Evaluation of the Structural Performance Behavior of Hotel Building Y in Palu City, Central Sulawesi, Indonesia using the Pushover Analysis Method after the 2018 Earthquake Event (SNI Approach for Earthquake-Resistant Buildings)

Ayuddin
Study Program of Civil Engineering for Building Construction (TSBG), Faculty of Engineering, Universitas Negeri Makassar, Indonesia
ayuddin@unm.ac.id (corresponding author)

Po-Chien Hsiao
Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, 43 Keelung Rd., Sec.4, Taipei City, 106, Taiwan
pchsiao@mail.ntust.edu.tw

Received: 26 November 2024 | Revised: 2 January 2025 | Accepted: 18 January 2025

 DOI: https://doi.org/10.48084/etasr.9723

ABSTRACT

The purpose of this research is to assess the structural performance level resulting from the assessment through ETABS software based on FEMA 440 regulations on the planning of the Y Hotel building in Palu City, Central Sulawesi, Indonesia after being analyzed by the pushover analysis method after the 2018 earthquake. The study subject is the upper structure of the Hotel Y building, namely the columns, beams, plates, and roofs. Data analysis techniques were carried out according to the rules of load simplification. Three-dimensional modeling of the building was conducted using the ETABS softwar before the analysis and pushover stages for performance evaluation. In accordance with the design of the Hotel Y building, the total height is 56 m with 15 stories, using reinforced concrete structures to provide optimal stability and strength. The basic Y-shape was chosen to maximize space distribution and increase visual appeal. The material qualities used were Fc' 35 Mpa and 30 Mpa, Fy' = 400 Mpa, Ec = 4700√(fc'), BJTP 24, and BJTD 40. The analysis of loading calculations was conducted in accordance with SNI 1727: 2020 and SNI 1726: 2019 standards, including dead load, live load, fixed additional load, rain load, roof live load, wind load, and earthquake load. The results of this study obtained an effective base shear force greater than the plan shear force, namely Vx = 3215.2914 kN > Vplan = 2059.5824 kN and Vy = 3255.9481 kN > Vrencana = 2059.5824 kN. The maximum total deviation in the X and Y directions is 0.002 mm and 0.002 mm, respectively, for maximum inelastic deviations of 0.0006 mm and 0.0009 mm, respectively, which means that the structural performance based on ATC-40 is in the Immediate Occupancy category.

Keywords-pushover analysis; structure performance level; FEMA 440

I. INTRODUCTION

Indonesia, as an archipelago located in the convergence zone of the Indo-Australian, Eurasian and Pacific plates, has a high level of seismic activity. The Indonesian city of Palu, located on the active Palu-Koro fault zone, is one of the most vulnerable areas to tectonic earthquakes. Earthquakes occurring in this region can trigger significant ground deformation, damage to building structures, and soil liquefaction. The impact of earthquakes can be quite severe, consisting of large economic losses, disruption to social activities, damage to building structures, and loss of human lives. In an effort to improve the resilience of buildings to earthquake disasters, the concept of Performance-based Design is gaining increasing attention. It is an innovative approach to structural planning that focuses not only on fulfilling the minimum requirements of building codes, but also on the ability of a building to maintain its primary function and protect its occupants during an earthquake of a certain intensity and in the analysis to reliably obtain the building response [1].

One of the key tools in the application of Performance-based Design is pushover analysis. This analysis allows engineers to evaluate in depth the non-linear behavior of a structure when subjected to gradually increasing lateral loads, allowing weak points and potential collapse mechanisms to be identified. Pushover analysis is a probabilistic analysis of structural systems with assessment of vulnerable structures in earthquake-prone regions [2, 3]. Pushover analysis has become a standard tool of civil engineering practice for the analysis of various structural typologies for building and bridge construction [4]. This analysis can well capture the specimen behavior related to peak base shear, initial stiffness, displacement of each floor, and plastic joint development [5]. Pushover analysis thus provides a solid foundation for effective earthquake mitigation design, enabling planners to make more informed decisions on material selection, structural member dimensions, and the overall earthquake-resistant system. In addition, pushover analysis also allows to determine the level of building failure that can be tolerated at various earthquake levels, allowing for more measured and economic planning. In addition, the evaluation of the seismic strength of building structures is usually conducted with the capacity design approach which takes into account the nonlinear response of the structure through a behavioral factor and, which takes into account several parameters including capacity. In seismic design codes, the actual seismic load is reduced by this factor to dissipate energy, reserve strength, and redundancy [6]. The application of Performance-based Design, the pushover analysis method that refers to the FEMA 440 standard is the main reference [17]. This standard provides a comprehensive framework for evaluating the capacity of a structure to resist earthquake and wind lateral loads [5]. By performing a pushover analysis based on FEMA 440, engineers can identify the building performance point, i.e., the condition at which the structure reaches a certain maximum deformation without suffering damage that endangers safety and can estimate the building response that occurs [17].

Through this analysis, structural performance can be categorized into levels such as Immediate Occupancy (IO), Life Safety (LS), or Collapse Prevention (CP). Comparison based on target displacement is performed by considering three target displacements, namely fulfil elastic, elastic to plastic, and plastic conditions on the capacity curve of the building frame [7, 8]. Various case studies have proven that the FEMA 440 approach is able to provide a very detailed picture of the behavior of structures when exposed to earthquakes, allowing for more effective mitigation planning. Pushover analyses are mainly performed using the concentrated plasticity model, which is established when the building reaches the yield point. The pushover method with reference to ATC-40 and FEMA 440 is effective in measuring building performance based on Immediate Occupancy to Life Safety levels [15, 17]. Damage control means that if the structure is subjected to an earthquake, the structure is still able to withstand it, with a very small risk of human casualties. With the pushover analysis approach, numerical simulations can be performed in capturing the global and local nonlinear seismic response of the structure.

In this research, the object of study is a Y-shaped hotel building located in Palu City. Y-shaped buildings have different lateral load distribution characteristics compared to square or rectangular buildings, requiring a more comprehensive analysis to determine the structural response to earthquake-induced lateral loads. Using ETABS software and the FEMA 440-based pushover analysis method, this study evaluates the performance of buildings in resisting earthquake lateral loads and identifies potential improvements needed to ensure that the building can function safely under earthquake conditions.

II. RESEARCH METHOD

A. General

This research was conducted using the quantitative data analysis method, where the data consist of numbers. In this study, pushover analysis was completed using the FEMA 440 method through the ETABS software, referring to SNI 1726 2019, SNI 1727 2020, and FEMA 440 [17].

B. Research Model

The research object used as the evaluation material in this study is the Hotel Y building located on Soekarno Hatta Street, Palu City, Central Sulawesi and is shown in Figure 1.

