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Optimization of Column Stirrup Selection (Square and Spiral) for Earthquake Resistance of 10-Storey Buildings

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A B S T R A C T

Earthquake-resistant building design is very important, especially in earthquake-prone areas such as Indonesia. The shape of the column cross-section and the ties' configuration greatly affect the building's stiffness when exposed to earthquake loads. Therefore, knowing the optimal tie configuration to increase earthquake resistance is important. This study aims to analyze the structural performance of a 10-story building using columns with spiral stirrups and square stirrups. Model 1 uses columns with square stirrups, Model 2 uses spiral stirrups, and Model 3 is a combination of both. Simulations were conducted using ETABS 18 software, where the base shear force, displacement, and inter-story drift as well as the collapse pattern and performance level of the structure were analyzed using the pushover analysis method to determine the effect of each configuration on the stiffness and ductility of the columns when receiving earthquake loads. Analysis of Variance (ANOVA) analysis was carried out to ensure that the differences in seismic performance between the three models were significantly validated. The results show that Model 2 has lower displacement and base shear force values and smaller inter-story drift than the other models, and the collapse pattern and structural performance level of Model 2 are also smaller than the other models. The ANOVA results showed no significant difference between the models. This is because the differences in displacement and drift values are relatively small. These findings can provide guidance for selecting the most efficient column tie configuration for resisting earthquake loads and achieving safety levels.

1. Introduction

Indonesia is part of the Pacific Ring of Fire and is one of the earthquake-prone countries. To ensure the safety of buildings in the event of an earthquake, building structures in Indonesia must be designed to specifications that can withstand dynamic loads due to earthquake vibrations [1]. These standards and regulations are intended to minimize building damage, protect lives, and maintain building function after an earthquake [2].

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Earthquake-resistant buildings are structures designed to resist the seismic forces they are exposed to [3] [4]. The structure that plays an important role in an earthquake-resistant building is the column [5] [6]. Columns are very important compressive structural elements in a building, so column collapse can be a critical point that causes the collapse of related floors and can even result in the total collapse of the entire structure [7][8]. At the time of collapse, columns with square stirrups experience brittle and sudden collapse, while columns with spiral stirrups are ductile (ability to deform before collapse) [7]. When an earthquake occurs, an earthquake-resistant structure is needed to minimize the number of victims due to building collapse. This makes comparing square and spiral columns essential for optimizing seismic structure performance [9]. Columns with proper stirrup configuration not only increase the axial load capacity but also provide the structure with the ability to absorb earthquake energy more effectively [10].

Structural performance refers to how well a building can handle an earthquake it was designed for [11]. The performance level of a structure can be determined based on the extent of structural damage caused by an earthquake with a certain return period [12]. In performance-based structural design, structures are usually designed to fulfill the purpose and functionality of the building, taking into account economic factors related to building repairs after an earthquake, without compromising the safety of building occupants [13]. One of the procedures that can be used to understand the collapse behavior of buildings due to earthquakes is nonlinear static analysis [14]. It is also known as pushover analysis or static thrust load analysis [15]. Pushover analysis is a nonlinear static analysis method in which a static horizontal force is applied to the center of mass of the building and gradually increased until the structure reaches a limit or collapse condition [16]. One approach in pushover analysis regulated by the ATC-40 (Applied Technology Council) guideline is the Capacity Spectrum Method [17]. The Capacity Spectrum Method is to plot the demand response spectrum and capacity curve in one format between spectral acceleration and spectral displacement. The capacity curve is a graphical representation of the strength of a structure that depends on the deformation capability of each structural component [18] [19].

Previous studies have shown that round columns are more effective at resisting shear failure but may experience flexural failure earlier compared to square columns. Round columns are more effective in resisting shear collapse, but round columns tend to experience flexural collapse faster [20]. Round columns are more efficient in terms of nominal moment capacity and deviation capacity than rectangular columns [21]. Axial force (P), shear force, and moment

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on square columns are greater than round columns [5], [20]. Based on previous studies, comparisons have only been made between columns with square stirrups and columns with spiral stirrups, focusing on the structural element behavior in terms of seismic performance. However, studies that specifically examine 10-story buildings have not been widely explored.

This study aims to analyze the structural performance of 10-story buildings using square and spiral column stirrup configurations. A Comparison of earthquake-resistant structural performance was conducted by examining the values of base shear force, displacement, and inter-story drift, as well as analyzing the collapse pattern and structural performance level using the pushover analysis method. This study provides practical recommendations for selecting optimal column designs to enhance earthquake resistance. The findings are expected to understand the relationship between column stirrup configurations and seismic behavior and guide engineers and designers in developing safer and more resilient structures in earthquake-prone regions.

