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Performance Analysis of Regular and Irregular Horizontal Multi-Story Buildings Structure

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ABSTRACT

This study investigates the effect of building shape on seismic performance in earthquake-prone areas such as Padang City. Using the Indonesian seismic standard SNI 1726:2019, three multi-story reinforced concrete buildings were modeled: a square (regular), a rectangular (regular), and an irregular plan. The analysis focused on internal forces, base shear, displacement, and drift ratio to evaluate differences in structural response. Results show that buildings with horizontal irregularities experience higher internal forces and displacements. The bending moments in irregular buildings are 4.84% higher than in rectangular buildings and 10.07% higher than in square buildings. Base shear is 1.53% and 3.04% higher, respectively. The maximum displacement differences reach 0.93 m (X direction) and 0.54 mm (Y direction). The average drift ratio in the X direction is about 0.56% for all models, while square-shaped buildings show smaller Y-direction drift. These findings highlight that plan irregularities significantly influence seismic performance, providing insights for safer structural design in seismic regions.

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1. INTRODUCTION

The rapid growth of the construction industry and urbanization has led to an increasing demand for multi-story buildings, serving as an effective solution to provide adequate space for the growing population. However, the construction of multi-story buildings involves not only aesthetic and functional considerations but also structural safety, particularly in earthquake-prone regions. One of the most seismically active areas in Indonesia is Padang City, located along the tectonic subduction zone on the western coast of Sumatra Island. Earthquakes in this region have the potential to cause severe structural damage to multi-story buildings, posing significant risks to occupants and surrounding environments. Therefore, understanding the structural behavior of multi-story buildings under seismic loads, particularly concerning their plan configuration, is essential for ensuring safety and resilience. The Indonesian National Standard SNI 1726:2019 provides guidelines for the seismic design of building structures, encompassing fundamental aspects of analysis, design procedures, and performance evaluation. Studies based on this standard contribute to a better understanding of seismic performance and provide a reliable reference for evaluating the safety of buildings located in high-risk zones such as Padang City.

Previous research has examined the effects of horizontal and vertical irregularities on the seismic response of multi-story reinforced concrete structures. Prayuda, Hakas et al. (2023) reported that both horizontal and vertical irregularities significantly influence the seismic behavior of reinforced concrete buildings, resulting in distinct responses even when using identical material properties. Similarly, Tata and Arbain (2021) demonstrated that dual structural systems along the strong axis (X) are more effective in controlling displacement compared to frame systems along the weak axis (Y), although some models still exhibited drift values exceeding design limits. Widorini, Trias et al. (2021) highlighted the critical role of shear wall placement in improving lateral stiffness and reducing horizontal displacement under seismic loads. Models with core shear walls were found to be the most effective in resisting lateral forces. In a related study, Desimaliana, Erma et al. (2022) concluded that U-shaped buildings demonstrate superior seismic performance, characterized by lower base shear and displacement values, and categorized under the Immediate Occupancy (IO) performance level according to FEMA-356. Hasibuan (2022) found that rigid diaphragms are more efficient in reducing displacement by up to 8% compared to semi-rigid diaphragms, while Efrida (2018) observed that infill walls significantly influence lateral stiffness—where reducing setbacks enhances ductility but decreases stiffness. Moreover, the Direct Displacement-Based Design (DDBD) approach investigated by Kartiko et al. (2021) and Siregar et al. (2021) resulted in higher base shear and drift values but remained within acceptable performance levels defined as Life Safety (LS) and Damage Control (DC).

Further studies, such as that by Parinang, Simatupang, and Nasjono (2023), revealed that site classification influences shear forces in progressive collapse scenarios. Likewise, Kholid (2023) and Pradono (2019) emphasized that buildings with geometric irregularities tend to exhibit higher story displacement and inter-story drift compared to regular configurations. From this review, it can be concluded that while many studies have explored the factors affecting seismic performance—such as irregularity, shear wall placement, and diaphragm stiffness—there remains a research gap in the comparative analysis of square, rectangular, and irregular building plans modeled under the specific seismic conditions of Padang City. Accordingly, this study aims to conduct a comparative evaluation of three plan configurations—square, rectangular, and irregular—to assess their influence on internal forces, base shear, displacement, and drift ratio based on SNI 1726:2019. The outcomes of this study are expected to enhance understanding of structural behavior and provide practical insights for safer and more efficient building design in earthquake-prone regions, particularly in Padang City.

