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Structural Response of Irregular Buildings: Influence of Geometry and Shear Wall Configurations

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Abstract. This paper delves into the structural response of irregular buildings, specifically focusing on the influence of geometry and shear wall configurations. Irregular buildings, with their intricate geometries and diverse structural elements, present unique design challenges, necessitating a thorough performance evaluation. Our study conducts a comparative analysis to gauge the impact of various geometric layouts and shear wall arrangements on structural behavior under seismic loading. A nine-story irregular building in Yogyakarta, Indonesia, is a compelling case study. We develop three models (M1, M2, and M3), each incorporating variations in geometry and shear wall configurations (T-shaped, L-shaped, and I-shaped). These models are rigorously analyzed using ETABS software to evaluate key structural responses, including lateral displacement, inter-story drift, and base shear forces. The results reveal that M3 exhibits the lowest base shear, at 24,961.46 kN, 7.582% lower than the existing model (M1). The lowest lateral displacements and inter-story drifts are observed in the x-direction for M2 (26.308 mm displacement, 10.061 mm drift) and in the y-direction for M3 (26.115 mm displacement, 9.339 mm drift). Additionally, the lowest drift ratio occurs on the first floor of M3, measuring 0.110% in the x-direction and 0.115% in the y-direction. These findings underscore the substantial impact of geometric variations and shear wall configurations on the structural response, providing valuable insights into optimizing irregular building designs to enhance seismic performance.

Keywords: irregular buildings, shear wall configurations, structural response, seismic performance, lateral displacement.

INTRODUCTION

The 2006 Yogyakarta Earthquake, which resulted in 5,700 fatalities and extensive damage, including the collapse of STIE “Kerja Sama” due to a soft-story failure, underscored the vulnerability of irregular buildings. This event highlighted the urgent need for improved structural design to mitigate seismic risks. Given the increasing urbanization and land constraints in cities, high-rise buildings are becoming more prevalent, necessitating the development of effective earthquake-resistant strategies.

One of the primary challenges in designing earthquake-resistant high-rise buildings is controlling lateral displacement and structural instability due to seismic forces. Shear walls are widely recognized as an effective solution for improving seismic performance, as they enhance stiffness and reduce inter-story drift [9]. However, in irregular buildings, the placement and configuration of shear walls become more complex due to the non-uniform distribution of mass and stiffness. Irregularities in building geometry, stiffness, and mass distribution can lead to increased torsional effects and uneven lateral load resistance, making these structures more susceptible to earthquake damage [1-3]. Shear walls in shapes such as T, L, and I are crucial in mitigating these effects by optimizing internal force distribution and minimizing structural deformations [4].

Several studies have investigated the influence of shear wall placement and configuration on seismic performance. Kalangi [6] found that shear walls aligned with the earthquake load direction provide excellent resistance against lateral forces. At the same time, Haque [13] emphasized the importance of symmetry in shear wall placement to minimize torsional effects. Additionally, research has shown that positioning shear walls at or near the building corners and along the longer sides can effectively counteract torsional forces and improve overall stability [11, 14]. Despite these findings, a gap remains in understanding the comparative impact of different shear wall shapes and configurations on irregular buildings under seismic loading.

This study addresses this gap by analyzing the effects of shear wall geometry and placement on key structural responses in high-rise irregular buildings, including base shear, displacement, inter-story drift, and drift ratio. These configurations pose a unique challenge, as the building mass is concentrated along the strong axis while the opposite mass is positioned in the weak axis direction under seismic loading. The irregularity in geometry, stiffness, and lateral load distribution makes these structures more vulnerable to earthquake damage. Additionally, structural irregularity leads to horizontal torsional moments due to the eccentricity between the center of mass and the center of rigidity. Therefore, this research focuses on the geometry variation and configuration of shear walls in irregular buildings to mitigate these challenges and enhance structural safety. By evaluating T, L, and I-shaped shear wall configurations, this study provides valuable insights into optimizing shear wall design for improved seismic resilience, with direct implications for the design and construction of earthquake-resistant multi-story buildings, ultimately improving safety and performance in seismically active regions.