2. Research Method

The research begins with data collection, focusing on the structural details of a 10-story building in West Jakarta. Preliminary design was conducted to estimate component dimensions based on building codes, serving as input for the structural modeling phase using ETABS 18. Load analysis follows, calculating dead, live, and earthquake loads, which are incorporated into the model to simulate seismic responses. Three models are used in the analysis: Model 1, with square stirrups; Model 2, with spiral stirrups; and Model 3, with a combination of both. Pushover analysis is then conducted to evaluate the building's seismic performance. Subsequently, a statistical analysis using ANOVA validates the differences in performance among the three structural models.

2.1 Data Collection

The building data collection phase focuses on a 10-story office building located in Slipi, West Jakarta. The building is situated on medium soil, has a floor height of 4 meters, and uses concrete with a compressive strength (fc’) of 30 MPa and steel with a yield strength (fy) of 420 MPa. The structural system employed in the building is the Special Moment Resisting Framing Systems (SRPMK) system.

2.2 Preliminary Design

A Preliminary design is carried out to estimate the dimensions of the structural components in accordance with relevant building codes. This step helps establish the initial layout of beams, columns, and other key structural elements that will form the foundation of

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the structural analysis. Preliminary design is carried out using Microsoft Excel software. The results of this preliminary design will be used as the basis for structural modeling with ETABS 18 software. The summary of preliminary design is described in **Table 1**.

Table 1. Preliminary Design Recapitulation

Component	Dimensions (mm)
Columns with Square Stirrups	900 x 900
Column with Spiral Stirrups	Diameter 1015.80
Beams	600 x 450
Thickness of Floor Plate	140

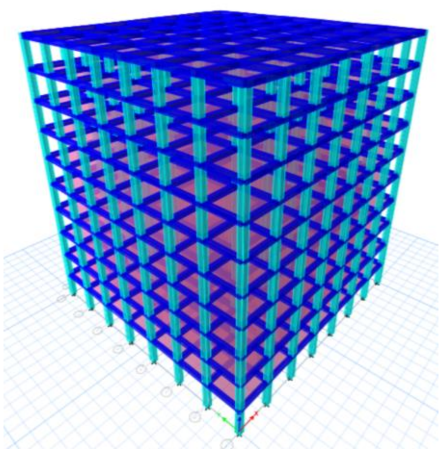
Source : Author Result Analysis (2024).

2.3 Load Analysis

Once the preliminary design is completed, the load analysis is performed. This includes calculating dead loads (DL), live loads (LL), and earthquake loads (EL). The dead and live loads are determined based on SNI 1727:2020 [22], while the earthquake load is analyzed using the static pushover method in line with SNI 1726:2019 [23]. Earthquake load analysis is crucial to this research, and it is conducted using the static equivalent method, with pushover analysis applied to simulate how the building responds to seismic forces as per SNI 1726-2019. The findings from this stage serve as a key input for the subsequent structural modeling.

2.4 Structural Modeling

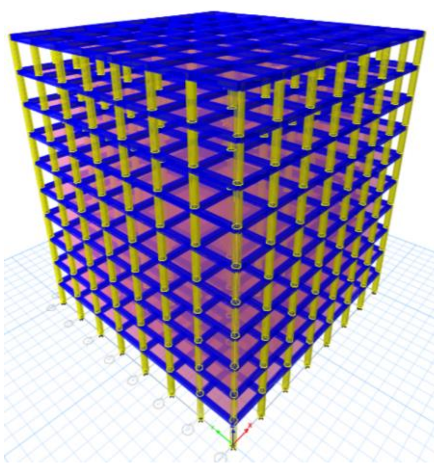
The building is modeled as an open-frame system, with the floor slabs considered diaphragms. The main structural frame, comprising beams and columns, is modeled using ETABS version 18. The software is utilized to generate an accurate representation of the building's behavior under load conditions.



(a)

Source : Author Result Analysis (2024).

Figure 1. Model 1



(b)

Source : Author Result Analysis (2024).

Figure 2. Model 2

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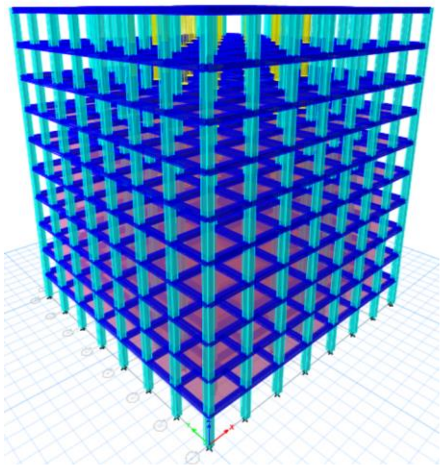

Source : Author Result Analysis (2024).

