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Performance-Based Seismic Analysis and Design of a Mid-Rise RC Guest House in a High Seismic Zone of Indonesia

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Abstract— This study presents the seismic-resistant structural design of a 3-storey guest house with a roof garden, located in Surabaya, Indonesia, an area classified as Earthquake Zone 6. The building is designed using a Special Moment Resisting Frame System (SMRFS) as per SNI 1726:2019, which is appropriate for high seismic risk areas. The equivalent static lateral force method is employed for seismic analysis. Structural modeling and upper-structure design are performed using ETABS, while sub-structure components such as pile caps and foundations are analyzed manually and supported by PCA Column software. The structural elements are designed according to Indonesian codes, including SNI 2847:2019 for reinforced concrete, SNI 1727:2020 for minimum loads, and SNI 2052:2017 for steel reinforcement. The final design yields column dimensions ranging from 200×400 mm to 600×600 mm and beam dimensions from 250×400 mm to 350×700 mm, with slab thicknesses of 120 mm and 150 mm. The results confirm that the structure meets strength, stiffness, and ductility requirements. This research ensures compliance with national standards while enhancing structural safety in high seismic zones.

Keywords: Structural Design, SPRMK, SNI, ETABS

1. Introduction

The design of a building's structural system must account for various types of loads, including dead loads (self-weight of the structure), superimposed dead loads (such as partition walls and finishes), live loads, and lateral loads resulting from wind or earthquakes. The primary objective is to achieve an optimal configuration that ensures both safety and structural efficiency in accordance with prevailing standards, particularly those stipulated by the Indonesian National Standards (SNI). The structural system comprises two major components: the superstructure (above ground) and the substructure (below ground), both of which must be designed to resist expected loads and maintain performance under seismic conditions.

This study focuses on the structural design of a three-story reinforced concrete (RC) guest house located in Surabaya, East Java, classified as Seismic Zone 6 under SNI 1726:2019. The analysis and design are performed using the Special Moment Resisting Frame System (SMRFS), which provides ductility and energy dissipation capabilities in high seismic zones [1], [2]. The Equivalent Static Lateral Force Method is employed for seismic analysis, which is appropriate for regular and symmetrical structures under 40

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meters in height [3]–[5]. Modeling and design are conducted using ETABS software, while pile cap and foundation analysis are performed manually and verified using PCA Column [6], [7].

Based on Table 1 of SNI 1726-2019, three common lateral force-resisting systems are typically used in Indonesia: (1) bearing wall systems, (2) moment-resisting frame systems, and (3) dual systems in which at least 25% of the seismic base shear is resisted by moment frames [8], [9]. Table 1 summarizes the allowed structural analysis procedures based on the building's seismic design category.

In the current project, the equivalent static method is deemed suitable due to the building's regularity, symmetrical mass distribution, and moderate height. This method assumes that the seismic force acting on the structure is equivalent to an inertial force derived from the mass and acceleration of the ground movement [10], [11]. The conceptual representation is illustrated in Figure 1.

Table 1. Permitted Structural Analysis Procedures Based on SNI 1726-2019 (Adapted from Table 16)

Seismic Design Category (SDC)	**Structural Configuration**	**Linear Static (Equivalent Static)**	**Response Spectrum (Modal)**	**Time History (Nonlinear)**
A, B, C	Regular and Irregular	Permitted	Permitted	Optional
D	Regular	Permitted (if height ≤ 40 m)	Permitted	Recommended
D	Irregular	Not Permitted	Required	Recommended
E, F	Regular	Not Permitted	Required	Recommended
E, F	Irregular	Not Permitted	Required	Required

The base shear force V acting on the building is calculated using the following Equation 1.

$$V = Cs.W \tag{1}$$

where *Cs* is the seismic response coefficient and *W* is the effective seismic weight of the structure. The value of *Cs* is determined by Equation 2:

$$Cs = \frac{S_{DS}}{(\frac{R}{I_e})} \tag{2}$$

in which S_{DS} is the design spectral acceleration, *R* is the response modification factor, and I_e is the importance factor of the structure [12], [13].

