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Structural Analysis and Design of a Multi-Storey Commercial Building Considering P-Delta and Expansion Joint Effects

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Abstract - The structural performance of multi-storey commercial buildings is significantly influenced by geometric nonlinearity and the provision of expansion joints. This paper presents the analysis and design of a multi-storey commercial building considering P-Delta effects and the behaviour of structures with and without expansion joints. A three-dimensional model of a G+10 commercial building (plan dimensions 70.9 m × 39.55 m) was developed in ETABS and analysed as per relevant Indian Standard codes for 10-, 15-, 20- and 25-storey configurations. Four model variants were compared: without P-Delta or expansion joint (A), with P-Delta only (B), with expansion joint only (C), and with both expansion joint and P-Delta (D). Linear static and nonlinear P-Delta analyses were performed under gravity, wind, seismic and temperature loading. Storey displacement, storey drift, base shear and member forces were extracted and compared. Results show that structures without expansion joints behave as a continuous system with higher axial forces and stiffness, while expansion joints reduce stress concentration and global displacement at the cost of localized moment increases near the joint. P-Delta effects increase lateral displacement and drift progressively with building height, becoming most significant in the 20- and 25-storey models. All computed drifts remained within IS 1893 permissible limits, confirming the structural adequacy of the design while highlighting the necessity of second-order analysis for tall structures.

Key Words: P-Delta analysis; expansion joint; multi-storey building; ETABS; storey drift; geometric nonlinearity; seismic analysis; wind load

1. INTRODUCTION

The rapid growth of urbanisation and commercialisation has led to an increasing demand for multi-storey commercial buildings. These structures are subjected to dead loads, live loads, wind loads, seismic forces and temperature variations, and their safe design requires a structural analysis approach that accounts for both linear and nonlinear behaviour.

A critical aspect of multi-storey design is the consideration of second-order, or P-Delta, effects, which arise from the interaction between axial loads (P) and lateral displacements (Δ), producing additional moments in structural members. As building height increases, P-Delta effects become more significant, potentially causing increased lateral deflection, higher member forces, and instability if neglected.

Expansion joints are another important factor governing the performance of large commercial structures. They accommodate movement due to temperature change, shrinkage, creep and seismic action; in their absence, such movements can induce significant stresses, cracking and deformation. By dividing a large structure into independent blocks, expansion joints reduce stress concentration and improve overall structural behaviour.

This study analyses and designs a multi-storey commercial building in two configurations – with and without expansion joints – and incorporates P-Delta analysis to evaluate the influence of geometric nonlinearity. The building is modelled as a three-dimensional space frame in ETABS, with load combinations applied accordingly Indian Standard codes, and both linear static and nonlinear P-Delta analyses are carried out to obtain storey displacement, storey drift, base shear and internal member forces.

1.1 Significance

This study evaluates the combined effect of P-Delta (second-order) analysis and expansion joints on the behaviour of multi-storey commercial buildings, providing a realistic understanding of structural performance that accounts for geometric nonlinearity – essential for tall structures. The comparative study of buildings with and without expansion joints helps identify their role in reducing

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stress, displacement, and improving durability, while also building practical knowledge of advanced structural analysis using ETABS.

1.2 Objectives

- To carry out the analysis and design of a multi-storey commercial building using ETABS software.
- To study the effect of expansion joints on the structural behaviour of the building.
- To analyse the structure with and without expansion joints and compare results.
- To evaluate P-Delta (second-order) effects on building response.
- To determine storey displacement, storey drift, base shear, and member forces.
- To ensure the design is safe and economical as per Indian Standard codes.
- To understand the importance of geometric nonlinearity in tall structures.

2. LITERATURE REVIEW

Sharma and Singh (2017) reported that structures without expansion joints behave as a continuous system, resulting in higher axial forces, increased stiffness and larger displacements. In contrast, expansion joints accommodate thermal and seismic movement and reduce stress concentrations, though they produce localised increases in bending moment near the joint.

Hoan and Nguyen (2021) studied uniform temperature load on long RC structures without expansion joints using ETABS models of varying length, finding that slab reinforcement increased by up to 48.2% due to thermal effects, underscoring the necessity of expansion joints or explicit temperature-load design.

