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Structural Performance Analysis of the SMK – SMAK Bogor Office Building Using the Pushover Analysis Method

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Abstrak: Indonesia is position at the convergence of four active tectonic plates along the Pacific Ring of Fire makes it one of the most seismically active countries in the world, placing educational facilities with high occupant density at significant risk during seismic events. Seismic performance studies on Bogor's expansion-jointed educational buildings under SNI 1726:2019 remain limited and critically needed. This study evaluates the seismic performance of the SMK–SMAK Bogor Education Office Building, which is structurally divided into three independent units (Buildings 1, 2, and 3) by two expansion joints, each employing a Special Moment Resisting Frame system. Both linear response spectrum analysis per SNI 1726:2019 and nonlinear static pushover analysis using the ATC-40 Capacity Spectrum Method were performed in ETABS, with foundations modeled as fixed supports focusing solely on superstructure behavior. All three buildings satisfy the 90% cumulative mass participation requirement by the 5th mode, and scaled dynamic base shear complies with the $V_{dynamic} \geq V_{static}$ criterion. Inter-story drift remains below the 2% allowable limit for Risk Category II. Performance level assessment places most structures at Immediate Occupancy, except Building 2 in the Y direction which reaches Life Safety. Ductility ratios range from 2.45 to 3.90 across all units, except Building 2 in the X direction which yields a ratio of 1.95, indicating low ductility and vulnerability to brittle failure. All buildings are deemed safe and operational following a design level seismic event; however, Building 2 in the X direction requires targeted structural strengthening to improve its seismic reliability.

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1. Introduction

Indonesia is a region with a high risk of earthquakes. This is due to its location at the intersection of four active tectonic plates: the Eurasian Plate, the Indo-Australian Plate, the Philippine Plate, and the Pacific Plate. Geographically, Indonesia lies along the Pacific Ring of Fire, a region characterized by high levels of seismic and volcanic activity along the edges of the Pacific Ocean [1]. In 2023, the country experienced 5,400 natural disasters, including 31 earthquakes and 4 volcanic eruptions. Earthquakes with significant tremors cause the earth's surface to shake or move, thereby impacting existing structures. These earthquakes have resulted in thousands of fatalities, the destruction of thousands of infrastructure and buildings, and require substantial costs for recovery and reconstruction [2]. The damage occurred due to many buildings being unable to maintain their structural integrity during the earthquake. To minimize the risk of such disasters, earthquake-resistant building construction is necessary.

The design of earthquake-resistant buildings is based on the building's shape and mass, which are characteristics that interact with seismic loads. An earthquake-resistant building is one capable of withstanding seismic forces, the magnitude of which is influenced by the characteristics of the earthquake, soil properties, and the building's structure itself [3]. In accordance with SNI 1726:2019, the SMK–SMAK Bogor vocational and senior high school office building was designed to optimally support administrative and educational operational functions. This building is classified in Category II according to SNI 1726:2019, where the risk level to life safety and property damage is the highest (1.0) [4]. This building has two expansion joints, allowing the seismic response of each section to be analyzed independently. Without expansion joints, stresses caused by temperature changes, differential settlement, and seismic loads cannot be safely dissipated, making the building structure susceptible to cracking in columns, beams, and floor slabs. Therefore, it is important to ensure that the displacement occurring in each zone is controlled, isolated, and does not affect one another.

Pushover analysis is a component of performance-based seismic design that uses computer-aided nonlinear static analysis to examine the inelastic behavior of structures under various earthquake intensities. This process involves applying specific static load patterns in the lateral direction, the magnitude of which is gradually increased until the structure reaches a target displacement or exhibits a specific collapse pattern [5]. Seismic performance-based design allows designers to assess a building's performance more accurately by considering the structure's response to actual seismic loads [6]. Pushover analysis using the capacity spectrum method in accordance with ATC-40 provides a performance point with a target displacement indicating that the building's performance level remains at the Immediate Occupancy (IO) level. The seismic design category for educational office buildings falls into the high-risk category for seismic activity; therefore, a pushover analysis of the building is required to ensure the safety and comfort of its occupants.

