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Comparison of the Performance of Structures With and Without Dilatation Joints at the East Java High Prosecutor's Office Building

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ABSTRACT: The condition of a building with vertical irregularities could affect the structure's response to seismic loads; therefore, a performance evaluation was required to ensure structural safety. This study aimed to compare the performance of existing buildings without expansion joints with that of structures incorporating expansion joints and to determine the required expansion joint spacing based on inter-storey deflection. The analysis was performed using ETABS v17 with the pushover method based on the criteria specified in FEMA 356 and FEMA 440, while inter-storey drift control was evaluated based on SNI 1726:2019. The results showed that all models complied with the inter-storey drift limits and were classified within the 'Safe' category. The installation of expansion joints resulted in reduced deflection, particularly in Block B, with maximum deflection values of 5.5 mm in the X-direction and 1.7 mm in the Y-direction, compared with 35.9 mm in the X-direction and 10.8 mm in the Y-direction for the existing structure. Based on the performance evaluation, most models were classified at the Immediate Occupancy (IO) level, except for Block A in the Y-direction, which was classified at the Life Safety (LS) level according to FEMA 440. The critical deflection analysis indicated that a minimum expansion joint gap of 4.43 mm was required. Consequently, the installation of expansion joints improved the control of lateral deformation while maintaining an acceptable level of structural performance under seismic loads.

KEYWORDS: Expansion joint; inter-story drift; pushover analysis; FEMA 356; structural performance.

1. Introduction

The National Earthquake Research Center reported that Surabaya is located along active fault lines, namely the Kendeng Fault and the Waru Fault, which have the potential to trigger earthquakes in the future [1]. As development in Indonesia continues, building construction has increased, requiring structural planning to account for surrounding environmental conditions [2]. In the modern era, growing demands for architectural aesthetics and limited land availability have encouraged the development of vertical buildings. However, vertically irregular architectural configurations can affect structural stability, particularly during earthquakes, because variations in structural stiffness, strength, mass, and dimensions may increase seismic response and building vulnerability [3]. Irregularly shaped buildings are generally more vulnerable to seismic loads because uneven distributions of mass and stiffness can induce torsional effects and increase structural deformation. The collapse of the Margalla Towers in Islamabad, Pakistan, during the magnitude 7.6 earthquake on October 8, 2005, demonstrated that building irregularities, when not adequately addressed through appropriate structural design and construction practices, can increase the risk of severe damage and collapse [4].

To address building irregularities, appropriate structural planning is required to ensure adequate performance under seismic loads. One commonly applied solution is the use of expansion joints, which divide a building into separate structural segments. This approach can improve deformation control, reduce torsional effects, and enhance the overall stability and safety of the structure [5]. An expansion joint provides separation between building sections to accommodate relative structural movement, particularly when adjacent sections have different structural systems, configurations, or heights. The expansion joint spacing should accommodate the maximum combined deflection of the adjacent structures, measured from their lateral restraint points, with a minimum gap width of 75 mm [7]. In addition to strength and stability, seismic-resistant building design should consider the structural capacity to withstand seismic loads and maintain acceptable performance beyond the elastic range. Pushover analysis is commonly used for this purpose as a nonlinear static procedure in which lateral loads are incrementally applied until the structure yields and enters the post-elastic range. This method enables the assessment of deformation capacity, structural response, and potential damage under seismic loading [6].

The seismic performance evaluation in this study refers to SNI 1726:2019, FEMA 356, and FEMA 440, which serve complementary functions in structural assessment. SNI 1726:2019 is used as the primary reference for determining seismic loading and seismic resistance requirements for buildings in Indonesia, whereas FEMA 356 is used to evaluate structural performance based on deformation criteria and defined performance levels. FEMA 440 is used to determine the performance point by considering the relationship between structural capacity and seismic demand in nonlinear static analysis. The performance levels include Operational, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The Operational level represents minor or negligible damage with no significant interruption to building operation, while IO indicates that structural strength and stiffness are largely maintained despite possible minor damage. At the LS level, significant structural damage and reductions in strength and stiffness may occur, although sufficient capacity remains to prevent collapse. CP represents severe structural damage approaching the collapse limit, with very limited residual strength and stiffness but prevention of complete structural collapse.

