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ANALYSIS OF REGULAR AND IRREGULAR BUILDINGS AGAINST EARTHQUAKE FORCES BASED ON SNI 1726:2019

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Abstract

This study analyzes the seismic performance of regular and irregular reinforced-concrete building structures according to the SNI 1726:2019 standard. Four twelve-story models were developed using a special moment-resisting frame system: three irregular structures with a re-entrant-corner configuration and one regular structure, using seismic parameters from the earthquake-prone Tarutung region, North Sumatra. Response-spectrum analysis was performed in ETABS, focusing on base shear, story shear, displacement, torsion, and column reinforcement. Results show that the regular model exhibits a coincident center of mass and center of rigidity, whereas the three irregular models show an eccentricity of 0.01-0.32 m, generating additional torsional moment of up to 3.52 kNm at the base column, compared with almost zero in the regular model. The irregular models with the sharpest re-entrant corner (Model 1) required the largest longitudinal column reinforcement (16D22) with the tightest transverse spacing, while the regular model (Model 4) required comparatively less reinforcement (12D22). All models satisfied the strong-column weak-beam requirement of SNI 2847:2019. These findings confirm that horizontal irregularity increases torsional demand and local reinforcement needs, underscoring the importance of strict compliance with seismic design codes when irregular building configurations are unavoidable.

Keywords: base shear; displacement; irregular building; SNI 1726:2019; Twist

INTRODUCTION

The Tarutung area, located in the Renun segment of the Great Sumatra Fault, is one of the areas with high tectonic activity in North Sumatra and has experienced a magnitude 6.0 Mw earthquake that caused damage to buildings and road infrastructure from mild to severe. This condition confirms that earthquakes are natural disasters that cannot be predicted with exact time and magnitude, so building structures in earthquake-prone areas must be designed to be able to withstand seismic forces that may arise (Ahmed et al., 2016).

The development of construction technology has also encouraged changes in the architectural form of multi-storey buildings. Buildings are no longer always designed with a regular square or rectangular plan, but rather follow the demands of aesthetics and land limitations resulting in irregular configurations. Based on SNI 1726:2019 concerning Earthquake Resilience Planning Procedures for Building and Non-Building Structures, building structures are classified as regular or irregular based on the criteria of horizontal and vertical irregularity of the plan.

Irregularity in the configuration of the structure is one of the main factors that reduce the seismic performance of buildings. Uneven mass and rigidity distribution causes the center of mass not to overlap with the center of rigidity; The distance between the two, called eccentricity, creates an additional torsional moment when the lateral force acts on the building. Unanticipated torque has been shown to be the main cause of severe damage to buildings affected by strong earthquake shocks (Ghimire & Chaulagain, 2021). One common form of horizontal irregularity is the re-entrant corner, which triggers a voltage concentration due to a sudden change in stiffness at the angle of the plan.

Various previous studies have confirmed the influence of structural irregularities on the seismic behavior of buildings. Hidayati et al. (2023) evaluated horizontal irregularities in the BASICS BRIN building in Bandung City and found that the structure experienced internal angular irregularities so that the diaphragm design style needed to be increased by 25% at the planning stage. Verma and Gagandeep (2023) compared three models of the same height irregular building using Staad Pro software and showed that differences in the shape of the plan had a significant effect on the deviation of the level of the ground, torque, and maximum shear. Sadat and Arslan (2023) developed a genetic algorithm to optimize seismic torque deviations in three-dimensional reinforced concrete buildings with plan irregularities. Bhatta et al. (2021) through a post-earthquake survey confirmed the high seismic vulnerability of buildings with vertical irregularities, while Hosseinlou and Labibzadeh (2024) examined the effect of aftershocks on regular and irregular structures of 3 and 8 storeys. Ankon (2020) compared the earthquake performance of low- and high-rise buildings in various earthquake zones and concluded that the maximum base displacement, deviation, and shear were greatly influenced by the intensity of the earthquake zone and the height of the building. In general, these studies agree that buildings with simple geometry and an even distribution of mass and rigidity in the plan and height are much more resistant to earthquake forces than structures with irregular configurations (Kostinakis & Athanatopoulou, 2020).