The ATC-40 capacity spectrum method graphically presents two types of spectra: the capacity spectrum, which illustrates a structure's capacity as a relationship between total base shear and lateral displacement; and the demand spectrum, which depicts the level of performance demands resulting from an earthquake with a specific return period [7]. The ATC-40 standard identifies the inelastic behavior of structures and determines the performance level of a building when subjected to seismic loads. In evaluating the seismic capacity of reinforced concrete structures, this method yields more accurate analyses [8]. The primary parameter in pushover analysis using the capacity spectrum method is the determination of the performance point. This point serves as a reference for assessing whether a building has sufficient capacity to resist lateral loads caused by earthquakes. Therefore, this study aims to evaluate the structural behavior of the SMK-SMAK Bogor educational office building under seismic loads using ATC-40 pushover analysis to determine performance criteria and structural performance levels for a building with two expansion joints, using ETABS software.

2. Methods

2.1. *Location and Time*

The research site, the SMK–SMAK Bogor Education Office Building, is located at Jalan Pangeran Sogiri No. 374, Tanah Baru, Bogor Utara District, Bogor City, West Java, Indonesia. This research was conducted from February to May 2025 at the Department of Civil and Environmental Engineering, Faculty of Agricultural Technology, IPB University.

2.2. *Tools and Materials*

The tools used were AutoCAD 2023, Microsoft Excel 2021, ETABS V.21.2.0, and the Indonesian Design Response Spectrum Application 2021. The data used in this study included as-built drawings and the 2017 Earthquake Map. The reference standards included SNI 1727:2020 on Minimum Design Loads and Related Criteria for Buildings and Other Structures [9], SNI 1726:2019 regarding Procedures

for Seismic Design of Building and Non-Building Structures [10], SNI 2847:2019 regarding Requirements for Structural Concrete in Buildings and Explanations [11], and ATC-40 regarding Seismic Evaluation and Retrofit of Concrete Buildings [12].

2.3. *General Building Description, Structural Modeling, and Loading*

The SMK–SMAK Bogor Education Office Building is an integrated administrative and academic facility that serves as a hub for coordinating teaching and learning activities, managing student and faculty data, and implementing structured vocational programs to support the development of competent graduates who are ready to enter the workforce or pursue higher education. The building consists of three floors with a flat concrete roof. However, structurally, the building is divided into three separate structures (Buildings 1, 2, and 3) due to structural separation (dilation joints) between them. The floor-to-floor height is 4 meters, resulting in a total building height of 12 meters (**Figure 1**).