METHODOLOGY

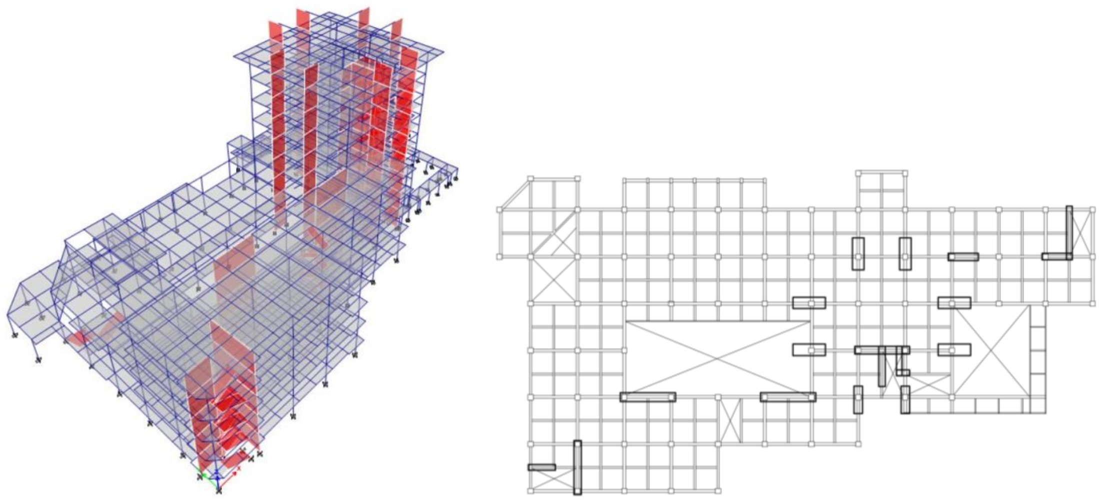
This study analyzes a 9-story reinforced concrete building in Yogyakarta, Indonesia, which serves as a learning center, chosen for its unique architecture and the need for innovative structural solutions. Each floor has a slightly different layout, creating horizontal irregularities. A 3D structural analysis was conducted using ETABS software. However, ETABS has limitations, as it cannot fully capture the complex, non-linear behavior of beam, column, and shear wall connections, which may result in simulation results that differ from actual earthquake responses [15, 18]. Figure 1 illustrates the typical 2nd-floor plan of the existing model, which compares structural responses based on shear wall placement and building geometry.

Figure 1 presents the typical building plan on the 2nd floor for the variation of the existing model (M1). The comparison variants involve buildings with existing shear walls, L-shaped shear walls, and straight-shaped or I-shaped shear walls (M2 and M3). This research adopts a unique approach by modifying the shear wall configuration and shape variation, categorized into three different models, to compare the structural responses. For this reason, it refrains from analyzing conventional structural elements such as beams, columns, and plates, offering a fresh perspective. The T-shaped existing shear wall is maintained in the configuration of both Models 2 and 3. Additionally, Model 2 is characterized by L-shaped shear walls, whereas Model 3 combines L- and I-shaped shear walls. This study comprises two research variables, as outlined in Table 1.

TABLE 1. Research Variables

Variable Type	**Description**
Independent	Shear wall shape (T, L, I), shear wall position.
Dependent	Base shear, displacement, inter-level deviation, and drift ratio

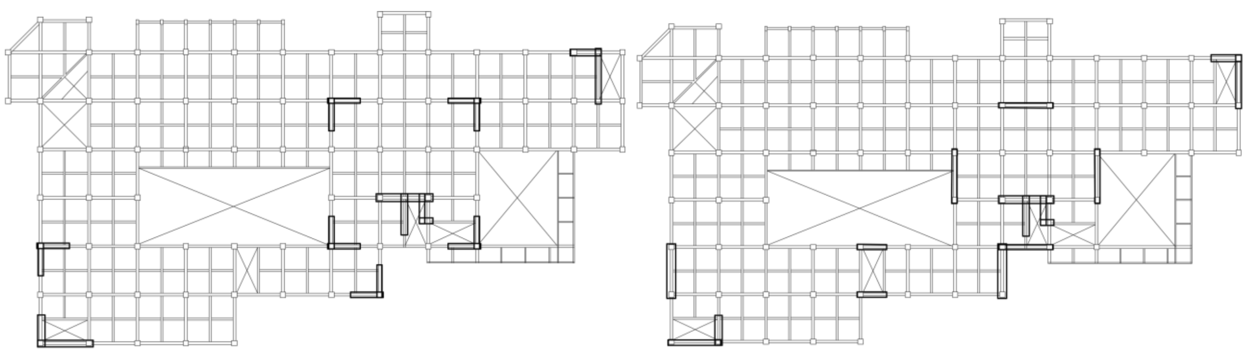
The initial design stage includes determining the structural model, building function, material quality, and estimated dimensions of the structural components, followed by calculating dead, live, and earthquake loads. Following this, the modeling and analysis of the structure in ETABS v18 with various shear wall placements were conducted, and the structural performance was compared to discuss the results.