Previous studies [7–9] investigated the application of expansion joints in buildings with H-, T-, and U-shaped floor plans, which represent horizontal irregularities. In contrast, limited attention has been given to buildings with vertical irregularities characterized by differences in elevation between adjacent building sections. Previous studies have also primarily examined differences in structural design parameters, such as member dimensions and reinforcement requirements, between buildings with and without expansion joints, rather than directly comparing their seismic performance levels. Therefore, this study aimed to evaluate and compare the seismic performance of an existing vertically irregular building without expansion joints with that of structures incorporating expansion joints using pushover analysis based on FEMA 356 and FEMA 440. The study also aimed to evaluate inter-storey drift in accordance with SNI 1726:2019 and to determine the required expansion joint spacing based on the critical inter-storey deflection of the adjacent building sections.

2. Materials and Methods

2.1. Research Framework and Structural Models.

This study evaluated and compared the seismic performance of an existing eight-storey building without expansion joints with that of the proposed structural configuration incorporating expansion joints. Structural modelling and analysis were performed using ETABS v17. To ensure a consistent comparison, identical structural element dimensions, material properties, and applicable loading parameters were maintained across the models. The structure was analysed using three configurations: the Existing Model, representing the complete eight-storey building without expansion joints and incorporating an elevation difference at the fourth floor; Expansion Joint Model A, representing the eight-storey section after structural separation; and Expansion Joint Model B, representing the adjacent four-storey section. The overall research procedure, including data collection, structural modelling, loading analysis, seismic performance evaluation, and comparison of the structural responses, is summarized in Figure 1.

