DOI:10.22337/2587-9618-2025-21-3-188-200

COMPARATIVE STUDY OF EARTHQUAKE-RESISTANT BUILDING DESIGN STANDARDS

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Abstract: Earthquakes are often disasters that cause significant damage to infrastructure, buildings, and even fatalities. As a result, many nations globally have established earthquake-resistant design standards to protect infrastructure, buildings, and human lives from the impacts of seismic events. The objective of this research is to assess how the implementation of earthquake-resistant construction standards influences the structural integrity and performance of buildings across Indonesia. The research was undertaken by comparing buildings designed based on SNI 1726:2019, Eurocode 8:2004, and IS 1893:2016. The method employed involves comparing both elastic and inelastic design results using pushover analysis for each standard to assess seismic performance using ETABS software as an analytical tool. Findings from the analysis reveal that structures designed following the SNI 1726:2019 required the smallest area of flexural reinforcement, followed by an increased requirement in Eurocode 8:2004, and the highest in IS 1893:2016. Furthermore, the nonlinear pushover analysis revealed that the performance point of SNI 1726:2019 was 8.38% higher than Eurocode 8:2004 and 24.03% higher than IS 1893:2016 in the X direction, and 12.15% higher than Eurocode 8:2004 and 27.76% higher than IS 1893:2016 in the Y direction.

Keywords: Design Standards, Disaster Risk Reduction, Earthquake-Resistant Buildings, Eurocode 8, IS 1893, SNI 1726, Structural Performance

СРАВНИТЕЛЬНОЕ ИССЛЕДОВАНИЕ СТАНДАРТОВ ПРОЕКТИРОВАНИЯ СЕЙСМОСТОЙКИХ ЗДАНИЙ

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Аннотация: Землетрясения часто являются катастрофами, вызывающими значительные повреждения инфраструктуры, зданий и даже человеческие жертвы. В связи с этим многие страны мира разработали стандарты сейсмостойкого проектирования, направленные на защиту инфраструктуры, зданий и человеческих жизней от последствий сейсмических событий. Цель данного исследования — оценить, как внедрение стандартов сейсмостойкого строительства влияет на структурную целостность и эксплуатационные характеристики зданий в Индонезии. Исследование проводилось путем сравнения зданий, спроектированных на основе стандартов SNI 1726:2019, Eurocode 8:2004 и IS 1893:2016. В качестве метода использовалось сравнение результатов упругого и неупругого расчета с применением метода пошагового анализа (pushover analysis) для каждого стандарта с целью оценки сейсмической устойчивости с использованием программного обеспечения ETABS в качестве аналитического инструмента. Результаты анализа показали, что конструкции, спроектированные в соответствии с SNI 1726:2019, требуют наименьшей площади гибкой арматуры, затем следует Eurocode 8:2004 с повышенными требованиями, и наибольшие требования предъявляет IS 1893:2016. Кроме того, нелинейный пошаговый анализ выявил, что точка эксплуатационной эффективности по SNI 1726:2019 была выше на 8,38 % по сравнению с Eurocode 8:2004 и на 24,03 % по сравнению с IS 1893:2016 в направлении X, а также на 12,15 % выше по сравнению с Eurocode 8:2004 и на 27,76 % выше по сравнению с IS 1893:2016 в направлении Y.

Ключевые слова: Стандарты проектирования, снижение рисков бедствий, сейсмостойкие здания, Еврокод 8, IS 1893, SNI 1726, эксплуатационные характеристики конструкций

1. INTRODUCTION

Seismic events, or earthquakes, occur as a consequence of energy release in the Earth's crust, leading to ground surface vibrations [1]. As earthquakes frequently inflict significant destruction on structures and critical infrastructure, they also pose serious risks to human safety and result in fatalities. Many countries around the world are at risk from seismic events. Indonesia, in particular, exhibits high vulnerability as a result of its location within the Pacific Ring of Fire, a zone distinguished by frequent and strong earthquakes. Given the frequency and intensity of earthquakes, safeguarding buildings to withstand seismic forces has become increasingly important. To mitigate the impacts of earthquakes, countries have developed seismic design standards to ensure that buildings can withstand seismic loads. As a result, the implementation of earthquake-resistant building design principles has become essential in the planning and development of infrastructure.

