

Comparative Seismic Analysis of Multi-Story RC Buildings under the Indonesian Seismic Code Using Static Equivalent and Response Spectrum Methods

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ABSTRACT

Indonesia's geographic position along the Pacific Ring of Fire exposes it to frequent and potentially devastating seismic events, necessitating reliable analytical methods for earthquake-resistant structural designs. While seismic design codes such as the Indonesian Seismic Code permit both linear static and dynamic analyses, the practical differences between the Static Equivalent Method (SEM) and Response Spectrum Analysis (RSA) remain insufficiently explored for multi-story Reinforced Concrete (RC) buildings. This study addresses this gap by comparing the seismic responses predicted by SEM and RSA for regular RC moment-resisting frame structures with two, four, six, and eight stories. Structural modeling and analysis were conducted using ETABS, and the evaluation focused on the key response parameters, including the total base shear and story-level seismic force distribution. The results indicate that RSA consistently predicts a higher base shear than SEM, with the discrepancy increasing as the building height increases. Additionally, the RSA captures a more dynamic and non-uniform seismic force distribution along the height, particularly in mid-level stories where the higher-mode effects become significant. These findings highlight the limitations of SEM in representing the dynamic behavior of taller structures and emphasize the suitability of RSA for more accurate seismic demand estimation in the performance-based design of mid- to high-rise RC buildings in seismically active regions.

Keywords-seismic analysis; static equivalent method; response spectrum analysis; reinforced concrete frame; earthquake-resistant design

I. INTRODUCTION

Indonesia is one of the most seismically active countries in the world due to its location along the Pacific Ring of Fire [1-

3]. The country has experienced several devastating earthquakes, with the 2018 Lombok and Palu events standing out because of their widespread impact. The Palu earthquake, which struck on 28 September 2018, had a moment magnitude

of 7.5 and an epicenter approximately 80 km north of Palu City. This event was notable for exhibiting super-shear rupture velocity, leading to severe ground motion [4]. The Lombok earthquake, occurring earlier on August 5, 2018, registered a moment magnitude of 7.0 and triggered over 10,000 landslides across the region [5].

Many existing buildings, although originally constructed in accordance with the prevailing standards of their time, now fall short of meeting the seismic performance requirements specified in the current codes [6-9]. This structural vulnerability places them at significantly higher risk of damage during seismic events. The threat is not hypothetical; over the past five decades, numerous earthquakes have caused extensive destruction to both architectural heritage and human life [10-12]. These recurring disasters have prompted the development of comprehensive frameworks for seismic risk management, with a dual focus on safeguarding human lives and preserving historically significant structures [13, 14].

Seismic analysis plays a critical role in this context; however, its complexity and scope can vary significantly, depending on the selected method. The choice of the analysis technique must strike a balance between accuracy and practicality, especially when assessing a large number of buildings or conducting preliminary evaluations [15-17]. Simplified approaches, such as the ESM, are often preferred because of their ease of implementation and cost efficiency. Although these methods may lack the precision of more advanced dynamic analyses, they provide rapid and economical means to estimate the seismic performance of structures and can serve as a valuable tool in early-stage assessments or large-scale evaluations [18].

The RSM has been widely adopted in seismic-resistant design, particularly for passive structural systems. This technique enables the direct estimation of peak structural responses under seismic excitation by utilizing predefined response spectra, eliminating the need for complex time-domain numerical simulations. Several studies have advanced the application of response-spectrum based designs. Authors in [19] introduced a standard mass-spring-damper model as an equivalent representation of actively controlled base-isolated structures, employing Linear Quadratic Regulator (LQR) control. In their approach, the maximum structural responses were derived from the response spectra, whereas the maximum control force was estimated using a newly developed control-force spectrum. Building on this, authors in [20, 21] expanded the use of control-force spectra to systems utilizing Adaptive Sliding Control (ASC)-based negative stiffness control and constant-gain state-feedback control for active base isolation. These methods facilitate the estimation of both the seismic responses and required control forces without relying on iterative simulation processes.

