

PUSHOVER ANALYSIS ON A MOSQUE BUILDING STRUCTURE WITH A TIERED ROOF SLAB

Naek Rizki Pandiangan¹, Ade Yuniati Pratiwi²

*Civil Engineering, Faculty of Engineering Lambung Mangkurat University
Jl. Jenderal Achmad Yani Km 35,5 Banjarbaru, Kalimantan Selatan – 70714*

E-mail: ¹anthonypandiangan@gmail.com; ²ade.pratiwi@ulm.ac.id

ABSTRACT

Damage to building structures poses a threat to the quality of the building, which will impact its functionality. Structural damage can be caused by earthquakes. This research aims to determine the performance level and the effect of variations in short column heights on the inter-story drift of a mosque building with a tiered roof slab in a pushover analysis. The pushover analysis in this study refers to FEMA 356 and ATC-40, by determining the target displacement value, drift ratio, collapse mechanism, and building performance level. In accordance with FEMA 356, the pushover analysis results show an Operational performance level with drift ratios in the X and Y directions of 0.451% and 0.458% respectively, which means the building only experienced minor damage and can still be used as normal. Based on ATC-40, the analysis results show an Immediate Occupancy performance with a drift ratio in the X and Y directions of 0.00368, so the building is in a safe condition and can be used immediately. The influence of variations in column height on inter-story drift shows that the higher the column, the larger the inter-story drift.

Keywords : Pushover Analysis, Target Displacement, Drift Ratio, Plastic Hinge, Performance Level, Tiered Roof Slab

1. INTRODUCTION

Damage to building structures poses a threat to the quality of the building, which will impact its functionality. Structural damage can be caused by weather exposure and natural disasters, one of which is an earthquake. Designing buildings that are resistant to earthquakes is a crucial aspect of structural planning to ensure the building does not collapse after an earthquake. (Saputra, 2020). Performance-based design shows, in the form of curves, the structural response during an earthquake and the resulting damage, which is analyzed using the pushover analysis method. (Mamesah, 2014).

This research analyzes an architectural mosque with a tiered roof slab that has varying short column heights. This study aims to determine the building's performance level and the effect of differences in short column heights on the inter-story drift of the mosque building with a tiered roof slab in a pushover analysis.

2. THEORITICAL STUDY

Building Performance Level

The building's performance level is determined based on the building's drift ratio after it experiences earthquake loads. The building's performance level indicates the extent of damage and the strength of the structure, which allows for an estimation of the future safety and functionality of the building (FEMA, 2000).

Structural performance levels based on FEMA 356 are as follows:

- a. Operational is when the building is in a condition without significant damage, allowing for normal operation.
- b. Immediate Occupancy (IO) is when the building condition shows no structural damage and non-structural components are safe, but its operation is disrupted due to mechanical issues.
- c. Life Safety (LS) indicates the presence of structural damage in some elements, resulting in a decrease in stiffness. The structure possesses sufficient strength to support the loads occurring at the verge of collapse.
- d. Collapse Prevention (CP) indicates that the building has experienced significant damage. The structure has lost most of its strength and stiffness but can still be used even though it is very close to the point of collapse.

Static Pushover Analysis

Static pushover analysis is an analysis method used to evaluate the performance of a structure under earthquake loads. The working principle of pushover analysis involves gradually applying increasing lateral loads to the structural model until it reaches a collapse condition (FEMA, 2000). The pushover curve based on FEMA 356 is as shown in Figure 1.

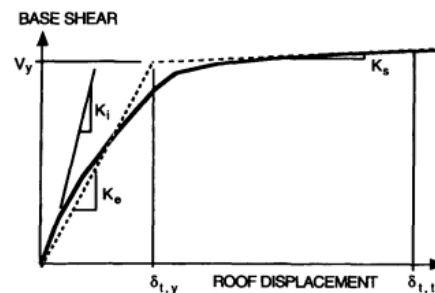


Figure 1. Pushover curve (FEMA, 2000)

Displacement Coefficient Method (FEMA 356)