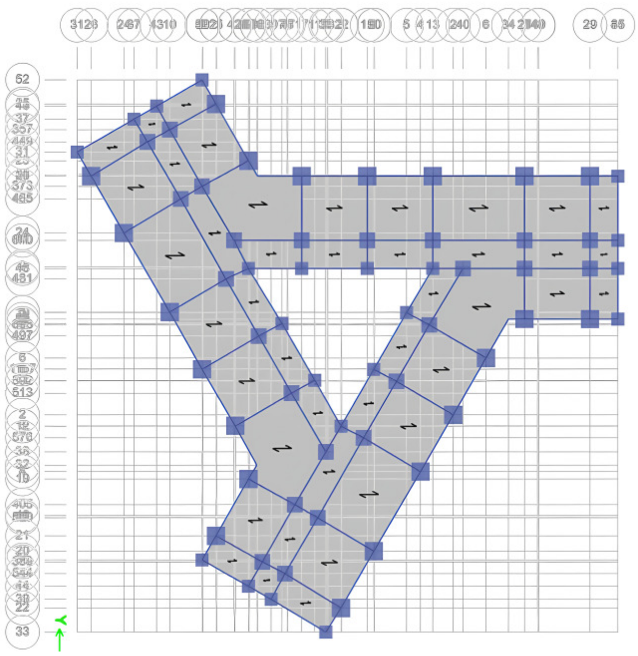

Fig. 1. Floor plan of Hotel Y.

The subject of this research is the upper structure, with:

- Concrete quality f’c= K400 and K350 (35 and 30 MPa, respectively).
- Steel Quality f’y = D40 400 MPa

- Modulus of elasticity of concrete Ec = 4700 √(f'c)
- Diameter ≤ 10 mm (code Ø) plain rebar BJTP 24 with yield strength fy = 240 MPa
- Diameter ≥ 20 mm (Code of D) ribbed rebar BJTD 40 with yield strength fy = 400 MPa
- Diameter ≥ 20 mm (code D) ribbed rebar BJTD 50 with yield strength fy = 400 MPa

The field data were used to create a 3-dimensional model using the ETABS structural software. Next, load analysis was conducted, considering Dead Load (DL), Live Load (LL), Additional Dead Load (ADL), Roof Live Load (LR), Rain Load (RL), Earthquake Load (EqL), and Wind Load. (WL). Then, a nonlinear static pushover analysis was conducted by defining plastic hinges on beams and columns. In this study, capacity curves, plastic hinges, and performance points were produced followed by the determination of the structural performance level according to FEMA 440 [17]. Similar research, such as that conducted on the Santa Maria Hospital building in Pemalang, showed that the pushover method with reference to ATC-40 and FEMA 440 is effective in measuring building performance based on Immediate Occupancy to Life Safety levels [15, 17]. Another study on the 7-storey reinforced concrete frame Education Building evaluated has met the minimum performance limit requirements (Life Safety) when reviewed based on the displacement and drift values of the pushover analysis results. The structure is classified as having a damage control performance level when reviewed based on FEMA 356 [16] and FEMA 440 [17]. Damage control means that if the structure is subjected to an earthquake, the structure is still able to withstand it, with a very small risk of human casualties. With the pushover analysis approach, numerical simulations can be performed in capturing the global and local nonlinear seismic response of the structure.

In this research, the object of study is a Y-shaped hotel building located in Palu City. Y shaped buildings have different lateral load distribution characteristics compared to square or rectangular buildings, requiring a more comprehensive analysis to determine the structural response to earthquake-induced lateral loads. Using ETABS software and the FEMA 440-based pushover analysis method, this study evaluates the performance of buildings in resisting earthquake lateral loads and identify potential improvements needed to ensure that the building can function safely under earthquake conditions.

III. RESULTS AND DISCUSSION

A. 3D Modeling

The modeling of the Hotel Y building is planned with a reinforced concrete structural model consisting of 15 floors with a total height of 56 m. Hotel Y is planned with 3 types of columns that have different dimensions and reinforcements, namely K1 (700×700 mm), K2 (700×700 mm), and K3 (500×500 mm). The beams consist of 3 types marked with codes B1 (300×700 mm), B2 (250×500 mm), and B3 (200×400 mm). In this planning, a slab with a thickness of 130 mm is used, and the roof structure uses a concrete deck. The 3D modeling was carried out in ETABS, as shown in Figure 2.

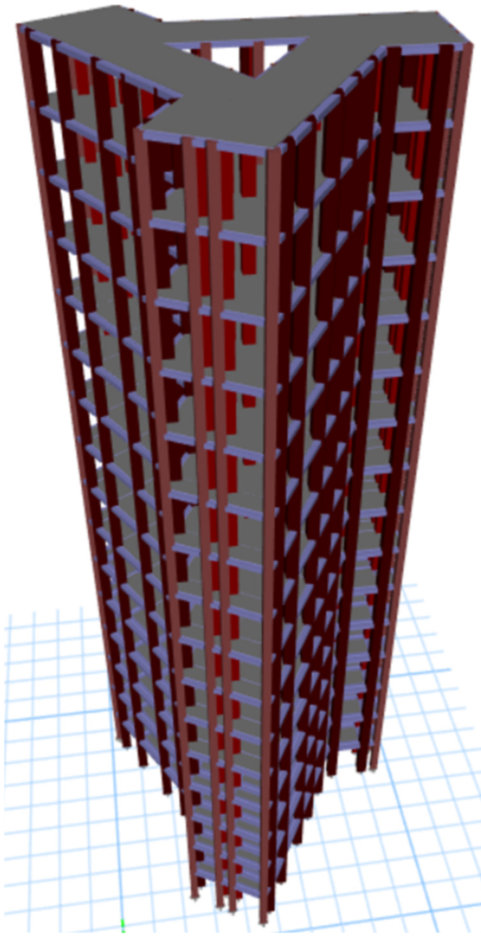

Fig. 2. The 3D model.

B. Load Analysis

Load analysis according to SNI 1727-2020, 2020, which starts with the calculation of additional DL on the floor slab of 1.44 kN/m^2, was applied to the slab as a uniform load. The additional DL on the beam of 0.88 kN/m^2 was applied to the frame beam as a continuous load. The additional DL on the roof of 1.32 kN/m^2 was applied as a uniform load. The LL with the load for rooms follows:

- Reception = 6.23 kN/m^2
- Main Lobby = 4.97 kN/m^2
- Cafe Resto = 4.97 kN/m^2
- Public Toilet = 1.86 kN/m^2
- Storage Room = 2.43 kN/m^2
- Lift = 3.83 kN/m^2
- Emergency Stairs = 4.14 kN/m^2
- Management Room = 2.61 kN/m^2
- Security Room = 2.45 kN/m^2
- Back Office = 1.20 kN/m^2

- Private Room = 1.63 kN/m^2
- Corridor = 2.49 kN/m^2
- Balcony = 3.15 kN/m^2
- Gym = 2.24 kN/m^2

Also, roof live load of 1.33 kN/m^2 and rain load of 0.20 kN/m^2 were considered.

Based on [8], regarding earthquake loads, the risk category for hotel buildings falls into category II, with a seismic importance factor of 1. The site classification is SE. The design response spectrum is shown in Figure 3. Earthquake load analysis based on puskim.pu.go.id in 2021 for X and Y direction earthquake loads according to the building's location was conducted and the following results were obtained:

- Ss = 0.15
- S1 = 0.6
- Sds = 0.80
- Sd1= 0.80
- Long Period = 12.

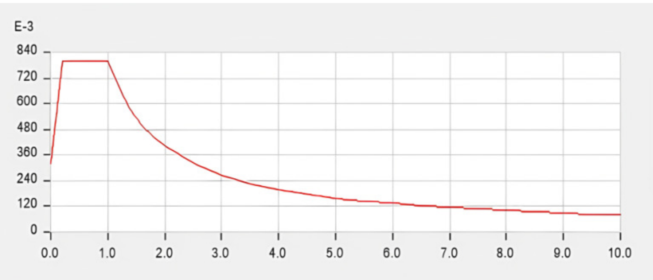

Fig. 3. Design spectrum response.