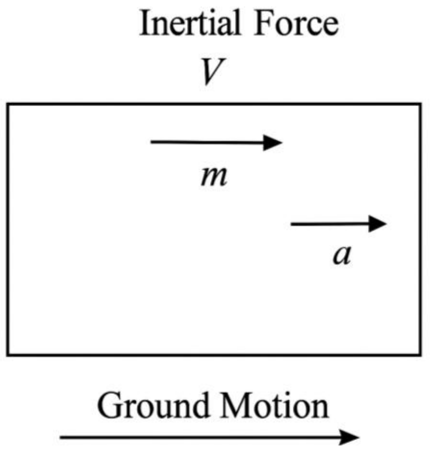

Figure 1. Inertial Forces Acting on a Rigid Body Due to Ground Motion

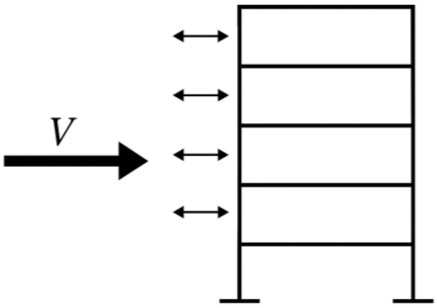

Figure 2. Seismic Base Shear Force Distribution Across Floors

The methodology employed in this project adheres to the seismic analysis workflow commonly implemented in civil engineering practice, including the definition of materials (concrete, steel, rebar), assignment of cross-sections (beams, columns, slabs), load patterns, mass sources, P-Delta effects, load combinations, and cross-section design. The structural model is developed in ETABS, and results are evaluated to ensure code compliance [14], [15].

Lateral stability is a key concern in seismic zones. Without adequate ductility and stiffness, buildings are vulnerable to torsional irregularities and collapse [16], [17]. Thus, code-based capacity design and attention to vertical and horizontal irregularities play critical roles in achieving seismic resilience [18]–[20].

In conclusion, this project adopts a code-compliant, performance-based approach to structural seismic design for a mid-rise building in a high seismic zone. The use of the equivalent static method ensures computational efficiency, while the application of ETABS and SNI standards guarantees accuracy in design and safety under earthquake loading conditions [21].

Irregular structures with uneven mass and stiffness distributions are particularly susceptible to seismic forces due to torsional irregularities and stress concentrations at re-entrant corners. While previous research has primarily focused on vertically irregular or symmetric buildings, this study investigates a six-story L-shaped reinforced concrete building using ETABS, utilizing both the ESM and RSA according to IS 1893:2016. A total of twelve models with different shear wall configurations are analyzed to evaluate base shear, drift, fundamental time period, torsional irregularity, and diaphragm rotation. The findings indicate that symmetrically placed shear walls in both the X and Y directions significantly mitigate displacements and torsional effects, whereas irregular placements heighten vulnerability. This research is particularly pertinent for Nepal, where L-shaped buildings are prevalent but often lack adequate seismic detailing.

2. Method

This study adopts a systematic approach to the structural analysis and design of a three-story reinforced concrete guest house with a roof garden, located in Surabaya, East Java. The building is situated in Seismic Design Category D and classified as Risk Category II based on SNI 1726:2019. The overall research flow is outlined in Figure 3, which illustrates the sequence from site investigation, data processing, modeling, load application, to the final structural design process. The methodology integrates geotechnical evaluation, material specification, loading analysis, and structural modeling using established codes and software.

The building site is located on Jalan Kapasari, Surabaya. The location and borehole testing points were identified using Google Earth and geotechnical surveys. The geotechnical data were derived from sondir tests conducted by PT Testana Engineering, Inc. These results were used to determine the site classification required to develop the seismic response spectrum for the project. Figure 4 shows the location of the sounding points. Schmertmann's method (1978) was used to classify the soil type and consistency by correlating cone penetration resistance (qc) and friction ratio (FR). The relationship between these parameters is presented in Figure 5, which serves as the basis for interpreting subsurface conditions. From the results of three soundings—S01, S02, and S03—it is concluded that the site consists predominantly of soft soil (SE), as shown in the estimated stratification profile in Figure 6.