(a) (b)

FIGURE 1. Building Plan-L Configuration with Existing Model (M1) (a) 3D and (b) 2D

Figure 1 illustrates that the irregular plan form can be characterized as L-shaped. The size and shape of the building's shear walls affect the amount of seismic force applied to it, so the building's seismic analysis must consider the shape of the shear walls [10]. The building's geometry variation and shear wall configuration are shown in the following figures.



(a) (b)

FIGURE 2. Building Plan Configuration with Shear Wall (a) M2 and (b) M3

Figure 2(a) illustrates the first variation, where shear walls are strategically placed at the building's corners, forming an L-shaped configuration. This arrangement is based on extensive literature studies and previous research, considering the building's center of mass. In irregular structures, placing shear walls near the center of mass is recommended to enhance stability and minimize structural deviations. L-shaped shear walls at each corner effectively reduce displacement and control torsional effects, thereby improving the overall seismic performance of the building [4].

Figure 2(b) presents the second variation, in which shear walls are positioned at both the corners and the center of the building, forming a straight-sided shear wall configuration. This placement aligns symmetrically along the x- and y-axes, ensuring a more uniform stiffness distribution. Studies have shown that structures with shear walls at all edges exhibit improved seismic performance, as demonstrated by reduced maximum displacement, lower story drift, and enhanced base shear resistance. This configuration contributes to a more stable structural response, reinforcing the conclusion that buildings with a well-distributed stiffness profile achieve better overall seismic resilience [18].

The research method employed in this study is dynamic analysis, precisely the Response Spectrum method, as outlined in SNI 1726-2019. This method was adjusted to the specific location of the building under study. The graph of the response spectrum results, which was instrumental in the loading in this study, is depicted in Figure 3.

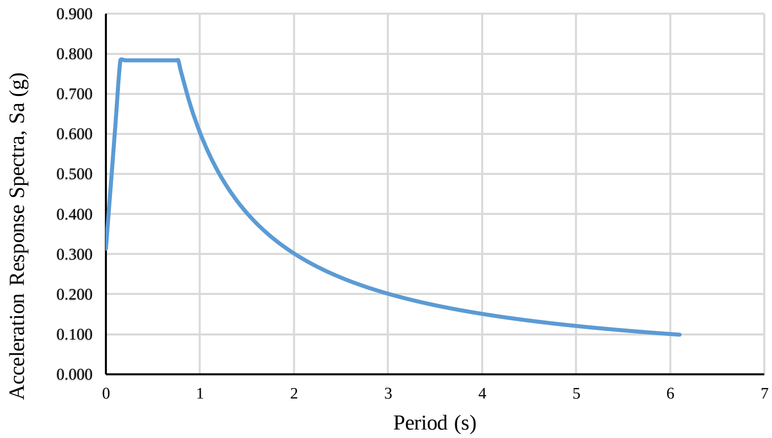


FIGURE 3. Yogyakarta Earthquake Spectrum Response Design

The structural data for this building is a combination of a structural frame system and shear walls in a 9-story building with a horizontal irregular configuration that functions as a learning center. The materials used for the study's beam, slab, column, and shear wall are 30 MPa concrete. The reinforcement with d ≤ 12 mm has a yield stress of 240 MPa, whereas the reinforcement with d > 12 mm has a yield stress of 420 MPa.

The dimensions of the structural components are based on the existing calculations. The largest beam dimension is 400 mm x 800 mm, the most significant square column is 800 mm x 800 mm, and the plate thickness is 130 mm. More details can be seen in Table 2 below.