2. RESEARCH METHODOLOGY

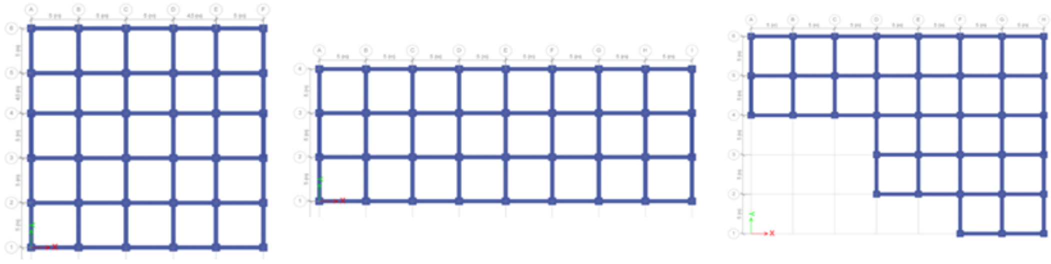
The research method employs a numerical approach based on dynamic analysis using the response spectrum method. The primary data include the building function (hospital), the use of a reinforced concrete structural system, the location in Padang City, and the soft soil classification according to actual site conditions. The secondary data pertain to structural design and seismic analysis, consisting of several Indonesian National Standards (SNI) as follows,

SNI 2847:2019, which specifies the requirements for the design of reinforced concrete structures, SNI 1727:2020, which defines the minimum design loads and related criteria for buildings and other structures, SNI 1726:2019, which provides the procedures for earthquake-resistant design of building and non-building structures and PPIUG 1987, which regulates the general loading requirements for building structures in Indonesia.

All of these standards were applied comprehensively throughout the modeling and analysis process, including the determination of seismic parameters (such as response spectrum and base shear), load combinations, and structural performance evaluation under seismic conditions. The integration of these codes is expected to ensure that the simulation results comply with national design criteria and accurately reflect the realistic structural behavior under earthquake excitation.

Once the required data for the analysis of multi-story buildings with regular and irregular horizontal structures is obtained, data processing is carried out, including a literature review, which involves studying the planning of multi-story buildings with regular and irregular horizontal layouts. Three models are compared to determine and obtain a building structure that performs better under seismic loads.

The compared models are square-shaped buildings, rectangular buildings, and irregular buildings. After completing the literature review, the next step is to gather structural data, where the structures of the three models of multi-story buildings with regular and irregular horizontal layouts are compared. Each of the three buildings has a floor area of 600 square meters and a height of 28 meters (7 stories). the data presented in **Figure 1**.



(a) (b) (c)

Figure 1. Floor Plans Of Regular and Irregular Multi-Story Buildings, (a) Square Buildings, (b) Rectangular Buildings, and (c) Irregular Buildings

Preliminary design is conducted for the structural elements. Next, static loads (live loads and dead loads), which are constant loads acting continuously on the structure, are input. Seismic loading is also considered to determine the risk category, building importance factor, seismic design category, seismic load analysis method, and lateral forces. Finally, structural performance analysis is conducted on multi-story buildings with regular and irregular horizontal layouts, aided by the ETABS software.

3. RESULTS AND DISCUSSION

The analysis of internal forces in beams is generally performed on each floor of the building. On each floor of the building, the largest internal forces acting on the beams are extracted, followed by a comparison and calculation of the difference ratio between the largest internal forces in the beams working on each of the modeled building structures.

The analysis of internal forces in columns on each floor of the building involves extracting the largest internal forces acting on the columns, followed by a comparison and calculation of the difference ratio between the largest internal forces in the columns working on each of the modeled building structures.

