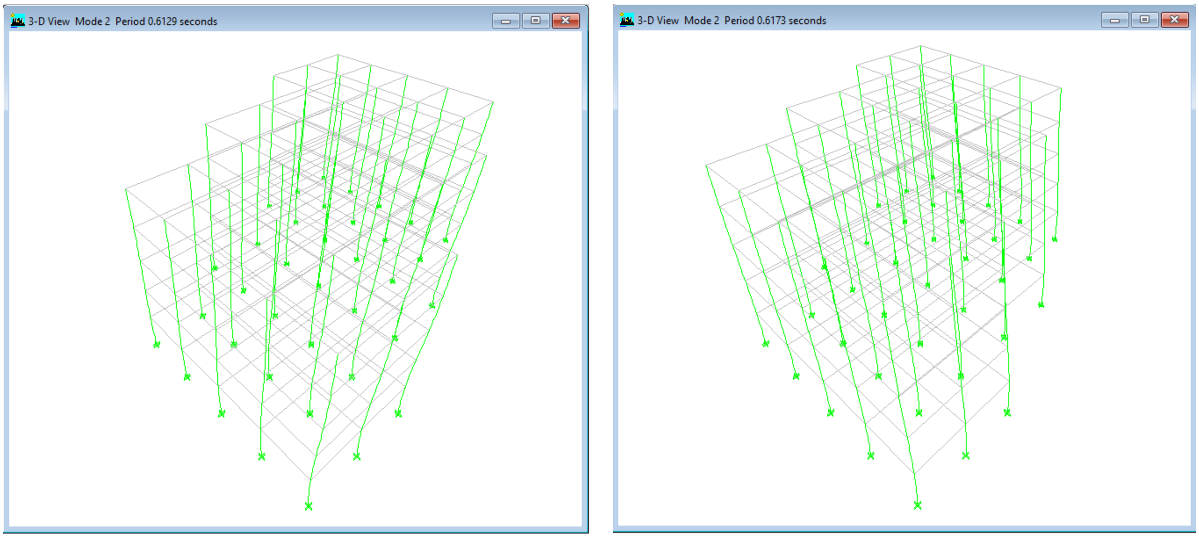
Figure 7. Natural Periods – Mode 1 for Each Standard

Table 2. Comparative Seismic Performance Parameters of Four Design Codes

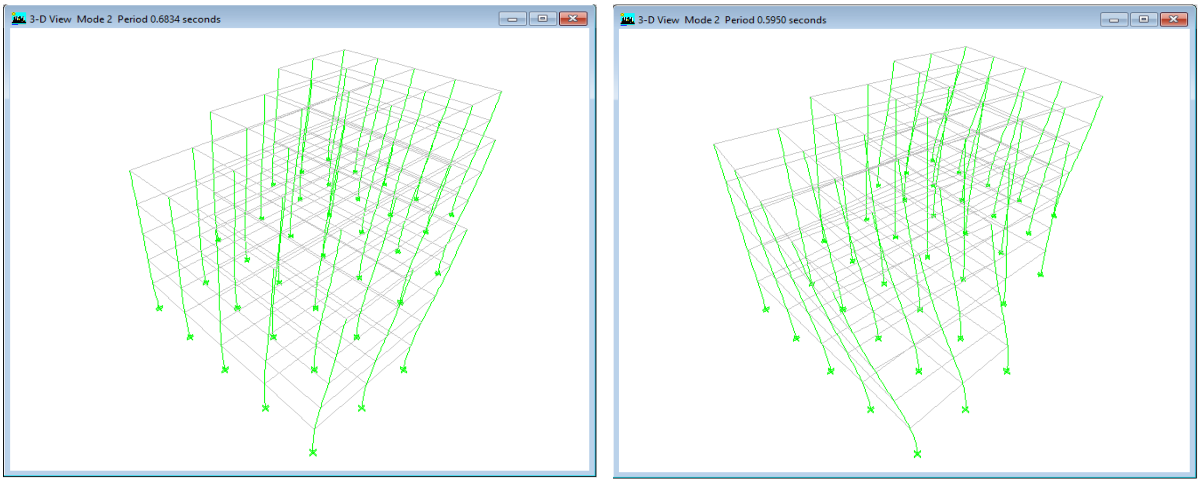
Design Code	**Base Shear (kN)**	**Roof Displacement (mm)**	**Stiffness Ratio (relative to SNI)**	**Ductility Index (μ)**
SNI 2847:2019	1050	58	1	4
NZS 3101:2006	1120	55	1.07	3.9
IS 456:2000	1000	72	0.85	4.5
JSCE 15:2007	1240	48	1.2	3.6

