Evaluation of Concrete Structure Seismic Performance through Pushover Analysis (Case Study: Amaris Hotel)

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Abstract
Due to its location within a highly seismic-prone region, Bandung City requires particular attention in the design and planning of safe and resilient structures. Amaris Hotel is one of the buildings located in Bandung City. This work seeks to analyze the displacement, drift, and levels of structural performance. This study utilizes the response spectrum analysis and the pushover method as its primary analytical techniques. The structural modeling was carried out using ETABS 18.1.0 software, referring to SNI 1726-2019, ATC-40, and FEMA-440. The analysis revealed inter-story drift at the roof level of 19.866 mm (X) and 26.263 mm (Y) from the response spectrum method, and 36.185 mm (X) and 53.284 mm (Y) from the pushover method. The roof displacement derived from the response spectrum method is 26.095 mm (X) and 27.668 mm (Y), while the pushover method yields 59.253 mm (X) and 59.992 mm (Y). Based on the ATC-40 and FEMA-440 standards, the structure demonstrates an Immediate Occupancy (IO) performance level, given that the drift ratio does not exceed 0.01. This result indicates that the building remains safe and operational following an earthquake, with only minor structural damage observed.

Keywords: response spectrum, pushover, drift, displacement, structural performance

1. Introduction

As a metropolitan area, Bandung is highly susceptible to seismic activity because of its closeness to five active faults—the Lembang, Legok Kole, Jati, CT (Cileunyi–Tanjungsari), and Cicalengka faults—linked to the Citarum Fault. This geographical condition places Bandung among the regions requiring special attention in infrastructure planning and development, particularly for multi-story buildings that are highly susceptible to the impacts of earthquakes.

The Amaris Hotel building in Bandung City serves as the object of this study. The structure consists of eight stories and one basement level. As a hotel facility, the building falls into Risk Category II. Being a commercial facility that accommodates various visitor activities, its structural system must be designed with careful consideration of safety and seismic resistance. The Amaris Hotel is categorized as Seismic Design Category D, with a total height of 27.6 m, and features a Type 2 horizontal irregularity—a re-entrant corner—formed when the floor plan projection surpasses 15% of the structural plan dimension in the relevant direction.

Pushover analysis, or static nonlinear analysis, is a procedure applicable to linear and nonlinear modeling in both 2D and 3D structural systems. This method incrementally applies static lateral loads at each floor's center of mass until the first plastic hinge appears in the structure. The load is progressively increased, producing considerable inelastic behavior until the structure reaches its failure threshold. Such analysis is essential for both existing and newly designed buildings to evaluate the seismic performance of the structure. This study seeks to evaluate the inter-story drift, displacement, and overall structural performance of the Amaris Hotel based on ATC-40 and FEMA-440 criteria.

1.1. Concept of Earthquake-Resistant Buildings

An earthquake occurs due to opposing forces acting on the elastic earth's crust. A seismic-resistant structure is designed to sustain earthquake loads via ductile response, so that despite reductions in strength and stiffness, total collapse is postponed, allowing occupants time for evacuation. Consequently, earthquake-resistant structures are capable of minimizing both losses and casualties during seismic events (Nugraha, et al. 2022)

The concept of earthquake-resistant design follows the Strong Column–Weak Beam principle, in which the strength of columns must exceed that of beams. This ensures that plastic hinges develop in beams rather than in columns, thereby maintaining controlled structural failure. In practice, plastic hinges are intentionally allowed to form in beams but must be avoided in columns during earthquakes. This design philosophy is characterized by flexibility and high ductility, enabling structures to be planned with a minimum seismic design level. Such mechanisms must be ensured through standardized procedures in earthquake-resistant structural design.

1.2. Static Pushover Analysis

In the static pushover method, an earthquake is represented by a set of static lateral loads acting at the floor's center of mass, which are incrementally increased until the first plastic hinge forms, and then continued until the structure exhibits notable post-elastic behavior (Utomo, Susanto and Wibowo 2012). Also known as nonlinear analysis, static pushover analysis is extensively employed in performance-based earthquake engineering.

The capacity and demand curves act as visual indicators of the outcomes derived from the pushover analysis. Performance describes the structure's ability to accommodate seismic demands resulting from ground motion, while capacity defines its strength to endure seismic loading. Therefore, the structural performance must be consistent with the available capacity to ensure compliance with design expectations (Siswanto and Prijasambada 2023).