In the displacement coefficient method, the pushover analysis curve is transformed into a bilinear shape (two straight lines), and then the equivalent linear elastic response is adjusted using coefficient factors to obtain the target displacement, δ (FEMA, 2000). The displacement coefficient method determines the target displacement using Equation (1).

$$\delta_t = C_0 C_1 C_2 C_3 S_a \left(\frac{T_e}{2\pi} \right)^2 g \quad (1)$$

Where, δ_t is the target displacement, R is the required elastic strength ratio, S_a is the spectral response acceleration, T_e is the effective fundamental period, V_y is the yield strength, w is the effective seismic weight, C_m is the effective mass coefficient, C_2 is the coefficient for calculating the effect of pinching on the load-deformation curve, C_3 is the coefficient to account for the increase in lateral displacements due to second-order effects, α is the post-yield stiffness ratio, C_0 is the coefficient related to building configuration, and g is the acceleration due to gravity. The determination of building performance levels based on FEMA 356 can be seen in the Table 1.

Table 1. Performance level FEMA 356 (FEMA, 2000)

Inter-Story Drift Limit	Building Performance Level			
	Operational	Immediate Occupancy (IO)	Life Safety (LS)	Collapse Prevention (CP)
Drift %	0,0-0,5	0,5-1,0	1,0-2,0	2,0-4,0

Capacity Spectrum Method (ATC-40)

In the capacity spectrum method, the performance of the structure is evaluated using the pushover curve that is transformed into a capacity spectrum through equations (ATC, 1996). The capacity spectrum method determines the target displacement using equation (2) through equation (5).

$$S_a = \frac{V/w}{\alpha_1} \quad (2)$$

$$S_d = \frac{\Delta_{roof}}{PF_1 \phi_{roof}, 1} \quad (3)$$

$$PF = \left[\frac{\sum_{i=1}^n \frac{(w_i \phi_{i1})}{g}}{\sum_{i=1}^n \frac{(w_i \phi_{i1}^2)}{g}} \right] \quad (4)$$

$$\alpha_1 = \frac{\left[\sum_{i=1}^n \frac{(w_i \phi_{i1})}{g} \right]^2}{\left[\sum_{i=1}^n \frac{(w_i)}{g} \right] \left[\sum_{i=1}^n \frac{(w_i \phi_{i1}^2)}{g} \right]} \quad (5)$$

Where S_a is the spectral acceleration, S_d is the spectral displacement, PF is the participation factor, W is the dead load, α_1 is the mass coefficient, ϕ_{i1} is the first structural response, V is the shear force, Δ_{roof} is the roof displacement, and w_i/g is the mass. The drift value is calculated using equation (6) and equation (7).

$$\text{Maximum drift} = \frac{D_t}{H} \quad (6)$$

$$\text{Maximum inelastic drift} = \frac{D_t - D_1}{H} \quad (7)$$

Where, D_t is the maximum displacement, D_1 is the displacement at the first floor, dan H is the building height. Building performance levels based on ATC-40 is shown in Table 2.

Table 2. Building performance level based on ATC-40 (ATC, 1996)

Drift Limit	Building Performance Level			
	Immediate Occupancy	Damage Control	Life Safety	Structural Stability
Maximum Drift	0,01	0,01 - 0,02	0,02	0,33 V_i/P_i
Maximum Inelastic Drift	0,005	0,005 - 0,015	No limit	No limit

Plastic Hinge

If a building structure is subjected to lateral loads under certain conditions, its beams and columns have the potential to form plastic hinges. A plastic hinge is a part of the structural frame that is designed to undergo flexural yielding due to displacements caused by the design earthquake, and this yielding area extends at least a length 'h' from the critical point of initial yielding (ACI, 2019).

Displacement control points, denoted by A, B, C, D, and E, provide information regarding the structural performance. The elastic condition of the structure is limited by the A-B interval. Within the B-C range, there are points IO, LS, and CP, each indicating a building performance level. Point C signifies the ultimate capacity, D describes the remaining strength afterward, and E represents total failure (FEMA, 2000). The relationship between displacement and force with respect to structural performance levels based on FEMA 356 can be seen in Figure 2.