Then, a load case for dynamic earthquake loads in the X and Y directions was created. Based on the wind map of Palu city, Indonesia, it has a basic wind speed of around 25 mph (40.2 km/h) with exposure B, a wind direction factor of 0.85, and a topographic factor (Kzt) of 1. These values were input into the load pattern for wind loads in the X and Y directions.

C. *Stages before Analysis*

Then, a load combination was created with 36 load combinations based on the Indonesian National Standard (SNI) 1726:2019 [9]. The mass sources were adjusted for self-weight and additional mass. The minimum requirements for additional loads in storage areas and partition loads have been regulated according to the Indonesian National Standard (SNI) 1727 article 4.3.2 [10]. Before conducting the running analysis, a model check was performed by applying the degree of freedom settings, load settings, selecting load combinations, and analysis running. The structural check is shown in Figure 4, indicating that the structure is in a safe condition.

D. *Structural Behavior Checking*

The structural behavior check with a 15% mode combination difference was then analyzed with SRSS, and the mode count check shows that the total response Sums Ux and Uy for mode 211 exceeded the minimum requirement. The mass participation values are shown in Figure 5. According to the provisions of [9], the base shear resulting from dynamic analysis (Vd) must have a value of 100% of the base shear resulting from static analysis (Vs). The static shear force in the X and Y directions is 2059.5824, while the dynamic shear force in the X and Y directions is 2073.4603 and 2067.9308, respectively. The results of the base shear analysis are shown in Figure 6, with the dynamic shear forces meeting the requirements.

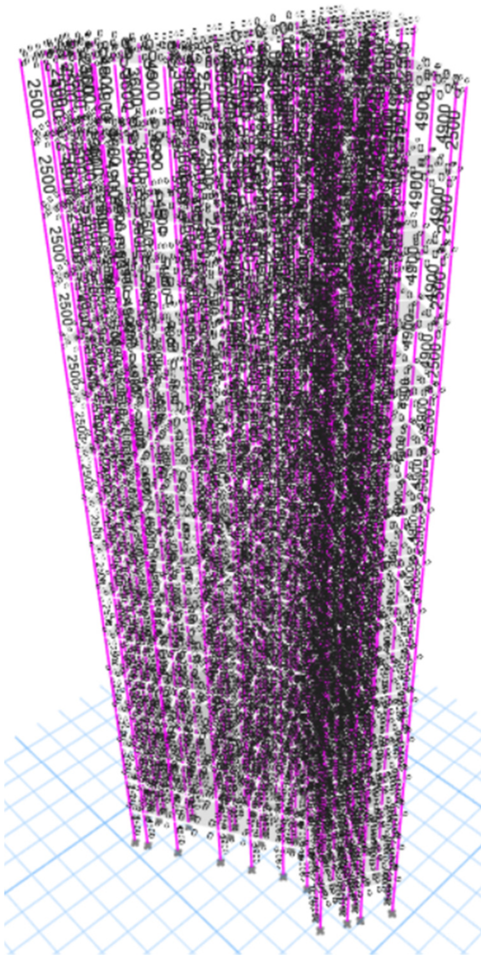

Fig. 4. Model check result.

E. *Nonliniar Static Analysis (Pushover Analysis)*

Pushover Analysis is a structural evaluation technique used to determine the strengths and weaknesses of a building when facing an earthquake. This analysis is conducted by gradually applying loads to a computer model of the building, simulating the effects of an earthquake, with the first mode including at least 90% mass participation [11]. The results of this analysis will show which parts of the building are most vulnerable to damage and how the building will collapse as a whole.

Modal Participating Mass Ratios

File Edit Format-Filter-Sort Select Options

Units: As Noted

Filter:

Case	Mode	Period sec	UX	UY	UZ	SumUX	SumUY	SumUZ	RX
Modal	202	0.023	0	0	0	0.9999	0.9999	0	0
Modal	203	0.023	0	0	0	0.9999	0.9999	0	0
Modal	204	0.023	0	0	0	0.9999	0.9999	0	0
Modal	205	0.023	0	0	0	0.9999	0.9999	0	0
Modal	206	0.023	0	1.109E-06	0	0.9999	0.9999	0	3.338E-06
Modal	207	0.023	0	0	0	0.9999	0.9999	0	1.169E-06
Modal	208	0.023	0	0	0	0.9999	0.9999	0	0
Modal	209	0.023	0	0	0	0.9999	0.9999	0	0
Modal	210	0.022	0	0	0	0.9999	0.9999	0	0
Modal	211	0.022	5.686E-06	9.164E-06	0	1	1	0	2.697E-05
Modal	212	0.022	9.164E-06	5.686E-06	0	1	1	0	1.674E-05
Modal	213	0.022	0	0	0	1	1	0	0
Modal	214	0.022	0	0	0	1	1	0	0
Modal	215	0.022	0	0	0	1	1	0	0
Modal	216	0.022	0	0	0	1	1	0	0

Record: << < 211 > >> of 300 Add Tables... Done

Fig. 5. Mass participation value.

Base Reactions

File Edit Format-Filter-Sort Select Options

Units: As Noted

Filter:

Output Case	Case Type	Step Type	FX kN	FY kN	FZ kN	MX kN-m	MY kN-m	MZ kN-m	X m
Eq X Seismik	LinStatic	Step By Step	-2059.5824	0.0011	0	-0.0403	-83831.3338	26935.1598	0
Eq X Seismik	LinStatic	Step By Step	-2059.5823	0.001	0	-0.0374	-83831.3283	29050.4957	0
Eq X Seismik	LinStatic	Step By Step	-2059.5826	0.0012	0	-0.0432	-83831.3393	24819.8238	0
Eq Y Seismik	LinStatic	Step By Step	0.0012	-2059.5844	0	83970.9896	0.0425	-21959.7015	0
Eq Y Seismik	LinStatic	Step By Step	0.001	-2059.5843	0	83970.9867	0.0371	-24032.8266	0
Eq Y Seismik	LinStatic	Step By Step	0.0013	-2059.5845	0	83970.9925	0.0479	-19886.5764	0
Eq X Dinamik	LinRespSpec	Max	2073.4603	1325.6667	0	46695.2577	73232.2677	21894.6927	0
Eq Y Dinamik	LinRespSpec	Max	1397.0423	2067.9308	0	72245.1936	49197.697	33243.4929	0

Fig. 6. Basic shear force

The stages in the Pushover analysis using ETABS software are.

1. Determining the point to be reviewed

The observation point is a reference point used to measure a deformation at the top of the building. The observation focus was chosen at point 29 of the roof deck.

2. Determining the nonlinear gravity case

In accordance with [9], gravitational loads include all dead loads, including additional dead loads with a load factor scale of 100%, and live loads with a load factor scale of 25% with the influence of nonlinear geometry and structural material during the desired gravitational loading phase.

3. Determining the nonlinear pushover case

Lateral loads are applied gradually, starting from the structural condition after the nonlinear gravity analysis. A lateral load factor of -1.0 is used to obtain positive displacement.

4. Modeling Plastic Hinges

Plastic hinges indicate the inability of a structural element such as columns and beams to resist forces in the structure. The commonly applied design principle is Strong Column - Weak Beam. The purpose of this principle is for the beam to experience damage first, thereby protecting other structural elements.