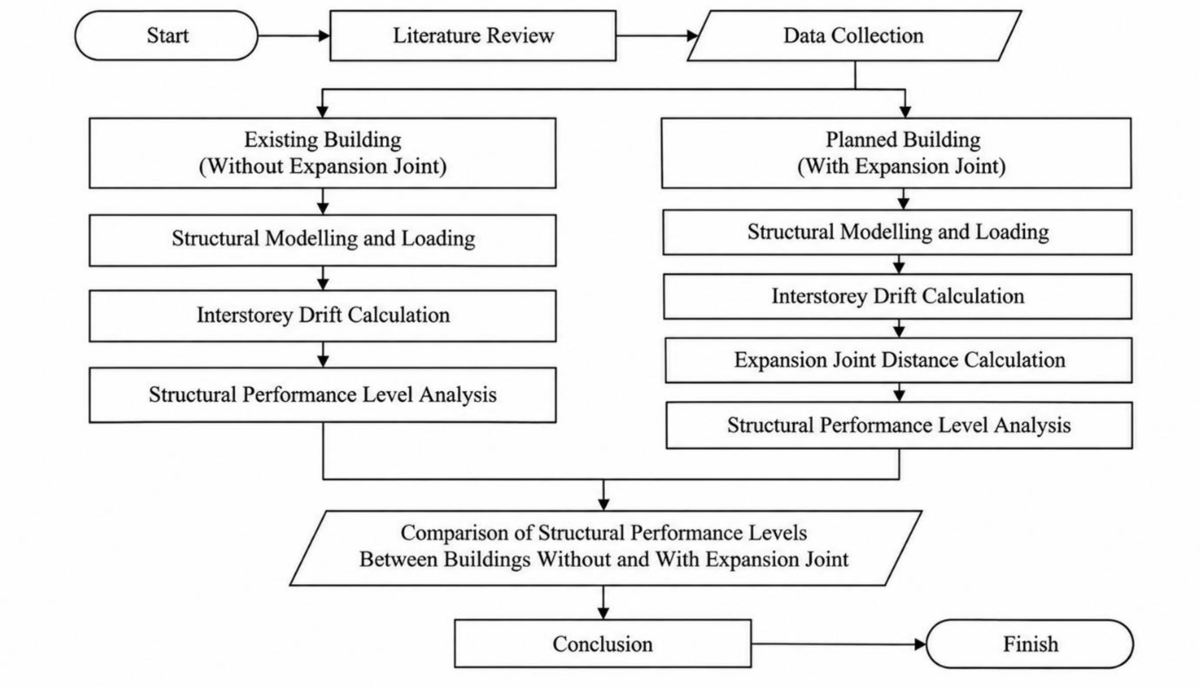


Figure 1. Research methodology flowchart.

2.2. Building and Material Properties.

The building data used for structural modelling were obtained from the existing building information. The structure consisted of eight storeys with a total height of 30.5 m, a length of 46.25 m, and a width of 22.00 m. The storey height was 3.30 m for Floors 1–3 and 4.00 m for Floors 4–8, resulting in vertical irregularity associated with differences in elevation and building configuration. Seismic input was defined using the Surabaya response spectrum obtained from RSA Cipta Karya. The structural concrete had a specified compressive strength (*f'c*) of 35 MPa. Both longitudinal and transverse reinforcement used BJTD 420 steel, with a yield strength (*Fy*) of 420 MPa and an ultimate tensile strength (*Fu*) of 545 MPa. These properties were consistently assigned to all structural models to ensure that differences in structural response resulted primarily from the introduction of expansion joints rather than variations in material or structural properties.

2.3. Structural and Loading Modelling.

The structural geometry, material properties, structural elements, and loading conditions were modelled in ETABS v17. The Existing Model was initially developed as a continuous structure without structural separation, whereas the proposed configuration divided the building into Models A and B using an expansion joint, as illustrated in Figure 2.2. Model A represented the eight-storey section, while Model B represented the four-storey section. This modelling approach enabled direct comparison of structural responses before and after the introduction of the expansion joint. The applied gravity and environmental loads were determined based on the existing building data and SNI 1727:2020. The load combinations considered in the analysis were 1.4(D+SD); 1.2(D+SD)+1.6L; 1.2(D+SD)+1.6L±0.5W; 1.2(D+SD)+1.6L±0.5RL; 1.2(D+SD)+1L±1.6W; 1.2(D+SD)+1L+0.5RL±1W; 1.2(D+SD)+1L±1W; 1.2(D+SD)+1L±1EQX; 1.2(D+SD)+1L±1EQY; 0.8(D+SD)+1L±1EQX; 0.8(D+SD)+1L±1EQY; and 0.9(D+SD)−1W, where D, SD, L, RL, W, EQX, and EQY represent the corresponding dead, superimposed dead, live, roof live, wind, and earthquake loads in the X- and Y-directions, respectively. The resulting models were subsequently used to evaluate the structural response, inter-storey drift, and seismic performance and to determine the required expansion joint spacing.