Faye and Raut (2022) reviewed RCC framed buildings with and without expansion joints at different locations and concluded that continuous buildings develop higher axial forces and displacement, while joints reduce global stress at the cost of localised moment concentration near the discontinuity.

Admile et al. (2023) assessed P-Delta effects in multistorey buildings with and without expansion joints, similarly observing higher axial force accumulation in continuous structures and emphasising the role of joints under seismic and thermal loading.

Sirsat and Pandit (2025) performed P-Delta analysis of multi-storey buildings in ETABS and confirmed that expansion joints allow independent thermal and seismic movement, reducing stress concentration while increasing bending moment locally near the joint.

Sharma and Singh (2025) in a follow-up comparative study, reaffirmed that expansion joints enhance structural safety, serviceability and durability, particularly in long buildings subject to significant temperature variation and seismic activity.

3. EXPANSION JOINT

Expansion joints are intentional separations provided in buildings to accommodate movement from temperature change, shrinkage, creep, seismic action and differential settlement. In long RCC structures, restrained movement induces significant internal stress; expansion joints divide the building into independent segments that can move freely without affecting overall structural integrity. IS 456:2000 recommends joints in long structures, while IS 3414:1968 provides spacing guidelines.

4. P-DELTA ANALYSIS

P-Delta analysis is a second-order analysis accounting for the additional moment generated when an axial load P acts through a laterally displaced position Δ, producing $M = P \times \Delta$. This moment is not captured by first-order (linear) analysis and becomes increasingly significant for tall, slender structures under lateral load.

5. METHODOLOGY

The overall methodology proceeded from plan development through model generation, expansion joint provision, load assignment, analysis, and comparison of results with and without P-Delta effects. A three-dimensional model of a G+10 commercial building (plan dimensions 70.9 m × 39.55 m) was developed in ETABS and analysed as per relevant Indian Standard codes for 10-, 15-, 20- and 25-storey configurations, with AutoCAD used for 2D drafting of the building plan.

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Four model variants were compared throughout: Model A – without P-Delta and without expansion joint; Model B – with P-Delta, without expansion joint; Model C – with expansion joint, without P-Delta; and Model D – with both expansion joint and P-Delta effects. Dead, live, wind, seismic and temperature loads were applied as per IS 875 (Parts 1, 2, 3 and 5) and IS 1893 (Part 1):2016, along with the prescribed load combinations, and both linear static and nonlinear P-Delta analyses were carried out to obtain storey displacement, storey drift, base shear and member forces.

- Plan: A commercial building plan of 70.9 m × 39.55 m was developed in AutoCAD, comprising office spaces, a central 3 m wide corridor, lift lobby, staircases and service/toilet blocks.
- Modelling: A 3D model was created in ETABS with a 10×6 bay grid. Material properties were defined for M30 concrete and Fe500 steel. Beam and column sections of 1000×600 mm, 1200×600 mm and 600×450 mm were used, with 150 mm thick slabs.
- Increasing storeys: The model was replicated for 10, 15, 20 and 25 storeys to study the influence of building height.
- Provision of expansion joint: A second model series was created with an expansion joint at the plan mid-length (35 m), dividing the structure into independent blocks separated by a 30 mm physical gap (calculated using $\Delta L = \alpha L_0 \Delta T$), each assigned a separate diaphragm to prevent force transfer.
- Load assigning: Dead, live, wind, seismic and temperature loads were applied as per IS 875 and IS 1893 (Part 1), along with the prescribed load combinations.
- Analysis: Both static and dynamic (response-spectrum) analyses were performed, with and without P-Delta effects, for each storey configuration and joint condition.
- Results: Storey displacement, storey drift, base shear and member forces (axial force, shear force, torsion and bending moment) were extracted and compared across the four model variants (A, B, C, D).

5.1 Building Plan and Structural Models

The architectural plan (Fig. 1) comprises office spaces of varying sizes arranged around a central 3 m wide corridor, with a lift lobby, staircases, service ducts and toilet blocks. The corresponding column layout (Fig. 2) was used to generate the 10×6 bay structural grid in ETABS. Figures 3 and 4 show the resulting three-dimensional ETABS wireframe models for the building without an expansion joint, for all four storey heights considered. The expansion joint was introduced at the building mid-length (35 m from the edge) by removing connectivity between beams, slabs and nodes along the joint line and providing a physical gap of 30 mm, with separate diaphragms assigned to each block (Fig. 5); Figures 6 and 7 show the resulting 3D models with the expansion joint for all four storey heights.