TABLE 2. Specification of Building Structural Elements

Code	Column (mm)	Code	Beam (mm)	Code	Slab (mm)
C1	800 x 800	B1-1	400 x 700	PL	130
C2	800 x 800	B1–W	400 x 700	PA	130
C3	400 x 700	B1-3	400 x 700		
C4-1	1000 x 1000 x 250	B2-W	400 x 800		
C4-2	700 x 700 x 250	B2-2	400 x 700		
C5	1150 x 700 x 250	BA-W	400 x 500		
C6	300 x 300	BA-2	300 x 500		
		BP1	150 x 700		
		BP2	150 x 500		
		BL	250 x 700		
		CB1	400 x 700		
		CBA	300 x 500		
		BF	150 x 300		
		B3	250 x 400		

The shear wall thickness of each model varies, with the thickest being 800 mm. More details on the shear wall thickness in each model are listed in Table 3.

TABLE 3. Specification of Building Structural Elements

Code M1	Thickness (mm)	Code M2	Thickness (mm)	Code M3	Slab (mm)
W1	400	W1	400	W1	400
W2	400	W2	400	W2	400

W2-A	400	W2-A	400	W3	400
W3	400	W3	400	W4	400
W4	400	W4	400	W5	400
W5	800	W5	400	W6	400
W6	800	W6	400	W7	400
W7	400				
W8	400				

This modeling is based on the reference of national standards applicable in Indonesia, namely SNI 1726-2019 concerning Procedures for Earthquake Resistance Planning for Building Structures, SNI 1727-2020 regarding Minimum Load Standards Used for Building Design, and SNI 2847-2019 regarding Structural Concrete Requirements [17-20].

ANALYSIS RESULTS AND DISCUSSION

The analytical results of the structural modeling include the structural responses in terms of mass, base shear, displacement, story drift, and drift ratio. These results are used in the structural design plan and to analyze the structure's response, enabling the determination of the influence and effectiveness of differences in geometry and configuration of shear walls, which have the most significant impact on the building structure.

Mass

The mass of the building is the sum of the overall dead load of each structural element and the live load used in planning, as per the SNI 1727-2020 reference. The analysis reveals a difference in base shear force resulting from changes in structural mass [12]. The building structure has mass and stiffness that can vibrate naturally without external forces. Model 1, the existing model, has the most significant mass compared to the other models (Table 4).

TABLE 4. Mass

Variation	Mass (kN)
M1	16403619.00
M2	15390684.38
M3	15160101.99

The most enormous mass among the three building models is found in Model M1, where the location of the shear walls, as shown in Figure 1, is on the outside in the direction of the x-axis and y-axis and at the center of the square building. The model with the most negligible mass is M3, where the shear walls are located at the corner, outside, and inside of the building, as shown in Figure 2(b). This location can occur due to differences in shear wall configuration. In Model M3, the L-shaped shear wall is positioned at the corner of the building, while the straight wall is located on the outer and inner sides, aligned with the x-axis and y-axis, respectively. Based on considerations for the placement and selection of shear wall shapes, Model 1 has the most shear walls due to the building's enormous mass.

Base Shear

Based on SNI 1726-2019 Section 7.9.1.4.1 on force scaling, if the response combination for the dynamic base shear force is less than 100% of the base shear force calculated through the static equivalent method, then the combination must be scaled by V/Vt. The resulting base shear force in the static equivalent analysis (V) and the combined response analysis (Vt).

Table 5 shows that the dynamic base shear requirements do not fulfill the 100% static base shear requirements in the x- and y-directions. So, it is necessary to scale the force by increasing the dynamic shear force. In the M2 Model, the dynamic shear force is smaller than the existing Model M1, so the required magnification scale is smaller than the other models. Given this model, the structure with shear walls in Model M2 is stiffer than those in the different models.

TABLE 5. Base Shear Scale-Up Factor

Variation	V_{static} (kN)	$V_{dynamic}$ (kN)	Control	Scale Up

	x-dir	y-dir	x-dir	y-dir	x-dir	y-dir	x-dir	y-dir
M1	27008.487	27008.487	14287.765	14626.640	Not Ok	Not Ok	1.8904	1.8466
M2	25340.695	25340.695	15549.060	14555.743	Not Ok	Not Ok	1.6298	1.7410
M3	24961.042	24961.042	13396.681	12410.623	Not Ok	Not Ok	1.8633	2.0113

The base shear shown in the figure and table below has been multiplied by the force scaling factor to fulfill the requirements of SNI 03-1726-2019. Table 6 below compares the structural mass and the resulting base shear. The structure's mass is also one factor that can affect the building's base shear. The decrease in mass affects the magnitude of base shear received by the building, where the decline in base shear is proportional to the reduction in mass.