Within the static pushover method, the performance point is obtained through the intersection of the capacity and demand spectrum curves. The point at which the capacity and demand curves intersect is identified as the performance point.

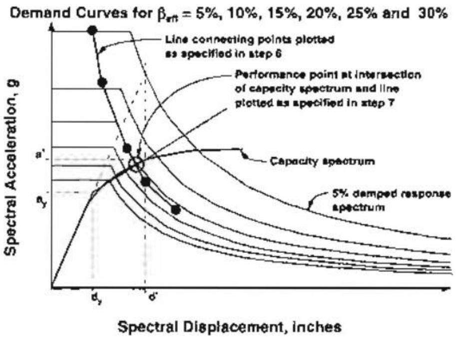

Fig. 1. Performance point curve

1.3. Interstory Drift

The inter-story drift (Δ) represents the relative displacement between the centers of mass of two adjacent floors, indicating the deformation demand of the structure under seismic loading. In cases where the center of mass is not vertically aligned, the displacement at the base story is corrected in accordance with the vertical projection of the center of mass from the story above (Manalip, Windah and Dapas 2014). The subsequent equation defines the calculation of the mass deflection at level x (δ_x) in millimeters.

$$\delta_x = \frac{C_d \delta_{xe}}{I_e} \quad (1)$$

The allowable inter-story drift at each level is defined by Δa, as presented in the following table.

Table 1: Allowable Inter-Story Drift, Δ_a

Structure	Risk Category		
	I , II	III	IV
Non-masonry shear wall buildings, up to 4 stories, with interior elements, partitions, ceilings, and cladding walls designed to accommodate inter-story movements	$0.025h_{sx}$	$0.020h_{sx}$	$0.015h_{sx}$
Masonry cantilever shear wall structures	$0.010h_{sx}$	$0.010h_{sx}$	$0.010h_{sx}$
Other masonry shear wall structures	$0.007h_{sx}$	$0.007h_{sx}$	$0.007h_{sx}$
All other structures	$0.020h_{sx}$	$0.015h_{sx}$	$0.010h_{sx}$

1.4. Building Performance Based on ATC-40

The maximum total drift, representing the structural displacement, can be evaluated through the following equation.

$$\text{Maksimum total drift} = \frac{Dt}{H} \quad (2)$$

Notes:

Dt = target displacement (m)

H = structural frame height (m)

According to ATC-40, the performance level of a building describes its condition after an earthquake, including the extent of physical damage, occupant safety, and the building's ability to remain functional or be reoccupied. The performance levels are categorized as follows:

Table 2: Drift Limits for Structural Performance Levels

Inter-Story Drift Limit	Structural Performance Levels			
	Immediate Occupancy	Damage Control	Safety Life	Structural Stavility
Maximum total drift	0.01	0.01-0.02	0.02	$0.33\frac{V_i}{P_i}$
Maximum inelastic drift	0.005	0.005-0.015	Not limited	Not limited

1.5. Building Performance Based on FEMA-440

FEMA 440, as a revision of FEMA 356, provides several improvements, notably the inclusion of modification factors C_1 and C_2 in the determination of the target displacement (δ_t). The FEMA 440 displacement coefficient approach provides a direct assessment of the maximum overall structural displacement. In this approach, the factors C_0, C_1, C_2, and C_3 are employed to modify the elastic response of the Single-Degree-of-Freedom (SDOF) system, thereby allowing the calculation of the maximum target displacement (elastic and inelastic) as expressed in the following equation.

$$\delta_t = C_0 . C_1 . C_2 . C_3 . S_a . \frac{T_e^2}{4\pi^2} . g \quad (3)$$

Notes:

δ_t = target displacement

C_0 = modification factor for converting the spectral displacement of the SDOF structure

C_1 = modification factor relating maximum inelastic displacement to linear elastic response displacement

C_2 = modification factor representing the effects of hysteresis shape, stiffness degradation, and strength deterioration on maximum displacement response

C_3 = modification factor accounting for increased displacement due to P-Delta effects

S_a = spectral response acceleration associated with the effective natural period in the considered direction

T_e = effective period of vibration

2. METHOD

2.1. Research Design

ETABS software version 18.1.0 was used to perform the pushover static analysis under seismic loads. This approach involves modeling three-dimensional structural elements, including columns, beams, slabs, and other related components. The output from ETABS version 18.1.0 is then analyzed, which includes inter-story drift values, displacements, and the performance point. Once the drifts are obtained, the structural performance can be evaluated based on ATC-40 and FEMA-440 to assess the potential seismic demands.