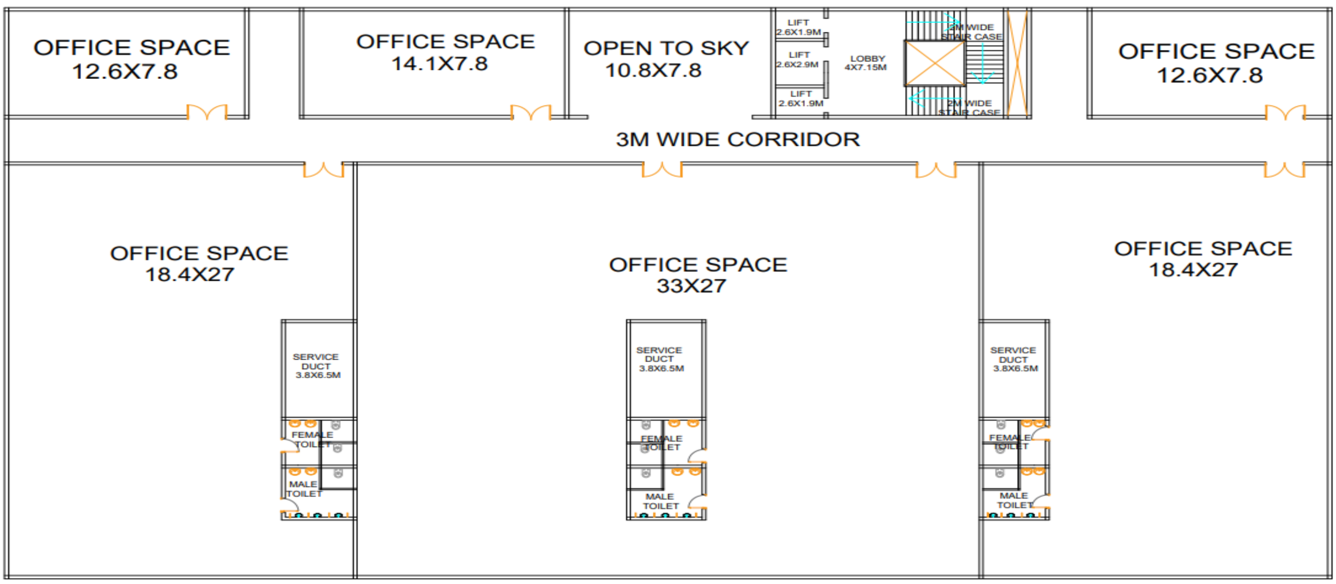

Fig. 1. Architectural plan of the commercial building (70.9 m × 39.55 m).

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Fig. 2. Column layout superimposed on the building plan.