Figure 3. Model 3

2.5 Structural Analysis

Following the modeling, structural analysis is conducted using response spectrum analysis in ETABS 18. This step yields important results such as base shear force, displacement, and inter-story drift, which provide insight into the building's seismic performance. The seismic design of structural elements was performed by detailing all the structural components, is input into ETABS 18. Pushover analysis is then performed to assess the seismic performance of the structure, allowing for detailed examination of the building's capacity to withstand earthquake forces. Based on the detailing of SRPMK structural components in accordance with SNI 1726-2019 and SNI 2847-2019, a recapitulation of the reinforcement is obtained as shown in **Table 2** and **3**.

Table 2. Beam Reinforcement Recapitulation

Rebar	Quantity of Reinforcement		
	Model 1	Model 2	Model 3
Top Support Longitudinal	7D22	7D22	7D22
Longitudinal Bottom Support	3D22	3D22	3D22
Top Field Longitudinal	4D22	4D22	4D22
Longitudinal Bottom Field	3D22	3D22	3D22
Support Stirrups	2D13 - 100	2D13 - 100	2D13 - 100
Field Strirrups	2D13 - 200	2D13 - 200	2D13 - 200

Source : Author Result Analysis (2024).

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Table 3. Column Reinforcement Recapitulation

Rebar	Quantity of Reinforcement		
	Model 1	Model 2	Model 3
Longitudinal	24D25	24D25	24D25
Support Stirrups	4D13 - 100	4D13 - 100	4D13 - 100
Field Strirrups	3D13 - 150	3D13 - 150	3D13 - 150

Source : Author Result Analysis (2024).

Once the design and analysis are complete, strength verification is conducted to ensure that the structure meets the necessary strength requirements. If the structure does not meet the criteria, the design and load assumptions are revisited. If the structure satisfies the strength requirements, the analysis proceeds to the next step. Performance and collapse pattern analysis is performed using Performance-Based Design (PBD) principles in accordance with ATC-40 guidelines. This analysis uses pushover analysis to evaluate the performance levels and failure patterns of the structure under seismic loading conditions. The study then moves to the comparison of displacement and inter-story drift across the three structural variations being studied: square columns, spiral columns, and a combination of both. This comparison is vital to understanding how different column configurations affect the building's ability to resist earthquake forces.

2.6 Statistical Analysis

Statistical analysis using Analysis of Variance (ANOVA) is conducted to statistically compare the results and ensure that the differences in seismic performance among the three models are significantly validated. The requirements that must be met beforehand are normality tests and homogeneity tests. The normality test used is Shapiro-Wilk because the data used in this study is less than 30 [24]. The Variance homogeneity test is one of the requirements in comparative analysis. The purpose of this test is to determine whether the variance of data from two or more groups is homogeneous (same) or heterogeneous (different) [25]. In this study, the independent variable (X) is the type of column: columns with square stirrups (Model 1), columns with spiral stirrups (Model 2), and a combination of both (Model 3). The dependent variables (Y) include the performance of earthquake-resistant structures and collapse patterns, displacement, interstory drift, structural performance level, and collapse pattern. The hypotheses tested are H_0 (no significant difference in displacement and inter-story drift between the three models) and H_1 (a significant difference exists between the models). The results of

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this statistical analysis are used to draw more convincing conclusions about the influence of column type on seismic performance. These results will provide statistical evidence of the effectiveness of each column configuration, supporting recommendations for the most optimal column design to enhance building resilience against earthquakes.

3. Results and Discussions

3.1 Base Shear Force Due to Spectrum Response Earthquake Load

The data presented in **Table 4** shows that Model 2 has a shear force value of 9714.1 kN, Model 1 is 9770.1 kN, and Model 3 is 9754.3 kN. The results of the base shear force due to the response earthquake load show that building model 2 has a smaller value than building model 1 and building model 3. The value of the base shear force due to the spectrum response earthquake load in building model 2 decreased by 0.573% and building model 3 by 0.162% from building model 1. Based on the results of the modeling and structural analysis, the building weight in Model 2 is the lightest compared to the other models. The lighter building weight affects the base shear force, as this force is influenced by the building weight and seismic response coefficient.