Sub-group B of the International Association for Bridge and Structural Engineering (IABSE) conducted a cross-country comparison of earthquake-resistant design regulations, identifying both the similarities and differences to uncover existing knowledge gaps [2]. In this context, comparative studies between seismic design standards are crucial. These studies aim to identify the strengths and weaknesses of each standard and to provide insights for the development of more effective building codes in Indonesia.

This research draws upon a number of prior studies that analyzed comparative standards for earthquake-resistant buildings in various countries. Building codes classify structures into varying levels of ductility categories and then determine and apply the relevant response modification factors, taking into account material properties, structural configuration, and detailing requirements. Despite variations in implementation, there is a significant convergence among modern national seismic codes regarding their overall design methodologies [3].

The infrastructure development in Gulf countries is widely regarded as exemplary, with many structural systems reportedly designed in accordance with European codes. Consequently, a critical evaluation of these codes is essential to support the adoption of best construction practices in emerging economies, including India [4]. Adhikari et al [5] compared four different seismic design codes using identical parameters, including site class, peak ground acceleration (PGA), building dimensions, and material specifications. Aksoylu et al [6] compared the Turkish seismic design standards with the American ASCE 7-16 code by evaluating several structural response parameters, namely seismic base shear force, roof displacement, time period, and inter-story drift.

Srikant et al [7] in their study conducted a comparative analysis of seismic responses using the Indian Standard through both static and dynamic methods. The results indicated that the static method produced more conservative outcomes, particularly at the top levels of the structure. The study conducted by Karthiga et al (2015) compared residential buildings designed in accordance with four seismic design codes: IS 1893 (Indian Standard), Eurocode 8, ASCE 7-10, and the British Standard using the SAP2000 structural analysis software. The study concluded that Eurocode 8 resulted in the most economical design, whereas IS 1893 produced the least economical outcome [8]. Mala et al [9] compared the seismic design standards NBC 105:1994 and NBC 105:2020 for reinforced concrete apartment buildings using pushover analysis in ETABS. The results demonstrated that NBC 105:2020 provides greater structural capacity compared to NBC 105:1994. Seismic analysis plays a crucial role in earthquake engineering, serving as an essential method to simplify the assessment of building responses under seismic loading. Historically, structural designs primarily focused on gravity loads, with seismic analysis

emerging as a more recent advancement in structural engineering practices [10].

Işık et al [11] compared in their study, which evaluates seismic risk and target displacement values by considering both measured and proposed peak ground acceleration (PGA) parameters for various earthquakes across different countries. Six nations with varying seismicity levels were selected for analysis, namely Bosnia and Herzegovina, Albania, Croatia, Iran, Türkiye, and Serbia, all of which fall within the scope of this research. Seismic design codes differ across regions and countries, each incorporating distinct control parameters aimed at improving the seismic performance of buildings. Extensive research has been conducted to evaluate the seismic behavior of existing structures [12]. By showing the limitations of pushover analysis when comparing structures built to older codes to new criteria, these findings advance the discipline [13].

Tapkire et al [14] noted that the design base shear specified in IS 1893 is lower than that in Eurocode 8, primarily due to the higher response reduction factor employed in IS 1893. A comparative analysis of various seismic design standards reveals a consensus on key characteristics essential for seismic-resistant structures, including simplicity, symmetry, uniformity, and redundancy. Suliman et al [15] compared the seismic performance of MRF-RC (Moment Resisting Frame – Reinforced Concrete) buildings by applying four distinct codes: the Ethiopian Building Code Standard (EBCS-8), the Egyptian Code for Design and Construction of Reinforced Concrete Structures (ECP-201), the Algerian Seismic Monitoring Code Regulations (RPA 99), and the Chinese Code for Seismic Design of Buildings (GB-50011). The comparative study involves modeling buildings of varying heights and configurations, followed by the simulation of realistic seismic events corresponding to different seismic zones. Through systematic analysis and performance evaluation, the study aims to identify optimal earthquake-resistant design strategies that achieve an effective balance between structural safety, cost-efficiency, and functional performance [16]. Kumar et al [17] compared four primary comparative parameters: maximum deflection, story shear, story drift, and maximum axial load. The analysis concludes that the inclusion of shear walls increases base shear capacity, enhances structural stability, and contributes to a reduction in axial forces.