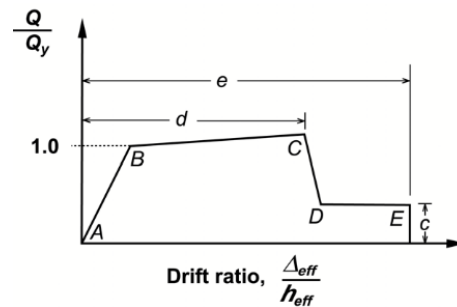


Figure 2. Relationship between displacement and force with respect to structural performance levels (FEMA, 2000)

Tiered Roof Slab

A tiered roof slab is a concrete roof that has multiple levels or is stepped. Stepped roof slabs are architectural elements that add aesthetic value to buildings. However, they also represent a form of irregularity in the building structure, which affects the building's structural behavior. Buildings with varying roof level heights will influence the inter-story drift. The inter-story drift value will increase if the height is also greater (Siajaya, 2018).

3. METHOD

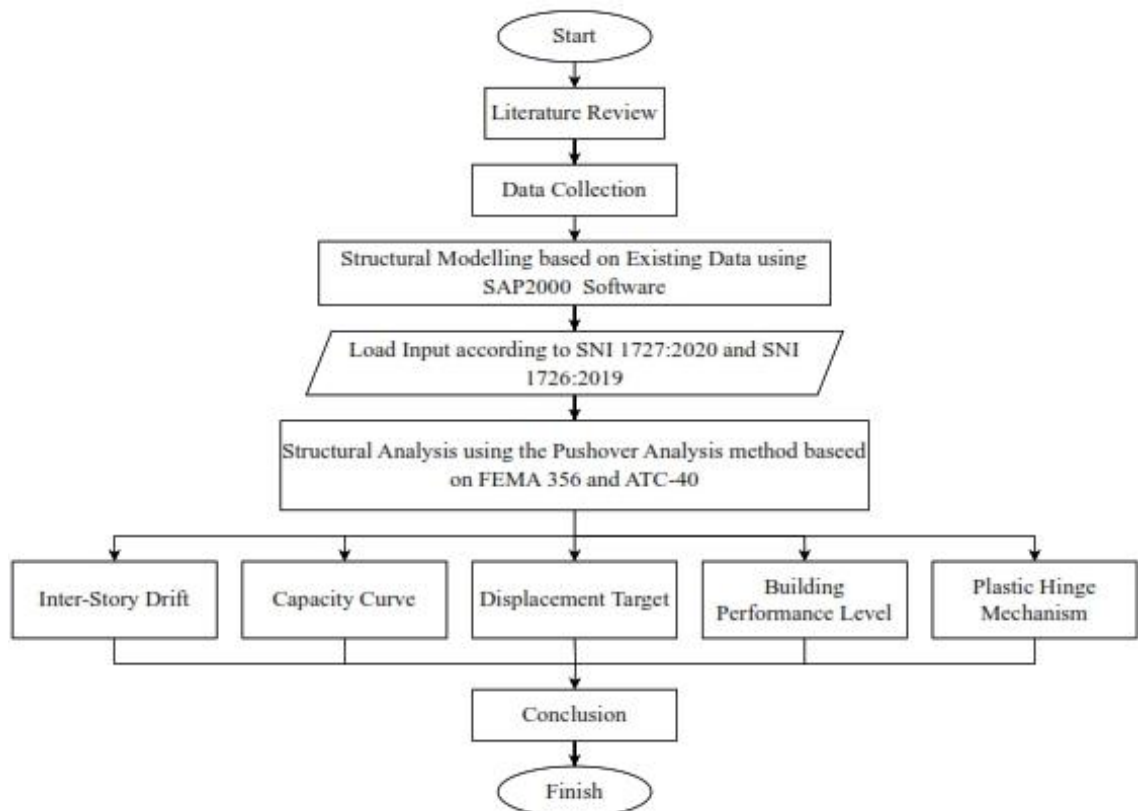


Figure 3. Research flowchart

Based on the flowchart in Figure 3, the research begins by conducting a literature review related to the study. Then, data on the building to be analyzed is collected. After the building data collection, structural modeling is performed using SAP2000 software. Load calculations for the building, including gravity loads and wind loads, are based on SNI 1727:2020 as well as SNI 1726:2019 as a reference for earthquake analysis. Subsequently, a structural analysis is carried out using the Pushover Analysis method, referring to FEMA 356 and ATC-40.

