Seismic Evaluation of the Magetan DPRD Building in East Java, Indonesia Using Pushover Analysis

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ABSTRACT

The Magetan Regional People's Representative Council (DPRD) government building was built in 2005 with an irregular Y-shaped pattern. This building is designed based on the SNI 1726:2002 earthquake standard. According to this standard a performance evaluation is necessary. One method to analyze its performance is the pushover analysis, which is a non-linear static analysis method that models the gradual structural response to the lateral loads until the point of collapse. This study aims to evaluate the performance of existing building structures employing pushover analysis to identify the plastic hinges created by different loads and determine the level of structural performance based on the ATC-40 criteria. The structural modeling is performed in the ETABS software, considering the geometric configuration, structural system, and load analysis. The load calculation analysis is carried out according to the SNI 1727:2020 and SNI 1726:2019 standards, including dead loads, live loads, additional dead loads, and earthquake loads. The results of this study suggest an effective modeled base shear force greater than the design shear force. The performance of the building is classified in the Immediate Occupancy (IO) category, indicating resistance and functionality against the earthquake events.

Keywords-existing building; pushover analysis; performance point; seismic evaluation

I. INTRODUCTION

Indonesia is located above three tectonic plates: the Eurasian, the Indo-Australian, and the Pacific. The Eurasian and Pacific plates move from east to southeast, while the Indo-Australian plate moves westward. Indonesia's inclusion to the Pacific Ring of Fire, a geologically active zone characterized by frequent tectonic plate movements, enhances its rate of natural disaster appearance [1, 2]. Based on the Indonesian Earthquake Source and Hazard Map SNI 1726:2019, the Magetan regency in East Java region and its surroundings are classified as areas with moderate to high earthquake risk [3].

The Magetan DPRD building is utilized for legislative activities, government administration, and public services. The building was built in 2005, prior to the latest earthquake regulations of SNI 1726:2019. Its Y-shaped geometric shape leads to distribution irregularities of mass and stiffness, such as variations in the floor height, lateral stiffness, mass eccentricity, or asymmetrical plan shapes. This building is classified as an irregular building. Irregular buildings are generally more susceptible to local collapse or severe damage during an earthquake due to the uneven distribution of internal forces [4-7]. Considering the importance of the building, the potential vulnerability due to its irregular shape, and its age of more than 15 years, a comprehensive evaluation of the building's structural performance is critical.

For this purpose, pushover analysis is employed. Pushover analysis is a non-linear static analysis method that provides an overview of the structure's capacity to withstand the lateral loads gradually until the structure reaches the point of collapse or target displacement. The result of this analysis is a capacity curve that represents the relationship between base shear and roof displacement. From this curve the level of structural performance can be determined, such as IO, Life Safety (LS), or Collapse Prevention (CP), based on the ATC-40 and FEMA 440 standards [8, 9].

Previous studies have proven the effectiveness of this method in evaluating the structural integrity of buildings. Authors in [10] applied the pushover analysis to evaluate the existing National Standardization Agency (BTN) of Indonesia building in Madiun City and concluded that its performance can be classified between LS and CP. Similarly, in [11], regarding the Pasar Besar parking Building in Madiun City, the results suggested that its performance level was between LS and CP. The pushover method has additionally been utilized on a nine story apartment building in Pokhara, Nepal [12]. The findings classified the building's performance level between IO and LS. Authors in [4] researched the performance of a Y-shaped hotel building in Palu City, Indonesia according to FEMA 440 standard. The maximum total displacement and maximum inelastic displacement for the X and Y directions on the fifteen story Y-shaped hotel reached values of 0.002 and 0.0006–0.0009 respectively. This classifies the building at the IO level. A comparison of the behavior of tall buildings with regular and irregular configurations was performed in [13]. The study concluded that regular buildings' seismic performance was better than irregular buildings in almost all cases. Lateral displacement in regular buildings is smaller than in irregular buildings [14]. According to [15, 16], pushover analysis can be employed to forecast the failure mechanisms and hence identify the weak elements.