Table 4. Base Shear Force Due to Spectrum Response Earthquake Load

Data	Model 1 (kN)	Model 2 (kN)	Model 3 (kN)
V Rsx	9770.1	9714.1	9754.3
V Rsy	9770.1	9714.1	9754.3

Source : Author Result Analysis (2024).

3.2 Displacement

From the results of the displacement analysis in the X and Y directions shown in **Figures 4** and **5** for the three models, it can be observed that there is no significant difference in displacement values between Building Models 1, 2, and 3. The displacement value in building model 2 decreased in the X direction by 0.643% and in the Y direction by 1.044%, while building model 3 in the X direction decreased by 0.365% and in the Y direction by 0.325% from building model 1. This is consistent with previous research that state displacement analysis on building structures with circular and square columns shows only minor differences. This condition is due to the design of all three models having the same column cross-sectional area and similar loading [4].

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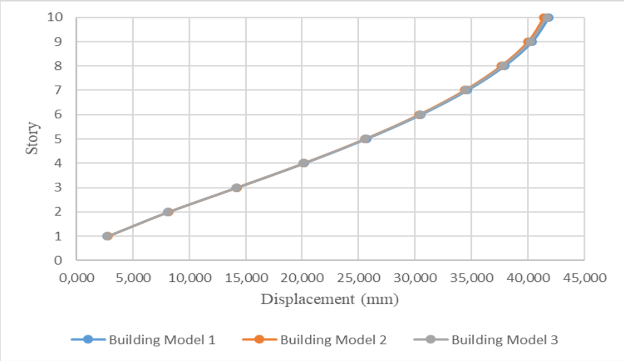
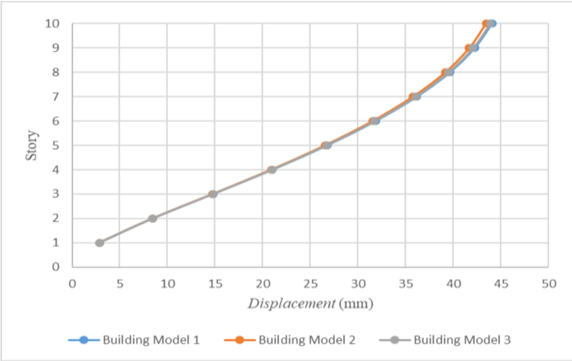


Source : Author Result Analysis (2024).

Figure 4. *X Axis Displacement*

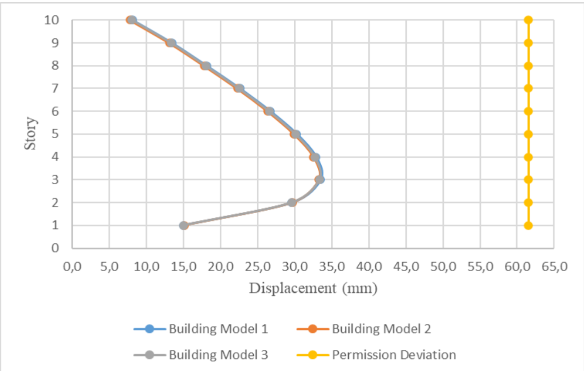


Source : Author Result Analysis (2024).

Figure 5. Y *Axis Displacement*

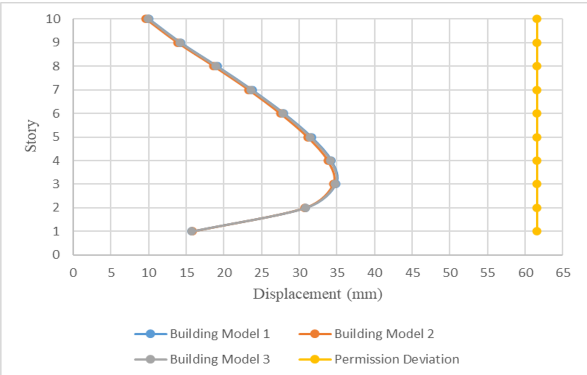
3.3 Inter-Story Drift

In planning a building, is important to consider safety and comfort factors. Therefore, it is necessary to limit the movement or deviation that occurs in the building during an earthquake. Based on the results of the inter-story drift in the X-axis and Y-axis directions due to the earthquake loads spectrum response shown in **Figures 6** and **7**, it is found that building model 2 has a better inter-story drift than building model 1 and building model 3. The average value of inter-story drift of building model 2 decreased by 1.043% in the X direction and 1.452% in the Y direction, while the decrease in model 3 was 0.477% in the X direction and 0.445% in the Y direction from building model 1. Previous research also stated that the displacement of round columns is smaller than square columns [4].