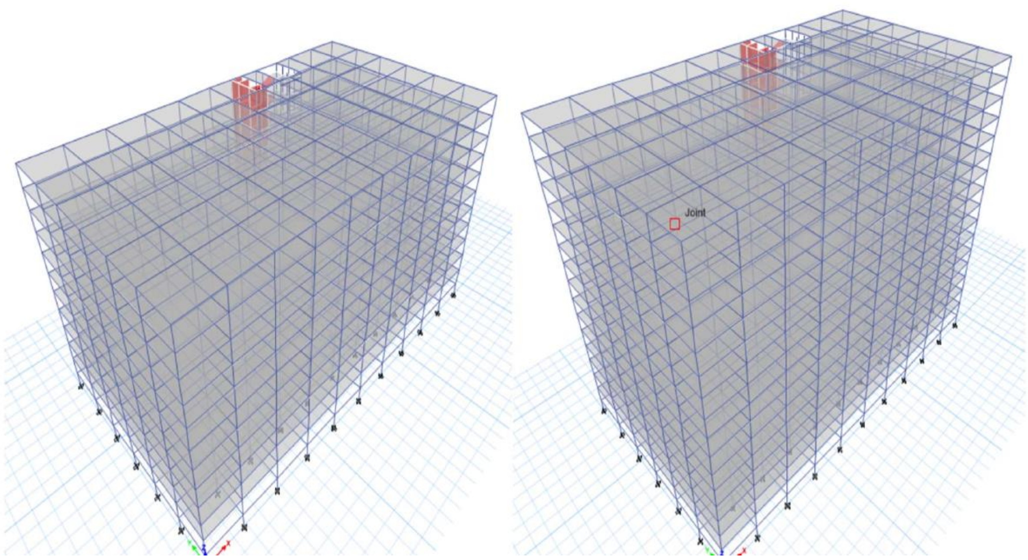

Fig. 3. ETABS 3D model without expansion joint: (a) 10-storey building; (b) 15-storey building.

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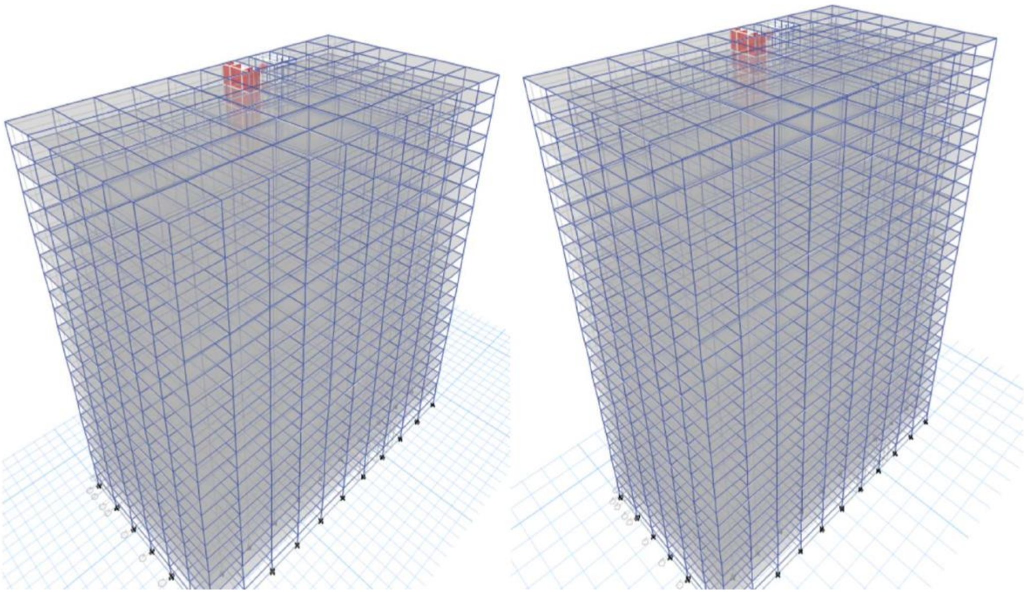

Fig. 4. ETABS 3D model without expansion joint: (a) 20-storey building; (b) 25-storey building.