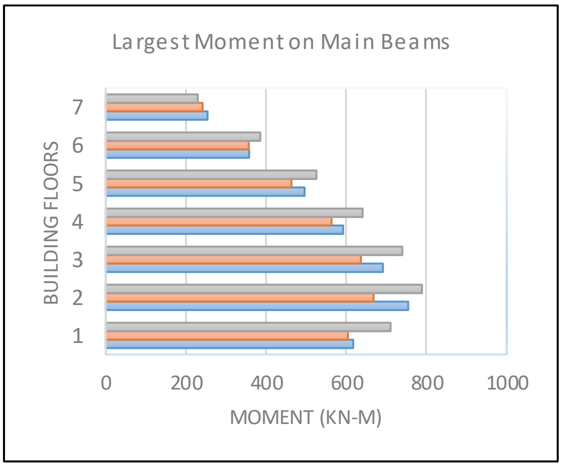


Figure 2. Comparison Chart of the Largest Moments in Beams

Based on the data presented in **Figure 2,** the building with an irregular horizontal layout carries a larger moment than the other two regular buildings with a difference ratio of 9.87% compared to the regular square-shaped building, which carries a smaller moment along the axis compared to the regular rectangular-shaped building with a difference of 8.09%.

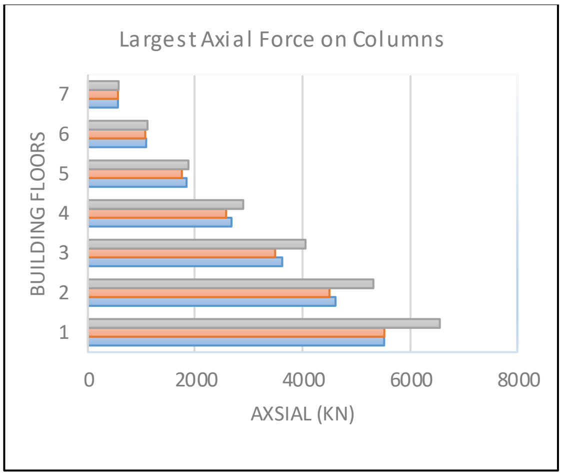


Figure 3. Comparison Chart of the Largest Axial Forces in Columns

Based on the data presented in **Figure 3**, it can be observed that the largest axial force occurs in the irregular horizontal building with a difference of 7.68% compared to the regular rectangular-shaped building and 9.81% compared to the regular square-shaped building. This is because the irregular building has a greater weight than the regular buildings with rectangular and square shapes being modeled.

However, based on the data presented in **Figure 4**, the regular square-shaped building carries a moment that is almost the same as the irregular horizontal-shaped building, with a difference ratio of only 0.21%. Meanwhile, the regular rectangular-shaped building carries a smaller moment than the irregular horizontal-shaped building, with a difference ratio of 4.59% and 5.11% compared to the regular square-shaped building. The comparison of base shear or seismic base shear forces yielded data showing that buildings with irregular horizontal layouts have the largest seismic base shear force, with a difference of 1.53% compared to the regular rectangular-shaped building and 3.04% compared to the regular square-shaped building.

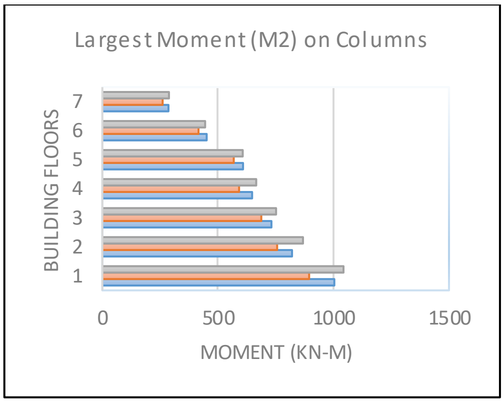


Figure 4. Comparison Chart of the Largest Moment (M2) in Columns

Figure 5 shows that columns in the irregular-plan building experience the largest M3 moments compared to the two regular models. The moment values are about 4–6% higher than those of the rectangular and square buildings. This increase results from uneven mass and stiffness distribution, which causes force concentration and torsional effects on certain columns. The trend is consistent with Figure 4 and with the internal force, axial load, and base-shear results, all indicating the highest structural response in the irregular model. These findings confirm that plan irregularity amplifies moment demand on vertical elements, requiring greater attention in seismic-resistant structural design.