Plastic joints are modeled on the beam cross-section in the support area with the assumption that the place where plastic joints are formed uses the M3 moment model. The ETABS structural analysis program has integrated the feature of automatic plastic hinge determination based on FEMA 440 standards [17]. For beam elements, this program uses relative distances of 0.05 and 1.0. This means that the program will automatically place two plastic hinges at a distance of 5% from the starting end and 100% from the ending end of the beam. To analyze damage to a column, the program uses a P-M2-M3 type plastic hinge model. This model considers the influence of axial force (P) and bending moment on the two main axes of the column (M2 and M3). By placing the plastic hinges at distances of 0.05 and 0.1 from the length of the column, the program assumes that column damage will begin at these points due to the combination of the acting forces.

5. Running analysis

The running process is carried out after setting the load cases to run, as shown in Figure 7.

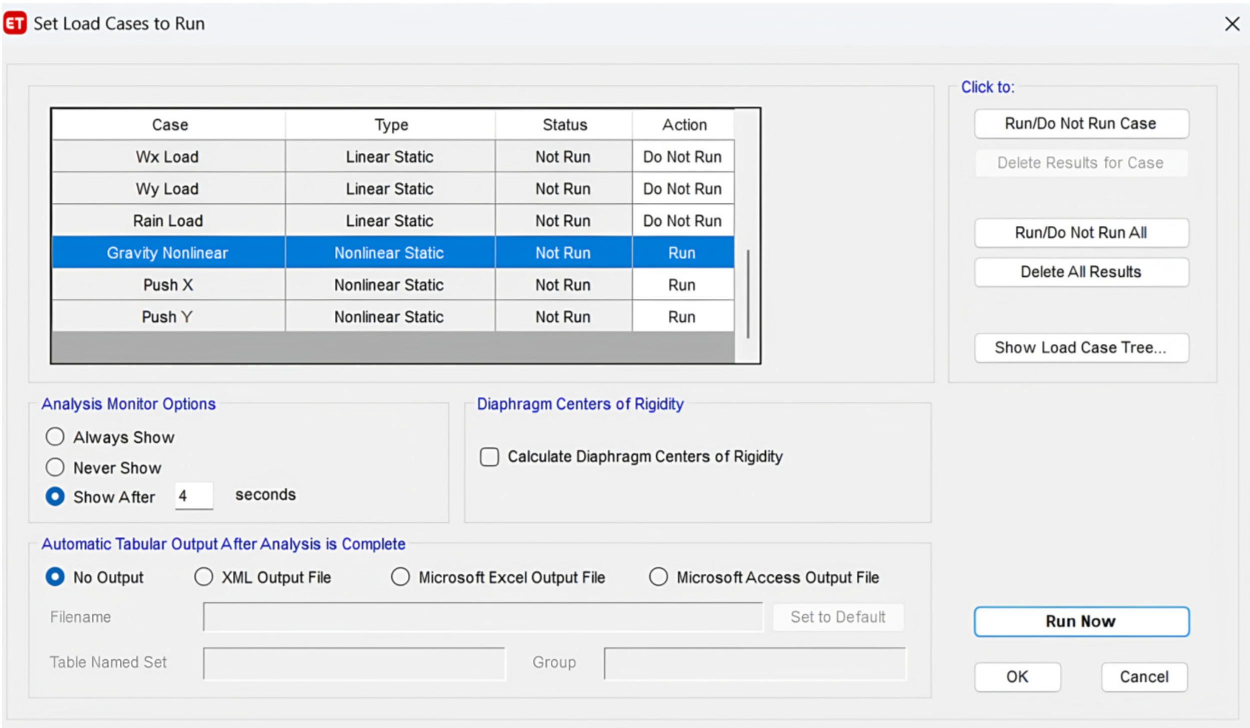

Fig. 7. Setting load cases to run.

F. Nonlinear Static Results (Pushover Analysis)

1) Capacity Curve

Pushover analysis produces a capacity curve that illustrates a structure's ability to withstand horizontal forces due to seismic loads. The performance of the structure for each approach is compared based on the capacity curve and the global damage pattern [12, 13]. This curve is obtained by gradually applying lateral push loads to the structural model until it reaches a collapse condition. The capacity curve is shown in Figures 8 and for the X and Y directions. In both cases, the capacity curve illustrates the nonlinear response of the structure to lateral loads in the X direction. The relationship between shear force and displacement is shown in steps 1-5. The comparison values of displacement and the shear force in the X and Y direction are shown in Tables I and II.

TABLE I. COMPARISON OF DISPLACEMENT AND SHEAR FORCE IN THE X DIRECTION

Step	X Direction	
	Displacement (mm)	Base shear force (kN)
0	0	0
1	75.89	2207.0304
2	114.723	3215.2914
3	114.734	3215.2867
4	193.646	4276.1862
5	204.399	4370.4638

TABLE II. COMPARISON OF DISPLACEMENT AND SHEAR FORCE IN THE Y DIRECTION

Step	X Direction	
	Displacement (mm)	Base shear force (kN)
0	0	0
1	68.184	1975.3205
2	122.101	3255.9481
3	122.112	3254.5991
4	210.121	4128.9867
5	0	0

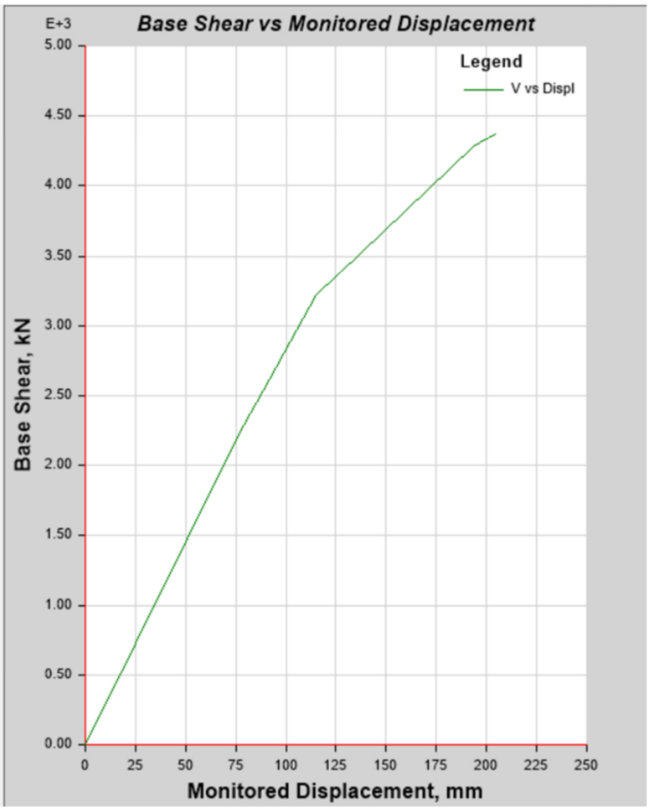

Fig. 8. X direction capacity curve.