This research focuses on comparing seismic design standards from several countries, namely the Indonesian National Standard (SNI) 1726:2019, Eurocode 8:2004, and Indian Standard IS 1893:2016, to analyze and understand their respective seismic parameters and the extent to which they affect the seismic loads imposed on building structures.

2. METHODS

The research methodology implemented in this study includes the following procedures:

1. Modeling the selected building using ETABS software.
2. Applying gravity loads to the structural model using ETABS software.
3. The fundamental period of the structure was obtained through modal analysis to assess the dynamic behavior of the structure.
4. Developing three separate models based on the specifications of different seismic codes: the Indonesian Standard (SNI 1726:2019), Eurocode 8, and Indian Standard IS 1893:2016
5. Applying lateral seismic forces, manually calculated according to the respective standards SNI 1726:2019, Eurocode 8, and IS 1893:2016, along with their respective load combinations.
6. Analyzing the models and presenting the resulting data in the form of graphs and tables.
7. A comparative evaluation of the analysis results was conducted, followed by drawing conclusions based on the findings of the study.

Building Specification

In this study, the building structural model is a reinforced concrete special moment-resisting frame system engineered to withstand both gravitational and seismic forces. A single structural model with identical geometry and gravity loading is used; however, variations are applied in the implementation of seismic loads. The building has a total length of 24 meters, a width of 13 meters, and a total height of 24 meters, consisting of 7 stories with a uniform story height of 4 meters. The structural elements include primary beams measuring 400 × 600 mm, columns of 600 × 600 mm, and floor slabs with a thickness of 120 mm. These elements are designed to support gravity loads comprising a dead load of 1.45 kN/m² and a live load of 2.4 kN/m². The applied seismic loads are based on three different seismic codes: SNI 1726:2019 (Indonesia), Eurocode 8:2004 (Europe), and IS 1893:2016 (India)

Time Period

The calculation of the equivalent static seismic load is carried out using a seismic coefficient that is determined by the natural vibration period of the structure. The seismic coefficient is essential for calculating the base shear force during the design of earthquake-resistant structures. The fundamental period of the structure is derived using modal analysis results simulated using ETABS software, and subsequently adjusted according to the requirements of each respective seismic design code to ensure compliance with the prescribed limitations [18].

Earthquake Load

Each seismic design standard has its own seismic parameters, procedures, and calculation provisions for seismic loading. As a result, the base shear force obtained from each standard will differ in magnitude. The resulting base shear is then distributed across each floor level of the building according to its height.

The seismic parameters based on SNI 1726:2016 used in this study include a Peak Ground Acceleration (PGA) of 0.3586g, a site classification of SE, a 1-second spectral acceleration (S_1) of 0.615, and a short-period spectral acceleration (Ss) of 0.65. The earthquake load is calculated using the following formula:

$$V = C_s W, \tag{1}$$

Subsequently, the equivalent static earthquake load is determined using Equation (2)

$$F = C_v V. \tag{2}$$

The equivalent seismic parameters based on the European standard include a Peak Ground Acceleration (PGA) of 0.3586, site class D, and a behavior factor of 5.85. The base shear force is calculated using the following formula:

$$Fb = Sd.(T1).m.\lambda \tag{3}$$

Subsequently, the equivalent static earthquake load is determined using Equation (4)

$$F_i = F_b . \frac{Z_i . m_i}{\sum Z_j . m_j} \tag{4}$$

The equivalent seismic parameters based on the Indian standard include a Peak Ground Acceleration (PGA) of 0.36, site class C, and an earthquake response modification factor (R) of 5. The base shear force due to seismic loading is calculated using the following formula:

$$Vb = Ah.W \tag{5}$$

Subsequently, the equivalent static earthquake load is determined using Equation (6)

$$Q_i = \left(\frac{W_i . h_i^2}{\sum_{j=1}^{n} W_j . h_j^2} \right) \tag{6}$$

The equivalent static load method is a simplified seismic analysis approach that estimates the structural response of buildings by representing

earthquake-induced forces as horizontal static loads applied at each story level [19] [20] [21]. The equivalent static seismic load is computed in accordance with various design codes, namely SNI 1726:2019, Eurocode 8:2004, and IS 1893:2016 along the x-axis; the results are summarized in Table 1.