The main focus of the present study is to evaluate the structure's lateral capacity, analyze the distribution of plastic hinges, and determine the level of structural performance. Considering the Magetan area's local conditions and references from previous studies, the results of this research are expected to contribute to the development of earthquake-resistant buildings, especially in buildings with irregular configurations.

II. METHODS

This study employs the quantitative data analysis method of pushover analysis according to ATC 40 criteria, utilizing the ETABS software. Gravity load analysis is performed according to SNI 1727:2020 and Earthquake Load (EQL) analysis according to SNI 1726:2019 [17, 3]. The beam and column structural reinforcement design complies with SNI 2847:2019 [18]. The structural system is designed with a special moment resisting frame system.

A. Research Models

The study focuses on the Magetan DPRD office building located in Jalan Pahlawan, Magetan, East Java, Indonesia. Its Y-shaped floor plan is illustrated in Figure 1, with different lateral load distribution characteristics than other shapes, such as rectangular. Consequently, a more comprehensive analysis is required to determine the structural response to the lateral loads due to earthquakes. The ETABS software, employs the pushover analysis according to the ATC-40 criteria, to evaluate the resistance of the investigated building on the lateral loads due to earthquakes [8]. Field data and as-built drawings are used to create a 3-dimensional model using ETABS structural analysis software. Furthermore, a load analysis is carried out by considering the Dead Load (DL), Live Load (LL), Additional Dead Load (ADL), and EQL.

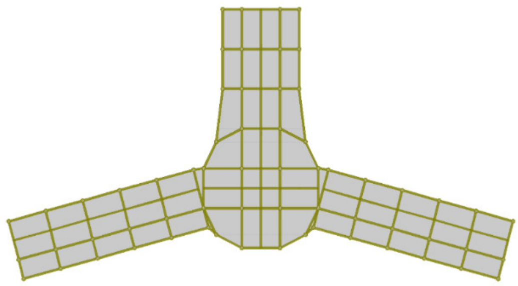


Fig. 1. Floor plan of DPRD Magetan building.

The next step is a non-linear static pushover analysis by defining plastic hinges in columns and beams. The analysis results will provide a capacity curve, plastic hinge distribution, and performance points.

III. RESULTS AND DISCUSSION

A. Modelling

This building consists of a reinforced concrete structure with four floors and a total height (*h*) of 16 m. The former is modeled with two types of circular columns with different dimensions and reinforcements, namely K1 and K2 with diameters of 600 mm and 500 mm, respectively. There are three types of beams coded as B1 (400×800 mm), B2 (300×600 mm), and B3 (200×500 mm). Additionally, a 120 mm thick plate is utilized and the roof plate structure consists of a 10 cm thick plate. The 3D model is illustrated in Figure 2.

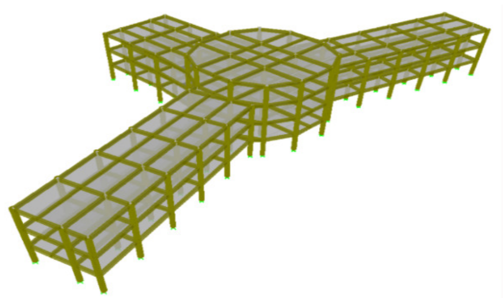


Fig. 2. 3D model of DPRD building.

This research focuses on the building's upper structure, with the following material data presented in Table I.

TABLE I. MATERIAL DATA

Variable	Value
Concrete quality (f'_c)	25 MPa
Weight per unit volume of concrete	24 KN/m^3
Concrete elastic modulus (E_c)	23,500 MPa
Yield stress (f_y) for bending reinforcement	400 MPa
Yield stress (f_y) for shear reinforcement	280 MPa
Elastic modulus of reinforcement (E_s)	200,000 MPa

B. Load Analysis

The weight of the structure is calculated by the software automatically. According to SNI 1727:2020, the load analysis begins by calculating the ADL on the floor slab of 1.5 KN/m^2, which is given to the slab as a uniform load and ADL on the roof slab of 1.0 KN/m^2. The LL for the room is as presented in Table II. Based on [3], the risk category of office buildings is included in category I, with a seismic importance factor 1. The site classification is medium soil SD. The response spectrum design is shown in Figure 3.