4. RESULT AND DISCUSSION

Inter-Story Drift Limits

According to SNI 1726:2019 Pasal 7.12.1 Tabel 20, the allowable inter-story drift (Δ_a) must not be exceeded by the inter-story drift that occurs. In this building, an inter-story drift limit of $0.01H$ is used. The inter-story drift is shown in Table 3.

Table 3. Inter-story drift limits

Floor	H (m)	Inter-story drift, $\Delta_{(x)}$ (mm)	Inter-story drift, $\Delta_{(y)}$ (mm)	Drift limits, Δ_a (mm)	Note
5	2,45	3,60	3,61	24,5	OK
4	1,50	0,77	1,29	15	OK
3	2,50	14,77	12,42	25	OK
2	4,95	32,74	34,48	49,5	OK
1	1,50	1,15	1,34	15	OK

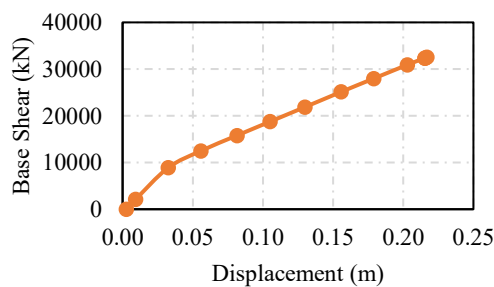
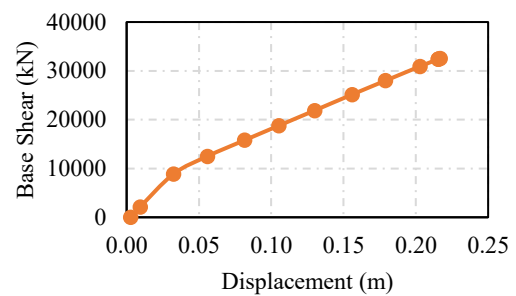
Based on the analysis results, it can be seen that the inter-story drift values are $< 0.01H$, thus the building meets the inter-story drift requirements. Research conducted by Sijaya (2018) shows similar results, namely that the higher the column, the greater the inter-story drift value will be.

Capacity Curve

The capacity curve is a simplification of the structural behavior when subjected to earthquake loads, shown in the form of a graph that plots the shear force acting at the base of the structure (base shear) against the displacement that occurs. From Table 4 it can be seen that the pushover analysis in the X-axis stops at step 12 and the Y-axis stops at step 11, resulting in displacement values for the X and Y axes of 0.217 m and 0.231 m, and base shear values for the X and Y axes of 32538.12 kN and 33468.37 kN. The relationship between displacement and base shear forms the capacity curve, which can be seen in Figure 4 and Figure 5.

Table 4. Relationship between Displacement and Base Shear in a structure

Step	X Axes		Y Axes	
	Displacement (m)	Base Shear (kN)	Displacement (m)	Base Shear (kN)
0	0,003	0,00	0,003	0,00
1	0,009	2108,94	0,009	2069,15
2	0,032	8895,20	0,032	8770,19
3	0,056	12497,79	0,055	12251,89
4	0,081	15786,44	0,083	15766,53
5	0,105	18763,16	0,107	18628,88
6	0,130	21879,58	0,130	21473,85
7	0,156	25140,81	0,155	24590,34
8	0,179	27985,57	0,179	27432,49
9	0,203	30925,88	0,205	30554,90
10	0,215	32380,22	0,229	33229,21
11	0,215	32380,08	0,231	33468,37
12	0,217	32538,12		


Figure 4. Capacity curve X Axes

Figure 5. Capacity curve Y Axes

Target Displacement - Displacement Coefficient Method (FEMA 356)

The displacement coefficient was calculated using SAP2000 software, and then the target displacement was calculated using equation (1) and the drift ratio using equation (6). The results of the target displacement and drift ratio calculations based on the displacement coefficient are shown in Table 5.