Although many studies on structural irregularities have been conducted, studies that specifically compare the seismic behavior of regular and irregular angular buildings using earthquake parameters specific to the Tarutung area based on SNI 1726:2019 are still limited. Therefore, this study aims to analyze and compare the seismic performance of four models of twelve-story building structures — three models with an irregular plan of deep angles and one model with a regular plan — which were analyzed using a spectrum response method based on earthquake data in the Tarutung area, North Sumatra. The parameters compared include basic shear force, level shear force, displacement, torque, and column reinforcement requirements. This research is limited to reinforced concrete structures with a Special Moment Bearing Frame System (SRPMK), analyzed linearly using ETABS software referring to SNI 1726:2019 and SNI

2847:2019, without reviewing the cost or foundation structure aspects. The results of this study are expected to provide a practical understanding for engineers regarding the structural consequences of choosing irregular plan configurations in earthquake-prone areas and the importance of compliance with the provisions of the applicable seismic design code.

RESEARCH METHODS

This study is a quantitative comparative analysis of four models of twelve-storey reinforced concrete building structures (total height 33 m, height between floors 3 m) which were analyzed using ETABS software with a linear response spectrum analysis method. The four models use a Special Moment Bearing Frame System (SRPMK) structure system with column dimensions of 60 x 60 cm, beam dimensions of 45 x 45 cm, concrete quality f'c 25 MPa, and reinforcement quality fy 500 MPa. The Model 1, Model 2, and Model 3 have plans with re-entrant corners in different cut-angle size variations, while the Model 4 has a 22 m x 20 m regular rectangular plan with no cut-off corners.

Earthquake data was taken from the Tarutung District, North Tapanuli Regency, North Sumatra Province (coordinates 2.0255 - 98.9602) with the classification of soft soil (SE) sites. The earthquake acceleration parameters used include short-period spectral acceleration Ss = 2.0761 g, spectral acceleration of 1 second period S1 = 0.9858 g, site coefficients Fa = 0.8 and Fv = 2.0, short-period design acceleration SDS = 1.11 g, 1-second period design acceleration SD1 = 1.23 g, and seismic design category (KDS) D. Buildings are categorized as category II risk (apartment/residential function) with an earthquake priority factor Ie = 1.00, the response modification coefficient R = 8, the stronger factor over the system Ω0 = 3, and the deflection magnification factor Cd = 5.5, according to the provisions of SNI 1726:2019.

The combination of loading refers to SNI 1726:2019 Articles 4.2.2 and 7.4.2, with the effect of the earthquake load (E) determined from the combination of the horizontal component (Eh = ρQe) and the vertical component (Ev = 0.2 SDS D), so that the combination factored by the earthquake load can be expressed as (1.2 + 0.2SDS)D + 1.0L ± ρ(0.3Ex ± Ey) and (0.9 - 0.2SDS)D ± ρ(0.3Ex ± Ey), along with their complementary orthogonal combinations. Prior to the analysis, each model was checked against the horizontal irregularity criteria of SNI 1726:2019, specifically the required deep angle irregularity to occur if the two dimensions of the plan projection from the inner angle location (Px/Lx or Py/Ly) exceed 15% of the dimensions of the plan in the direction under review.

The design of the column repetition refers to the provisions of SRPMK in SNI 2847:2019, including the limitation of column dimensions (Article 18.7.2.1), longitudinal reinforcement ratio of 1%-6% of gross cross-sectional area (Article 18.7.4.1), transverse reinforcement spacing in the plastic joint zone (Article 18.7.5.3), as well as the requirement of a strong column-weak beam (SCWB) which requires the amount of nominal bending strength of the column that meets at a joint to be at least 1.2 times the amount of nominal bending strength of the framing beam to the joint, $\sum Mnc \geq 1.2 \sum Mnb$ (National Standardization Agency, 2019). The shear force of the column design (Ve) is determined from the maximum bending strength (Mpr) at both ends of the column, with a value that must not exceed the shear force generated by the maximum bending force of the beam framing to the joint. The critical columns in each model, i.e. the columns with the largest deep force on the ground floor, were analyzed for cross-sectional capacity using an interaction diagram (SP Column) to obtain the actual longitudinal and transverse reinforcement requirements.