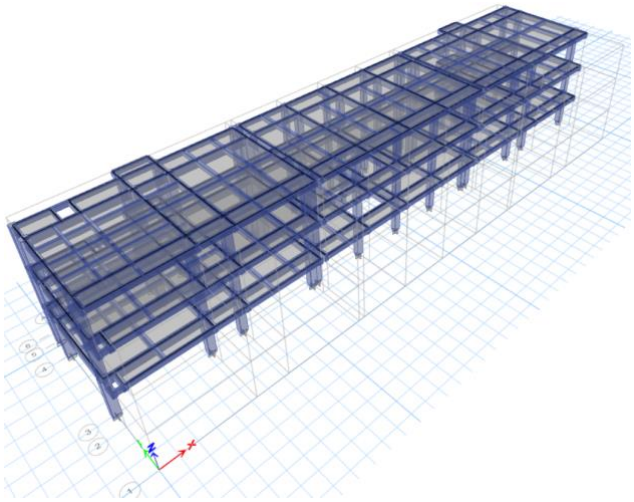


Figure 1. Typical floor plan of a 3D structure

Structural modeling was performed by creating separate models for each building in ETABS. This structural modeling was based on the as-built drawings obtained, and the modeled structural components include columns, beams, and slabs. The foundation was modeled as a fixed support at the base of the structure, which means that the analysis focused solely on the behavior of the superstructure (including columns, beams, and floor slabs) without explicitly accounting for the contribution of the flexibility or capacity of the substructure. Based on the as-built drawings, the concrete strength for the columns, beams, and slabs is Fc' 25 MPa. The steel (rebar) grades used are BJTS 420 for the main reinforcement and BJTP 280 for the stirrups. The concrete used has a density of 24 kN/m³ with a modulus of elasticity of 23.500 MPa, and the steel (rebar) used has a density of 78.5 kN/m³ with a modulus of elasticity of 200.000 MPa.

The loads input into ETABS follow the guidelines of SNI 1727:2020 [9] for dead load (DL), live load (LL), and super dead load (SDL) and SNI 1726:2019 [10] for earthquake load (EL) response spectrum. Load combinations use the ultimate limit state method to evaluate the structural conditions when approaching or reaching its maximum capacity, as presented in **Table 1**.

Table 1. Ultimate limit state loading combination [9]

No.	Combination
ULS1	1,4D
ULS2	1,2D + 1,6L + 0,5(Lr atau R)
ULS3	1,2D + 1,6(Lr atau R) + (L atau 0,5W)
ULS4	1,2D + 1,0W + L+ 0,5(Lr atau R)

No.	Combination
ULS5	0,9D + 1,0W
ULS6	1,2D + Ev + Eh + L
ULS7	0,9D – Ev + Eh

Earthquake load analysis was performed using response spectra in accordance with SNI 1726-2019 [9]. The office building located in Bogor is classified as Site Class D (moderate soil). The earthquake acceleration data derived from the response spectra are presented in **Table 2**, while the response spectrum graph is shown in **Figure 2**.

Table 2. Design seismic response spectrum parameters [9]

Parameters	Value
Kelas situs	SD (Tanah Sedang)
PGA MCEG (g)	0.4869
SS MCEr (g)	1.0434
S1 MCEr (g)	0.4762
T_L (detik)	20
T_0 (detik)	0.1538
Ts (detik)	0.7688
Sds (g)	0.7531
Sd1 (g)	0.5790

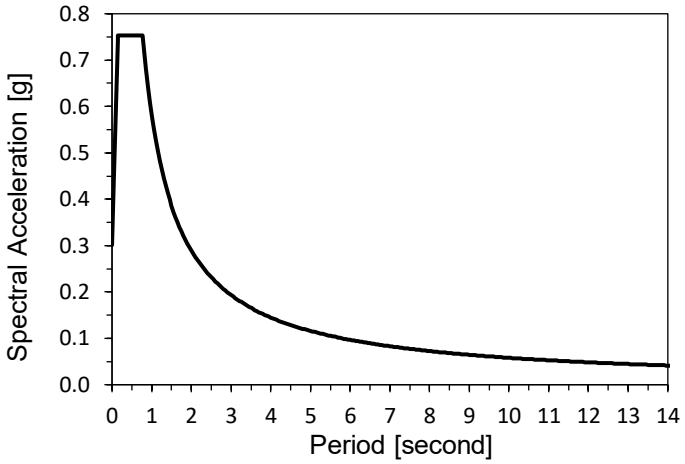


Figure 2. Spectral response curve for the city of Bogor with soil site class SD

2.4. *Structural Compatibility Analysis*

The parameters to be reviewed, as specified in SNI 1726:2019 [10], include the number of modes/mass participation, fundamental period, seismic base shear, drift limit, and structural ductility, as well as ATC-40 [12], to assess the structural performance of a building under seismic loads. Mass participation analysis includes a sufficient number of vibration modes so that the total combined mass participation reaches 100% of the structural mass. The total mass participation obtained must exceed 90%. If the base shear resulting from the combination of mode response analysis (V_t) is 100% of the base shear calculated using the equivalent static method (V), then the analysis result must be multiplied by the correction factor V/V_t. The design-to-allowable level deviation must not exceed the allowable level deviation, where the building exhibits controlled deformation and does not sustain significant damage that could endanger structural stability. Seismic base shear and drift limit are reviewed to determine structural adequacy prior to pushover analysis. Ductility reflects the structure's ability to absorb seismic energy through permanent deformation without experiencing sudden collapse [10]. Structural performance levels reflect the building's physical condition after an earthquake, potential safety risks to