Quantitatively, the stiffness ratio disclosed that JSCE 15-2007 was about 1.20 times stiffer than SNI 2847:2019 and 1.12 times stiffer than NZS 3101:2006. Conversely, IS 456-2000 exhibited a ductility index of 4.5, approximately 25 % higher than JSCE's ductility index of 3.6, signifying superior energy dissipation capacity under inelastic deformation. The base shear ratio also highlights that JSCE 15-2007 provided 18% higher lateral load resistance than SNI 2847:2019 and 12% higher than NZS 3101:2006.

These quantified comparisons clearly illustrate the distinct design philosophies embedded in each standard: JSCE 15-2007 prioritizes stiffness and safety, IS 456-2000 emphasizes ductility and flexibility, while SNI 2847:2019 and NZS 3101:2006 maintain a balanced compromise between strength, stiffness, and economy. Figure 9 and Figure 10 visualize these performance differences in both X and Y directions [34][35].



SNI 2847-2019 NZS 3101:2006



IS 456-2000 JSCE 15-2007

Figure 8. Natural Periods – Mode 2 for Each Standard

Overall, the results of this study are in agreement with previous research on seismic performance evaluation of reinforced concrete systems. Ayuddin and Bindhu [33] confirmed that nonlinear approaches provide reliable insight into structural behavior under seismic loading. Furthermore, material characteristics also play a crucial role, as highlighted by Kalaimani and Srinivasan [26], where variations in concrete properties significantly affect structural strength and durability. These findings support the present study, in which slab thickness and reinforcement directly influence stiffness, ductility, and seismic response.

Story Shear, Drift, and Displacement

Figure 11, Figure 12, Figure 13, Figure 14, Figure 15 and Figure 16 display the results for story shear, inter-story drift, and lateral displacement. JSCE maintained the highest story shear resistance, whereas IS 456-2000 allowed the most considerable drift and displacement values, illustrating a distinct trade-off between stiffness and ductility [36][37]. SNI and NZS again demonstrated balanced performance between these two extremes.

JSCE's enhanced stiffness reduced displacement and drift, thereby raising seismic safety and reducing damage potential in critical facilities located in high-seismicity regions. This performance is crucial for ensuring life safety, maintaining structural integrity, and minimizing downtime. Conversely, IS 456-2000 supports greater lateral movement, allowing structures to absorb and dissipate seismic energy; however, it may lead to non-structural damage and service interruptions.

SNI 2847:2019 and NZS 3101:2006 fell within the middle spectrum, offering both sufficient ductility and acceptable stiffness levels, making them appropriate for regions with moderate seismic activity or for buildings where a balance between performance and economy is desired.

These findings confirm that the choice of design standard should consider the seismic risk level, construction practices, and desired structural performance. Selection should not rely solely on code prescriptions but also on performance-based evaluation, ensuring buildings are both safe and serviceable throughout their lifecycle.