2.2. Project Technical Data

The case study analyzed in this research is the Amaris Hotel by Santika, with the following specifications:

Location : No. 176, Sukaasih, Bojongloa Kaler District, Bandung City, West Java

Building Function : Hotel

Building Height : 27.6 m

Number of Floors : 8 stories + 1 basement

Concrete Strength, fc' : 33.2 MPa and 29.05 MPa

Steel Strength, fy : 400 Mpa

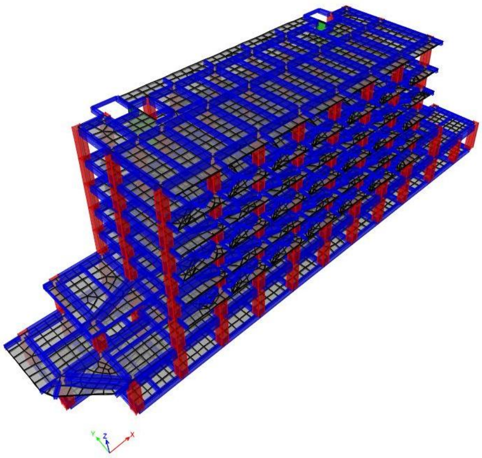

Fig. 2. Structural model of Amaris Hotel by Santika

3. RESULTS AND DISCUSSION

3.1. Dynamic Analysis Using the Response Spectrum Method

3.1.1. Earthquake Acceleration Parameters

The Amaris Hotel by Santika, located in Bandung City, applies the following seismic acceleration parameters: Risk Category II, Site Classification SE (soft soil), with values of S_s = 1.1395 g and S_1 = 0.4997 g. Consequently, the site acceleration parameters are obtained as S_{DS} = 0.7509 g and S_{D1} = 0.7331 g.

The structural system of the Amaris Hotel by Santika employs a "dual system with a special moment-resisting frame capable of resisting at least 25% of the prescribed seismic forces, combined with special reinforced concrete shear walls to provide structural stability." The response modification factor (R) is 7, the overstrength factor (Ω_0) is 2.5, and the deflection amplification factor (C_d) is 5.5.

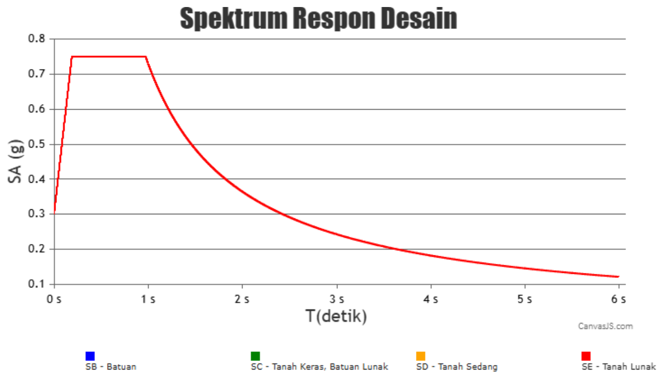

Fig. 3. Design response spectrum

3.1.2. Seismic Base Shear

The supplementary seismic design parameters are listed below:

Natural period of the structure, T_x = 0.687 s

Natural period of the structure, T_y = 0.697 s

Seismic response coefficient, C_s = 0.1073

Effective seismic weight, W = 79740.25 kN

Seismic base shear, V_{static} = C_s X W = 8553.33 kN

The base shear verification is conducted to evaluate the seismic forces implemented in ETABS 18.1.0 using the response spectrum curve. In compliance with SNI 1726:2019, if the calculated dynamic base shear (Vdynamic) is smaller than the static base shear (Vstatic), the dynamic response results shall be adjusted using a scale factor $f_x = \frac{V_{static}}{V_{dynamic}}$.