occupants, and necessary actions for the building in post-earthquake conditions. The performance level of a building is categorized based on the extent of physical damage, the risk to occupant safety resulting from the damage, and the building's ability to remain functional after an earthquake [12].

2.5. *Plastic Joints Modeling and Pushover Analysis*

The pushover analysis will produce a pushover curve that will be used to determine the structural performance level. This analysis begins by applying gradually increasing loads at each floor center of gravity until a displacement is reached that causes the formation of at least one plastic hinge. Modeling of plastic hinges in building structures is applied to beam elements with DOF (Degrees of Freedom) M2 and M3 and columns with DOF P-M2-M3. The locations of the plastic hinges are applied at positions 0.1 and 0.9 of the span length at both ends of the beams and columns. Pushover analysis is performed based on ATC-40 guidelines using the capacity spectrum method (CSM) [12].

2.6. *Determination of Structural Performance Levels Based on ATC-40*

The results of the nonlinear static analysis were evaluated against the performance limits specified in ATC-40, as shown in **Table 3**. The parameter used was the drift limit for building structural elements [12].

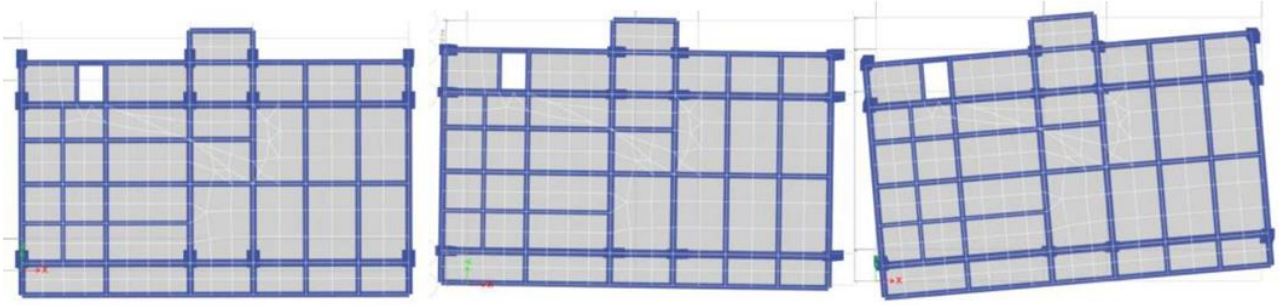
Table 3. Structural performance level

Parameters	Performance Level			
	Interstory Occupancy	***Damage Control***	***Life safety***	***Collapse Prevention***
Maximum total drift	0.01	0.01-0.02	0.02	$0.33V_i/P_i$
Maximum inelastic drift	0.005	0.0005-0.015	There are no limits	There are no limits

3. Result and Discussion

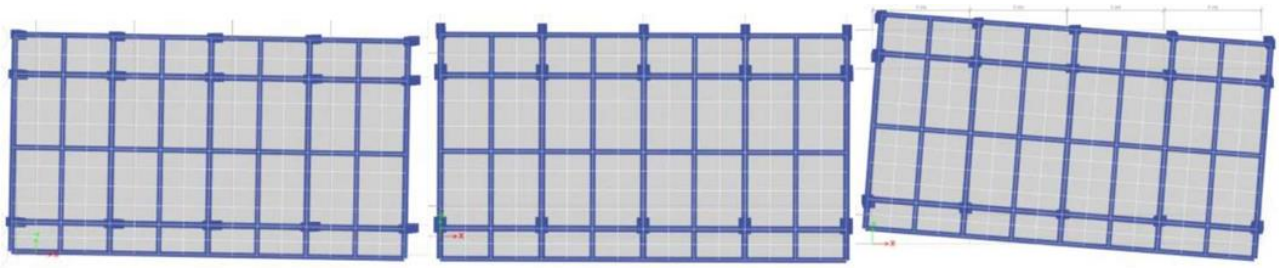
3.1. *Mode Shape Pattern and Number of Vibration Modes*