Table 1. The static earthquake load x direction

Floor level	SNI 1726:2019 (Ton)	Eurocode 8:2004 (Ton)	IS 1893:2016 (Ton)
Roof	51,16	52,46	69,69
6	59,14	64,54	73,49
5	45,78	53,79	51,04
4	33,46	43,03	32,66
3	22,34	32,27	18,37
2	12,64	21,51	8,17
1	4,77	10,76	2,04

The equivalent static seismic load is computed in accordance with various design codes, namely SNI 1726:2019, Eurocode 8:2004, and IS 1893:2016, along the y-axis. The results are summarized in Table 2.

Table 2. The static earthquake load y direction

Floor level	SNI 1726:2019 (Ton)	Eurocode 8:2004 (Ton)	IS 1893:2016 (Ton)
Roof	51,58	52,44	69,69
6	59,69	64,51	73,49
5	46,27	53,76	51,04
4	33,88	43,01	32,66
3	22,67	32,26	18,37
2	12,86	21,50	8,17
1	4,88	10,75	2,04

Subsequently, the magnitude of the equivalent static earthquake load at each floor level was plotted in a graph illustrating the relationship between the seismic load and the height of each floor, resulting from seismic actions in the x direction and y direction, as shown in Figure 1 & 2.

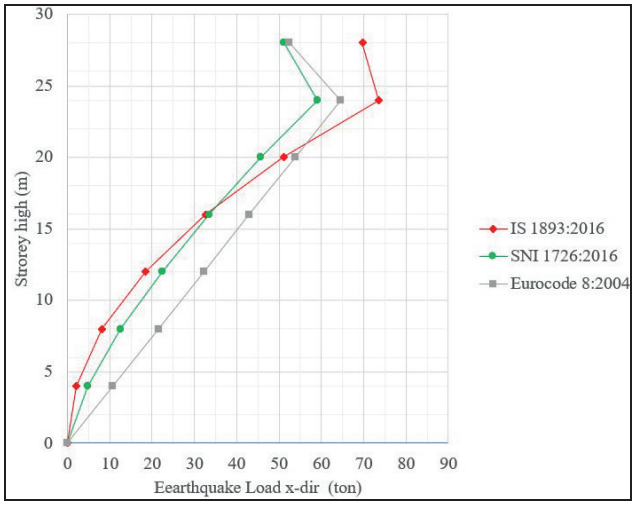


Figure 1. Graph of equivalent static earthquake forces in x direction

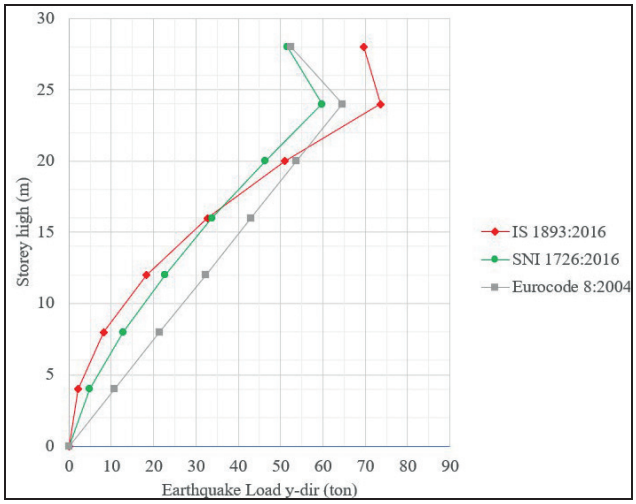


Figure 2. Graph of equivalent static earthquake forces in y direction

Modeling

The three-dimensional structural modeling includes beam, column, floor slab elements, and boundary conditions. In addition to the geometry, material properties of concrete and reinforcement, as well as load applications and load combinations, are also defined within the software ETABS. The structural layout configuration and the 3D model are presented in Figure 3.