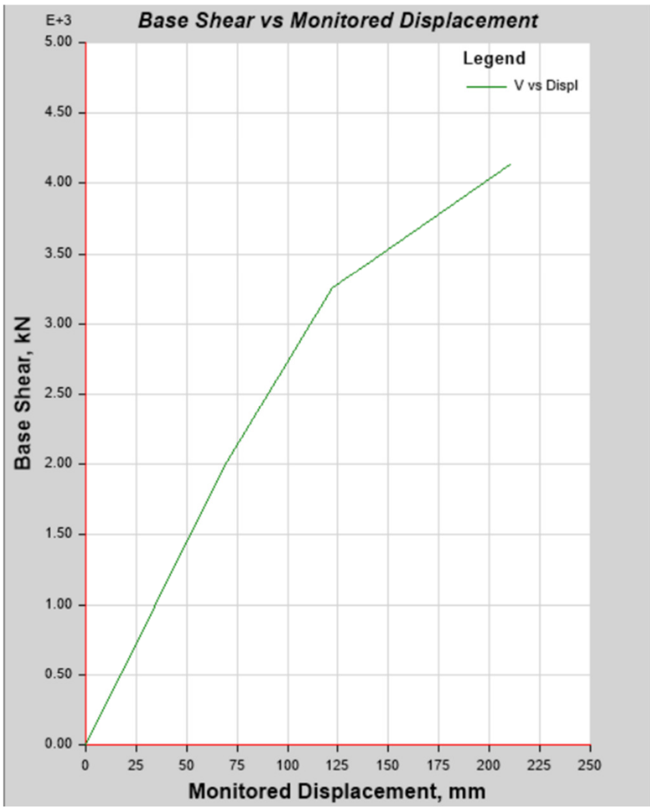

Fig. 9. Y direction capacity curve.

As can be seen on Table I, the structure shows an increase in displacement and base shear as the load steps increase. The maximum displacement achieved is 204.399 mm and the maximum base shear is 4370.4638 kN at step 5. The structure has the ability to withstand significant deformation due to its good ductility, as evidenced by the increase in displacement reaching 204.399 mm without a significant decrease in base shear.

Table II shows that the structure reached the maximum displacement of 210.121 mm and the maximum base shear force of 4128.9867 kN at step 4. This indicates the maximum capacity of the structure to resist lateral forces in the Y direction. The structure is capable of withstanding a significant displacement of up to 210.121 mm without experiencing a significant decrease in base shear force. This indicates that the structure has good ductility to withstand lateral loads due to an earthquake.

2) Formation of Plastic Hinges

The analysis of the plastic hinge mechanism will produce a plastic hinge distribution diagram and a three-dimensional visualization depicting the maximum damage condition of the structure [14]. Color description on plastic joints is shown in Table III. Table IV shows the distribution results of the number of plastic hinges that occur for each displacement due to the push load in the X direction.

TABLE III. COLOR DESCRIPTION ON PLASTIC JOINTS

Symbol	Description	Explanation
A	Operational	Indicates that the structure is in fully operational condition with no significant signs of deterioration exhibited in the structural and non-structural elements.
IO	Immediate Occupancy	The structure has sustained minor, but not significant damage which does not affect the stability or the main function of the building.
LS	Life Safety	Indicates that the structure has sustained greater damage, both in structural and non-structural elements, but this damage is still within tolerable limits.
CP	Collapse Prevention	The structure has suffered severe damage and may have already experienced a significant loss of stiffness and capacity.

TABLE IV. DISTRIBUTION OF PLASTIC HINGES IN THE X DIRECTION

Step	X Direction		A-IO	IO-LS	LS-CP	>CP	Total
	Displacement (mm)	Base shear force (kN)					
0	0	0	5630	0	0	2	5632
1	75.89	2207.0304	5631	0	1	0	5632
2	114.723	3215.2914	5631	0	0	1	5632
3	114.734	3215.2867	5631	0	0	1	5632
4	193.646	4276.1862	5632	0	0	0	5632
5	204.399	4370.4638	5632	0	0	0	5632

This structure demonstrates quite good performance in facing increased lateral loads up to step 5. Most elements remain at the Immediate Occupancy (IO) and Life Safety (LS) performance levels, indicating that the structure can still safely withstand loads [17]. However, the presence of two elements at the >CP level in step 0 indicates that there are elements that are vulnerable or already weak before the analysis begins. This could be an indication to evaluate or strengthen these elements to improve the overall performance of the structure. In Figure 10, plastic hinges are shown at step 5 in the X direction.

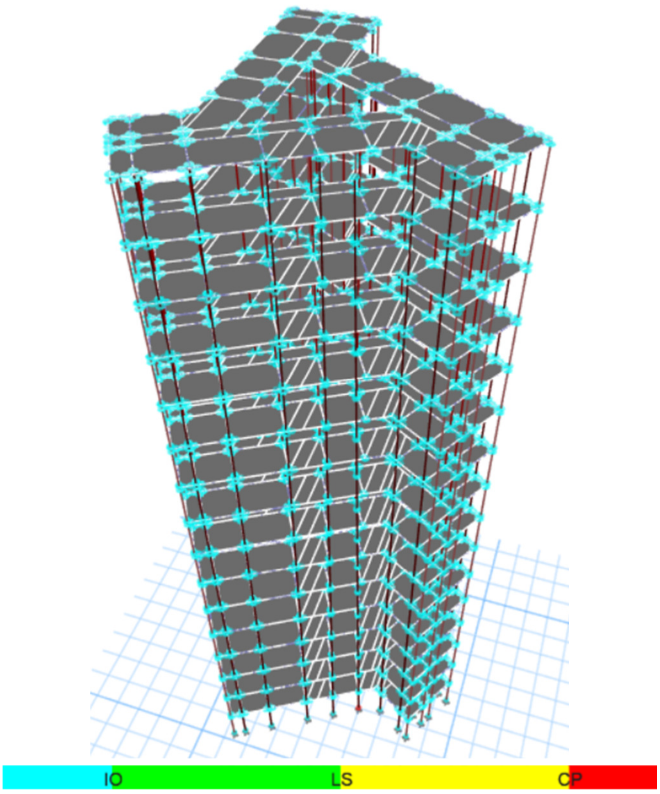

Fig. 10. Plastic joint placement at step 5. X-direction.

Table V shows the distribution results of the number of plastic hinges that occur for each displacement due to the push load in the Y direction.

TABLE V. DISTRIBUTION OF PLASTIC HINGES IN THE Y DIRECTION

Step	X Direction		A-IO	IO-LS	LS-CP	>CP	Total
	Displacement (mm)	Base shear force (kN)					
0	0	0	5632	0	0	0	5632
1	68.184	1975.3205	5632	0	0	0	5632
2	122.101	3255.9481	5631	0	1	0	5632
3	122.112	3254.5991	5631	0	0	1	5632
4	210.121	4128.9867	5631	0	0	1	5632

The structure generally remains in a safe condition up to step 4, with most elements at the Immediate Occupancy (A-IO) and Life Safety (IO-LS) levels. This indicates that the structure is still capable of withstanding lateral forces with a deformation level that is still safe. However, at step 4, there is one element that reaches the >CP condition, which indicates that there is an element that is already vulnerable to failure or collapse under the given displacement and shear force, so this element may require special attention or additional reinforcement to improve the structural performance [17]. The needed plastic hinges at step 4 in the Y direction are shown in Figure 11.