Authors in [22] investigated the influence of different slab systems on the seismic performance of a multi-story building in Madinah, Saudi Arabia. This study compared flat, solid, and hollow block slabs. The results indicated that the slab type significantly affected the seismic response. The hollow block system exhibited the lowest base shear and bending moments, whereas the flat-slab system exhibited the highest. In terms of

the story displacement and column forces, the hollow block system demonstrated a favorable drift control, whereas the solid slab system showed a superior overall structural performance.

Furthermore, authors in [23] proposed a response spectrum-based method tailored for active base-isolated structures incorporating Equivalent Input Disturbance (EID)-based control. By decomposing the EID system into feedforward and state-feedback components, they derived the response and control force spectra that capture the relationship between the maximum responses and control system parameters. Collectively, these studies underscore the effectiveness of response-spectrum-based frameworks in streamlining the seismic design, providing analytical boundaries for control force requirements, and reducing the dependence on computational trial-and-error procedures.

Given the increasing demand for seismic-resilient designs and the evolving complexity of analytical techniques, it is essential to evaluate the applicability and accuracy of different seismic analysis methods. This study aims to investigate and compare the seismic response of a multi-story RC building using two commonly employed approaches: the SEM and the RSA. Although SEM remains widely used owing to its simplicity and compliance with the design codes for regular low- to mid-rise structures, it offers a more refined approach that considers the dynamic characteristics and multiple mode contributions, making it more suitable for taller or irregular buildings.

The main contribution of this research lies in providing a comparative assessment of the structural response parameters, such as the base shear, story displacement, and inter-story drift, derived from SEM and RSA. The study highlights the limitations of simplified static analysis when applied to multi-story buildings and demonstrates the benefits of dynamic analysis in capturing the true seismic behavior of structures. The proposed approach enables structural engineers and designers to select appropriate analysis methods based on the building characteristics and seismic risk, contributing to safer and more efficient seismic design practices in earthquake-prone regions such as Indonesia.

II. METHODOLOGY

This study evaluates and compares the seismic performance of RC moment-resisting frame buildings subjected to earthquake loading using both SEM and RSA, as prescribed by the Indonesian seismic design code SNI 1726:2019 [24].

Four RC building models with 2-story, 4-story, 6-story, and 8-story were analyzed in this study. All buildings share the same structural layout and plan dimensions. Each model adopts a regular configuration without setbacks or irregularities in the elevation. The planned layout of the buildings is shown in Figure 1. The vertical loading applied to each structure consisted of a superimposed dead load of 2.0 kN/m² and a live load of 2.5 kN/m², which were uniformly distributed across all floor levels. These loads were assigned to simulate realistic usage scenarios for typical offices or residential buildings and were applied consistently across all models [25].

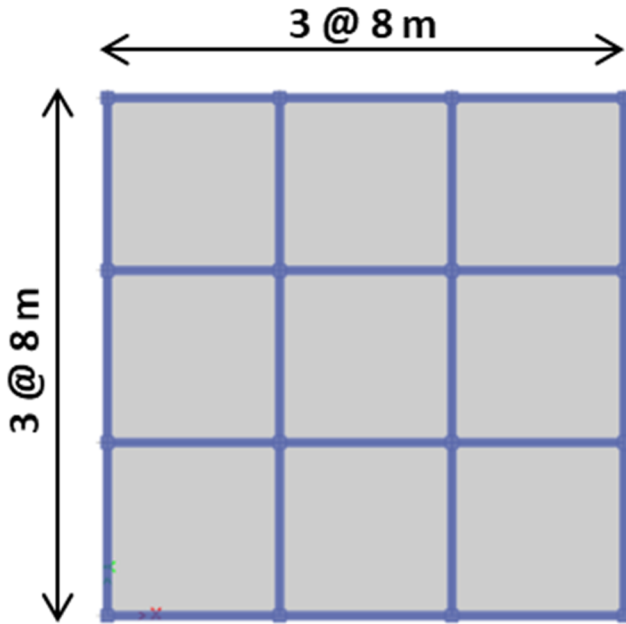


Fig. 1. Building plan used for analysis.