Source : Author Result Analysis (2024).

Figure 6. X-axis Inter-Story Deviation



Source : Author Result Analysis (2024).

Figure 7. Y-axis Inter-Story Deviation

3.4 Building Structure Performance Analysis

Determining the performance level of the building structure can use the capacity spectrum method by combining the capacity graph generated in the pushover analysis together with the demand spectrum at one time. The results of the structure performance level are shown in **Table 5**.

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Table 5. Structure Performance Level

Performance Point	Structure Performance Level		
	Model 1	Model 2	Model 3
X Axis Direction	291.9	290.7	292.4
Drift Total	0.0073	0.0072	0.0073
Level (ATC - 40)	IO	IO	IO
Y Axis Direction	323.15	317.76	323.31
Drift Total	0.0081	0.0079	0.0081
Level (ATC - 40)	IO	IO	IO

Source : Author Result Analysis (2024).

It was found that building models 1, 2, and 3 all achieved Immediate Occupancy (IO) performance levels in both the X-axis and Y-axis directions. Despite achieving the same performance level across these models, the total drift values reveal that model 2 has the lowest drift, indicating enhanced structural stability compared to models 1 and 3. This result is attributed to the smaller base shear force, displacement, and inter-story drift observed in model 2. These findings align with previous research, which demonstrated that buildings using circular columns achieved lower performance points than those with square columns [6]. The Immediate Occupancy (IO) condition indicates that the building remains safe during an earthquake, with minimal structural failures, no significant damage, and can be immediately reoccupied.

3.5 Analysis of Building Collapse Patterns

Based on the collapse patterns that occur in building models 1, 2, and 3 plastic joints are first formed in the beam, this indicates that building models 1, 2, and 3 have fulfilled the requirements of strong-column weak-beam.

The occurrence of plastic joints in the column indicates that the structure has reached the limit of collapse. In this study, plastic joints in the X-axis direction in the columns first occurred at step 18 (building model 1 and building model 3) and at step 19 (building model 2), while in the Y-axis direction they first occurred at step 20 (building model 1 and building model 3) and at step 21 (building model 2). Based on this, it indicates that building model 2 using columns with spiral stirrups is superior because the collapse of the columns is slower than building models 1 and 3. This finding is in line with previous research that found the collapse pattern in buildings using round columns is better than buildings using square columns [6].

3.6 Statistical Data Analysis Method

The normality test has a significance value> 0.05 so it can be continued with the homogeneity test and ANOVA test. The homogeneity test value is > 0.05 so it is homogeneous

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(the same). After the normality and homogeneity requirements are met, the test continues with the One-Way ANOVA test with the results shown in **Table 6**.

Table 6. ANOVA Test Results

Description	ANOVA
Displacement X	1.000
Displacement Y	0.999
Inter-Story Drift X	0.998
Inter-Story Drift Y	0.996

Source : Author Result Analysis (2024).

Since all three data have significance values > 0.05, H_0 is accepted H_1 is rejected. The hypothesis means that there is no significant difference between building model 1, building model 2, and building model 3. Therefore, based on statistical analysis, the difference in column types with square and spiral stirrups is not significant. This is because the buildings have similar displacement values and Inter-Story Drift values. This is in line with previous research shows that the displacement and inter-story drift values of columns with square stirrups and columns with spiral stirrups have no significant difference [4] [6].

4. Conclusion

This study concludes that the use of spiral ties in columns of a 10-story building, as demonstrated in building model 2, provides the most effective seismic performance compared to other structural configurations. The spiral ties improve the ductility of the columns, allowing for better energy absorption and reduced risk of brittle failure during an earthquake. The findings indicate that the building model achieves the smallest base shear force, displacement, and inter-story drift values, confirming its superior structural performance under seismic loads. These results underscore the importance of selecting appropriate column tie configurations to enhance the overall seismic resilience of a building, particularly in earthquake-prone areas. Furthermore, the collapse pattern observed in all models fulfill the strong-column weak-beam mechanism, ensuring that plastic hinges form in beams first, which helps prevent sudden and catastrophic column failure. This validates the structural integrity of model 2 as the optimal choice for maintaining building safety during seismic events. This study was able to demonstrate how spiral ties in columns can significantly improve the seismic performance of mid-rise buildings. This is of great significance for engineers and designers, as it provides a practical approach to optimizing column design for better earthquake resistance, thereby reducing the risk of structural collapse and enhance public safety in seismic regions.

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