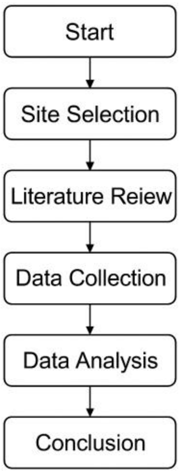

Figure 3. Research Flow Chart

Figure 4. Location of Sondir Points

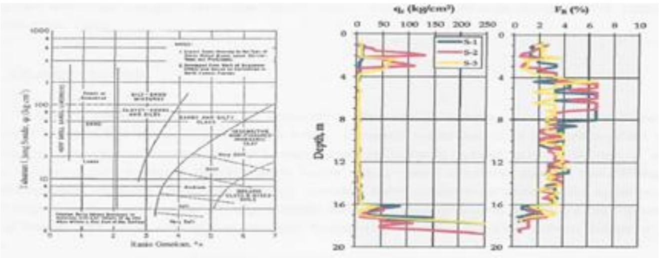

Figure 5. Soil Classification System Based on Schmertmann Method

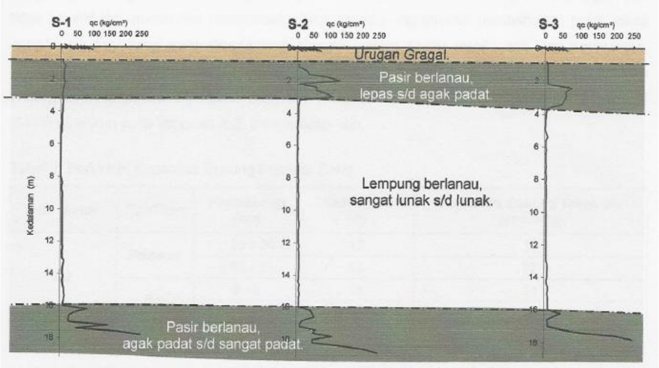

Figure 6. Estimated Local Soil Stratification

The structural materials adopted in this study follow the specifications outlined in Indonesian National Standards. The concrete used throughout the building—including columns, beams, floor slabs, stairs, lintels, and practical columns—has a characteristic compressive strength of 25 MPa at 28 days. Steel reinforcement consists of plain bars (BjTP 280) for diameters less than 10 mm, with a yield strength of 280 MPa, and deformed bars (BjTS 420b) for diameters equal to or greater than 10 mm, with a yield strength of 420 MPa, both in accordance with SNI 2052:2017.

Loading scenarios are defined in accordance with SNI 1727:2020, which regulates the minimum loads for the design of buildings and other structures. The total gravity load includes the self-weight of structural elements such as slabs, beams, columns, and walls, which is calculated automatically by ETABS using material densities of 2400 kg/m^3 for concrete and 7850 kg/m^3 for reinforcement. Additional dead loads such as floor finishes and partition walls, along with live loads due to occupancy, are also considered. These loads are further combined with seismic loads to form design load combinations for both upper and lower structural systems.

For the superstructure, load combinations follow SNI 2847:2019 and include the effects of seismic loads in two orthogonal directions. These combinations account for various factored proportions of dead loads, superimposed dead loads, live loads, and horizontal earthquake effects in the X and Y directions. The analysis is conducted using ETABS to determine internal forces and design each structural member accordingly. For the foundation and substructure system, which includes pile caps and bored piles, the load combinations are derived using the Allowable Stress Design (ASD) method. These combinations are intended to capture the maximum possible axial and lateral load effects transmitted from the superstructure into the ground.

The structural system employed in this project is the Special Moment Resisting Frame System (SMRFS), which is recommended by SNI 1726:2019 for buildings located in high seismic zones and having regular configurations. Given the soft soil conditions at the site and the classification of Surabaya within Earthquake Zone 6, the building falls under Seismic Design Category D. Furthermore, considering the function of the building as a guest house or lodging facility, it is categorized as a risk category II structure, with an associated seismic importance factor of 1.0 as per national code provisions.