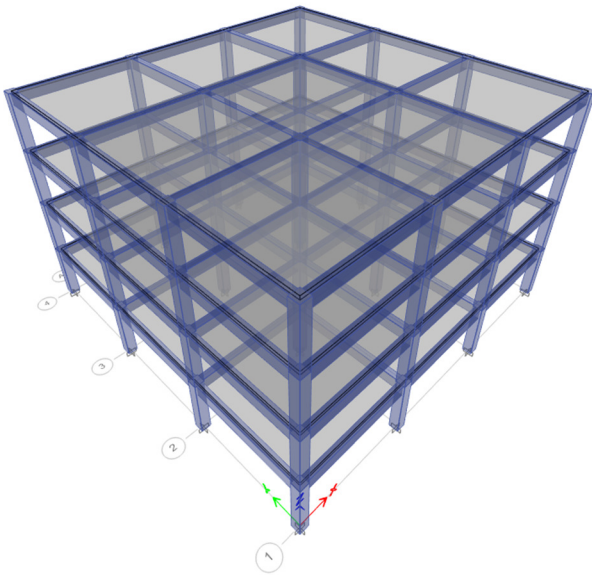


Fig. 2. 3D model of 4-story structure in ETABS.

The seismic parameters used in this study were based on the location in Manado, Indonesia. According to the seismic hazard map provided in SNI 1726:2019, the spectral acceleration parameters were $S_s = 1.0329 \text{ m/s}^2$ and $S_l = 0.4592 \text{ m/s}^2$, representing the short-period and 1-second period spectral acceleration, respectively. The site was classified as stiff soil (Class D) based on its geotechnical characteristics.

Three-dimensional (3D) models of each building configuration were developed using ETABS software [26]. The beams and columns are modeled using frame elements to accurately represent their flexural and axial behaviors, whereas

the slabs are modeled using shell elements to capture the membrane and bending actions. A typical representation of the structural model is depicted in Figure 2.

SEM is a simplified linear static procedure, commonly used for low to mid-rise structures that exhibit regularity in planning and elevation. In this method, the lateral seismic force is calculated as a function of the building's total seismic weight and design spectral acceleration adjusted by the appropriate response modification factors. Therefore, the total base shear (V) is determined using a direct formula based on the total seismic weight of the structure and the design spectral response acceleration:

$$V = C_s W \quad (1)$$

where C_s is the seismic response coefficient defined by the spectral shape, soil conditions, structural period, and response modification factor, and W is the total seismic weight. The resulting base shear is distributed vertically along the building height according to the relative story mass and height.

The RSA is a linear dynamic method that captures the structural response more accurately by considering the contributions of multiple vibration modes. Unlike SEM, the RSA does not directly compute the total base shear using a static formula. Instead, it determines the modal base shear contributions from each vibration mode using the spectral acceleration values and combines them statistically. The response of each mode i is calculated as:

$$R_i = \Gamma_i \Phi_i S_a(T_i) \quad (2)$$

where R_i is the peak modal response (displacement, force, or acceleration), Γ_i is the modal participation factor for mode i , Φ_i is the mode shape vector for mode i , and $S_a(T_i)$ is the spectral acceleration corresponding to period T_i .

Modal responses were combined using the Square Root of the Sum of the Squares (SRSS) method, which is appropriate for structures with well-separated natural vibration modes because it assumes limited modal coupling and allows the statistical combination of the peak responses from individual modes. This approach enables RSA to provide a more refined and realistic estimation of the seismic effects compared to the static methods, particularly in cases where multiple modes contribute significantly to the overall structural response. By applying both SEM and RSA to identical structural models, this study identifies the differences in seismic demand predictions and evaluates their implications, focusing on key parameters, such as the base shear, seismic force distribution and story drift. These parameters form the basis for comparing SEM and RSA, offering insights into the suitability of each method for buildings with varying heights and dynamic characteristics.