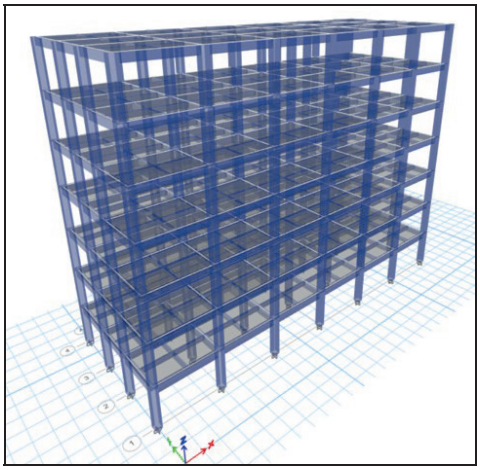


Figure 3. 3D Representation of the building structure

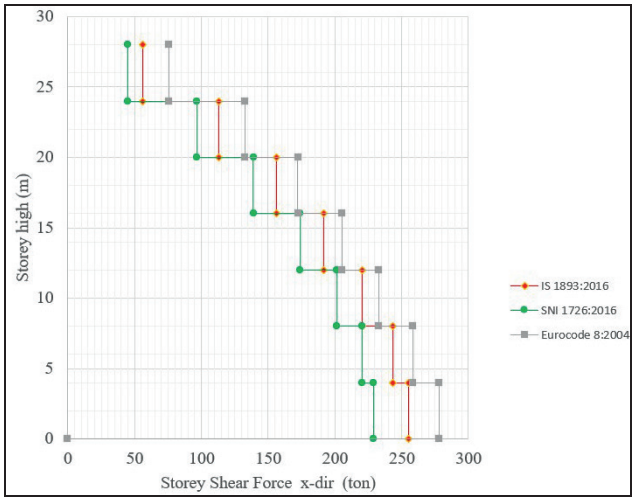


Figure 4. Graph of story shear force in the x-direction

3. RESULT AND DISCUSSION

The findings of this research include a comparative evaluation of seismic base shear forces, inter-story drift, flexural reinforcement requirements for beams and columns, and the structural performance of the building following nonlinear pushover analysis.

Comparison of Base Shear Forces

According to the findings, the seismic base shear forces measured in the x-direction, ranked from highest to lowest, are as follows: Eurocode 8:2004 with 278.37 tons, followed by IS 1893:2016 with 255.46 tons, and SNI 1726:2019 with 229.29 tons. In the y-direction, the base shear values also follow a similar trend: Eurocode 8:2004 with 278.23 tons, IS 1893:2016 with 255.54 tons, and SNI 1726:2019 with 231.83 tons. This outcome is attributed to the differences in seismic coefficients, where Eurocode 8:2004 has the highest coefficient at 0.717, followed by IS 1893:2016 at 0.0659, and SNI 1726:2019 at 0.059.

A comparison of the third-story shear forces among the three standards is presented in a graph illustrating the relationship between story height and the magnitude of story shear force, as shown in Figures 4 and 5.

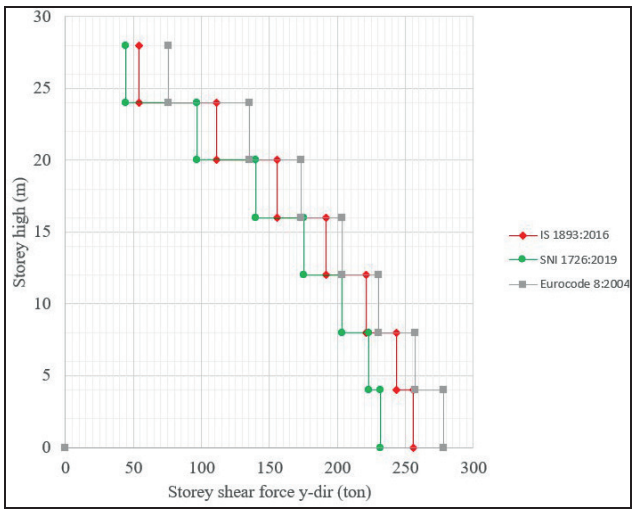


Figure 5. Graph of story shear force in the y-direction

Comparison of Inter-story Drift

Seismic loading causes relative lateral displacement between stories, known as inter-story drift. To ensure structural safety under seismic loads, the inter-story drift values are limited according to the respective seismic design codes. However, the magnitude of inter-story drift does not always correlate directly with the seismic base shear values. This is because some codes, such as IS 1893:2016, do not include a drift amplification factor, resulting in the smallest drift values among the three codes when compared to SNI 1726:2019 and Eurocode

8:2004. Additionally, the allowable drift limit prescribed by IS 1893:2016 is also the most stringent, contributing further to the reduced drift values. A comparison of inter-story drifts is presented in Figures 6 & 7.