Any structure subjected to dynamic seismic forces will experience vibrations with specific patterns. The mode shapes indicate the direction of the building's vibrations in response to load combinations, including seismic loads acting on the structure [13]. The results of the modal analysis for the office building model are presented in **Table 4**. The mode shapes of the office building can be seen in **Figure 3 - 5**. The results show that Building 1 and Building 2 in the first pattern undergo translation along the X-axis, the second pattern undergoes translation along the Y-axis, and the third pattern undergoes rotation around the Z-axis, while Building 3 exhibits a different pattern, where the first pattern is dominated by a translation along the Y-axis, the second pattern undergoes a translation along the X-axis, and the third pattern undergoes a rotation around the Z-axis.



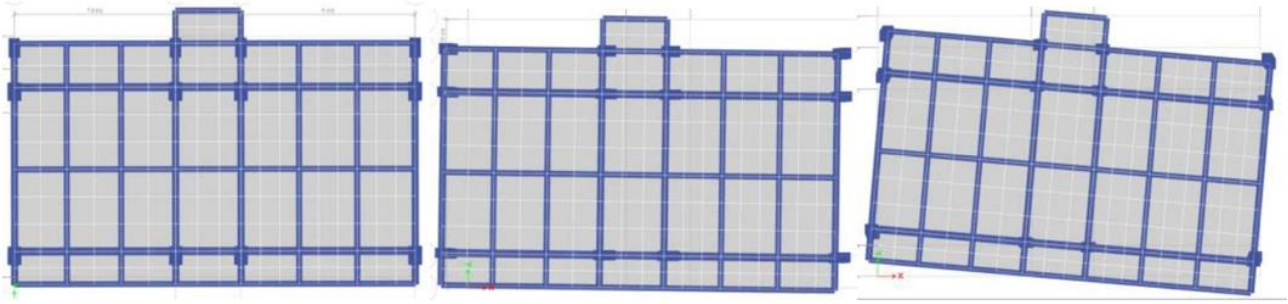
(a) (b) (c)

Figure 3. Building mode shapes 1 (a) mode 1 (b) mode 2 (c) mode 3



(a) (b) (c)

Figure 4. Building mode shapes 2 (a) mode 1 (b) mode 2 (c) mode 3



(a) (b) (c)

Figure 5. Building mode shapes 3 (a) mode 1 (b) mode 2 (c) mode 3

Building 2 consistently has a longer natural period than the other two buildings (**Table 4**). The natural period is influenced by the stiffness and mass of the building; the more flexible a structure is or the greater its mass, the longer its natural period tends to be. The longer period in Building 2 indicates that it has lower structural stiffness or greater mass compared to Building 1 and Building 3. Meanwhile, the similarity in period values between Building 1 and Building 3 suggests that both have relatively similar dynamic characteristics.