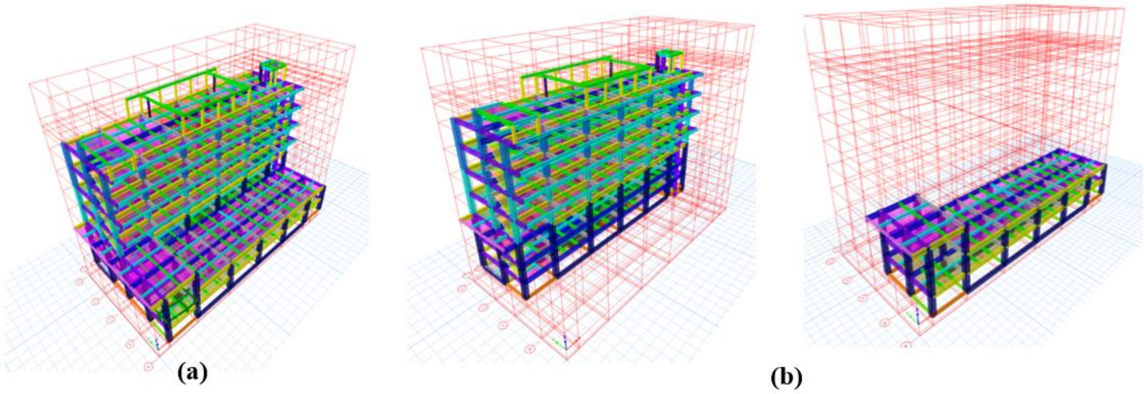


Figure 2. Structural Models Used in the Analysis: (A) Existing Building Without Expansion Joints, (B) Proposed Building Configuration with Expansion Joints.

3. Results and Discussion

3.1. Comparison of Shear Forces

Inter-storey drift was evaluated to determine the lateral deformation response of the existing building and the two structural models incorporating expansion joints. In accordance with Table 20 of SNI 1726:2019, the allowable inter-storey drift for the building, which was designed as a Special Moment Resisting Frame (SMRF) and classified under Risk Category

III, was determined as $0.015h_{sx}$, where h_{sx}represents the storey height below Level x. The calculated drift values were subsequently compared among the Existing Model, Expansion Joint Model A, and Expansion Joint Model B in both the X- and Y-directions. As presented in Table 1, the lateral deformation in the X-direction generally increased with building height. The Existing Model exhibited the largest value, reaching 35.9 mm at Storey 8, whereas Expansion Joint Model A reached 32.5 mm at the same level. Thus, separating the structure slightly reduced the maximum X-direction deformation of the eight-storey section. Expansion Joint Model B, which consisted of only four storeys, showed considerably smaller values, with a maximum of 5.5 mm at Storey 4. At Storey 3, Model A showed a slight increase from 5.2 to 5.9 mm compared with the Existing Model, indicating that the introduction of the expansion joint did not produce a uniform reduction at every level. Nevertheless, the overall response showed improved control of lateral deformation after structural separation.

Table 1. Comparison of Inter-story Drifts in the X-direction.

Strory	Inter-story drift		
	Existing	*Dilatation A*	*Dilatation B*
	ΔX (mm)	*ΔX (mm)*	*ΔX (mm)*
8	35.9	32.5	-
7	32.7	29.9	-
6	27.7	25.8	-
5	21.1	20.3	-
4	13.5	13.5	5.5
3	5.2	5.9	2.4
2	1.5	1.5	0.9
1	0.0	0.0	0.0

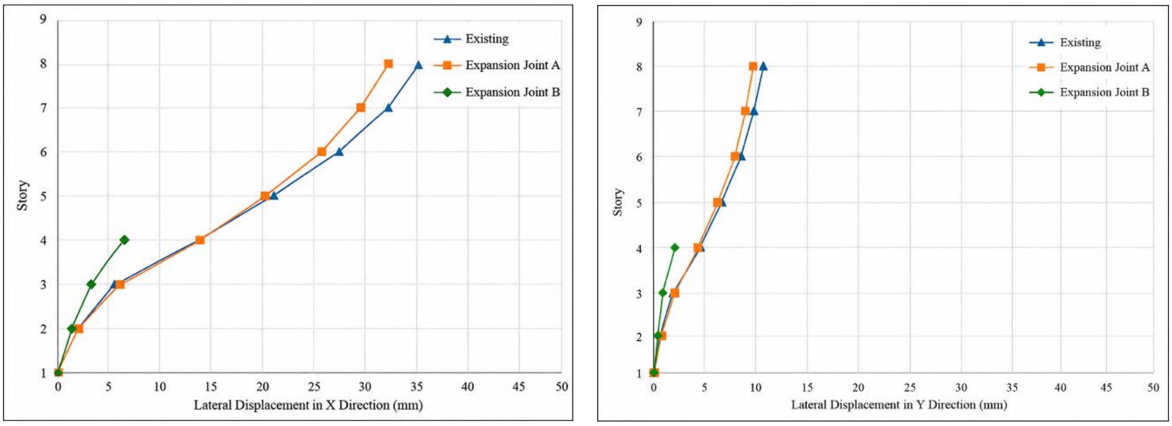
A similar trend was observed in the Y-direction, as shown in Table 2, although the deformation values were substantially smaller than those in the X-direction. The maximum deformation of the Existing Model was 10.8 mm at Storey 8, which decreased to 9.8 mm in Expansion Joint Model A. Model B again exhibited the smallest deformation, reaching a maximum of only 1.7 mm at Storey 4. At Storey 3, Model A showed a small increase from 1.6 to 1.8 mm, while identical values were obtained for the Existing Model and Model A at Storeys 4 and 2. These results indicate that structural separation generally reduced deformation in the Y-direction, although its influence varied across individual storeys.