TABLE 6. Base Shear

Variation	Mass (kN)	Base Shear X (kN)	Base Shear Y (kN)
M1	16403619.00	27009.575	27009.512
M2	15390684.38	25341.838	25341.575
M3	15160101.99	24962.017	24961.459

The base shear values presented in the table above are based on the first mode shape, as it represents the initial shape of the building after it receives earthquake forces from the ground. Taking the base shear value from mode one also avoids any twisting or rotation of the building found in subsequent modes. The results of this comparison show that the base shear force decreases from M1 to M3. This decrease in base shear force is due to the reduction in structural mass ($V = Cs \cdot W$). The following comparison graph for each model is presented in Figure 4.

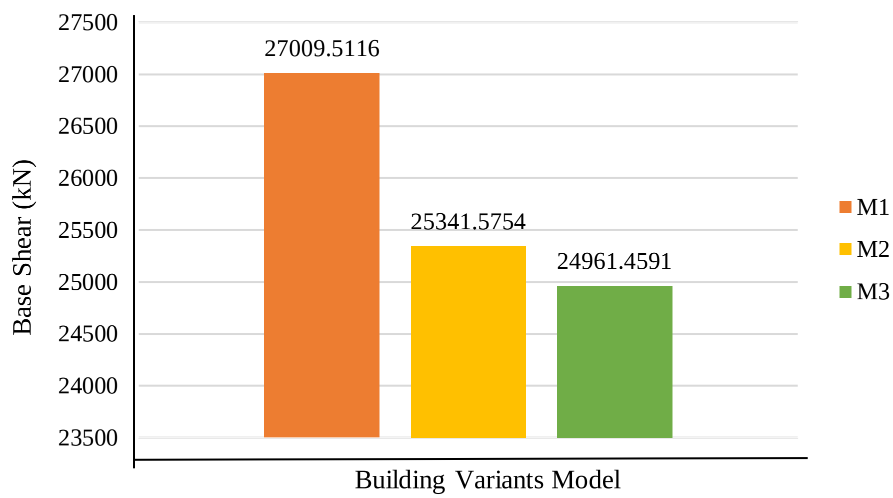
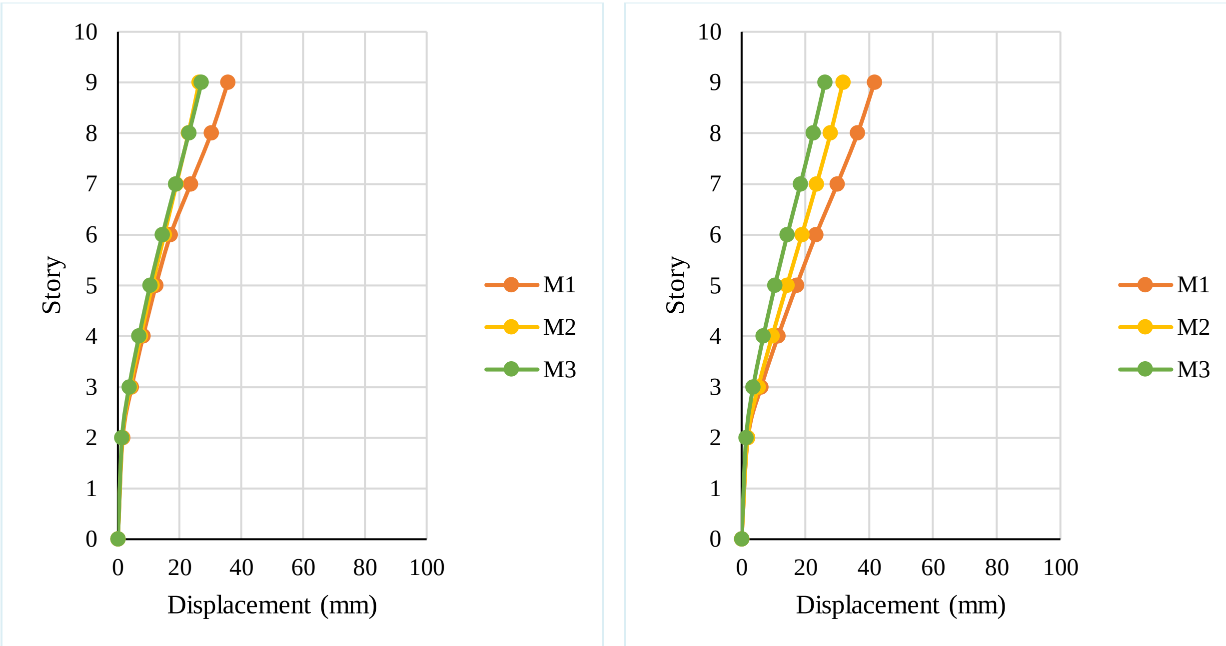