TABLE II. LIVE LOAD

Room	**Load (KN/m^2)**
Office	2.40 KN/m2
Lobby	4.79 KN/m2
Plenary session room	4.79 KN/m2
Corridor	4.79 KN/m2
Roof	0.96KN/m2

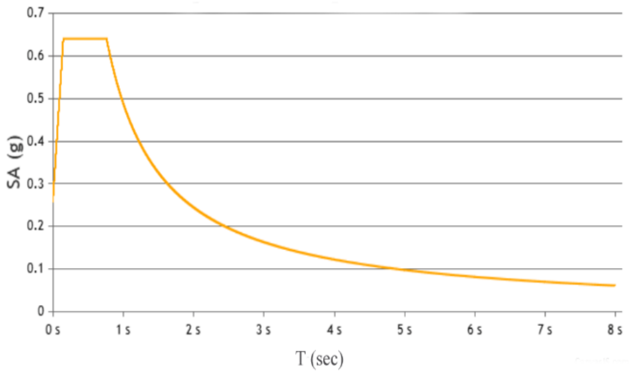


Fig. 3. Spectrum response design.

The EQL analysis based on the website for spectra design by the Ministry of Public Works in Indonesia and on the building location yielded the results presented in Table III [19].

TABLE III. EARTH LOAD ANALYSIS RESULTS

Variable	**Value**
Spectral acceleration at short periods (S_s)	0.8419
Spectral acceleration at 1st sec (S_1)	0.3942
Site coefficient for S_s (F_a)	1.158
Site coefficient (F_v)	1.902
Design spectral acceleration at short periods (S_{ds})	0.65
Design spectral acceleration at 1st sec (S_{d1})	0.50

From the data in Table III, the seismic response coefficient (C_s) is 0.081. If the total building weight (W) is 21864 KN, then the base shear due to the EQL (V) is equal to 1776 KN and is calculated using:

$$V = C_s \cdot W \quad (1)$$

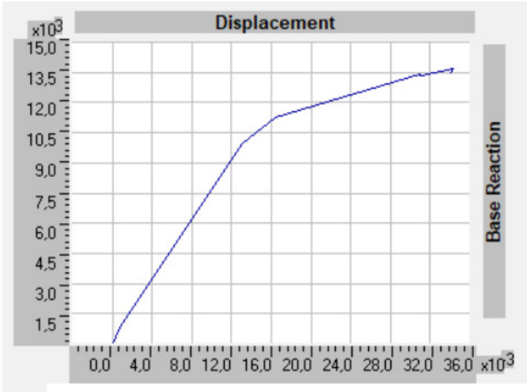
A load combination is created with 18 load combinations based on the SNI 1726:2019. The mass source is adjusted to the self-weight and additional mass. The minimum requirements for the additional loads on the storage area and partition loads have been regulated by SNI 1727:2020 section. Before conducting a running analysis, a model check is carried out by applying the degree of freedom settings, load settings, and load combinations.

C. Pushover Analysis

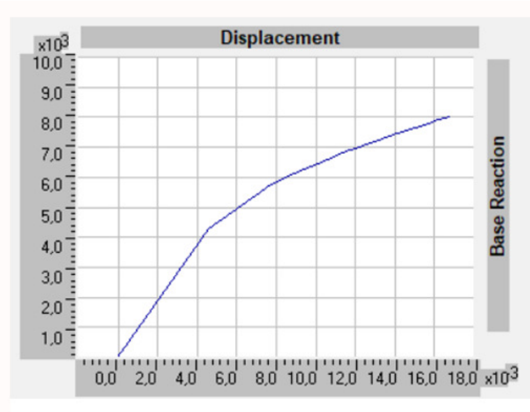
The pushover analysis identifies the structural capacity, evaluates the ductility, and determines the structure's seismic performance. According to [20], the procedure of pushover analysis is:

1. Create the structural model based on field data, including geometry, materials, and as built drawing.
2. Define the materials and apply them to the structure, including the mechanical properties and non-linear behavior
3. Define and assign frame sections to the structural elements, including beams and columns. Define and assign the slab structure as well.
4. Define the loads and enter them into the structural model, including gravity loads, and earthquake loads.
5. Define the load combinations used for analysis based on SNI 2847:2019, including combinations of gravity and earthquake loads.
6. Assign the properties of plastic hinges in beams and columns. Assign the axial force and bending moment (P M2 M3) hinges for columns, and the shear (V2) and flexural (M3) hinges for beams.
7. Define the static non-linear case by assigning two load cases to the structure model: a gravity load case and a pushover load case. The target of roof displacement is set at 0.64 m.
8. Run the analysis and the static non-linear analysis until it is complete.
9. Finally, the results are obtained in the form of a pushover curve, plastic hinge distribution, and performance point. Determine the performance level of the structure.