Table 2. Comparison of Inter-story Drifts in the Y-direction

Strory	Inter-story drift		
	Existing	*Dilatation A*	*Dilatation B*
	ΔX (mm)	*ΔX (mm)*	*ΔX (mm)*
8	10.8	9.8	-
7	9.9	9.0	-
6	8.4	7.8	-
5	6.4	6.1	-
4	4.1	4.1	1.7
3	1.6	1.8	0.8
2	0.5	0.5	0.3
1	0.0	0.0	0.0

The overall deformation patterns are further illustrated in Figure 3.1, which provides a clearer comparison of the structural responses in the X- and Y-directions. Figure 3.1(a) demonstrates that deformation in the X-direction was consistently greater than that in the Y-direction shown in Figure 3(b), indicating that the structure was more susceptible to lateral deformation along the X-axis. The difference between the Existing Model and Expansion Joint

Model A became more evident toward the upper storeys, whereas Model B exhibited substantially lower deformation because of its lower building height and corresponding structural characteristics.



(a) **(b)**

Figure 3. Graph Comparing Inter-story Drifts in the X-direction (a); Graph Comparing Inter-story Drifts in the X-direction (b).

Overall, the results from Tables 1 and 2 and Figure 3.1 demonstrate that the introduction of expansion joints influenced the lateral deformation response of the building. Expansion Joint Model A generally exhibited lower deformation than the Existing Model, particularly at the upper storeys, although slight increases occurred at some lower levels. Expansion Joint Model B exhibited the lowest deformation in both directions, with maximum values of 5.5 mm in the X-direction and 1.7 mm in the Y-direction. The lower response of Model B was associated with its lower building height and consequently different lateral stiffness characteristics. These findings indicate that separating vertically irregular building sections using expansion joints can improve deformation control and reduce the interaction between building segments of different heights. The observed trend is also consistent with the findings reported in [8], where buildings incorporating expansion joints exhibited lower lateral deformation than corresponding structures without structural separation.

3.2. Expansion Gap.

The required expansion joint gap was determined from the relative lateral displacement of the adjacent structural blocks at their critical interface. In this study, the fourth floor was selected because it represented the uppermost level shared by the eight-storey Block A and the four-storey Block B. The Y-direction governed the expansion joint assessment, with displacement values of 4.1 mm for Block A and 1.7 mm for Block B. Based on the combined relative displacement of the two independently responding blocks, the required expansion joint gap was determined to be 4.43 mm. Although the calculated gap was only 4.43 mm, this value was smaller than the specified minimum expansion joint width of 75 mm. Therefore, a gap of 75 mm was adopted for the proposed structural configuration. The adopted width provided sufficient clearance to accommodate the relative lateral movement of the adjacent blocks under seismic loading and reduced the potential for structural contact or pounding. Thus, the design was governed by the minimum prescribed expansion joint requirement rather than by the calculated displacement demand.