Table 3: Verification of Structural Base Shear

Parameter	X (kN)	Y (kN)
Vstatic	8553.33	8553.33
Vdynamic before correction	5784.599	5961.759
Vdynamic after correction	8553.34	8553.33
Vdynamic ≥ Vstatic	OK	OK

3.1.3. Interstory Drift

The interstory drift resulting from seismic excitation serves as an indicator for evaluating the building's seismic performance according to the developed structural model. In accordance with SNI 1726:2019, the calculated drift (Δ) must remain within the permissible limit defined by the allowable drift (Δ_a). The calculation of the drift ratio is carried out based on the data and parameters obtained from the results of the structural analysis.

Table 4: Interstory Drift due to Response Spectrum Load

Story	Displacement		Elastic Drift		h	Inelastic Drift		Drift Limit	Check
	δeX (mm)	δeY (mm)	δeX (mm)	δeY (mm)	(mm)	ΔX (mm)	ΔY (mm)	(mm)	
Roof	26.095	27.668	3.612	4.775	4000	19.866	26.263	61.538	OK
Story 7	22.483	22.893	3.997	4.252	3400	21.984	23.386	52.308	OK
Story 6	18.486	18.641	4.135	4.347	3400	22.743	23.909	52.308	OK
Story 5	14.351	14.294	3.743	4.231	3400	20.587	23.271	52.308	OK
Story 3	10.608	10.063	3.675	3.670	3400	20.213	20.185	52.308	OK
Story 2	6.933	6.393	4.703	4.309	5000	25.867	23.700	76.923	OK
Story 1	2.230	2.084	2.230	2.084	5000	12.265	11.462	76.923	OK

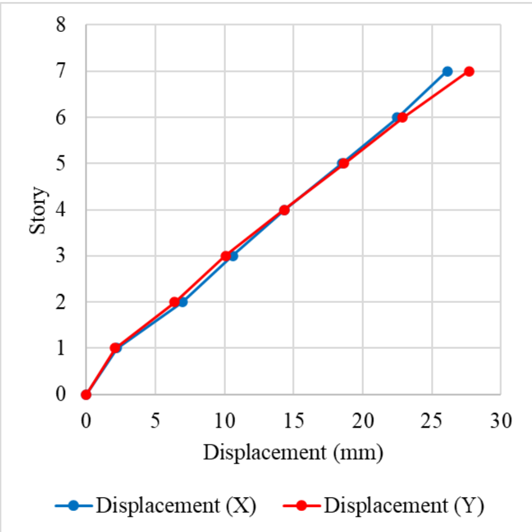

Fig. 4. Displacement due to response spectrum earthquake load

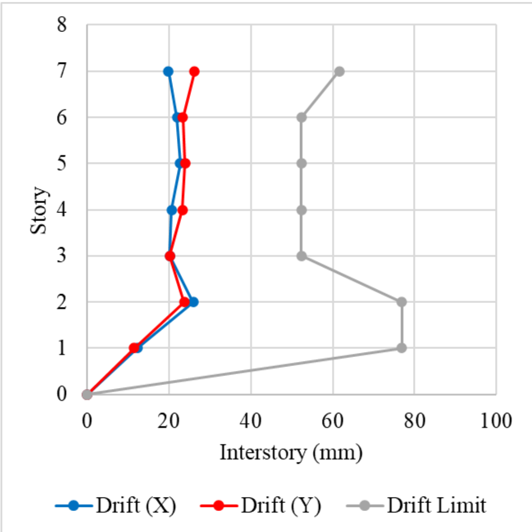

Fig. 5. Interstory drift due to response spectrum earthquake load

3.2. Static Analysis Using the Pushover Method

3.2.1. Capacity Curve

The pushover analysis in the X-direction (Fig. 6) was completed at step 27 with a displacement of 552 mm and a base shear of 224,055.31 kN. The number of yielded points that appeared was 318, which falls within the IO–LS performance level.

Meanwhile, the pushover analysis in the Y-direction (Fig. 7) was completed at step 24 with a displacement of 552 mm and a base shear of 242,889.52 kN. The number of yielded points recorded was 267 at the IO–LS level, 8 at the LS–CP level, and 8 at the >CP level.
The yielded points are illustrated in the following figures.