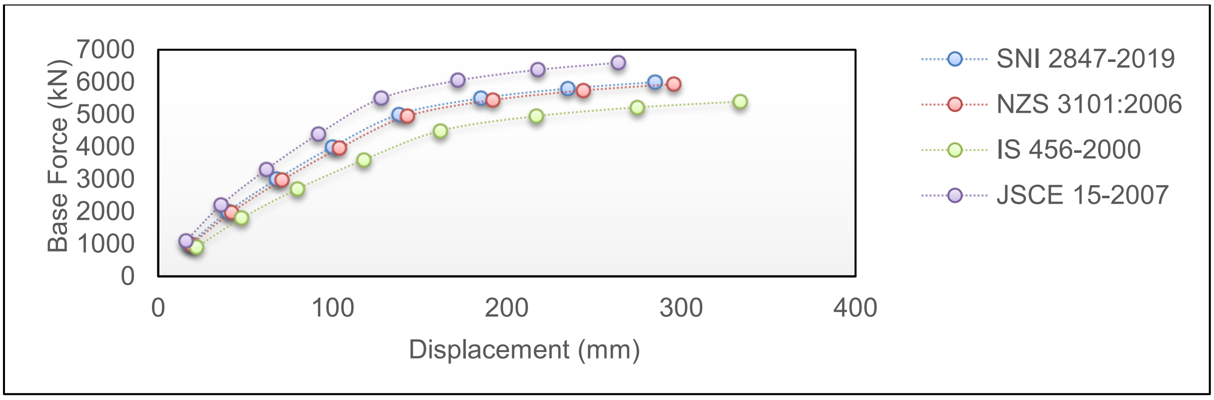


Figure 9. Pushover Curve in X Direction

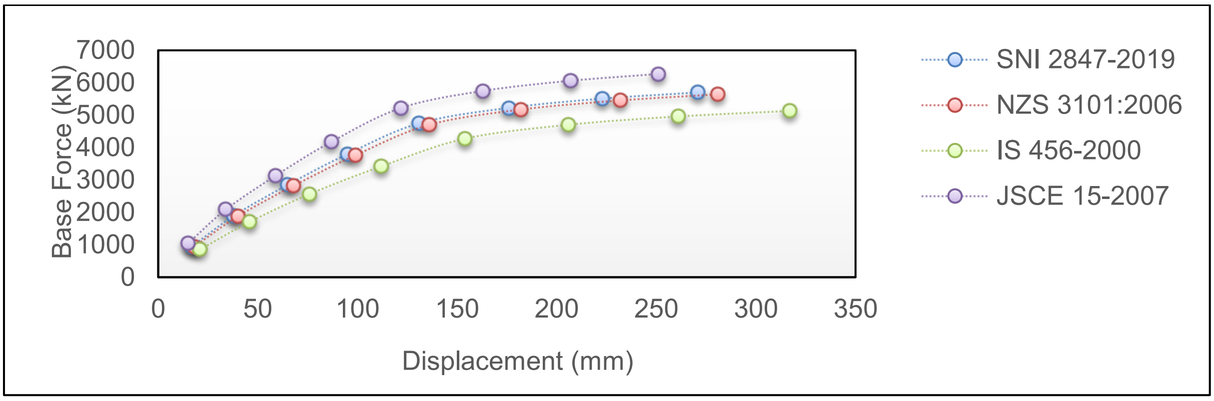


Figure 10. Pushover Curve in Y Direction

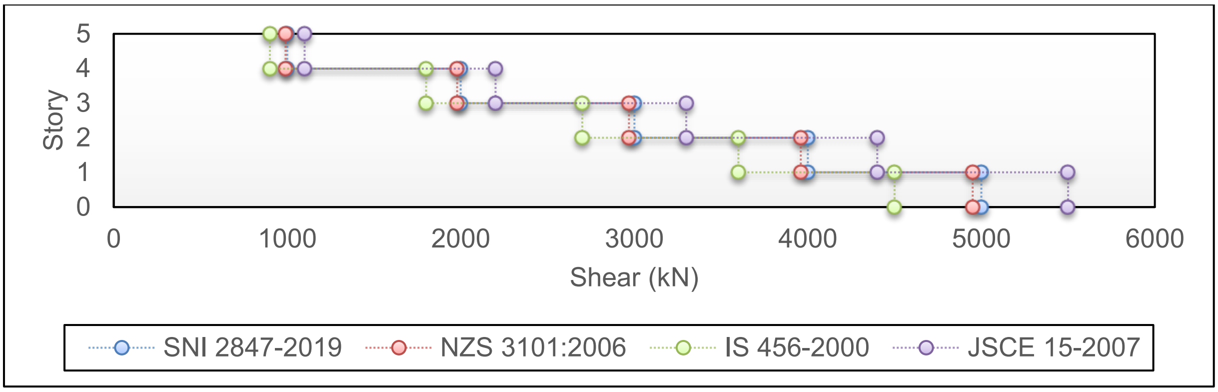


Figure 11. Story Shear – X Direction

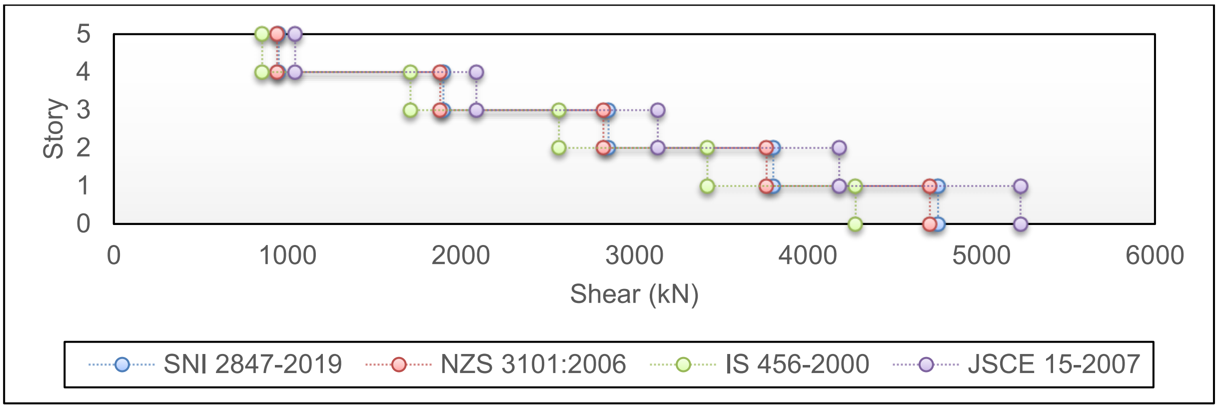


Figure 12. Story Shear – Y Direction