III. RESULTS AND DISCUSSION

This section presents and compares the base shear results obtained from SEM and RSA for 2-story, 4-story, 6-story, and 8-story RC moment-resisting frames. The purpose of this comparison is to understand how each method estimates the seismic demand as the number of stories increases.

Figure 3 demonstrates that the base shear values obtained from the RSA were consistently higher than those obtained from the SEM for all building heights. For the 2-story building, the difference was relatively small, with the RSA predicting a slightly higher base shear of 1,300 kN compared to 1,100 kN for the SEM. However, as the number of stories increased, the gap between the two methods became more pronounced. In the case of the 8-story building, the RSA produces a base shear exceeding 5,000 kN, which is significantly higher than 3,900 kN estimated by the SEM.

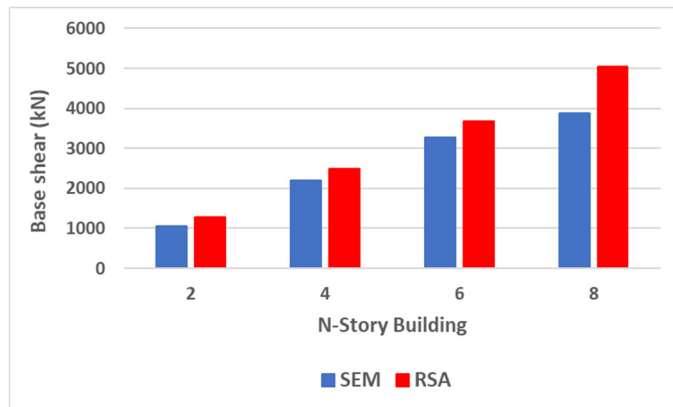


Fig. 3. Base shear obtained from SEM and RSA for the 2-story building.

This trend highlights the increasing influence of the higher vibration modes in taller structures, which are not adequately captured by SEM. Given that SEM relies on a simplified distribution of lateral forces based on the fundamental period and mass of the structure, it tends to underestimate the seismic demand, particularly in buildings where higher-mode participation becomes significant. However, RSA incorporates the contribution of multiple modes and better reflects the dynamic characteristics of the structure, leading to more accurate and often more conservative estimates of the base shear. In addition to the base shear, the distribution of seismic forces along the height of the structure provides critical insights into how different analysis methods interpret the structural responses under seismic loading. Figure 4 presents the story-wise lateral force distribution for a 4-story building using SEM and RSA.

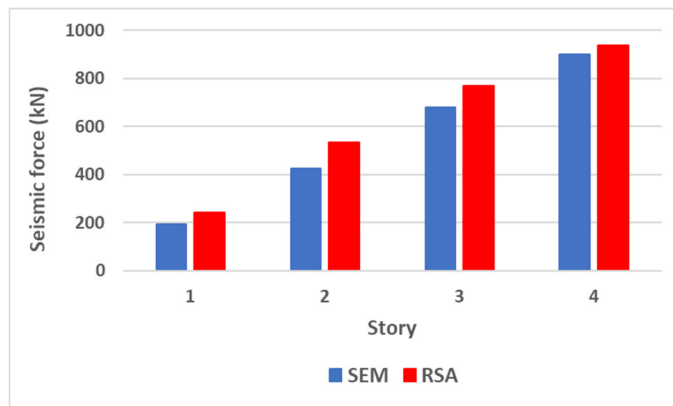


Fig. 4. Seismic force distribution from SEM and RSA for 4-story building.

The results reveal that both methods follow the expected trend of increasing lateral force with height, in accordance with the typical triangular distribution pattern. However, notable differences were observed in the magnitudes of the lateral forces at each story. In the first story, the RSA produced a seismic force of 250 kN, which was higher than the 190 kN estimated by the SEM. This pattern continued in the upper stories, where the RSA consistently predicted higher lateral forces than the SEM. The disparity becomes more pronounced at intermediate levels, particularly at the second and third stories, where the RSA estimates 530 kN and 760 kN, respectively, compared with 440 kN and 670 kN from the SEM. At the top story, the difference is less significant, with both methods yielding similar values of approximately 910 kN for RSA and 890 kN for SEM.