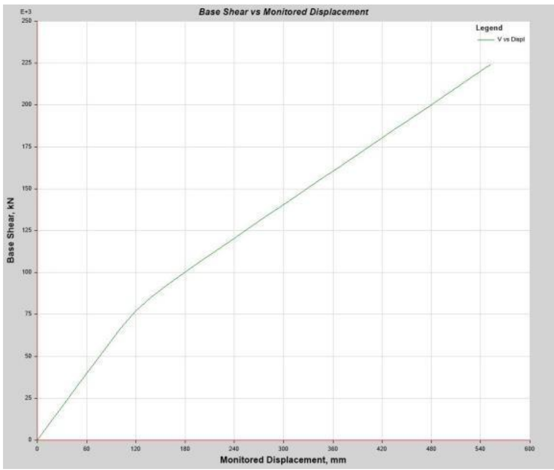

Fig. 6. Capacity curve of pushover analysis in the X-direction

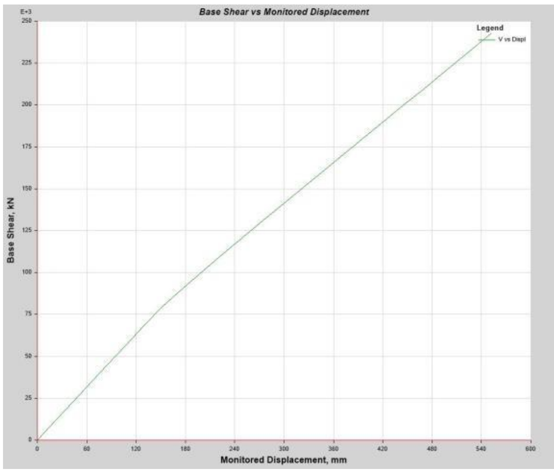

Fig. 7. Capacity curve of pushover analysis in the Y-direction

Fig. 8 shows the first yielding point in the X-direction, which occurred on a beam located at Axis C on the 3rd floor, classified within the IO–LS level. Meanwhile, Fig. 9 shows the first yielding point in the Y-direction, which occurred on a secondary beam located between Axes 4 and 5 on the 5th floor, also classified within the IO–LS level.

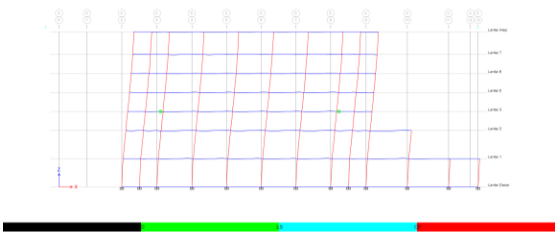

Fig. 8. First beam yielding point (X) 15/27

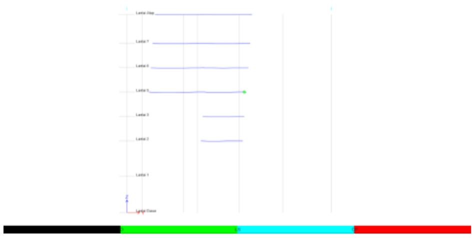

Fig. 9. First beam yielding point (Y) 12/24

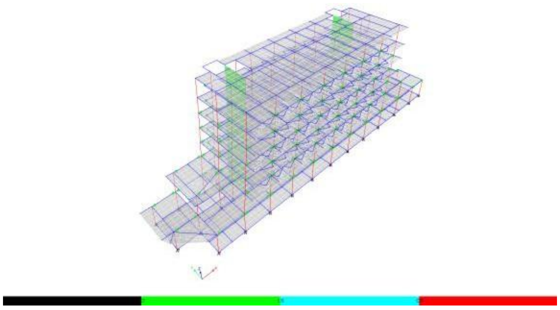

Fig. 10. Yielding points (X) 27/27

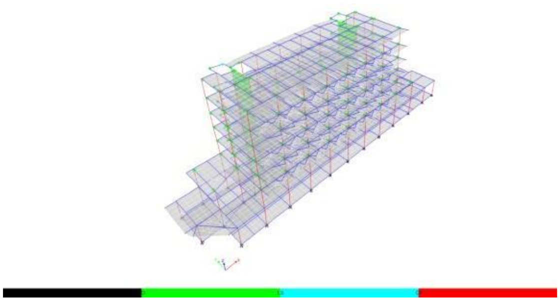

Fig. 11. Yielding points (Y) 24/24

3.2.2. Performance Point

The performance point is identified at the intersection of the capacity curve and the demand spectrum, both represented in Acceleration–Displacement Response Spectrum (ADRS) format. The target displacement derived from this intersection serves as the basis for assessing the structural performance level. Figures 12 and 13 illustrate the analysis outcomes associated with the performance point.