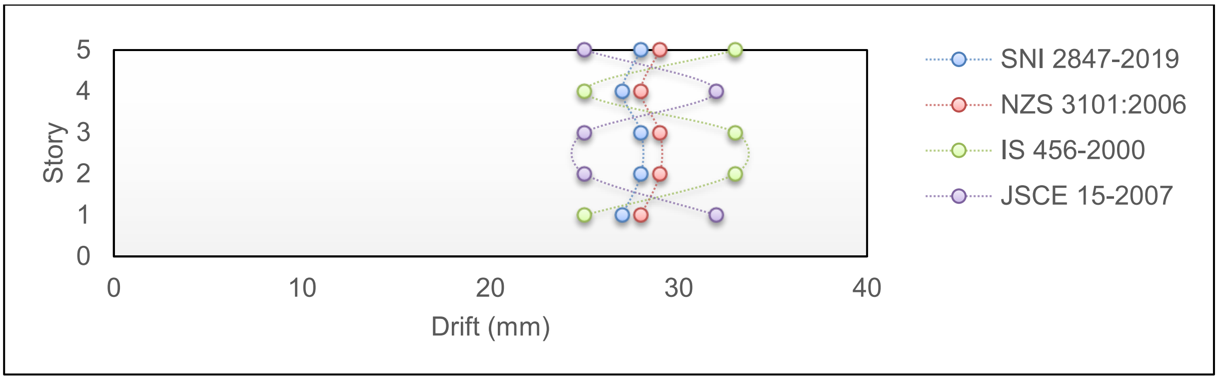


Figure 13. Story Drift – X Direction

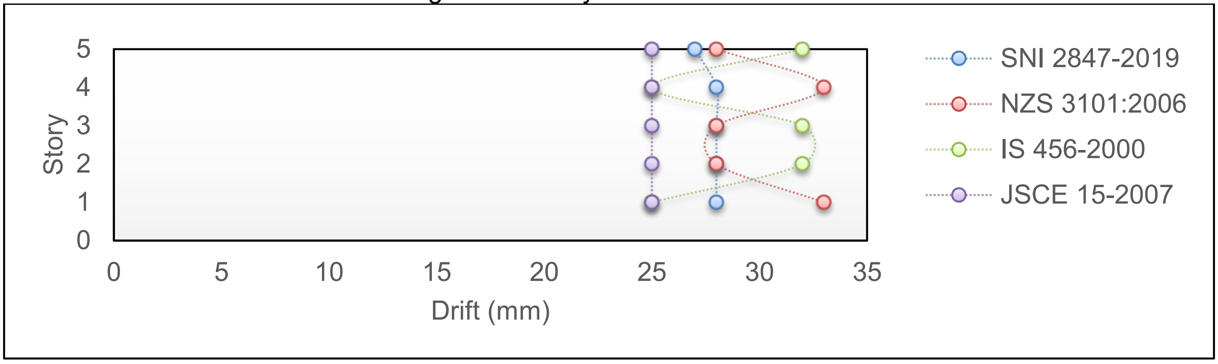


Figure 14. Story Drift – Y Direction

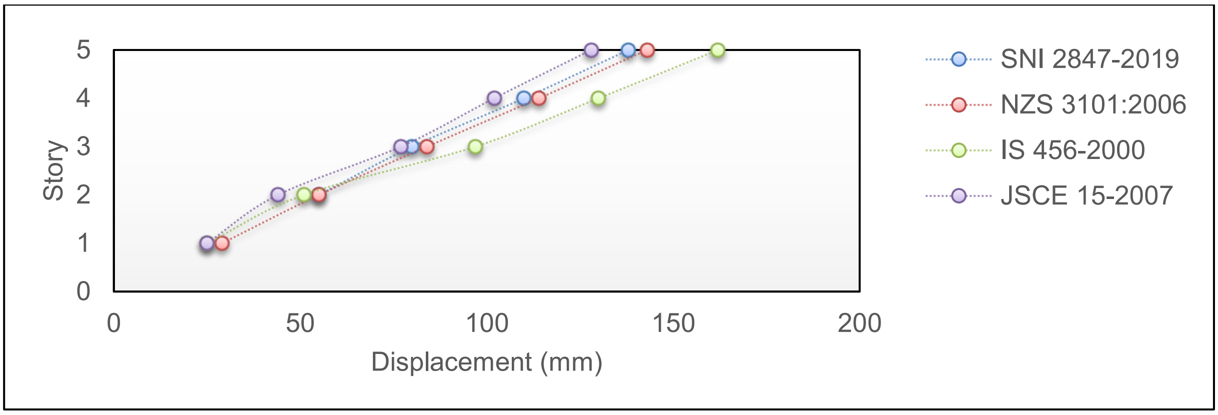


Figure 15. Story Displacement – X Direction

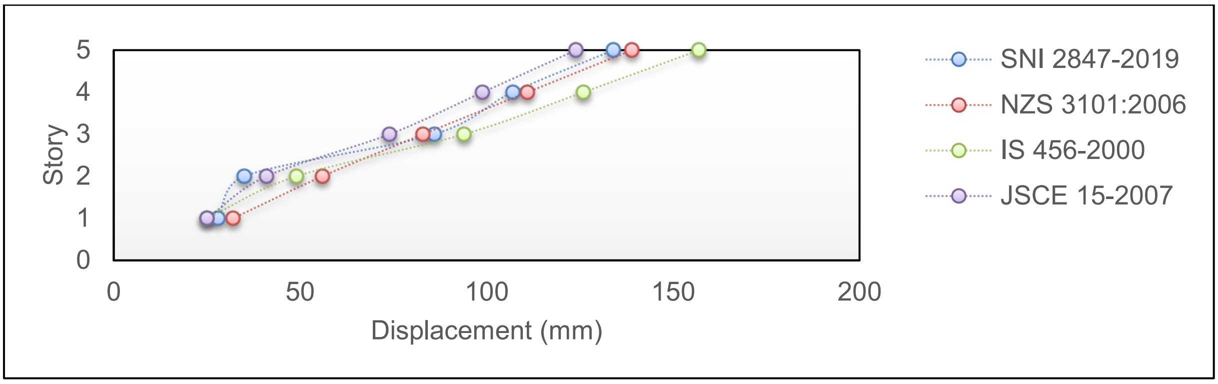


Figure 16. Story Displacement – Y Direction

Story Drift Ratio

Figure 17 and Figure 18 display drift ratios: lowest in JSCE 15-2007 (maximum stiffness), highest in IS 456-2000 (maximum flexibility), and balanced in SNI and NZS. Uniformity in drift ratio across stories ensures consistent structural deformation and prevents soft-story failures.