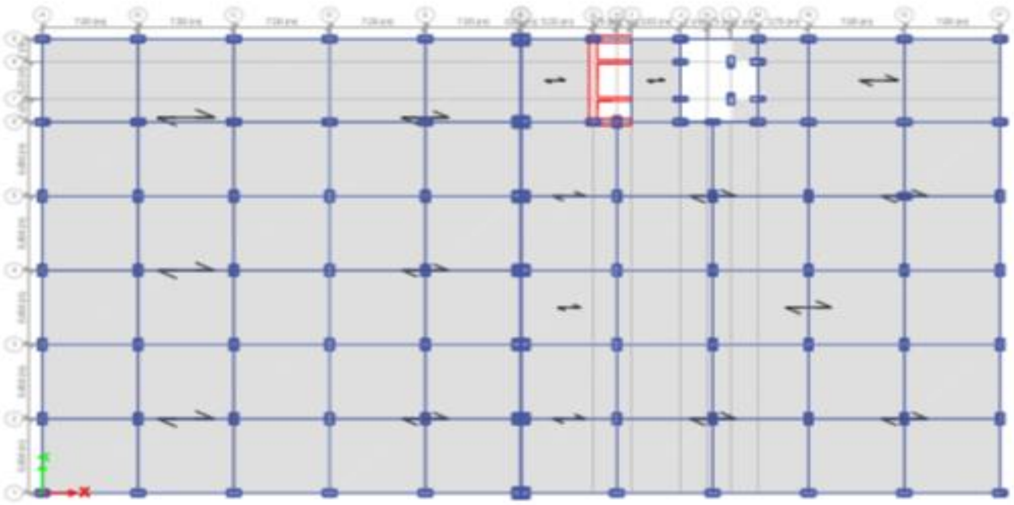

Fig. 5. ETABS plan view showing the expansion joint at the building mid-length (35 m), separating the two independent blocks.

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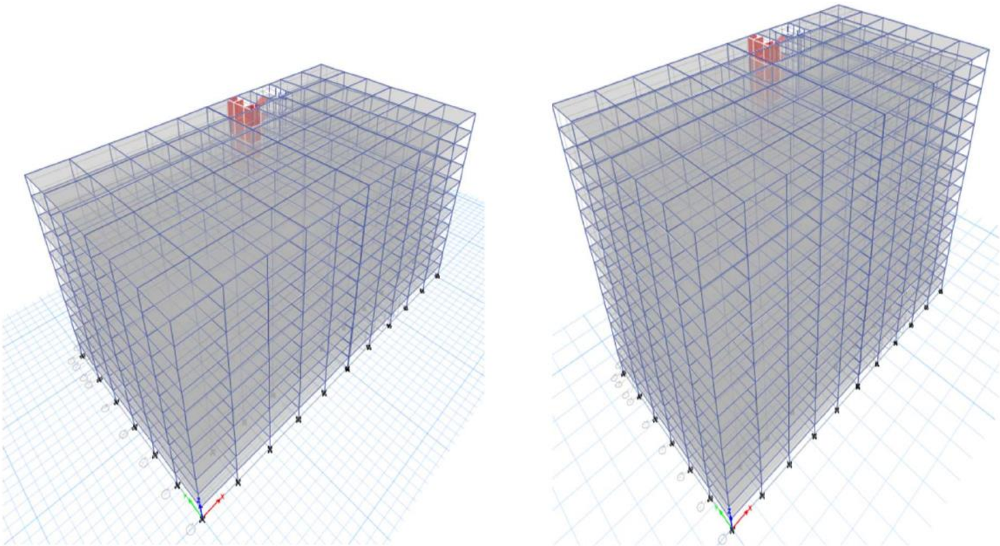

Fig. 6. ETABS 3D model with expansion joint: (a) 10-storey building; (b) 15-storey building.

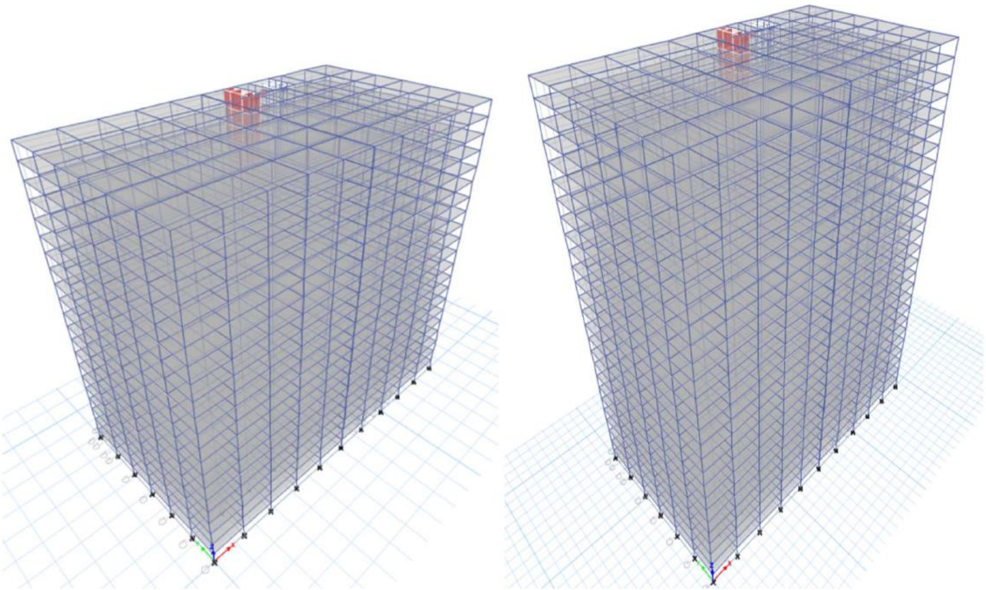

Fig. 7. ETABS 3D model with expansion joint: (a) 20-storey building; (b) 25-storey building.