Pushover analysis produces a capacity curve that describes the ability of the structure to resist the horizontal forces due to seismic loads. The structure's performance for each approach is compared based on the capacity curve and the global damage pattern. These curves are obtained by applying lateral push loads gradually to the structure model until it reaches the failure condition. The capacity curves are shown in Figure 4(a) for the X direction and Figure 4(b) for the Y direction. The capacity curves describe the structure's non-linear response to the lateral loads in both cases. The relationship between the base shear force and displacement is attained in steps 1-8 in the X direction and steps 1-17 in the Y direction. The values of displacement and base shear force in the X and Y directions are displayed in Tables IV and V. As presented in Table IV, an increase to the lateral load leads to and increase to the shear and displacement. The maximum achieved displacement and base shear are 33.8 mm and 13681 KN, respectively. The structure can withstand significant deformation due to its good ductility.



(a)



(b)

Fig. 4. Capacity curve in (a) X and (b) directions.

TABLE IV. BASE SHEAR IN X DIRECTION

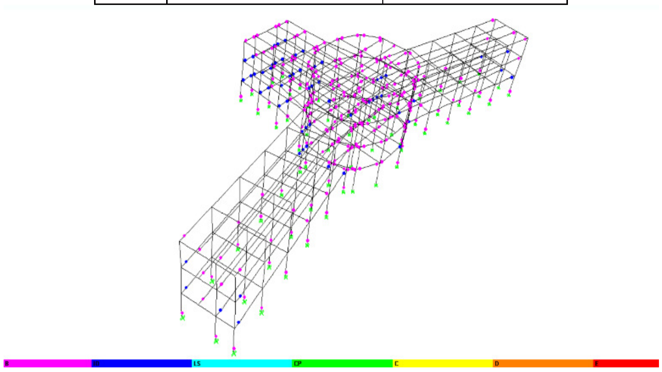
Step	Displacement (mm)	Base shear (kN)
0	0.8	0
1	0.8	0
2	13.0	807
3	16.5	9967
4	31.0	11268
5	31.0	13397
6	31.1	13325
7	34.3	13338
8	33.8	13681

Table V suggests that the structure reaches a maximum displacement of 16.8 mm and a maximum base shear force of 8033 KN at the 17th step. This indicates that the maximum capacity of the structure can withstand lateral forces in the Y direction. The structure can withstand significant displacements of up to 16.8 mm without experiencing a significant decrease in the base shear.

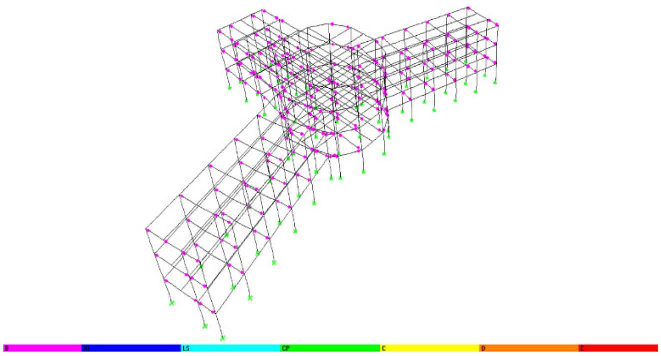
Additionally, Table VI presents the results of the distribution of the number of plastic hinges that occur for each displacement due to lateral loads in the X and Y directions. Most elements remain at the IO - LS performance levels, indicating that the structure can still withstand the load safely. Figure 5(a) illustrates the plastic hinges formed at Step 3 in the X direction.