3.3. Structural Performance Level.

The seismic performance of the Existing Model and the two expansion joint models was evaluated using nonlinear static pushover analysis in ETABS v17. Structural performance levels were determined according to FEMA 356 and FEMA 440 based on the calculated target displacement and corresponding drift ratio. The evaluation considered both the X- and Y-directions to identify whether structural separation affected the seismic performance of the building. The parameters obtained for the FEMA 356 evaluation of the Existing Model in the X-direction are presented in Table 3. The FEMA 356 analysis of the Existing Model in the X-direction was characterized by a spectral acceleration (*Sa*) of 0.3928 and an effective period (*Te*) of 1.436 s. The modification coefficients *C0*, *C1*, *C2*, and *C3* were subsequently used to establish the target displacement for the pushover evaluation. These parameters resulted in a target displacement of 0.262 m and a drift ratio of 0.86%, corresponding to the Immediate Occupancy (IO) performance level. This result indicates that, under the evaluated seismic demand, the Existing Model was expected to retain adequate structural strength and stiffness with relatively limited damage.

Table 3. FEMA 356 pushover parameters for the Existing Model in the X-direction.

Sa	Te	C0	C1	C2	C3
0,3928	1,436	1,3	1	1	1

The same FEMA 356 procedure was subsequently applied to all structural configurations in both principal directions. The resulting target displacements, drift ratios, and structural performance classifications are summarized in Table 4. All structural configurations were classified at the Immediate Occupancy (IO) performance level according to FEMA 356. The Existing Model produced drift ratios of 0.86% and 0.88% in the X- and Y-directions, respectively. Following structural separation, Block A exhibited drift ratios of 0.86% in the X-direction and 0.98% in the Y-direction, indicating that the introduction of the expansion joint did not uniformly reduce the performance-related displacement response of the taller block. In contrast, Block B exhibited lower drift ratios of 0.62% and 0.79% in the X- and Y-directions, respectively. Despite these differences, all models remained within the same IO performance category, indicating that the structures maintained acceptable seismic performance under the FEMA 356 criteria.

Table 4. Summary of Structural Performance Level Analysis using FEMA 356.

Type of Structure	Sa	Te	C0	C1	C2	C3	(δT)	Drift Ratio	Performance Level
Existing (X)	0,3928	1,436	1,3	1	1	1	0,262	0,86%	IO
Exsisting (Y)	0,3811	1,48	1,3	1	1	1	0,270	0,88%	IO
8-story expansion joint (Block A) (X)	0,3928	1,436	1,3	1	1	1	0,262	0,86%	IO
8-story expansion joint (Block A) (Y)	0,3437	1,641	1,3	1	1	1	0,299	0,98%	IO
4-story expansion joint (Block B) (X)	0,6075	0,345	1,3	2,89	1	1	0,068	0,62%	IO
4-story expansion joint (Block B) (Y)	0,6075	0,345	1,3	2,16	1	1	0,087	0,79%	IO

The structural performance was also evaluated using FEMA 440 to examine the sensitivity of the performance classification to a different nonlinear evaluation procedure. The FEMA 440 results for the Existing Model, Block A, and Block B are summarized in Table 5.

FEMA 440 produced slightly different displacement demands and performance classifications compared with FEMA 356. The Existing Model remained at the IO level in both directions, with drift ratios of 0.90% and 0.94% in the X- and Y-directions, respectively. Block B also remained within the IO level and exhibited the lowest drift ratios, at 0.21% in the X-direction and 0.41% in the Y-direction. Block A was classified as IO in the X-direction, with a drift ratio of 0.87%; however, its Y-direction response reached 1.04% and was classified as Life Safety (LS). This was the only case in which the performance classification differed from IO.