RESULTS AND DISCUSSION

Research Findings

The results of the analysis included the examination of horizontal irregularities, the position of the center of mass and center of stiffness, the basic shear force, the level of shear force, displacement, torque, and column reinforcement requirements in the four structural models.

Examination of the angular irregularity criteria in SNI 1726:2019 (angular projection ratio in Px/Lx or Py/Ly > 15%) shows that Model 1, Model 2, and Model 3 are all classified as deep angle irregular, with a projection ratio between 16.7% to 58.3% in both directions, while Model 4 does not show irregularity (0% ratio) so it is categorized as a regular structure, as summarized in Table 1.

Table 1. Examination of Angular Irregularities in SNI 1726:2019

Models	Lx (m)	Px (m)	Px/Lx	Ly (m)	Py (m)	Py/Ly	Status
Model 1	24	4	16,7%	24	6	25,0%	Irregular
Model 2	24	14	58,3%	24	10	41,7%	Irregular
Model 3	24	14	58,3%	28	14	50,0%	Irregular
Model 4	22	0	0%	20	0	0%	Regular

Source: research data processing, 2024

The results of the analysis of the center of mass and center of rigidity confirm a pattern consistent with the regularity status of each model. Model 4 shows no difference between the center of mass and the center of rigidity on the entire floor (0.000 m), which means that the lateral force acts exactly on the center of rigidity without creating eccentricity. In contrast, the three irregular models showed varying eccentricities between floors: Model 1 was 0.009-0.257 m, Model 2 was 0.001-0.093 m, and Model 3 was 0.018-0.340 m. The greatest eccentricity occurs in the Model 3 which has the most significant proportion of cut angles in both directions of the plan.

The basic shear forces of the four models are presented in Table 2 and Figure 1. The minimum base shear force occurs in Model 3 with an X direction value of 1430.25 kN and Y direction of 1475.11 kN, while the maximum base shear force occurs in Model 2 with an X direction value of 1556.43 kN and Y direction of 1556.43 kN. The difference in the base shear value between models reflects the variation in fundamental vibration period affected by the mass distribution and stiffness in each of the plan configurations.

Table 2. Fourth Basic Shear Force Structure Model

Models	Shift Base Direction X (kN)	Shift Base Direction Y (kN)
Model 1	1446,28	1443,86
Model 2	1556,43	1556,43
Model 3	1430,25	1475,11
Model 4	1518,14	1411,12

Source: ETAB analysis results, 2024

Figure 1. Comparison of the Fourth Basic Shear Force of the Structure Model

The distribution of level shear forces across the model shows an accumulation pattern from the top to the base of the building as is typical of the behavior of multi-storey structures. On the ground floor (Story 1), the shear force of the X directional level ranged from 1430.25 kN (Model 3) to 1556.43 kN (Model 2), while on the upper floor (Story 11) the value of the sliding force of the level was much smaller, ranging from 219.38 kN (Model 3) to 237.90 kN (Model 2). Comparisons between models show that the minimum X directional level shear force value consistently occurs in Model 3, while the maximum value occurs in Model 2 across building heights. In the Y direction, the minimum value occurs on Model 4 and the maximum value remains on Model 2.

Table 3. Level Sliding Forces on Ground Floors and Top Floors

Models	Slide Level X - Story 1 (kN)	Slide Level X - Story 11 (kN)	Y-Level Slide - Story 1 (kN)	Y-Level Slide - Story 11 (kN)
Model 1	1446,28	222,46	1443,86	222,30
Model 2	1556,43	237,90	1556,43	237,90
Model 3	1430,25	219,38	1475,11	223,58
Model 4	1518,14	225,86	1411,12	215,72

Source: ETAB analysis results, 2024

The maximum displacement value occurs on the top floor (Story 11) of each model, as summarized in Table 4. In the X direction, the minimum displacement value occurs on Model 4 (43.68 mm) and the maximum value on Model 3 (50.34 mm). In the Y direction, a different pattern is shown with the minimum value on the Model 3 (45.41 mm) and the maximum value on the Model 4 (47.33 mm). This difference in pattern indicates that the lateral stiffness in the X and Y directions is not uniform in models with irregular plans, whereas in Model 4 the two directions are relatively balanced due to their symmetrical plans.