Table 4. Vibration period of the education office building

Mode Shape	**Building 1 period (s)**	**Building 2 period (s)**	**Building 3 period (s)**
1	0.607	0.794	0.656
2	0.547	0.687	0.644
3	0.485	0.612	0.568

3.2. *Mass Participation*

The mass participation from the combination of vibration modes must account for at least 90 percent of the total actual mass in each orthogonal horizontal direction analyzed in the structural response model [14]. Conversely, if mass participation remains below 90%, it means there are still parts of the structure that have not contributed to the seismic response. Consequently, the calculated base forces and displacements tend to be smaller than the values that should occur [15]. Based on the analysis results in ETABS, the three buildings have cumulative mass participation values in the UX and UY directions exceeding 90% in the 5th mode. The cumulative values in the UX direction for each building, in order, are 95.1%, 94.6%, and 94.0%, while those in the UY direction are 95.7%, 97.0%, and 95.5%. This comparison indicates that the three buildings have relatively similar mass distribution patterns, although there are minor variations in the number of modes required to achieve a minimum mass participation of 90% in each direction.

3.3. *Base Shear*

The base shear obtained from dynamic response spectrum analysis must be equal to or greater than 100% of the base shear calculated using the equivalent static method. Force scaling is required to ensure that $V_{dynamic} \geq V_{static}$, in accordance with the requirements of SNI 1726:2019. **Table 5** shows that the scaling factors for the base shear in the X and Y directions are 1.203 and 1.164, respectively. By applying these factors, the dynamic base shear is obtained as 1648.23 for the X and Y directions.

The base shear force is distributed vertically along the height of the structure in the form of horizontal forces at each floor level. The sum of the horizontal forces at each level yields the floor shear force, which is the shear force occurring at the base of the respective floor. These forces cause displacement and deflection at each floor level of the building [16]. The floor shear force in the office building exhibits the greatest displacement on the lowest floor, as shown in **Figure 6**. This is because the lower floor of the building bears the greatest gravitational and lateral loads.

Table 5. Seismic base shear

Building model	Direction	V_{static} (kN)	$V_{dynamic}$ (*unscaled*) (kN)	Scale factor	$V_{dynamic}$ (*scaled*) (kN)
Building 1	X	579.49	493.35	1.175	579.69
	Y	579.49	482.03	1.203	579.88
Building 2	X	578.14	448.69	1.289	578.36
	Y	578.14	500.30	1.156	578.35
Building 3	X	564.83	459.58	1.230	565.28
	Y	564.83	472.71	1.195	564.89

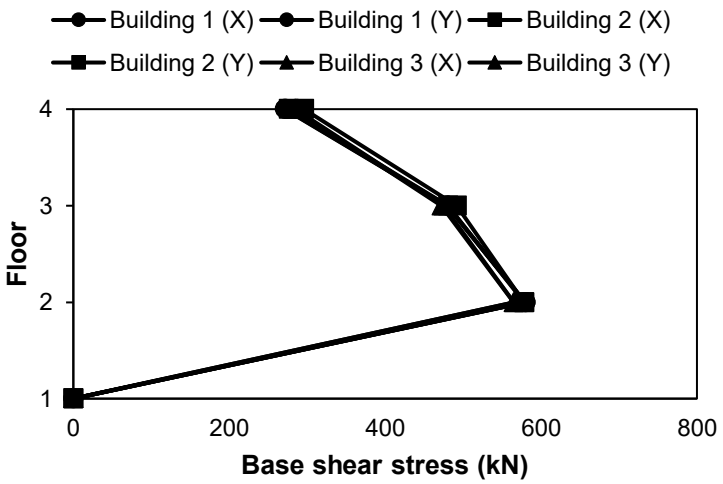


Figure 6. Shear forces in educational office buildings

3.4. *Drift Limit*

Inter-story drift reflects the degree of horizontal deformation on each floor due to seismic forces. The educational office building falls into Risk Category II with a permitted inter-story drift of 2%. The drift in both directions (X and Y) for each building is shown to be less than the maximum permitted limit (**Figure 7**). Inter-story drift values below the maximum limit indicate that the structure has sufficient stiffness to resist lateral forces without experiencing excessive deformation. Good stiffness helps prevent the soft story phenomenon, where one floor experiences significantly greater drift than the others, which can lead to local failure. This indicates that the office building structure remains within safe deformation limits under seismic loads.