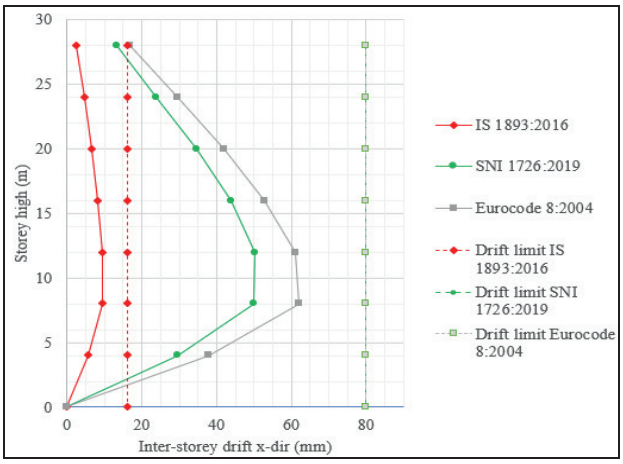


Figure 6. Graph of of inter-story drift in the x-direction

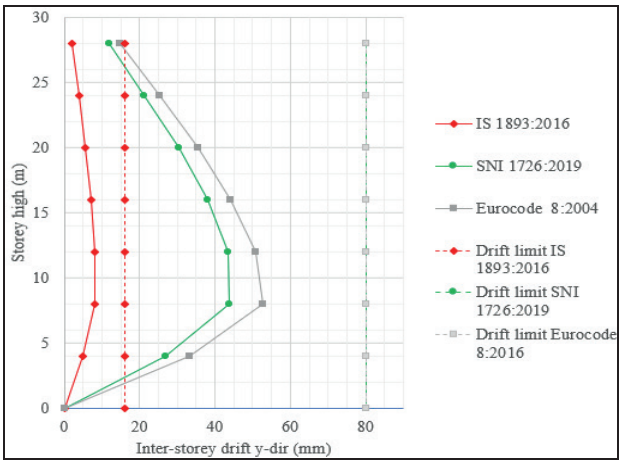


Figure 7. Graph of of inter-story drift in the y-direction

Story Lateral Displacement

he linear distribution of seismic forces on each floor in Eurocode 8:2004 results in the largest horizontal displacement among SNI 1726:2019 and IS 1893:2016, as shown in Figures 8 & 9.