5.2 Analysis

Both static and dynamic analyses were carried out in ETABS. Static analysis extracted deformed shapes and internal forces (bending moment, shear force) under static load cases, with section properties adjusted to satisfy deflection limits per IS 456:2000. Dynamic analysis comprised separate wind analysis under +X, –X, +Y, –Y directions, and seismic analysis using response spectrum load cases (EQX, EQY) from which storey displacement, storey drift and base shear were extracted. Twenty-six load combinations were applied in total, including 1.5(DL+SDL), 1.5(DL+LL+SDL), and factored combinations of dead, live, superimposed dead, wind and seismic loads with factors of 1.2, 1.5 and 0.9 as prescribed in the relevant Indian Standard codes.

6. DESIGN SPECIFICATIONS

Table 1 summarises the principal design specifications of the building common to all storey configurations analysed.

Table-1: Design specifications of the building

Specification	Value
Plan dimensions	70.9 m × 39.55 m

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Number of storeys	10, 15, 20, 25
Bottom storey height	2.5 m
Typical storey height	3.3 m
Slab thickness	0.2 m
Wall thickness	0.23 m (outer), 0.12 m (inner)
Maximum column size	1.0 m × 0.6 m
Maximum beam size	1.0 m × 0.6 m
Grade of steel	Fe500
Grade of concrete (beam/column)	M30
Floor finish load	1.5 kN/m²
Live load	4 kN/m² (general), 4.5 kN/m² (corridor/staircase)
Expansion joint width	30 mm

6.1 Seismic Details

Table-2: Seismic design parameters (Zone III)

Parameter	Value
Seismic zone	III
Zone factor (Z)	0.16
Response reduction factor (R)	5
Importance factor (I)	1
Soil condition	Medium, Type II

6.2 Wind Load Details

Table-3: Wind load design parameters

Parameter	Value
Location	Tirupati
Basic wind speed, Vb	39 m/s
Probability factor, k1	1
Terrain category	2, Class B
Topography factor, k3	1
Importance factor, k4	1

7. RESULTS AND DISCUSSION

Structural analysis of the commercial building was carried out in ETABS considering dead load, live load, wind load, earthquake load, P-Delta effects and expansion joint effects, for building heights of 10, 15, 20 and 25 storeys. Four model variants were compared throughout: Model A – without P-Delta and without expansion joint; Model B – with P-Delta, without expansion joint; Model C – with expansion joint, without P-Delta; and Model D – with both expansion joint and P-Delta effects. Results are reported for the governing load combinations 1.5(DL+LL+SDL), 1.2(DL+LL+SDL+WLx), 1.2(DL+LL+SDL+EQx) and the temperature load case, at the topmost storey of each configuration.

For all comparisons, Model A denotes the structure without P-Delta and without expansion joint effects, Model B with P-Delta and without expansion joint, Model C with expansion joint and without P-Delta, and Model D with both expansion joint and P-Delta effects. Results are reported at the topmost storey of each building height (10, 15, 20 and 25 storeys), with both X-axis and Y-axis response given, for the four governing load cases: 1.5(DL+LL+SDL), 1.2(DL+LL+SDL+WLx), 1.2(DL+LL+SDL+EQx) and Temperature.

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7.1 Storey Displacement

Tables 4–7 present the top-storey displacement (mm) in both the X- and Y-directions for all four storey heights, under each of the four load cases.