For structures that are regular in plan and elevation, with a total height below 40 meters, the Indonesian seismic code permits the use of the Equivalent Static Method (ESM) for seismic analysis. Thus, this project utilizes the equivalent lateral force procedure to calculate the seismic demand, which is then distributed to each floor based on mass and height. In conducting the structural analysis, the response modification factor is taken as $R = 8$, representing the ductility of the special moment frame. The overstrength factor is set to $\Omega_0 = 3$ to account for redundancy and energy dissipation, and the deflection amplification factor is $Cd = 5.5$, used to estimate realistic displacement demands under seismic loading. The complete structural analysis procedure applied in this project follows the guidelines and limitations set forth in SNI 1726:2019 for buildings within Seismic Design Category D.

In summary, the methods employed in this research integrate geotechnical evaluation, material specification, load determination, and structural modeling using ETABS and manual calculations. All processes are conducted in accordance with the latest editions of SNI standards, ensuring that the design results are both structurally sound and compliant with national seismic safety regulations.

3. Results and Discussion

The analysis and structural design results of the Guest House building project in Surabaya are comprehensively evaluated in this chapter. The upper structure is first analyzed, focusing on the B1 beam located at the second floor between gridlines C3 to C5, with a cross-sectional dimension of 350 × 700 mm. Using ETABS v18.1, a factored moment Mu(-) = 595 kNm was obtained. This value is used to verify compliance with SNI 2847:2019, where axial load conditions, span-to-depth ratio, and dimensional proportions are assessed. The axial load Pu = 0 kN is well below the 0.1f'cAg limit of 612.5 kN, satisfying code requirements. The beam's effective depth is 639 mm, and with a span of 9 m, the span-to-depth ratio is 14.1 (> 4), fulfilling the minimum criteria. Additionally, the width-to-height ratio is 0.5 (> 0.3), and the minimum width requirement of 250 mm is met with a beam width of 350 mm.

For flexural design under Condition 1 (negative moment at right support), the section is designed using D22 bars. The design moment Mu(-) = 595.30 kNm results in a required steel area As = 2814.64 mm^2. The design satisfies minimum reinforcement checks, leading to the installation of 8D22 in two layers, yielding As,t = 3042 mm^2. Condition 2, with the same Mu(-), uses identical reinforcement detailing. Under Condition 3 (positive moment at midspan), Mu(+) = 297.60 kNm requires As = 1307.6 mm^2, resulting in 4D22 bars installed in one layer. The calculated design moment Mn = 342.60 kNm is greater than Mu = 297.6 kNm and fulfills SNI requirements, including tension-controlled behavior.

For Condition 4, involving sway to the left with positive moment, reinforcement detailing mirrors Condition 3. The positive moment capacity also exceeds the code requirement of 1.2 times the adjacent negative moment. All reinforcement ratios are within permissible limits (ρ = 0.0068 < ρmax = 0.019), confirming adequate safety.

Mid-span flexural design for Mu = 544 kNm follows similar procedures with the same beam dimensions and reinforcement type. For shear design under earthquake loading, the plastic hinge formation at beam ends is considered. Probable moment capacities (Mpr) are computed for all four sway conditions, with the maximum value being 848.84 kNm. Figure 7 illustrates the shear and moment diagram from the 1.2DL + 1.0LL load combination, where Vu,g = 281.7 kN on the left side. The maximum design shear V_u = 402.93 kN is compared with the concrete shear contribution Vc = 191.0 kN. Thus, the required shear reinforcement Vs = 211.93 kN is well below the maximum capacity V_s,max = 718.55 kN, and 2-legged stirrups with ds = 10 mm at s = 100 mm are sufficient.