TABLE V. BASE SHEAR IN Y DIRECTION

Step	Displacement (mm)	Base shear (kN)
0	0.0	0
1	0.2	199
2	4.6	4252
3	7.4	5639
4	7.5	5655
5	8.5	6010
6	8.6	6021
7	10.9	6702
8	11.0	6705
9	11.5	6850
10	11.7	6895
11	11.8	6904
12	14.0	7422
13	14.1	7464
14	14.2	7468
15	15.9	7852
16	16.0	7875
17	16.8	8033



(a)



(b)

Fig. 5. Plastic hinges of step 3 in (a) X and (b) Y directions.

Table VI portrays the results of the distribution of the number of plastic hinges that occur for each displacement due to the lateral load in the Y direction. Until step 10, the structure remains safe with the majority of the elements at the B-IO level. After step 10, some elements begin to form plastic hinges at the IO-LS level indicating that the structure can still endure lateral forces with a safe level of deformation. The required plastic hinges are shown in Figure 5(b).

In both the X and Y directions, the plastic hinge first occurs in the beam precisely on the 2nd floor and then spreads to the beams of the next floor before finally forming a plastic hinge in the column. Plastic hinges occur in weaker or lower capacity structural components compared to other structural parts. This behavior can be attributed to the fact that the weak part initially reaches its elastic limit and then experiences plastic deformation. Plastic hinges occur gradually until the building collapses. The occurrence of plastic hinges starting from the beam suggests that the structural planning of this building fulfills the concept of Strong Column-Weak Beam (SCWB) structural planning. Understanding the mechanism behind the plastic hinge is crucial in predicting the structural collapse in the event of an earthquake. Structural strengthening should be prioritized on the structural components that plastic hinges are likely to develop.

TABLE VI. PLASTIC HINGES IN X AND Y DIRECTIONS

Step	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	>E	Total
X Direction									
0	1964	0	0	0	0	0	0	0	1964
1	1697	258	9	0	0	0	0	0	1964
2	1631	275	58	0	0	0	0	0	1964
3	1550	188	199	27	0	0	0	0	1964
4	1549	188	200	27	0	0	0	0	1964
5	1549	188	200	27	0	0	0	0	1964
6	1515	197	215	37	0	0	0	0	1964
7	1515	197	215	37	0	0	0	0	1964
8	1964	0	0	0	0	0	0	0	1964
Y Direction									
0	1964	0	0	0	0	0	0	0	1964
1	1833	131	0	0	0	0	0	0	1964
2	1714	250	0	0	0	0	0	0	1964
3	1710	254	0	0	0	0	0	0	1964
4	1671	293	0	0	0	0	0	0	1964
5	1669	295	0	0	0	0	0	0	1964
6	1598	366	0	0	0	0	0	0	1964
7	1596	368	0	0	0	0	0	0	1964
8	1590	374	0	0	0	0	0	0	1964
9	1587	377	0	0	0	0	0	0	1964
10	1586	378	0	0	0	0	0	0	1964
11	1552	370	42	0	0	0	0	0	1964
12	1552	356	56	0	0	0	0	0	1964
13	1549	350	65	0	0	0	0	0	1964
14	1530	243	191	0	0	0	0	0	1964
15	1528	240	196	0	0	0	0	0	1964
16	1526	208	230	0	0	0	0	0	1964
17	1964	0	0	0	0	0	0	0	1964

The performance level of a structure is a parameter that describes the extent to which a structure can withstand earthquake loads without experiencing excessive damage or loss of function. The intersection point between the capacity and demand curves is called the performance point and indicates the damage expected to the structure. The capacity spectrum method determines the performance point according to the ATC-40 guidelines.

The analysis produces a capacity spectrum curve and a demand spectrum curve that are displayed as an ADRS graph in Figures 6 and 7. Figure 6 shows the performance point of this building in the X direction. At that point it is evident that the base shear is 11208 KN and its displacement value is 16.303 mm with a spectral acceleration (S_a) of 0.629 g. The structure is within the safe limit and does not experience structural failure in this condition. The spectral displacement capacity of the structure is 45.416 mm.