Scientific Implications

JSCE is ideal for high-seismic regions requiring high stiffness and minimal drift, while IS 456-2000 is more suitable for low- to moderate-seismic zones where ductility and deformation capacity are prioritized. SNI 2847:2019 and NZS 3101:2006 maintained a balanced trade-off between stiffness and ductility, making them appropriate for regions with moderate seismic hazards and limited construction budgets.

The findings emphasize that slab thickness not only affects moment and reinforcement but also governs seismic performance—thicker slabs provide higher stiffness and base shear resistance, but they also reduce ductility. The statistical comparison further demonstrates that a 20% increase in stiffness (as in JSCE) could reduce inter-story drift by approximately 15%, thereby improving serviceability under strong-motion events.

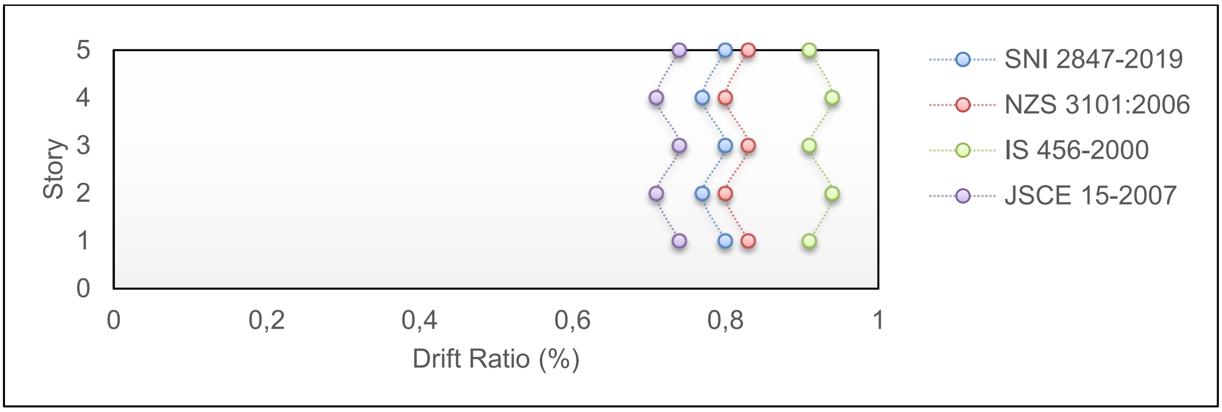


Figure 17. Story Drift Ratio – X Direction

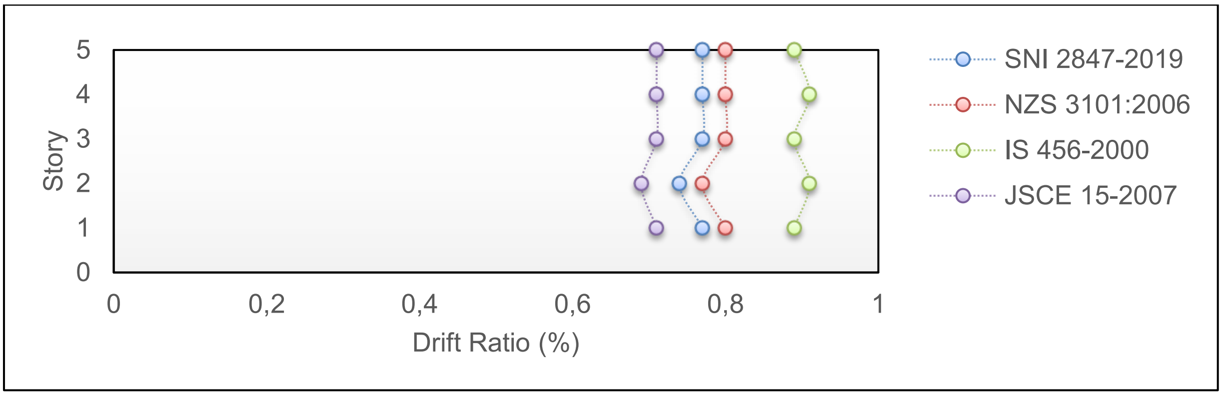


Figure 18. Story Drift Ratio – Y Direction

Linear relationships between design parameters have enabled engineers to optimize flat slab systems in accordance with targeted performance levels, resource efficiency, and regional seismic demands.

Practical Implications

The comparative findings among the four design codes—SNI 2847:2019, NZS 3101:2006, IS 456:2000, and JSCE 15-2007—offer significant implications for structural engineers and policy makers in Indonesia. From a practical design perspective, the results indicate that the choice of design code directly influences the stiffness, ductility, and overall seismic safety of flat slab systems.

For Indonesian engineers, adopting SNI 2847:2019 remains appropriate for moderate seismic zones, as it provides a balanced compromise between stiffness and ductility while maintaining cost efficiency and constructability. However, in high-seismic regions, such as Sumatra or eastern Indonesia, the study suggests that incorporating design provisions inspired by JSCE 15-2007 could significantly improve lateral stiffness (up to 20% higher than SNI) and reduce inter-story drift by approximately 15%, enhancing both serviceability and post-earthquake functionality.

Meanwhile, IS 456:2000, although less stiff, has demonstrated greater ductility and could be advantageous in regions where energy dissipation and deformation capacity are prioritized over initial stiffness. The NZS 3101:2006 standard unveiled strong compatibility with SNI provisions and could serve as a valuable secondary reference for developing future revisions of Indonesian seismic codes.