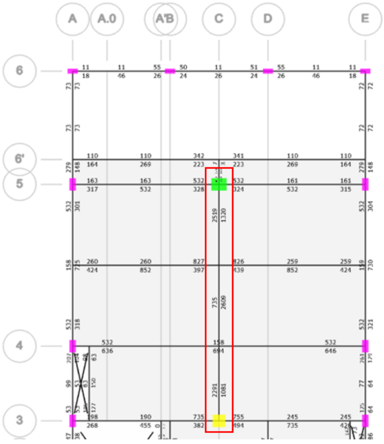

Figure 7. Shear and Moment Diagram of Beam B1 under 1.2DL + 1.0LL Combination

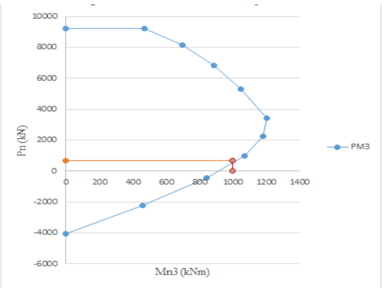

Figure 8. Interaction Diagram for Column K1 (Level 1 to Level 2, Major Axis)

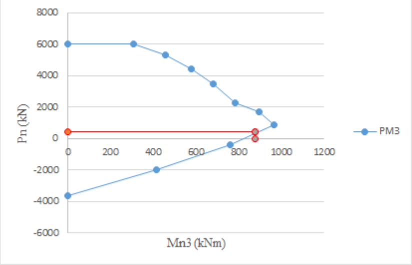

Figure 9. Interaction Diagram for Column K1 (Level 2 to Level 3, Major Axis)

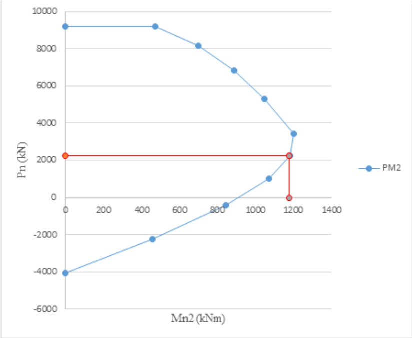

Figure 10. Interaction Diagram for Column K1 (Level 1 to Level 2, Minor Axis)

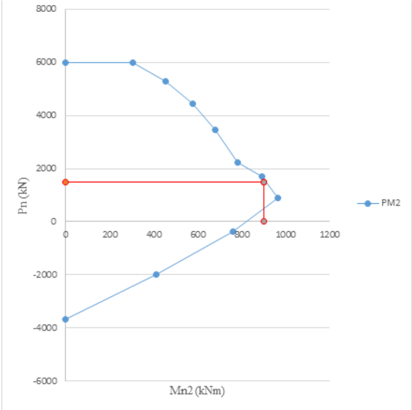

Figure 11. Interaction Diagram for Column K1 (Level 2 to Level 3, Minor Axis)