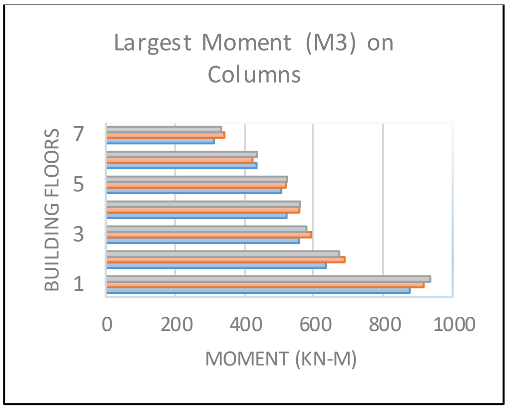


Figure 5. Comparison Chart of the Largest Moment (M3) in Columns

The comparison of seismic base shear or base shear forces presented in **Table 1,** reveals that buildings with irregular horizontal shapes have the largest seismic base shear, with a difference of 1.53% compared to rectangular-shaped regular buildings and 3.04% compared to square-shaped regular buildings. Meanwhile, square-shaped regular buildings have the smallest seismic base shear, with a difference of 1.53% compared to rectangular-shaped regular buildings.

In the comparison of displacements, the largest displacements occur in buildings with irregular horizontal shapes, with a difference of 0.925 mm in the x-direction and 0.539 mm in the y-direction compared to regular rectangular-shaped buildings. Meanwhile, the smallest displacements occur in square-shaped regular buildings, with a difference of 1.58 mm in the x-direction and 2.40 mm in the y-direction compared to irregular-shaped buildings.

Table 1. Base shear comparison

Arah	Base Shear (kN)			Difference	Difference	Difference
	PP	P	KTB	KTB & PP	KTB & P	PP & P
Vx	8673.020	8540.036	8807.845	1.531	3.041	1.533
Vy	8673.020	8540.036	8807.845	1.531	3.041	1.533

Table 2. Comparison of X-Direction Displacements

Floors	Displacement (X) (mm)			Difference KTB & PP	Difference KTB & P	Difference PP & P
	PP	P	KTB			
7	41.75	42.767	43.414	1.664	0.647	1.017
6	38.553	39.247	39.971	1.418	1.811	0.694
5	33.836	34.45	35.091	1.255	1.827	0.614
4	27.362	27.808	28.305	0.943	1.756	0.446
3	20.235	20.543	20.931	0.696	1.854	0.308
2	12.335	12.495	12.699	0.364	1.606	0.160
1	4.735	4.793	4.869	0.134	1.561	0.058
Average				0.925	1.580	0.471

Table 3. Comparison of Y-Direction Displacements

Floors	Displacement (X) (mm)			Difference KTB & PP	Difference KTB & P	Difference PP & P
	PP	P	KTB			
7	41.782	36.56	41.612	0.170	5.052	5.222
6	37.911	33.329	36.883	1.028	3.554	4.582
5	33.187	29.25	32.37	0.817	3.120	3.937
4	26.819	23.661	26.033	0.786	2.372	3.158
3	19.747	17.564	19.163	0.584	1.599	2.183
2	11.875	10.672	11.545	0.330	0.873	1.203
1	4.39	4.081	4.335	0.055	0.254	0.309
Average				0.539	2.403	2.942