Table 5. Summary of Structural Performance Level Analysis using FEMA 356

Type of Structure	Sa	Te	C0	C1	C2	C3	(δT)	Drift Ratio	Performance Level
Existing (X)	0,393	1,436	1,3	1,04	1,01	1	0,274	0,90%	IO
Exsisting (Y)	0,381	1,48	1,3	1,05	1,01	1	0,288	0,94%	IO
8-story expansion joint (Block A) (X)	0,393	1,436	1,3	1,01	1	1	0,265	0,87%	IO
8-story expansion joint (Block A) (Y)	0,344	1,641	1,3	1,05	1	1	0,316	1,04%	LS
4-story expansion joint (Block B) (X)	0,608	0,345	1,3	1,01	1	1	0,023	0,21%	IO
4-story expansion joint (Block B) (Y)	0,64	0,452	1,3	1,05	1	1	0,044	0,41%	IO

Overall, the FEMA 356 and FEMA 440 evaluations indicated that the Existing Model and the structures incorporating expansion joints generally achieved the Immediate Occupancy performance level. This finding is consistent with the results reported in [10], where structures with and without expansion joints were also found to achieve IO performance. The exception was Block A in the Y-direction under FEMA 440, which was classified at the Life Safety level. The difference between the FEMA 356 and FEMA 440 results reflects differences in the procedures and coefficients used to characterize nonlinear structural response and seismic demand. Importantly, the results also show that introducing an expansion joint did not necessarily improve the performance level of every structural block or loading direction; rather, its principal benefit was the separation of structural segments and control of relative lateral movement. Nevertheless, none of the evaluated cases reached the Collapse Prevention level, indicating that the proposed expansion joint configuration maintained an acceptable overall seismic performance under the conditions considered in this study.

4. Conclusions

Based on the analysis, the implementation of expansion joints effectively controlled the lateral deformation of the vertically irregular building, although the magnitude of improvement varied between the structural blocks and loading directions. Expansion Joint Model B exhibited the greatest reduction in deformation, with maximum values of 5.5 mm in the X-direction and 1.7 mm in the Y-direction, compared with 35.9 mm and 10.8 mm, respectively, for the existing structure. The calculated expansion joint gap based on the critical relative displacement was 4.43 mm. Because this value was smaller than the specified minimum requirement, a 75 mm expansion joint gap was adopted to provide adequate clearance for relative movement between the adjacent building blocks and to minimize the potential for seismic pounding. The nonlinear seismic performance evaluation further demonstrated that the existing and expansion-joint models generally achieved the Immediate Occupancy (IO) performance level according to FEMA 356 and FEMA 440. Under FEMA 356, all evaluated models and loading directions were classified as IO. Under FEMA 440, most models also remained at the IO level; however, Expansion Joint Block A in the Y-direction was classified as Life Safety (LS), with a drift ratio of 1.04%. This difference indicates that structural separation did not necessarily improve the performance classification in every direction, particularly for the taller block. Nevertheless, none of the evaluated models reached the Collapse Prevention (CP) level. Overall, the results demonstrate that expansion joints can provide more controlled lateral deformation, accommodate differential movement between building sections of different heights, reduce the potential for interaction or pounding during earthquakes, and maintain an acceptable level of seismic performance. The present study was limited to a relatively simple vertically irregular building consisting of two sections with different heights and was evaluated using nonlinear static pushover analysis. Future studies should investigate buildings with more complex vertical and plan irregularities, greater numbers of storeys, and different structural systems and expansion joint configurations. Further research should also consider nonlinear dynamic time-history analysis using multiple ground-motion records to evaluate relative displacement and seismic pounding more comprehensively. Such investigations would provide a broader understanding of the effectiveness of expansion joints and support more robust design recommendations for vertically irregular buildings in earthquake-prone regions.

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Author Contribution

Risky Surya Ardiansyah : Conseptualization, Methodology, Data Collection, Software Operator, Data Analysis, Writing. Bantot Sutriono : Supervision, Validation, Visualization, Writing – Review & Editing.

Competing Interest

All authors should disclose any financial, personal, or professional relationships that might influence or appear to influence their research.

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