The performance point is obtained in the Y direction at a base shear of 7152 KN and a displacement value of 12.816 mm, as depicted in Figure 7. Table V shows the performance points for the X and Y directions.

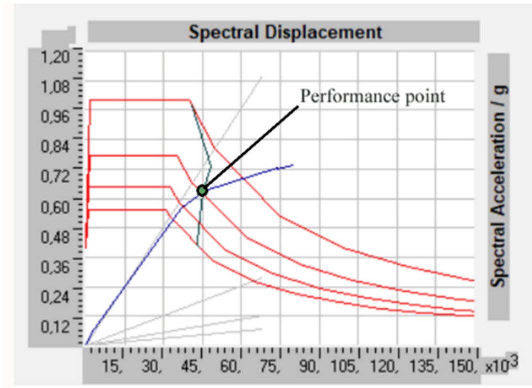


Fig. 6. Performance point in X direction.

According to SNI 1726:2019, the displacement limit is set at 0.025 of the *h*, therefore being 400 mm. Since 400 mm is significantly greater than D in the X direction with a value of 16.303 mm and in the Y direction with a value of 12.816 mm. Subsequently, the building's displacement performance is considered satisfactory. In addition, the base shear values exceed the design shear, with 11208 KN and 7152KN for V in the X and Y directions, respectively, compared to the 1776 KN of the plan. According to ATC-40, sufficient lateral strength is demonstrated when the capacity curve surpasses the demand curve.

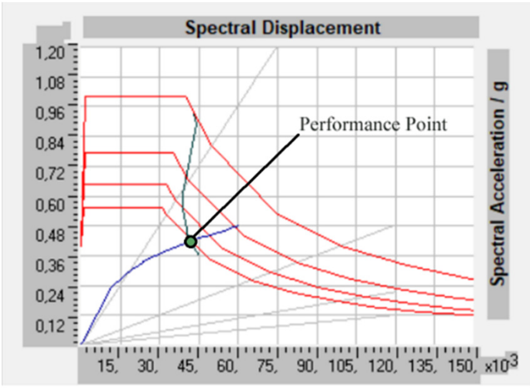


Fig. 7. Performance point in Y direction.

TABLE VII. PERFORMANCE POINT

Variable	Direction	
	X	*Y*
V (KN)	11208	7152
D (mm)	16.303	12.816
S_a (g)	0.629	0.415
S_d (mm)	45.416	41.659
T_{eff} (sec)	0.539	0.634
B_{eff}	0.092	0.196

The global structural performance level can be determined based on the ratio of the roof displacement value to the *h* of the building. The maximum drift and maximum inelastic drift can be calculated using (2) and the values from Table VII. In the inelastic drift, the displacement *D* is calculated using the value from Table VII minus the respective value of displacement from step 1 in Tables IV and V for the X and Y directions respectively:

$$\delta = \frac{D}{h} \quad (2)$$

The performance point is determined from the intersection of the capacity and demand spectra. Figures 6 and 7 present the intersection of the capacity and demand spectra, confirming the IO level per ATC-40. The building's performance level is evaluated using the calculated maximum and inelastic drifts. Applying (2) to both directions, the maximum drift is 0.00102 and 0.0008 for the X and Y directions, respectively. Similarly, utilizing (2), the maximum inelastic drift is 0.00097 and 0.00079 for the X and Y directions, respectively. According to the calculated IO drift values the structure meets the IO performance level, with minimal damage and no need for retrofitting.

IV. CONCLUSIONS

This study successfully proved the effectiveness of the pushover analysis method on the Magetan Regional People's Representative Council (DPRD) Building, with an irregular Y-shape. The structural performance analysis employed according to the ATC-40 standard is expected to contribute to the development of earthquake-resistant building planning, especially in the Magetan area and its surroundings.

The findings suggest that the maximum drift of this building structure's X and Y directions reached 0.00102 and 0.0008. Similarly, the maximum inelastic drift for the X and Y directions was calculated to be 0.00097 and 0.00079, respectively. These results confirm that the building is classified under the IO level, indicating safety and usability after an earthquake event. The pushover analysis also produces a plastic hinge distribution that exhibits weak structural elements, thus suggesting potential elements that require retrofitting.

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