FIGURE 4. Base Shear

Displacement

Displacement represents the distance from the initial position resulting from the building's response to lateral forces. The displacement comparison is due to differences in building structure models in all shear wall structure models.



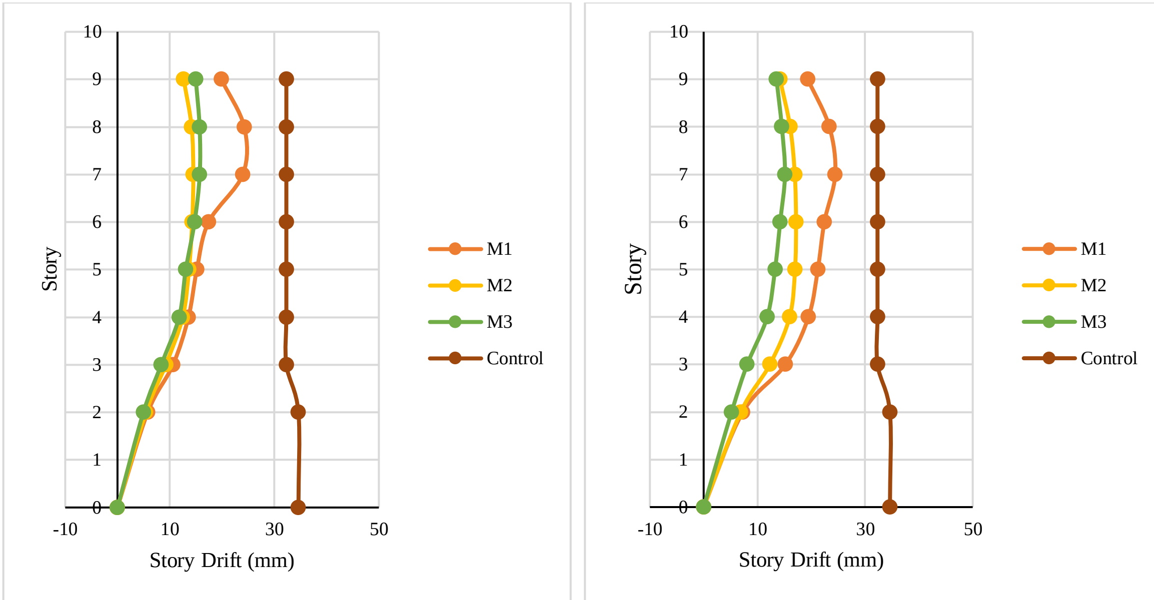
(a) X-direction (b) Y-direction

FIGURE 5. Displacement Comparison

Figure 5 presents the displacement comparison; the most significant displacement in the X direction is observed in the existing structural Model (Model 1), which is 35.638 mm. The Y direction is also included in the existing structural Model (Model 1), which has a displacement of 41.669 mm, thus placing the existing structural Model (Model 1) as the one with the highest displacement. The lowest displacement in the X direction is achieved by the structural model with the L-shape shear wall shape (Model 2), which is 26.308 mm. In the Y direction, the structural model achieves the lowest displacement with the Straight shear wall shape (Model 3), which is 26.115 mm. Model 2 for the X direction exhibits a 26.180% smaller displacement than the existing structural Model, and Model 3 for the Y direction shows a 37.328% smaller displacement than the existing structural Model. This result is similar to that of Patria and Haq [3], who showed that the greater the base shear value, the greater the displacement value. Overall, Model 3 is the most optimal structural model for reducing displacement in this building.