Table 5. Calculation results based on the displacement coefficient

Note	Axes	
	X	Y
Te	0,656649 sec	0,661984 sec
C ₀	0,562106	0,566644
C ₁	1	1
C ₂	1	1
C ₃	1	1
Sa	0,852814	0,845941
g	9,81 m/s ²	9,81 m/s ²
δ _t	0,0514 m	0,0523 m
Drift Ratio	0,451%	0,458%

Target Displacement - Capacity Spectrum Method (ATC-40)

The target displacement based on the capacity spectrum method was calculated with the aid of SAP2000 software, and then the maximum drift and inelastic maximum drift values were calculated using equation (6) and equation (7). The results of the target displacement and drift ratio calculations based on the ATC-40 capacity spectrum method are shown in Table 6.

Table 6. Analysis results based on the capacity spectrum

Axes	Performance Point				
	V (kN)	D _t (m)	D ₁ (m)	Maximum Drift	Inelastic Maximum Drift
X	10313	0,042	0,00534	0,00368	0,00322
Y	10261,4	0,042	0,00726	0,00368	0,00305

Building Performance Level

Based on the calculation results of the target displacement and drift ratio, the analysis using FEMA 356 shows an Operational performance level, meaning the building is in a condition without significant damage. Meanwhile, the ATC-40 analysis indicates an Immediate Occupancy performance level, which means the building remains in a safe condition, the risk of casualties and structural damage is very small, and it can be readily reused. The values of the target displacement, drift ratio, and structural performance level are presented in Table 7.

Table 7. Building Performance Level

Axes	Parameter	Pushover Analysis Result	
		FEMA 356	ATC-40
X Axes	Drift Ratio	0,451%	0,00368
	Performance Level	Operational	Immediate Occupancy
Y Axes	Drift Ratio	0,458%	0,00368
	Performance Level	Operational	Immediate Occupancy

Plastic Hinge Mechanism

Based on the capacity curve, it was found at step 3 where the displacement is $0,056 \text{ m} > \delta_t$. The plastic hinge mechanism at step 3 in Figure 6 and Figure 7 shows an Immediate Occupancy performance level.

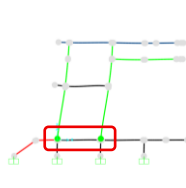


Figure 6. Plastic hinge at step 3 in the X direction

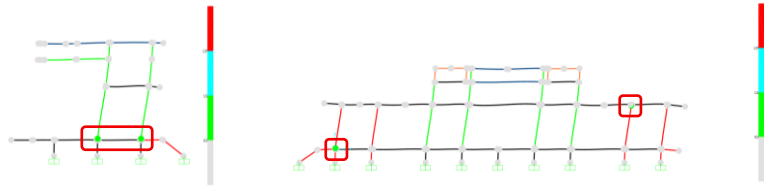


Figure 7. Plastic hinge at step 3 in the Y direction

5. CONCLUSION

Based on the results of the analysis, the following conclusions can be drawn:

1. Based on the inter-story drift checks in the X and Y directions, the maximum inter-story drift that occurs in the building is $22.79 \text{ mm} < 0,01H$ therefore it is concluded that the building meets the inter-story drift limit requirements.
2. The inter-story drift in a tiered roof slab structure with variations in short column heights shows that the taller the column, the greater the inter-story drift that occurs.
3. Based on FEMA 356, the target displacements on the X and Y axes are 0.0514 m and 0.0523 m, respectively. Meanwhile, based on ATC-40, the target displacement on both the X and Y axes has the same value of 0.42 m.
4. Based on the plastic hinge mechanism, the displacement that occurs at step 3 has a value of $0.056 \text{ m} > \delta_t$, with the plastic hinges formed according to SAP2000 software indicating an Immediate Occupancy performance level.
5. The building performance level based on FEMA 356 is Operational with drift ratios on the X and Y axes of 0.451% and 0.458%, respectively. Meanwhile, based on ATC-40, the building performance level is Immediate Occupancy with a drift ratio of 0.00368 on both the X and Y axes.

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