From a policy standpoint, these findings highlight the need for periodic updates of SNI 2847 to incorporate international best practices, particularly regarding nonlinear modeling, ductility demand, and capacity design principles. Encouraging the integration of pushover and performance-based seismic design approaches in Indonesian practice could further improve the resilience of reinforced concrete flat slab systems. Furthermore, collaboration between academia, professional associations, and code committees is essential to translate research outcomes like this into practical design guidelines, ensuring that structural safety and economic feasibility remain aligned with the national development agenda.

CONCLUSION

This study has provided a comprehensive comparison of the seismic performance of flat slab structures based on four international design standards: SNI 2847-2019, NZS 3101:2006, IS 456-2000, and JSCE 15-2007. The analysis revealed that differences in slab thickness, reinforcement requirements, moment distribution, and nonlinear behavior were significantly influenced by each standard’s design philosophy and seismic safety considerations. Among the evaluated standards, JSCE 15-2007 demonstrated superior stiffness and seismic resistance due to its more conservative approach, including thicker slabs and higher reinforcement demands. In contrast, NZS 3101:2006 and SNI 2847-2019 have offered a balanced strategy that optimizes material use while maintaining safety under moderate seismic conditions. IS 456-2000, although less rigid, depicted favorable ductile behavior, indicating its suitability for regions with lower seismic intensity.

The scientific findings of this study contribute to a better understanding of how design standards affect structural performance in seismic zones. By quantifying the relationships between slab thickness and reinforcement, as well as interpreting nonlinear pushover responses, this research has offered a valuable framework for evaluating structural efficiency and safety. These insights are especially relevant for structural engineers and decision-makers aiming to adapt flat slab designs to local seismic demands, resource availability, and construction constraints.

Looking forward, further studies are encouraged to examine the long-term performance of flat slabs under repeated seismic loading and aging effects. Moreover, the integration of innovative materials, such as high-strength concrete and fiber-reinforced composites, may provide new pathways for enhancing both strength and ductility in flat slab systems. Future research may also explore harmonization strategies among international design standards to develop globally adaptable guidelines that ensure structural resilience while optimizing material and economic efficiency.

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