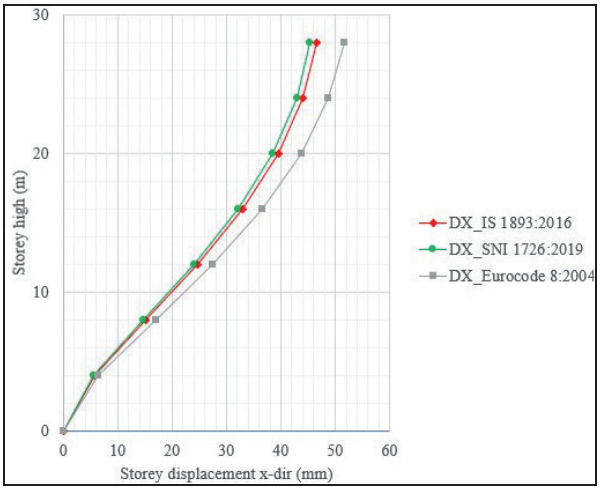


Figure 8. Graph of lateral displacement in the x-direction

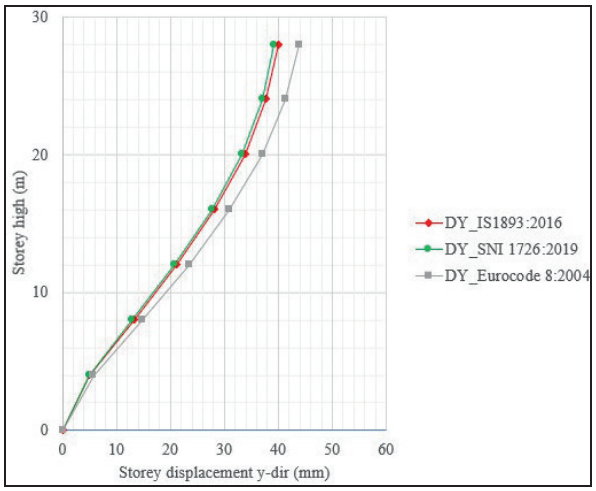


Figure 9. Graph of lateral displacement in the x-direction

Comparison of Performance Points

Nonlinear analysis methods are becoming increasingly important for evaluating the safety of structures under seismic loads. While traditional linear elastic analysis methods are sometimes inadequate to fully reflect the structural capacity limits, nonlinear static analyses, such as pushover analysis, provide more reliable results in determining the performance levels and collapse mechanisms of structures [22]. The maximum base shear that the structure can bear is outlined by push-over analysis. The building performance level combines the performance level of structures and non-structural components [23]. This

method aims to simulate the inelastic behavior of the structure by incrementally applying lateral loads until a collapse mechanism is formed. The analysis is based on the capacity-demand approach, and the parameters used in the evaluation of the pushover analysis results are the base shear that can be resisted by the building structure and the roof displacement, followed by the determination of the structural performance [24] [25].

Based on the pushover analysis in the X direction, it was found that the highest performance point, with a maximum base shear of V = 9,711.86 kN and a roof displacement of Δ = 0.261 m, was obtained using the Indonesian code. This was followed by the Eurocode, which resulted in a maximum base shear of V = 8,960.99 kN and a roof displacement of Δ = 0.189 m. The Indian code produced the lowest performance point, with a maximum base shear of V = 7,830.30 kN and a roof displacement of Δ = 0.116 m. The performance point resulting from the pushover analysis in x direction is presented in Table 3.

Table 3. Performance Point x-direction

Code	Performance point	
	Shear V in kN	Displacement in m
Indonesian code	9,711.9	0.26
Euro code	8,960.9	0.19
Indian code	7,830.3	0.12

Based on the pushover analysis in the Y direction, the highest performance point was also achieved using the Indonesian code, yielding a maximum base shear of V = 10,855.49 kN and a roof displacement of Δ = 0.248 m. Eurocode followed with a base shear of V = 9,679.50 kN and a roof displacement of Δ = 0.178 m. The Indian code again produced the lowest values, with a maximum base shear of V = 8,496.60 kN and a roof displacement of Δ = 0.109 m. The performance point resulting from the pushover analysis in y direction is presented in Table 4.

Table 4. Performance Point y-direction

Code	Performance point	
	Shear V in kN	Displacement in m
Indonesian code	10.855,5	0,25
Euro code	9.679,5	0,18
Indian code	8.496,6	0,11

The comparison of shear forces at the performance point is illustrated in the graph presented in Figures 10 and 11.

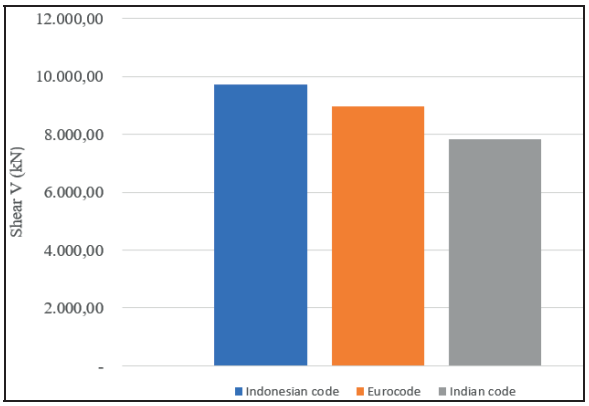


Figure 10. Comparison graph of shear forces at the performance point in the x-direction

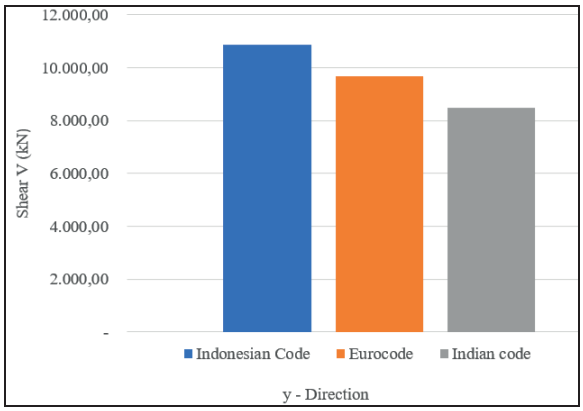


Figure 11. Comparison graph of shear forces at the performance point in the y-direction

Comparison of capacity curves

The pushover analysis results yield capacity curves representing the relationship between base shear and top displacement of the building structure, providing insights into the strength and ductility of the structure under increasing seismic loads. A comparison of the capacity

curves based on SNI 1726:2019, Eurocode 8:2004, and IS 1893:2016 is presented in Figures 12 and 13.