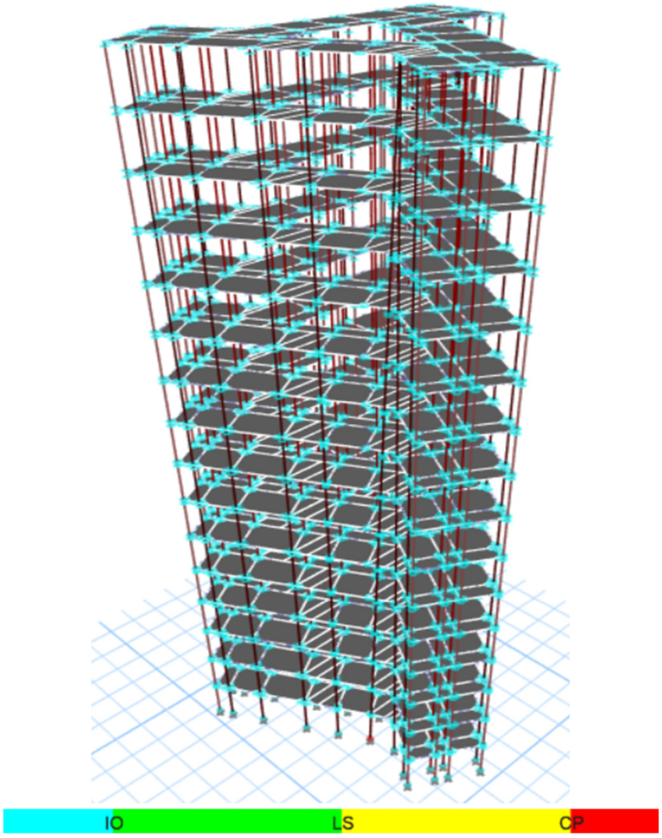

Fig. 11. Plastic joint placement at step 4. Y-direction.

G. Structural Performance Level

The structural performance level is a parameter that describes the extent to which a structure can withstand earthquake loads without experiencing excessive damage or loss of functionality. Performance points were determined using the capacity spectrum method according to FEMA 440 guidelines. FEMA 440 method is an improvement of the FEMA 356 method based on the displacement coefficient/DCM [16, 17]. The performance level categories based on FEMA are shown in Table VI. Figure 12 shows the performance point mode FEMA 440 in the X direction. The intersection of the capacity curve (green) and the demand curve indicates the performance point of the structure. This intersection point indicates that the structure can withstand earthquake loads up to a spectral displacement value of approximately 114.723 mm with a spectral acceleration (Sa) of 0.25 g. Under these conditions, the structure is within safe limits and does not experience structural failure. The spectral displacement capacity of the structure is 2106.539 mm. The ductility ratio of 7.847 indicates that the structure has good ductility, allowing it to undergo significant deformation without sudden collapse. The secant period (2.332 s) and the effective period (2.762 s) indicate that the structure experiences period elongation when entering the inelastic condition, which occurrs when the structure begins to undergo plastic deformation. The effective damping ratio (Beff) of 0.104 indicates that the structure has excellent energy dissipation capacity.

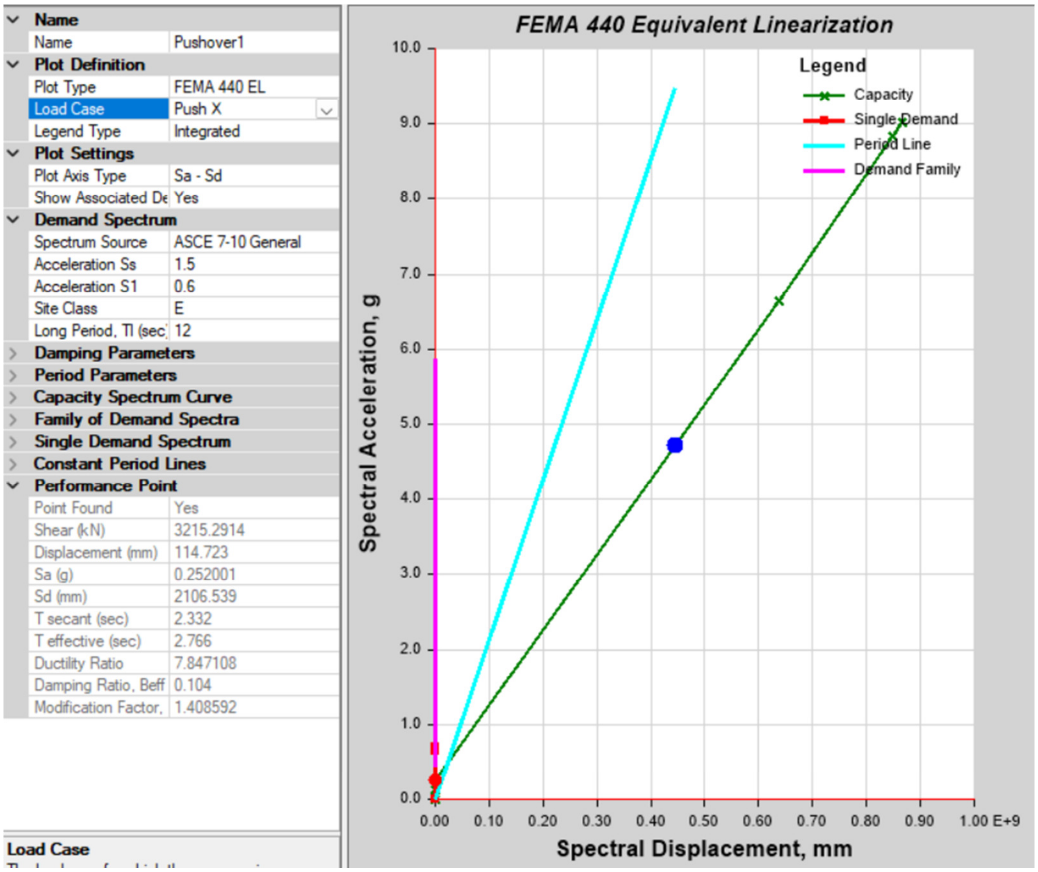

Fig. 12. Performance point FEMA 440 method X-direction.

TABLE VI. PERFORMANCE LEVEL CATEGORIES BASED ON FEMA 440

Type	**Performance Level Target**		
	IO	**LS**	**CP**
	Light	**Moderate**	**Severe Damage**
Primary	Fine cracks in several locations. No collapse occurred.	Serious failure of beams, chipping of concrete cover, shear cracking of ductile columns, and chipping of non-ductile concrete columns.	Many cracks and plastic hinges on ductile structural elements. Cracks on several non-ductile columns. Severe damage to the short columns
Secondary	Concrete cover peeling on several beams and columns. Flexural cracks on beams and columns.	Many cracks and plastic hinges on ductile elements. Cracks on several non-ductile columns. Severe damage.	Excessive concrete spalling on columns and beams. Severe damage to joints and several bent reinforcements.
Drift	1% temporary	2% temporary 1% permanent	4% temporary permanent

From the maximum shear value (3215.2914 kN) and the maximum displacement (114.723 mm), it is evident that this structure has a sufficiently high capacity to withstand lateral loads. This value supports the safety of the analyzed structure against earthquakes. The modification factor of 1.408 indicates an adjustment for inelastic response, suggesting that the structure has already considered factors that will enhance earthquake resistance. There are 5 steps and coordinates for the intersection of the capacity curve and capacity spectrum curve when using the ADRS format [17]. Table VII shows the results of calculating the capacity of the building structure to spectral displacement and acceleration in the X direction using the Acceleration-Displacement Response Spectrum format. (ADRS). At each step, there is an increase in the values of Sd and Sa, indicating an improvement in the building's capacity to withstand displacement and acceleration due to seismic loads. In the final step, the high Sa capacity value demonstrates the structure's ability to withstand significant acceleration approaching 9g, indicating the structure's resilience against high seismic loads. Figure 13 shows the performance point of the FEMA method in the Y direction.