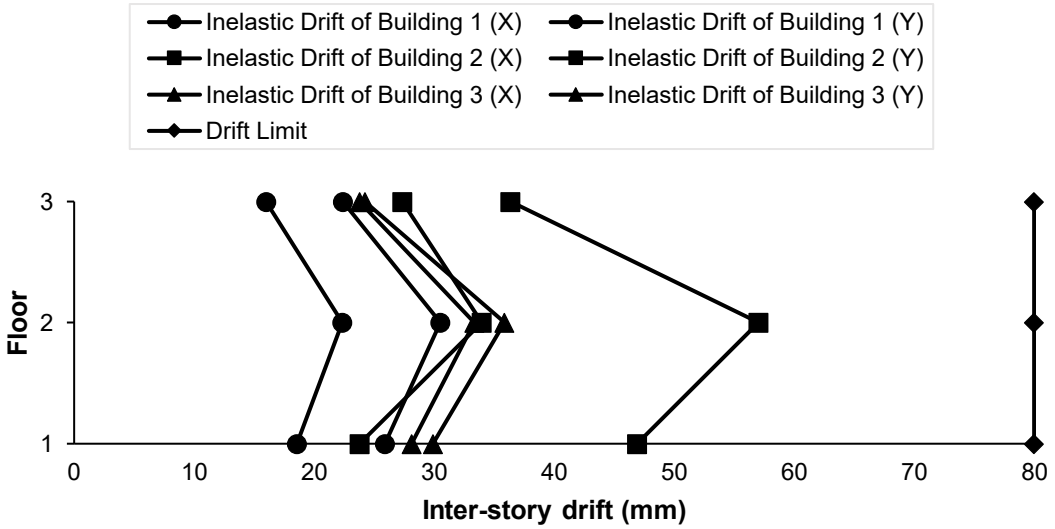


Figure 7. Drift limit for the education office buildings

Figure 8 shows the results of the elastic analysis for each building under seismic loading, aimed at validating the potential for damage caused by building-to-building collisions. All three buildings experienced displacements in the same direction and did not move in opposite directions, thereby avoiding the risk of collision between the buildings. This is supported by the fact that the maximum absolute displacement values on the opposing sides of the buildings at the expansion joint remain within safe limits. The uniformity of displacement directions between the buildings indicates that the three structures behave harmoniously as a single building system connected via expansion joints, so there are no significant differences in vibration phases that could trigger pounding or structural collisions between adjacent buildings.

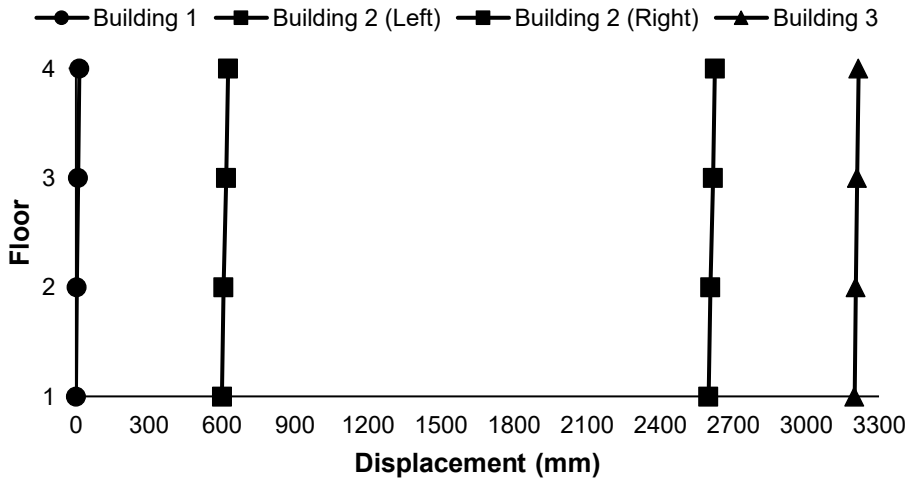


Figure 8. Displacement of each educational office building due to expansion joint

3.5. *Performance – Based Seismic Engineering* (PBSE)

PBSE is an approach to the design and evaluation of building structures that focuses on specific performance under seismic loads. This approach emphasizes a deep understanding of a structure's nonlinear response to ensure that buildings can achieve the desired performance level in accordance with the predicted earthquake intensity.