Table 4. Maximum Displacement on the Top Floor (Story 11)

Models	X Story Displacement 11 (mm)	Y Story Displacement 11 (mm)
Model 1	43,97	46,19
Model 2	45,83	45,83
Model 3	50,34	45,41
Model 4	43,68	47,33

Source: ETAB analysis results, 2024

The torque values on the ground floor columns of the four models are presented in Table 5 and Figure 2. The maximum torque occurs in Model 1 of 2.139 kNm (Story 1) with a peak value between floors reaching 3.52 kNm in Story 4, torque in Model 2 is relatively much smaller (0.371 kNm in Story 1, peak 1.01 kNm), torque in Model 3 is the smallest among irregular models (0.019 kNm in Story 1, peak 0.32 kNm), while Model 4 does not show any torque value at all (0.00 kNm) at the entire height of the building because there is no eccentricity between the center of mass and the center of stiffness.

Table 5. Torque Value on the Column of Each Structure Model

Story	Model 1 Torque (kNm)	Model 2 Torque (kNm)	Model 3 Torque (kNm)	Model 4 Torque (kNm)
Story 11	0,871	0,422	0,159	0,00
Story 8	2,259	0,744	0,308	0,00
Story 4	3,521	1,015	0,138	0,00
Story 1	2,138	0,371	0,019	0,00

Source: ETAB analysis results, 2024

Figure 2. Comparison of the Fourth Torque of Structure Models

The calculation of column reinforcement needs follows the provisions of SRPMK SNI 2847:2019 and is verified against the strong column-weak beam (SCWB) requirement using the force in the critical column on the ground floor of each model. The results of the recapitulation are presented in Table 6. In Model 1, the C38 column received an axial force Pu = 4473.29 kN with Mux moments = 199.11 kNm and Muy = 194.23 kNm, requiring longitudinal reinforcement of 16D22 with transverse reinforcement of 5D13-75 in the pedestal zone and 5D13-120 in the field zone; the value of ΦMn/Mu = 1.248 indicates that the cross-sectional capacity is still adequate. A similar pattern occurs in the Model 2 (column C41, reinforcement 16D22) and Model 3 (column C41, reinforcement 16D22), while the Model 4 as a regular structure only requires longitudinal reinforcement 12D22 with a transverse 4D13-100/120, lighter than the three irregular models. SCWB checks on all critical models showed OK results, namely two times the nominal moment of the column (2Mnc) is always greater or equal to 1.2 times the number of nominal moments of negative and positive beams that frame to the joint (2Mnc ≥ 1.2(Mn- + Mn+)), so that the mechanism of the weak beam plastic joint is maintained in all four models.

Table 6. Recapitulation of the Fourth Critical Column Reinforcement of the Structure Model

Model (Column)	Pu (kN)	Torque (kNm)	Longitudinal reinforcement	Focus	Field Sengkang
Model 1 (C38)	4473,29	2,139	16D22	5D13-75	5D13-120
Model 2 (C41)	4483,47	0,371	16D22	5D13-75	5D13-120
Model 3 (C41)	4449,98	0,019	16D22	5D13-75	5D13-120
Model 4 (C47)	4043,05	0,000	12D22	4D13-100	4D13-120

Source: SP Column analysis results, 2024

Analysis / Discussion

The findings of this study are consistent with the structural torsion mechanism described by Ghimire and Chaulagain (2021), namely that the lateral force acting on a building with a center of mass not implying with the center of rigidity will produce a torsional moment equal to the result of the lateral force with the eccentricity between the two points. The eccentricity-free Model 4 (0.000 m across the floor) experiences no torque at all, while the three irregular models experience torque proportional to the level of eccentricity — the Model 1 and Model 3 with the greatest eccentricity (up to 0.257 m and 0.340 m) produce a much more significant torque pattern than the Model 2 which has a relatively small eccentricity (maximum 0.093 m). This pattern reinforces the findings of Verma and Gagandeep (2023) that the shape of the plan, not just the height of the building, is a determinant factor of the amount of torque and level deviation in irregular structures.