Figure 12. Pilecap Layout for PC4

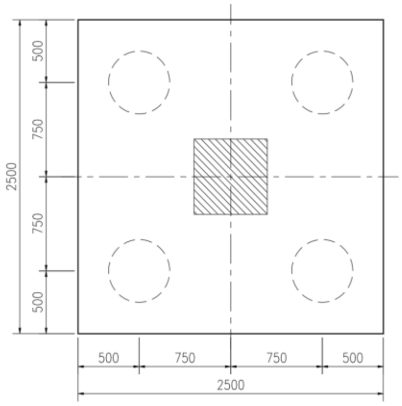

Figure 13. Geometric Dimensions of Pilecap PC4

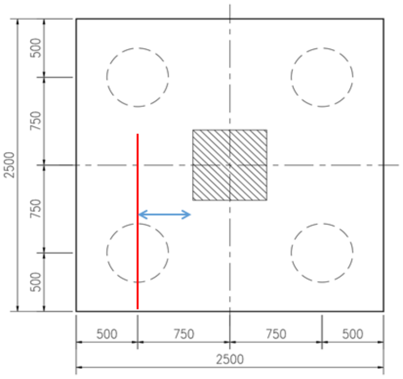

Figure 14. One-Way Shear Check Configuration

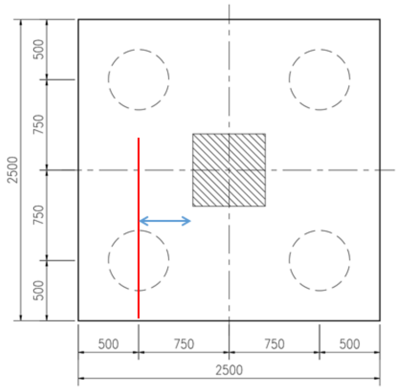

Figure 15. Two-Way Shear Check Configuration

Torsion in beam B1 is minimal (Tu = 1.03 kNm). The cross-section satisfies torsional strength requirements, and the calculated torsion is below the limit, allowing torsion reinforcement to be neglected.

Manual analysis of column K1 includes checks on dimensional limits and reinforcement ratio. The column dimension is 600 × 600 mm, satisfying the minimum side length and dimensional ratio. Required reinforcement As = 7454 mm^2 is provided using 20D22 bars (As = 7603 mm^2), meeting the required steel ratio (ρ = 2.112%). Strong column-weak beam (SCWB) checks for both directions confirm adequacy. In direction As3, the total beam moment capacity ΣMb = 1356.7 kNm is less than the column moment capacity ΣMc = 2075 kNm. Figures 8 and 9 display the interaction diagrams for K1 columns at different levels, validating SCWB compliance. In direction AsC, ΣMc = 1875 kNm exceeds ΣMb = 1304.58 kNm, confirming code compliance. Figures 10 and 11 present corresponding interaction diagrams.

For the substructure, pilecap PC4 is examined. Figure 12 shows the pilecap layout, consisting of four bored piles with 500 mm diameter and 45.75-ton axial capacity. Figure 13 illustrates the pilecap geometry. Shear checks for one-way and two-way sliding are performed, where the critical distance from the column face (450 mm) is within effective depth (1100 mm) and half-depth (550 mm), respectively, eliminating the need for detailed shear checks. Figures 14 and 15 depict the respective configurations. Reinforcement for pilecap bending is calculated manually, with Mu = 5463 kNm. Required steel area As = 4914 mm^2 is provided using D22-100 (As = 7603 mm^2), and top reinforcement uses D19-100 (As = 5670 mm^2 > As,min = 3960 mm^2), ensuring full compliance with code requirements.

4. Conclusion

This study has successfully analyzed and designed the structural system of a three-story reinforced concrete Guest House building with a rooftop garden located in Surabaya, East Java, following the provisions of SNI 1726:2019 and SNI 2847:2019. The seismic performance of the structure was assessed using the Equivalent Static Method (ESM), which is permitted for buildings under 40 meters in height with regular configurations. The structure was classified under Seismic Design Category D with an importance factor of 1.0, suitable for a medium-risk occupancy such as lodging facilities. The structural system adopted a Special Moment Resisting Frame (SMRF) characterized by high ductility and adequate energy dissipation capacity, utilizing response modification factor R = 8, overstrength factor $\Omega_0 = 3$, and deflection amplification factor Cd = 5.5.

The beam design, particularly for element B1, demonstrated full compliance with the strength, dimension, and reinforcement provisions of the code. Both flexural and shear capacities were satisfied under the most critical loading combinations, with appropriate detailing of longitudinal and transverse reinforcements. Torsional effects were found to be negligible, allowing simplification of design without compromising safety. The column design for element K1 also satisfied dimensional and reinforcement ratios, with strong column–weak beam (SCWB) provisions verified through interaction diagrams in both major and minor axes, ensuring global stability of the frame during seismic excitation.

Furthermore, substructure evaluation, specifically the pilecap system, confirmed that the arrangement of bored piles and reinforcement detailing provided sufficient resistance against flexural and shear demands. Sliding checks, both one-way and two-way, indicated safe configurations without the need for additional reinforcement measures. Overall, the structural system proved to be well-designed and resilient against both gravity and lateral earthquake loads, providing a safe and functional solution for mid-rise guest accommodations in seismic-prone urban environments.

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