Table-4: Top-storey displacement under 1.5(DL+LL+SDL) (mm)

Storeys	X-axis (mm)				Y-axis (mm)			
	A	B	C	D	A	B	C	D
10	3.65	4.48	3.76	3.90	5.83	7.34	3.87	3.90
15	3.95	5.00	5.71	5.82	6.73	8.55	6.53	6.64
20	5.93	6.04	7.82	8.04	10.90	11.20	9.37	9.60
25	6.57	6.73	9.87	10.27	14.32	13.85	12.26	12.70

Table-5: Top-storey displacement under 1.2(DL+LL+SDL+WLx) (mm)

Storeys	X-axis (mm)				Y-axis (mm)			
	A	B	C	D	A	B	C	D
10	2.92	3.58	3.03	3.037	4.66	5.87	0.93	0.947
15	3.95	4.00	4.56	4.65	6.73	6.84	1.24	1.27
20	4.74	4.83	6.25	6.40	8.72	8.96	1.44	1.60
25	5.25	5.39	7.90	8.21	10.65	11.08	1.79	1.88

Table-6: Top-storey displacement under 1.2(DL+LL+SDL+EQx) (mm)

Storeys	X-axis (mm)				Y-axis (mm)			
	A	B	C	D	A	B	C	D
10	17.55	19.61	11.38	11.48	7.11	1.14	0.91	0.96
15	17.99	18.44	9.96	10.16	8.67	0.476	1.10	1.13
20	9.91	10.40	9.86	10.174	4.84	4.94	1.447	1.49
25	10.28	11.39	10.34	10.83	6.07	6.29	1.72	1.80

Table-7: Top-storey displacement under Temperature load (mm)

Storeys	X-axis (mm)				Y-axis (mm)			
	A	B	C	D	A	B	C	D
10	19.09	19.13	14.85	14.88	21.126	21.21	12.99	13.00
15	20.38	20.49	14.69	14.78	23.42	23.593	13.45	13.47
20	19.77	19.92	14.25	14.39	24.07	24.38	13.49	13.50
25	19.16	19.33	13.90	14.10	25.11	25.609	13.32	13.34

Displacement: Across all four load cases, storey displacement increases progressively with building height in both the X- and Y-directions, with the 25-storey configuration showing the largest values in every case. Under the gravity combination 1.5(DL+LL+SDL), Models C and D (with expansion joint) show larger X-direction displacement than Models A and B at every height, with the gap widening from roughly 3.8–3.9 mm at 10 storeys to 9.9–10.3 mm versus 6.6–6.7 mm at 25 storeys; the Y-direction shows the opposite trend, with Models A and B exceeding C and D at every height. Under wind loading (WLx) the same pattern holds in both directions: Models C and D exceed A and B in X, while Models A and B substantially exceed C and D in Y – the Y-direction gap is striking, with Models A/B reaching 10.7–11.1 mm against just 1.8–1.9 mm for Models C/D at 25 storeys, since the expansion joint interrupts the long Y-direction diaphragm. Under temperature loading, Models A and B show consistently higher displacement than Models C and D in both directions at every height, confirming that expansion joints are specifically effective at reducing thermally-induced movement.

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7.2 Storey Drift

Tables 8–11 present the top-storey drift (mm) in both the X- and Y-directions for all four storey heights, under each of the four load cases.

Table-8: Top-storey drift under 1.5(DL+LL+SDL) (mm)

Storeys	X-axis (mm)				Y-axis (mm)			
	A	B	C	D	A	B	C	D
10	0.60	0.673	0.63	0.633	0.79	0.924	0.825	0.828
15	0.66	0.66	0.84	0.85	1.18	1.19	1.00	1.02
20	0.81	0.83	1.21	1.23	1.59	1.63	1.50	1.52
25	0.97	1.02	1.56	1.62	1.46	2.06	2.00	2.06

Table-9: Top-storey drift under 1.2(DL+LL+SDL+WLx) (mm)

Storeys	X-axis (mm)				Y-axis (mm)			
	A	B	C	D	A	B	C	D
10	0.462	0.537	0.504	0.505	0.65	0.739	0.66	0.828
15	0.528	0.531	0.676	0.68	0.94	0.957	0.808	0.818
20	0.65	0.663	0.97	0.99	1.27	1.31	1.201	1.22
25	0.72	0.745	1.25	1.29	1.58	1.65	1.603	1.65

Table-10: Top-storey drift under 1.2(DL+LL+SDL+EQx) (mm)