In addition to the seismic force distribution, the lateral displacement and story drift are critical parameters for evaluating the deformation performance and serviceability of multi-story buildings under earthquake loading. Figure 5 displays the lateral displacement profile of the 4-story building. The results show that the RSA consistently predicts higher displacements at all levels compared with the SEM. For instance, the lateral displacement at the roof level (story 4) is 24.7 mm under RSA compared to 22.6 mm under SEM. This trend is observed throughout the structure, with the RSA yielding approximately 13%-15% higher displacement, reflecting its ability to account for higher-mode contributions and modal mass participation.

The difference became more pronounced in the story drift ratio, as evidenced in Figure 6. The RSA predicts higher drift ratios at all levels, particularly at the second and third stories, which exhibit maximum drift values of 2.07 and 1.65, respectively. In contrast, the SEM produces lower peak drifts of 1.86 and 1.53 at the same levels. This suggests that the RSA is more sensitive to dynamic amplification in the mid-height region, which is critical for identifying the potential soft-story behavior and localized damage concentration. Additionally, both methods show a decrease in drift toward the top story, but the RSA consistently reports marginally higher values.

These results highlight the dynamic nature of the RSA method, which considers the modal participation of multiple vibration modes and the corresponding mode shapes. Unlike the SEM, which applies a static lateral load pattern based primarily on the first mode, the RSA captures the contributions of the higher modes that influence the internal force distribution across the building height. This results in a more balanced and often more critical estimation of the seismic demand, particularly in mid-height stories, which are prone to increased inertial effects and inter-story drift under dynamic excitation.

The present study focuses on comparing SEM and RSA under the Indonesian seismic code SNI 1726:2019. By applying site-specific spectral parameters representative of Manado, Indonesia. This research provides the first systematic assessment of the differences in base shear, lateral force distribution, and inter-story drift for multi-story RC moment frames designed to local code provisions. Unlike previous studies, which were mainly limited to global base shear

comparisons [22, 23], this study offers a detailed evaluation of the displacement and drift behavior, which are essential for the performance-based design and for ensuring structural safety under Indonesia's high seismic hazard conditions. These insights address a critical gap in the regional literature and contribute practical guidance for engineers designing earthquake-resilient buildings in Indonesia.

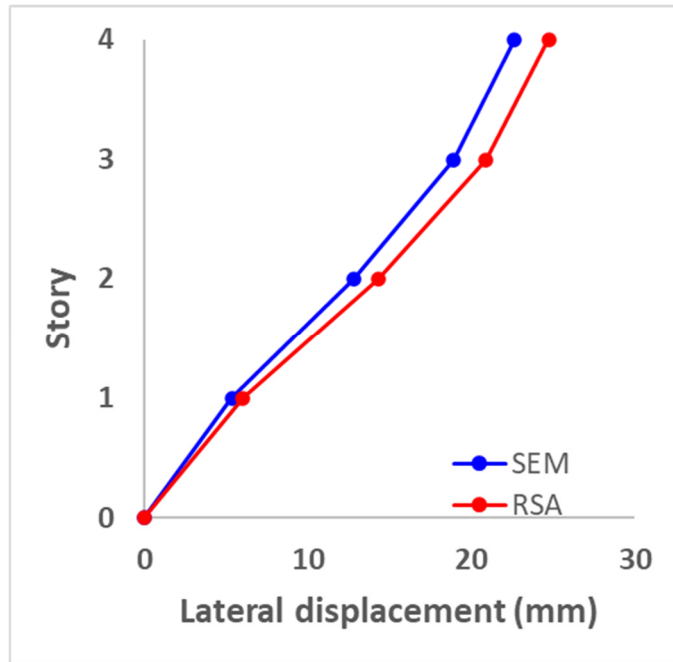


Fig. 5. Lateral displacement obtained from SEM and RSA.