TABLE VII. CAPACITY CURVE CALCULATION OF X-DIRECTION

Step	**X Direction**	
	Sd Capacity (mm)	**Sa Capacity (mm)**
0	0	0
1	152.115	0.121773
2	339.925	0.251983
3	636313634	6.643084
4	847143451	8.835069
5	865862330	9.029867

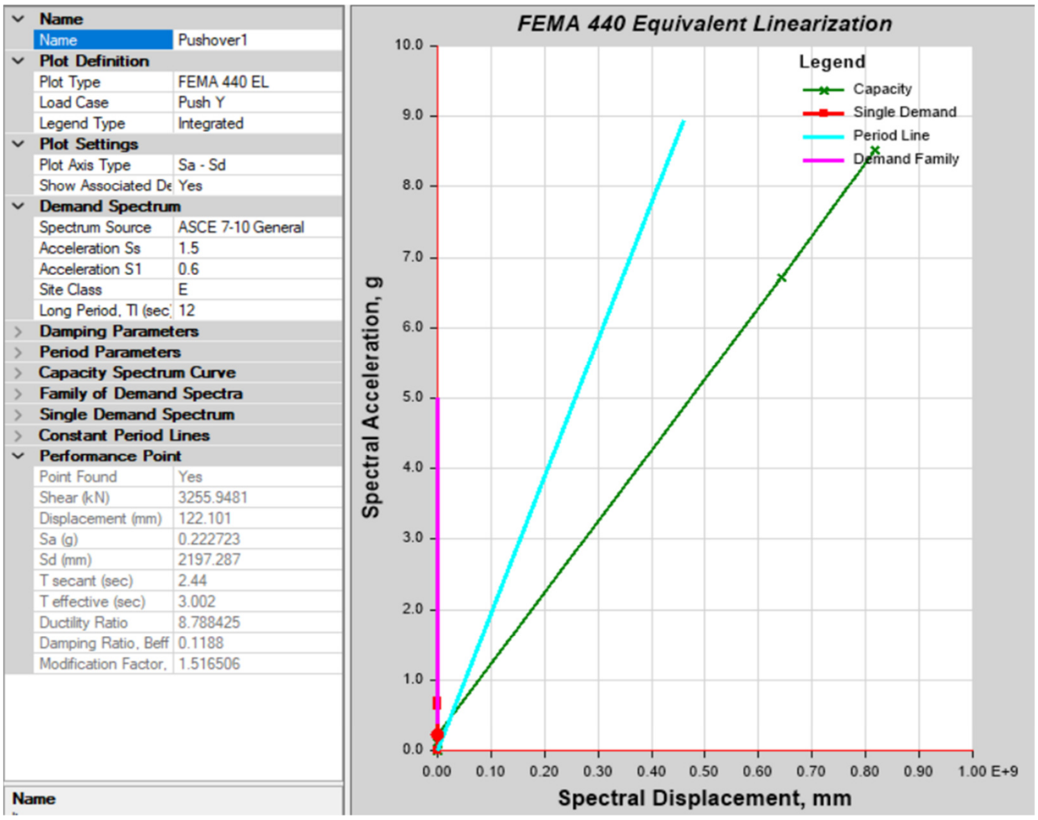

Fig. 13. Performance point FEMA 440 method Y-direction.

The capacity curve (green line) shows the ability of the structure to withstand increasing displacement and spectral acceleration with the addition of lateral loads. The points of the capacity curve and the performance point curve show that the structure can withstand earthquake lateral forces up to a displacement of 122.101 mm and a shear force of 3255.9481 kN which are within the specified safety limits. The spectral acceleration at the performance point is 0.222723 g. This indicates the acceleration experienced by the structure at that maximum displacement. The spectral displacement capacity of the structure is 2197.287 mm. The instantaneous period of 2.44 s indicates the vibration period of the structure under a certain condition. The effective period of 3.002 s reflects the effective period after considering inelastic deformation. The ductility ratio of 8.788425 and the effective damping ratio of 0.1188 indicate that the structure has quite good flexibility and sufficient capability to reduce vibration energy from an earthquake. The modification factor of 1.516506 indicates the influence of additional factors in the earthquake analysis, such as the inelastic behavior factor.

There are 4 steps and in calculating the intersection coordinates of the capacity curve and the capacity spectrum curve when using the ADRS format. The ADRS format of the capacity curve calculations for the Y direction is shown in Table VIII. At the initial step, both spectral displacement and spectral acceleration start from zero. As the load increases, spectral displacement experiences a significant increase, reaching a maximum value of 818244447 mm at step 4. Meanwhile, spectral acceleration also increases, starting from 0.101918 g at step 1 to 8.53097 g at the last step. This value reflects the response of the structure to the increased earthquake load in the Y direction, demonstrating the capacity and flexibility of the structure in facing the horizontal forces induced by the earthquake.

TABLE VIII. Y-DIRECTION ADRS FORMAT CAPACITY CURVE CALCULATION

Step	Y Direction	
	Sd Capacity (mm)	Sa Capacity (mm)
0	0	0
1	134.71	0.101918
2	328.789	0.222704
3	643799913	6.724324
4	818244447	8.53097

TABLE IX. PERFORMANCE POINT VALUES OF FEMA 440

Direction	V (kN)	D (mm)	S_a (g)	S_D (mm)	T_{eff} (s)	B_{eff}
X	3215.29	114.73	0.25	2106.54	2.76	0.104
Y	3255.95	122.10	0.22	2197.29	3.02	0.118

The analysis results in capacity spectrum curves and demand spectrum curves are displayed in the form of ADRS graphs in Figures 12 and Figure 13. The point of intersection shown between the two curves is called the performance point and indicates the expected level of damage to the structure [17]. A summary of the analysis results is presented in Table IX.

The displacement limit according to [9] is determined as:

$$0.025 \text{ h} = 0.025 \times 56000 = 1400 \text{ mm} \quad (1)$$

where the value of 1400 mm is still greater than Dx = 114.723 mm and Dy = 122.101 mm and the building's displacement performance is considered good. The effective base shear values in the linear state in both directions were obtained, each greater than the planned base shear value, which is stated as:

$$Vx = 3215.2914 \text{ kN} > Vplan = 2059.5824 \text{ kN} \quad (2)$$

$$Vy = 3255.9481 \text{ kN} > Vplan = 2059.5824 \text{ kN} \quad (3)$$

FEMA-440 equivalent linearization that is already built-in in the ETABS v2018 program comes from statistical analysis of a large number of responses to various ground motions [15, 16]. The needed parameter to know the performance level of a structure is the average drift value of each floor where the total floor height is 56 m = 56000 mm. The determination of the structural performance level (Table VI) is calculated as follows.