Table 6. Performance level of educational office buildings

Building model	Direction	Inelastic roof displacement (mm)	Target roof displacement (mm)	Maximum inelastic	Maximum total drift	Performance level
Building 1	X	74.50	118.81	0.004	0.01	IO
	Y	61.53	95.37	0.003	0.01	IO
Building 2	X	123.28	153.34	0.003	0.01	IO
	Y	97.82	137.36	0.003	0.01	LS
Building 3	X	91.09	118.67	0.002	0.01	IO
	Y	94.60	126.81	0.003	0.01	IO

Although there are variations in the magnitude of displacement among the structures for each building, most displacement ratios remain below the thresholds set by ATC-40 for the IO category (**Table 6**). Building 2 in the Y-direction achieved an LS (Life Safety) structural performance level, indicating that the structure sustained moderate damage, yet the occupants were protected from the risk of collapse. This indicates that all three buildings exhibit good seismic response and adequate deformation capacity, and are sufficiently rigid to prevent significant structural or non-structural damage during an earthquake event. The IO performance level also provides confidence that the buildings can be immediately reoccupied after an earthquake, making them suitable for critical facilities requiring operational continuity.

3.6. *Structure Ductility*

Structural ductility is the ability of a building to undergo continuous plastic deformation after exceeding the elastic limit when subjected to excessive loads [17]. Based on **Table 7**, it can be seen that all structures exhibit ductility levels in the moderate ductility category with ductility ratios ranging from 2.45 to 3.90, except for Building 2 in the X direction, which yields a ductility ratio of 1.95 and is therefore classified as low ductility. The low two-way ductility of Building 2 in the X direction (μ = 1.95) is due to low lateral stiffness in that direction, as evidenced by the longest vibration period (T_1 = 0.794 s) among all units, resulting in a very large initial yield deformation (123.28 mm) such that the remaining post-yield inelastic deformation reserve before reaching the maximum limit (Δu = 240 mm) becomes very narrow and yields a low ductility ratio. This condition is exacerbated by the absence of additional lateral restraint elements such as shear walls in the X-direction, so that the entire lateral load is supported solely by the SRPMK portal frame, whose energy dissipation capacity is limited.

Table 7. Ductility of educational office buildings

Building Model	Direction	*Maximum structure deflection* (mm)	*Inelastic drift* (mm)	*Ductility ratio*	Description
Building 1	X	240	47.50	3.22	*Moderate ductility*
	Y	240	61.53	3.90	*Moderate ductility*
Building 2	X	240	123.28	1.95	*Low ductility*
	Y	240	97.82	2.45	*Moderate ductility*
Building 3	X	240	91.09	2.63	*Moderate ductility*
	Y	240	94.60	2.54	*Moderate ductility*

4. Conclusion

The seismic performance evaluation of the SMK–SMAK Bogor Education Office Building confirms that all three buildings satisfy SNI 1726:2019 requirements for mass participation, base shear, and inter-story drift, with ATC-40 pushover analysis placing most structures at Immediate Occupancy level and Building 2 in the Y direction at Life Safety level, indicating that all buildings remain safe and operational following a design-level seismic event. The most critical finding is the low ductility of Building 2 in the X direction (μ = 1.95), caused by low lateral stiffness that produces a large initial yield displacement

narrowing the post-yield deformation reserve, for which structural interventions including shear wall addition and column confinement improvement are recommended, while future research should incorporate nonlinear time-history analysis using site-specific ground motion records to more accurately quantify structural risk under actual cyclic seismic loading.

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