Story Drift

According to SNI 1726-2019, Article 7.8.6, the deviation between levels must be determined in the calculation to ensure compliance with the permitted deviation between levels. Drifts in buildings, exclusive of mass irregularity, are greater than those in structures inclusive of mass irregularity [1]. The building function in this study is as a learning center building, which, according to SNI 1726-2019, is in seismic design category D, then based on SNI 1726-2019 Article 7.3.4.2 for seismic design category D, which does not have torsional irregularities, the redundancy factor (ρ) must be 1.3. The permissible deviation between floors with risk category IV was 0.010. The comparison of the story drift that occurs due to the different building structure models is as follows.



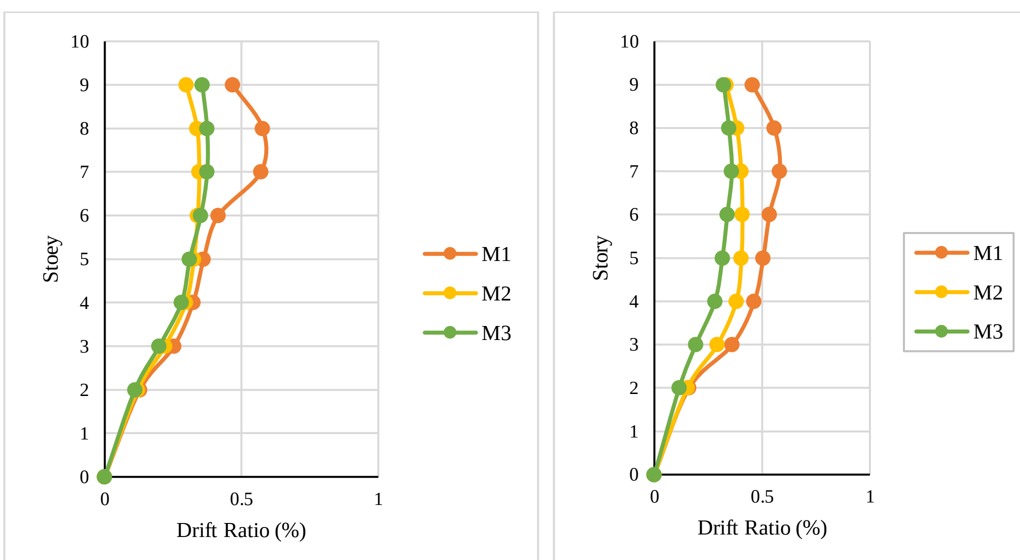
(a) X-direction (b) Y-direction

FIGURE 6. Story Drift Comparison

Based on the above inter-level deviation comparison (Figure 6), the inter-level deviation of all models meets the permitted limit. The most significant inter-level deviation is observed in the X direction for the existing structural model (Model 1) and is also present in the Y direction for the same model. Therefore, the existing structural model (Model 1) is identified as the one with the highest inter-level deviation. The most extreme decrease in deviation at the 8th floor in the X direction between Model 2 and Model 1 is 10.061 mm, representing a 41.50% decrease. Based on the overall deviation graph between levels, Model 3 is the most optimal structural model compared to the other two models.

Drift Ratio

The drift ratio is computed based on the inter-level deviation and height. Figure 7 compares the drift ratio due to different building structural models.



(a) X-direction (b) Y-direction

FIGURE 7. Drift Ratio Comparison

The drift ratio indicates whether the building being analyzed is rigid or flexible. The smaller the drift ratio, the more rigid the building. Based on the results of the above calculations, the most significant drift ratio is observed in the X direction on the 8th floor of the existing structural Model (Model 1) and in the Y direction on the 7th floor of the existing structural Model (Model 1). Thus, the existing structural Model (Model 1) has the highest drift ratio. The lowest drift ratio for both the X and Y directions is on the 1st floor of Model 3. Based on the overall drift ratio graph above, Model 3 is the most optimal structural model compared to the other two models.

CONCLUSION

The analysis of shear wall variations according to SNI 1726-2019 guidelines reveals that the Straight-Shape shear wall (Model 3) is the most effective configuration. Model 3 demonstrates the lowest base shear, minimal displacements, and the most negligible story drift, resulting in the smallest drift ratio and superior to other models. The symmetrical layout of the shear wall along the XY-axis, positioned close to the center of mass, proves to be the optimal configuration for buildings subjected to static and dynamic earthquake loads. It is recommended that the effects of shear wall placement on torsional behavior and internal force distribution require further investigation to optimize earthquake-resistant design.

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