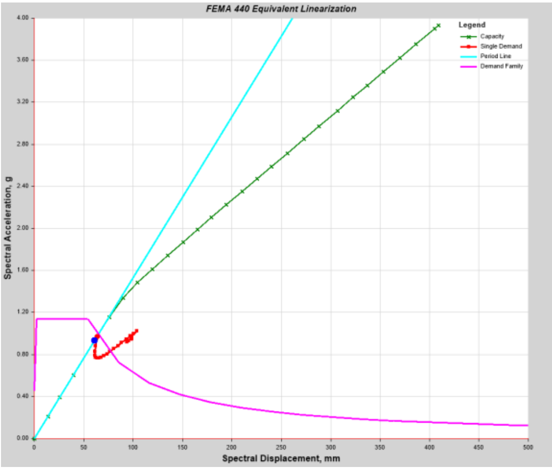

Fig. 12. Capacity spectrum (ADRS format) in the X direction

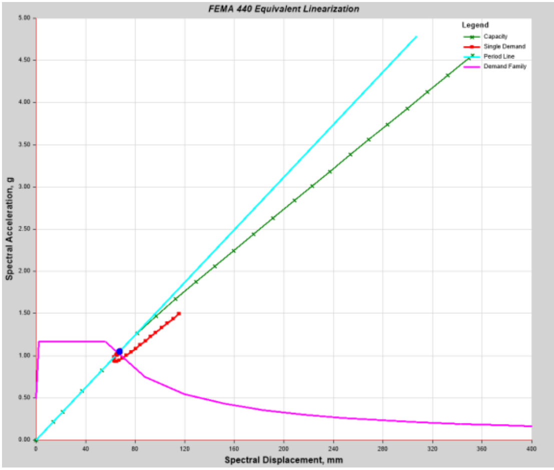

Fig. 13. Capacity spectrum (ADRS format) in the Y direction

Table 5: Performance Point

Parameter	X	Y
Sa (g)	0.973026	1.014736
Sd (mm)	63.61	65.04

3.2.3. Interstory Drift

Table 6 summarizes the interstory drift values of the building induced by seismic loads acting in the X and Y directions.

Table 6: Interstory Drift Due to Pushover Earthquake Loads

Story	Displacement		Elastic Drift		h	Inelastic Drift		Drift Limit	Check
	δeX	δeY	δeX	δeY		ΔX	ΔY		
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
Roof	59.253	59.992	6.579	9.688	4000	36.185	53.284	61.538	OK
Story 7	52.674	50.304	7.591	8.769	3400	41.751	48.230	52.308	OK
Story 6	45.083	41.535	8.358	9.106	3400	45.969	50.083	52.308	OK
Story 5	36.725	32.429	8.212	9.098	3400	45.166	50.039	52.308	OK
Story 3	28.513	23.331	8.754	8.336	3400	48.147	45.848	52.308	OK
Story 2	19.759	14.995	12.861	9.951	5000	70.736	54.731	76.923	OK
Story 1	6.898	5.044	6.898	5.044	5000	37.939	27.742	76.923	OK