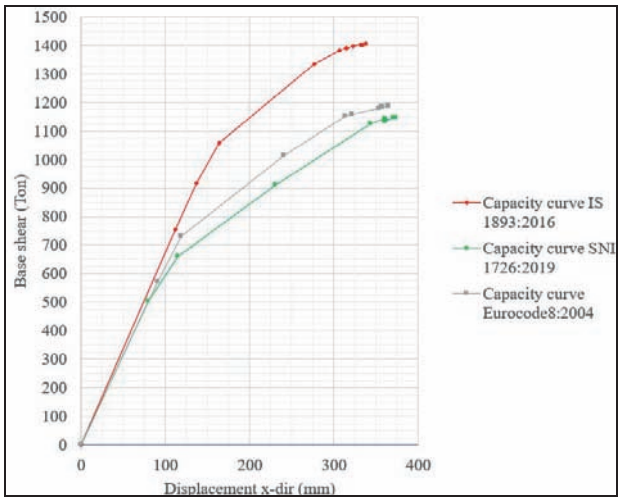


Figure 12. Comparison of capacity curves in the x-direction

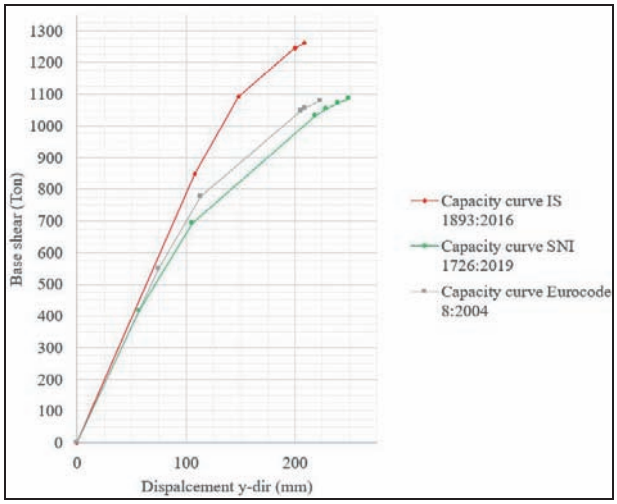


Figure 13. Comparison of capacity curves in the y-direction

The comparison of capacity curve graphs shows that the building designed based on SNI 1726:2019 undergoes the highest total deformation after the initial yielding (elastic stage), followed by inelastic deformation up to the failure point, compared to those designed using Eurocode 8:2004 and IS 1893:2016. This indicates that SNI 1726:2019 produces the most ductile structural performance among the three design codes.

4. CONCLUSION

From the analysis and discussions outlined in the preceding chapter, the following conclusions have been derived:

- Eurocode 8:2004 produced the highest seismic base shear, amounting to 278.23 tons, followed by the Indian Standard IS 1893:2016 with 255.54 tons, and the Indonesian Standard SNI 1726:2019 with 231.83 tons. This difference is attributed to the fact that Eurocode 8 uses the highest seismic force coefficient, followed by the Indian Standard and then the Indonesian Standard.
- The inter-story drift results indicated that IS 1893 yielded the lowest drift values, primarily because it does not incorporate a deflection amplification factor in the calculation.
- The performance point obtained from the pushover analysis indicated that structures designed in accordance with SNI 1726:2016 exhibited the highest values compared to those designed using Eurocode 8 and IS 1893:2016. This suggests that structures designed under SNI 1726:2019 demonstrate superior ductility performance.
- Building structures designed in accordance with SNI 1726:2019 demonstrated the highest levels of ductility, efficiency, and cost-effectiveness. In contrast, structures designed using IS 1893:2016 exhibited the lowest ductility and were found to be the least economical.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the Institut Teknologi Sepuluh Nopember for this work, under the project scheme of the Publication Writing and IPR Incentive Program (PPHKI) 2025.

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