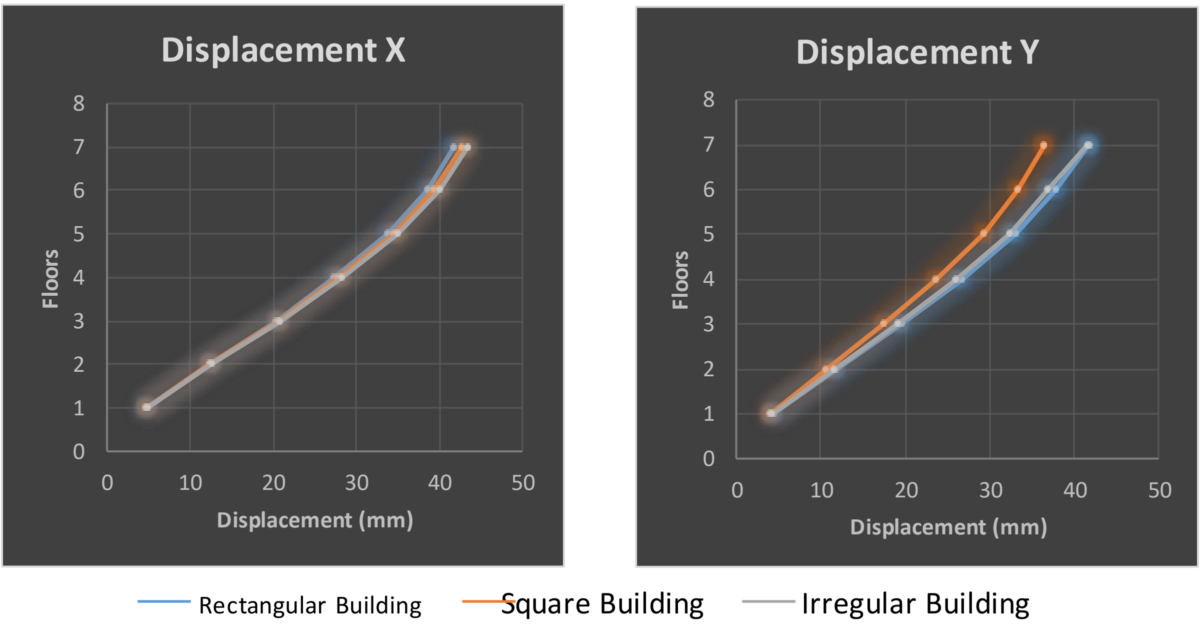


Figure 6. Comparison Chart of Displacement in the X and Y Directions

For rectangular-shaped regular buildings compared to square-shaped regular buildings, the differences in displacements are 0.47 mm in the x-direction and 2.94 mm in the y-direction, as presented in **Table 2 and Table 3.** The comparison of drift ratio involves comparing the ratio of displacements between floors in regular and irregular horizontal buildings. The ratio in question is the difference in floor displacement under inelastic drift conditions divided by the height spacing per floor. Based on the analysis conducted presented in **Figure 6**, the ratio of floor displacements in the x-direction in the three modeled buildings is nearly the same, but the irregular horizontal-shaped building has the largest ratio of floor displacements among the three modeled buildings. In the ratio of floor displacements in the y-direction, the smallest inter-floor displacement occurs in the regular square-shaped building, while the inter-floor displacement in the irregular horizontal-shaped building and the regular rectangular-shaped building is almost the same. However, on the seventh floor, the ratio of inter-floor displacement in the irregular horizontal-shaped building is significantly larger than that in the rectangular-shaped building.

Table 4 presents the inter-story drift ratios in the X and Y directions for the three building models. The results indicate that the irregular-plan building has the highest drift ratios, followed by the rectangular building, while the square-shaped building shows the smallest values. The average drift ratio in the X direction is around 0.56% for all models, but in the Y direction, the square-shaped building exhibits smaller values compared to the others. This finding shows that horizontal irregularity increases relative floor displacements, especially at the upper stories. However, all drift ratio values remain below the maximum limits specified in SNI 1726:2019, indicating that the structural performance of all models still meets seismic safety requirements.

Table 4. Comparison of X-Direction Drift Ratios

Floors	Floor height	Drift Ratio (X) (%)			Drift Ratio (Y) (%)		
		PP	P	KTB	PP	P	KTB
7	4000	0.293	0.323	0.316	0.355	0.296	0.433
6	4000	0.432	0.440	0.447	0.433	0.374	0.414
5	4000	0.593	0.609	0.622	0.584	0.512	0.581
4	4000	0.653	0.666	0.676	0.648	0.559	0.630
3	4000	0.724	0.738	0.755	0.722	0.632	0.698
2	4000	0.697	0.706	0.718	0.686	0.604	0.661
1	4000	0.434	0.439	0.446	0.402	0.374	0.397