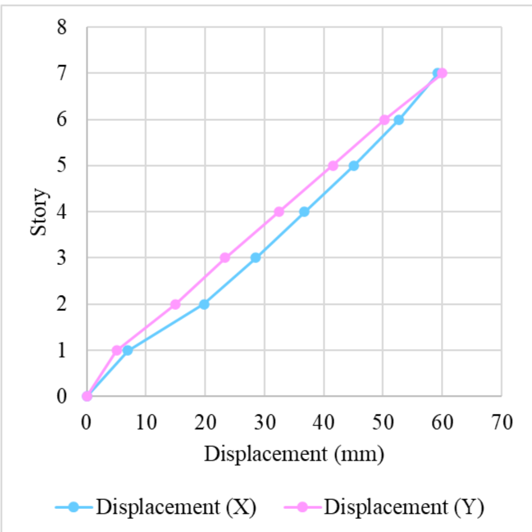

Fig. 14. Displacement due to pushover earthquake loads

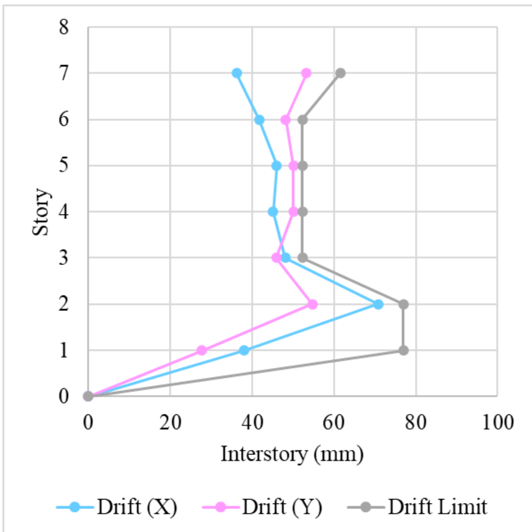

Fig. 15. Interstory drift due to pushover earthquake loads

Comparison between the two analysis methods shows that the displacement values obtained from the static pushover method are greater than those from the dynamic response spectrum method. One of the main advantages of static pushover analysis is its capability to identify the yielding points within the structure, offering a more comprehensive depiction of the potential collapse mechanism of the building. The graphical analysis and calculations indicate that the drift at the second floor is larger compared to other floors, due to the first and second floors having a height of 5 meters, which is greater than the upper floors that are approximately 3.4 meters. According to the column stiffness formula ($K = \frac{4EI}{L}$), the greater the column height (L), the smaller the stiffness value (K).

3.3. Structural Performance Level

3.3.1. Structural Performance Level Based on ATC-40

The calculated drift ratio value is less than 0.01, suggesting that the Amaris Hotel by Santika building satisfies the Immediate Occupancy (IO) performance level. This implies that the structure maintains safety, experiences minimal structural damage under seismic loading, and is suitable for immediate reoccupation following the earthquake.

Table 7: Summary of Structural Performance Levels According to ATC-40

Analysis	**Response Spektrum**		**Pushover**	
Direction	***X***	***Y***	***X***	***Y***
Total Displacement	26.095 mm	27.668 mm	59.253 mm	59.992 mm
Drift Ratio	0.000945	0.001002	0.002147	0.002174
Performance Level	Immediate Occupancy	Immediate Occupancy	Immediate Occupancy	Immediate Occupancy

3.3.2. Structural Performance Level Based on FEMA-440

The calculated drift ratio value is less than 0.01, suggesting that the Amaris Hotel by Santika building satisfies the Immediate Occupancy (IO) performance level. This implies that the structure maintains safety, experiences minimal structural damage under seismic loading, and is suitable for immediate reoccupation following the earthquake.

Table 8: Summary of Structural Performance Levels According to FEMA-440

Direction	**X**	**Y**
Sa (g)	0.973026	1.014736
Te (sec)	0.514	0.529
C0	1.46	1.46
C1	0.9646	0.9698
C2	1.0015	1.0011
C3	1	1
δt	0.009245	0.010269
Drift Ratio	0.000335	0.000372
Performance Level	Immediate Occupancy	Immediate Occupancy

4. CONCLUSIONS

Based on the analysis results, it can be concluded that:

1. The inter-story drift values of Amaris Hotel due to seismic loads using the dynamic analysis with the response spectrum method at the roof level are 19.866 mm in the X-direction and 26.263 mm in the Y-direction. Meanwhile, the inter-story drift using the static pushover analysis at the roof level is 36.185 mm in the X-direction and 53.284 mm in the Y-direction.
2. The displacement values of Amaris Hotel due to seismic loads using the dynamic analysis with the response spectrum method at the roof level are 26.095 mm in the X-direction and 27.668 mm in the Y-direction. Meanwhile, the displacement using the static pushover analysis at the roof level is 59.253 mm in the X-direction and 59.992 mm in the Y-direction.
3. According to ATC-40, the drift ratio values obtained from the dynamic response spectrum analysis are 0.000954 in the X-direction and 0.001002 in the Y-direction, while the drift ratios from the static pushover analysis are 0.002147 in the X-direction and 0.002174 in the Y-direction. According to FEMA-440, the drift ratios are 0.000335 in the X-direction and 0.000372 in the Y-direction. Since all drift ratios are less than 0.01, the structural performance of Amaris Hotel falls into the Immediate Occupancy (IO)

category, indicating that the building is safe and remains functional after an earthquake, with minimal structural damage.

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