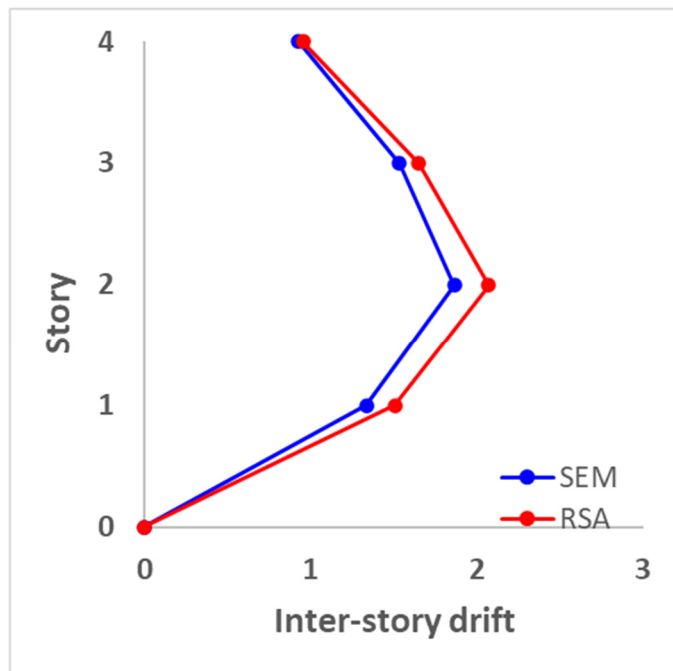


Fig. 6. Inter-story drift obtained from SEM and RSA.

This comparison underscores the importance of using RSA for structures, where an accurate representation of the force distribution is essential, particularly in design situations involving vertical irregularities, stiffness discontinuities, or mass eccentricities. By distributing forces more realistically along the height, RSA offers improved reliability in predicting the seismic demand of the structural elements and contributes to more resilient seismic design outcomes.

IV. CONCLUSIONS

This study presents a comparative evaluation of the seismic response of Reinforced Concrete (RC) moment-resisting frame buildings using the Static Equivalent Method (SEM) and Response Spectrum Analysis (RSA), as outlined in the Indonesian seismic design code SNI 1726:2019. The analysis was performed on 2-story, 4-story, 6-story, and 8-story structures, focusing on the base shear, seismic force distribution, lateral displacement, and inter-story drift as primary indicators of the structural performance under earthquake loading.

The results indicate that RSA consistently predicts higher base shear values than SEM, and the discrepancy becomes more significant as the building height increases. This highlights the limitations of SEM in capturing the dynamic behavior, particularly for mid-rise to high-rise structures, where higher vibration modes play a substantial role. While SEM remains adequate for preliminary design in low-rise buildings with regular geometry, it may underestimate the seismic demand in more complex systems, potentially leading to unsafe or non-conservative designs.

In addition, the RSA produced a more dynamically representative force and deformation profile along the building height. The former revealed higher inter-story drift ratios at intermediate levels, which SEM did not capture, demonstrating its advantage in identifying the potential soft-story behavior and localized damage risks.

Compared to prior studies that have explored the effect of the material systems or code evolution on the seismic performance, this research contributes a focused comparison between SEM and RSA, applied under the current Indonesian code provisions, using a consistent modeling framework. Unlike previous studies, which were limited to base shear comparisons, this study incorporates a detailed assessment of the force distribution and drift behavior, which is key for the performance-based design.

Although SEM remains a useful tool for the preliminary analysis and design of regular low-rise structures, RSA is more suitable for detailed seismic assessments, especially for buildings with greater heights or irregularities. Incorporating RSA in the design process improves the accuracy of estimating the seismic demands, thereby enhancing the reliability and resilience of buildings in seismically active regions such as Indonesia.

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DATA AVAILABILITY

Data analysis <https://zenodo.org/records/15244916>.

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