Interestingly, the basic shear force and the level shear force are not always directly proportional to the level of irregularity of the plan. Model 2, although classified as an irregular deep angle with the second largest projection ratio (58.3% in the X direction), actually produces the highest basic shear force among the four models. This suggests that the basic shear force is influenced more by the total mass and fundamental vibratory period of the structure than solely by the degree of irregularity of its plan, in line with the observation of Kostinakis and Athanatopoulou (2020) that the non-uniform distribution of mass and rigidity exerts complex influences that are not always linear on the global response of the structure. In contrast, torque proved to be the most consistent parameter distinguishing seismic performance between regular and irregular structures in this study, as shown in Figure 2, where the three irregular models are clearly separated from the zero-rated Model 4 along the height of the building.

The structural consequences of such torque are reflected in the need for column reinforcement. All three irregular models require 16D22 longitudinal reinforcement with tighter spacing (75 mm in the focus zone), while the regular Model 4 only requires 12D22 with looser spacing (100 mm). The difference in reinforcement requirements of about 33% in this longitudinal reinforcement confirms the economic implications of the selection of irregular plan configurations, in line with the conclusion of Bhatta et al. (2021) that structural irregularities increase the need to strengthen structural components around the irregularity zone. Nevertheless, all models — both regular and irregular — still meet the requirements of strong column-weak beam SNI 2847:2019, which shows that with proper detailing design, buildings with irregular configurations can still be planned safely against the brittle collapse mechanism of columns, as emphasized by Sadat and Arslan (2023) regarding the importance of optimizing the design of vertical elements in structures with plan irregularities.

These findings have practical relevance especially for developing countries such as Indonesia, where land efficiency demands often drive irregular building plan selection. The results of the study confirm that although structural irregularities are structurally more efficient in terms of base shear, torque, and reinforcement requirements, the irregularity of the plan does not mean that it cannot be planned safely as long as all provisions of SNI 1726:2019 and SNI 2847:2019, especially related to horizontal irregularity examination, enlargement of diaphragm design style, and verification of strong column-weak beam, are consistently fulfilled at the planning stage.

CONCLUSION

Based on the results of the analysis of four models of twelve-story building structures with Special Moment Bearing Frame System, it can be concluded that Model 4 as a regular structure does not show a difference between the center of mass and the center of rigidity, while Model 1, Model 2, and Model 3 as an irregular structure of deep angles show eccentricity between 0.001 m to 0.340 m. The minimum base shear force occurs in Model 3 (1430.25 kN in the X direction; 1475.11 kN in the Y direction) and the maximum in the Model 2 (1556.43 kN in both directions), with a similar pattern applicable to the distribution of level shear forces across the floor. The maximum displacement value of the X direction occurs in the Model 3 and the minimum in the Model 4, while the minimum in the Y direction occurs in the Model 3 and the maximum in the Model 4, indicating non-uniform lateral rigidity in the irregular plan.

The maximum torque occurs in the critical column of the Model 1 of 2.139 kNm and the smallest value in the Model 4 of 0.00 kNm, confirming that the eccentricity of the plan is the main determinant factor of the amount of structural torque. The column reinforcement requirements on the Model 1, Model 2, and Model 3 use 16D22 longitudinal reinforcement with 5D13 transverse reinforcement, while the Model 4 uses 12D22 longitudinal reinforcement with 4D13 transverse reinforcement, which is lighter than the three irregular models. All models are declared to meet the requirements of strong column-weak beam SNI 2847:2019. These results confirm that regular buildings with better seismic performance than irregular buildings, but irregular plans can still be planned safely if compliance with SNI 1726:2019 and SNI 2847:2019 is consistently met.

For further development, it is recommended to conduct a time history analysis to capture the nonlinear dynamic behavior of the structure more accurately, as well as further analysis of the lower structure or the foundation of the four building models that have not been reviewed in this study.

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