*PP : Rectangular Building ; P : Square Building; KTB : Irregular Building

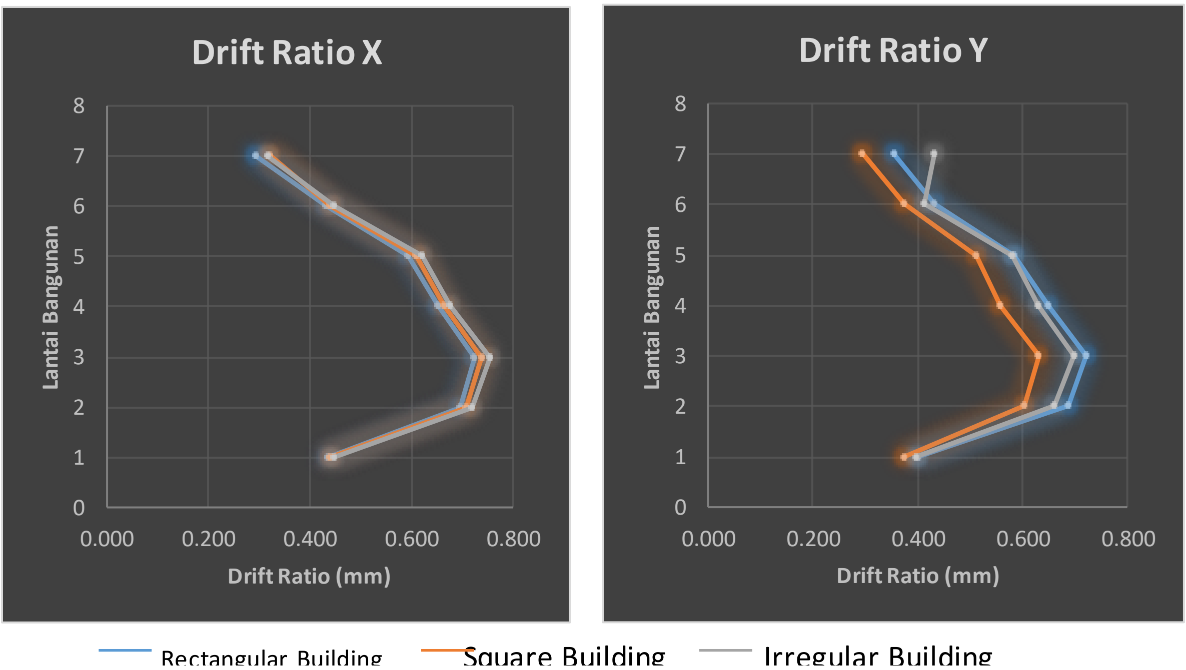


Figure 7. Comparison Chart of Drift Ratio in the X and Y Directions

Table 5. Comparison of Structural Performance Levels Based on ATC 40

Performance Level	X Direction	Y Direction
Rectangular Building	Immediate Occupancy	Immediate Occupancy
Square Building	Immediate Occupancy	Immediate Occupancy
Irregular Building	Immediate Occupancy	Immediate Occupancy

Figure 7 illustrates the comparison of inter-story drift ratios in both X and Y directions for all three building models. The results show that the irregular-plan building has the highest drift ratios in both directions, while the square-shaped regular building records the smallest values. The rectangular building exhibits intermediate performance. Although the differences in the X-direction are relatively small, the irregular model shows noticeably greater drift at the top story, indicating reduced lateral stiffness due to geometric irregularity. These results are consistent with the displacement data in **Figure 6**, confirming that horizontal irregularity leads to larger inter-story movements. Nevertheless, all models remain within the Immediate Occupancy performance level according to ATC 40, meaning that the overall structural performance still meets the seismic design requirements.

From the data presented in **Table 5**, both the regular and irregular buildings modeled fall into the "immediate occupancy" category. This is because the maximum total drift values obtained for each building are smaller than 0.01, and the maximum total inelastic drift is less than 0.005, by the structural performance level requirements based on ATC 40.In this category, the building's structural condition can fully withstand both vertical and horizontal base shear forces. Structural damage is very minimal, the risk to human life during damage is very low, and the building can be immediately reoccupied.

4. CONCLUSION

The largest internal forces generally occur in buildings with irregular horizontal layouts, meaning that the forces acting on buildings with irregular shapes are greater than those in regular-shaped buildings. The base shear in irregular horizontal-shaped buildings is 1.53% greater than in rectangular-shaped buildings and 3.04% greater than in square-shaped buildings. In the comparison of displacements, the largest displacement occurs in buildings with irregular horizontal layouts, with a difference of 0.93 mm in the x-direction and 0.54 mm in the y-direction compared to the regular rectangular-shaped building. The ratio of inter-floor displacements for each building does not show significant differences. The drift ratio in the x-direction is almost the same for each building, averaging 0.56%. However, in the y-direction, square-shaped buildings have smaller drift ratios compared to rectangular buildings and irregular buildings, averaging 0.48%. Further research is needed for the comparative analysis of structural performance in buildings with regular and irregular horizontal shapes, with variations in other building shapes. The analysis is carried out by SNI 1726-2019, with more complex structural usage and modeling.

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