The maximum total deviation value is calculated by:

$$\text{Maximum Total Deviation} = \frac{\text{Dt}}{\text{Htotal}} \quad (4)$$

$$\text{X direction} = \frac{114.723}{56000} = 0.002 \quad (5)$$

X direction $= 0.002$ (Immediate Occupancy)

$$\text{Y direction} = \frac{122.101}{56000} = 0.002 \quad (6)$$

Y Direction $= 0.002$ (Immediate Occupancy)

The maximum inelastic deviation value is calculated by:

$$\text{Maximum Inelastic Deviation} = \frac{\text{Dt} - \text{Dt1}}{\text{Htotal}} \quad (7)$$

$$\text{X direction} = \frac{114.723 - 75.89}{56000} = 0.0006 \quad (8)$$

X direction $= 0.0006$ (Immediate Occupancy)

$$\text{Y direction} = \frac{122.101 - 68.89}{56000} = 0.0009 \quad (9)$$

Y direction $= 0.0009$ (Immediate Occupancy)

The maximum total displacement values obtained were 0.002 mm in the X direction and 0.002 mm in the Y direction, with maximum inelastic displacements of 0.0006 mm and 0.0009 mm, respectively. Therefore, according to the FEMA 440 method, the structure is categorized into the Immediate Occupancy category (IO) class. This means that the main elements of the building, such as columns and beams, do not experience significant damage [17]. There is no permanent displacement that poses a danger and the overall structure for strength and stiffness is intact. The risk of casualties due to structural failure is also very low. Therefore, this building can be immediately reused without a long time needed for repairs. An overview of research results illustrates that the research gap in pushover analysis of Y-shaped buildings in active earthquake regions is still quite significant. Previous research has not focused on Y-shaped buildings specifically, resulting in a lack of understanding of the structural behavior of these buildings under lateral earthquake loads, which remains unanswered. In addition, specific planning standards for Y-shaped buildings in Indonesia have not been thoroughly developed. Therefore, the presence of the results of this research makes a major contribution to filling the gaps that have occurred so far by presenting an analysis of the behavior of Y-shaped building structures against earthquake lateral loads using the FEMA 440-based pushover method in strong earthquake path areas, especially in the city of Palu, Central Sulawesi, Indonesia.

IV. CONCLUSION

In contrast to previous studies that focused on square or rectangular buildings, this study successfully demonstrated the effectiveness of the pushover method on Y-shaped buildings using the FEMA 440 standard. These results contribute to the development of earthquake-resistant building planning in strong earthquake regions, especially in eastern Indonesia located in Mamuju city, West Sulawesi, and provide data for improved design of Y-shaped buildings.

Based on the obtained results, the maximum total displacement and maximum inelastic displacement for the X and Y directions in the structure of the 15-story Hotel Y building reached values of 0.002 and 0.0006–0.0009. This indicates that the building lies at the Immediate Occupancy level (IO). This means that the structure is in a safe condition against lateral earthquake forces and can be used after an earthquake with minimal damage to structural and non-structural elements.

ACKNOWLEDGMENT

The authors would like to express gratitude to all the lecturers of the Study Program of Civil Engineering for Building Construction, Faculty of Engineering, Universitas Negeri Makassar and the Department of Civil and Construction Engineering, National Taiwan University of Science and Technology for their support in this research.

REFERENCES

[1] A. M. Worku and P.-C. Hsiao, "An improved first-mode-based pushover analytical procedure for assessing seismic performance of special moment resisting frame building structures," *Engineering Structures*, vol. 252, Feb. 2022, Art. no. 113587, https://doi.org/10.1016/j.engstruct.2021.113587.

[2] M. Barbato, Q. Gu, and J. P. Conte, "Probabilistic Push-Over Analysis of Structural and Soil-Structure Systems," *Journal of Structural Engineering*, vol. 136, no. 11, pp. 1330–1341, Nov. 2010, https://doi.org/10.1061/(ASCE)ST.1943-541X.0000231.

[3] R. Shehu, "Implementation of Pushover Analysis for Seismic Assessment of Masonry Towers: Issues and Practical Recommendations," *Buildings*, vol. 11, no. 2, Feb. 2021, Art. no. 71, https://doi.org/10.3390/buildings11020071.

[4] R. Venezia and A. Lupoi, "The choice of the control displacement in pushover analysis of bridges: a case study," *Procedia Structural Integrity*, vol. 62, pp. 796–808, Jan. 2024, https://doi.org/10.1016/j.prostr.2024.09.108.

[5] Z. Wang, P. Martinez-Vazquez, and B. Zhao, "Pushover analysis of structures subjected to combined actions of earthquake and wind," *Engineering Structures*, vol. 221, Oct. 2020, Art. no. 111034, https://doi.org/10.1016/j.engstruct.2020.111034.

[6] D. Samadian, I. B. Muhit, A. Occhipinti, and N. Dawood, "Surrogate models for seismic and pushover response prediction of steel special

moment resisting frames," *Engineering Structures*, vol. 314, Sep. 2024, Art. no. 118307, https://doi.org/10.1016/j.engstruct.2024.118307.

[7] M. Bhandari, S. D. Bharti, M. K. Shrimali, and T. K. Datta, "Assessment of proposed lateral load patterns in pushover analysis for base-isolated frames," *Engineering Structures*, vol. 175, pp. 531–548, Nov. 2018, https://doi.org/10.1016/j.engstruct.2018.08.080.

[8] M. H. Soleimani-Babakamali and M. Zaker Esteghamati, "Estimating seismic demand models of a building inventory from nonlinear static analysis using deep learning methods," *Engineering Structures*, vol. 266, Sep. 2022, Art. no. 114576, https://doi.org/10.1016/j.engstruct.2022.114576.

[9] *SNI 1726 (2019), Tata Cara Perencanaan Ketahanan Gempa Untuk Struktur Bangunan Gedung Dan Nongedung*. Jakarta, Indonesia: Standar Nasional Indonesia, 2019.

[10] *RSNI2 1727 (2018), Beban minimum untuk perancangan bangunan gedung dan struktur lain*. Jakarta, Indonesia: Standar Nasional Indonesia, 2018.

[11] *ASCE 41–13 (2013), Seismic Evaluation and Upgrade of Existing Buildings*. Reston, VA, USA: American Society of Civil Engineers, 2013.

[12] R. S. Olivito and S. Porzio, "A new multi-control-point pushover methodology for the seismic assessment of historic masonry buildings," *Journal of Building Engineering*, vol. 26, Nov. 2019, Art. no. 100926, https://doi.org/10.1016/j.jobe.2019.100926.

[13] A. P. Bakalis and T. K. Makarios, "Seismic enforced-displacement pushover procedure on multistorey R/C buildings," *Engineering Structures*, vol. 229, Feb. 2021, Art. no. 111631, https://doi.org/10.1016/j.engstruct.2020.111631.

[14] S. Malla, M. Alagirisamy, P. Dangol, and O. P. Giri, "Comparative Analysis of an Apartment Building using Seismic Codes NBC 105:1994 and NBC 105:2020 (A Case Study)," *Engineering, Technology & Applied Science Research*, vol. 14, no. 4, pp. 15916–15922, Aug. 2024, https://doi.org/10.48084/etasr.7858.

[15] *ATC-40 (1996), Seismic Evaluation and Retrofit of Concrete Buildings*. Redwood City, CA, USA: Seismic Safety Commission, 1996.

[16] *FEMA 356 (2000), Prestandard and Commentary for The Seismic Rehabilitation of Buildings*. Washington, DC, USA: Federal Emergency Management Agency, 2000.

[17] *FEMA 440 (2005), Improvement of Nonlinear Static Seismic Analysis Procedures*. Washington, DC, USA: Federal Emergency Management Agency, 2005.