Storeys	X-axis (mm)				Y-axis (mm)			
	A	B	C	D	A	B	C	D
10	0.99	1.03	0.607	0.610	0.495	0.59	0.676	0.676
15	0.983	0.99	0.745	0.75	0.726	0.745	0.821	0.83
20	0.844	0.89	1.019	1.04	1.16	1.19	1.20	1.22
25	0.907	1.00	1.29	1.33	1.98	2.12	1.607	1.65

Table-11: Top-storey drift under Temperature load (mm)

Storeys	X-axis (mm)				Y-axis (mm)			
	A	B	C	D	A	B	C	D
10	1.56	1.564	1.58	1.93	1.70	1.706	0.73	0.78
15	1.65	1.67	1.23	1.24	1.66	1.67	0.66	0.67
20	1.56	1.58	1.14	1.16	1.73	1.76	0.58	0.59
25	1.46	1.50	1.06	1.09	1.88	1.95	0.54	0.55

Storey drift: Storey drift follows a broadly similar pattern to displacement across all four load cases, increasing with building height and remaining within the IS 1893 permissible limit of 0.004 times storey height (13.2 mm for a typical 3.3 m storey) throughout. Models C and D show higher X-direction drift than A and B under gravity, wind and seismic loading, while Models A and B show higher Y-direction drift under wind and temperature loading at most heights. P-Delta inclusion (Model B vs. A, Model D vs. C) consistently increases drift in both directions, with the increase most pronounced at 20 and 25 storeys.

7.3 Axial Force in Critical Column

Tables 12–15 present the peak axial force P (kN) recorded in the governing column (C8) for all four storey heights, under each of the four load cases.

Table-12: Peak axial force, column C8, under 1.5(DL+LL+SDL) (kN)

Storeys	A	B	C	D
10	-1380.95	-1369.47	-1417.13	-1417.38

15	-8384.78	-8385.99	-7580.67	-7580.34
20	-14556.01	-14559.44	-13560.92	-13559.67
25	-20175.69	-20182.22	-19493.16	-19490.06

Table-13: Peak axial force, column C8, under 1.2(DL+LL+SDL+WLx) (kN)

Storeys	A	B	C	D
10	-1104.76	-1095.58	-1133.71	-1133.91
15	-6707.82	-6708.79	-6064.54	-6064.28
20	-11644.81	-11647.55	-10848.74	-10847.74
25	-16140.55	-16145.77	-15594.53	-15592.06

Table-14: Peak axial force, column C8, under 1.2(DL+LL+SDL+EQx) (kN)

Storeys	A	B	C	D
10	-1102.47	-1102.58	-1127.75	-1127.91
15	-6685.28	-6685.23	-6046.86	-6046.29
20	-11628.24	-11629.63	-10832.42	-10830.98
25	-16119.52	-16122.77	-15580.90	-15577.91

Table-15: Peak axial force, column C8, under Temperature load (kN)

Storeys	A	B	C	D
10	-577.40	-577.47	-65.77	-65.67
15	-3189.00	-3190.07	-427.98	-428.10
20	-5438.53	-5440.41	-632.76	-633.49
25	-7433.37	-7436.94	-723.51	-725.50

Axial force: Continuous structures without expansion joints (Models A, B) exhibit higher peak column axial force than jointed structures (Models C, D) under gravity, wind and seismic loading at every height, reflecting the load-sharing behaviour of an undivided frame; the relative difference narrows somewhat at greater height as overall axial demand increases in both configurations. Under temperature loading the contrast is much sharper: axial force in the unjointed Models A and B is roughly an order of magnitude larger than in the jointed Models C and D at every height (for example −7433 kN versus −724 kN at 25 storeys), since the continuous frame develops substantial restrained thermal force that the expansion joint relieves almost entirely. P-Delta inclusion produced only a marginal change in peak axial force at every height and load case, confirming that P-Delta primarily affects lateral response (displacement and drift) rather than gravity- or temperature-dominated axial force.

7.4 P-Delta Sensitivity

P-Delta sensitivity: Comparing Models A-B and C-D across all load cases shows that the increase in displacement, drift and (to a lesser extent) axial force attributable to P-Delta effects grows with building height, being modest for 10- and 15-storey models but becoming structurally significant for the 20- and 25-storey models, indicating that second-order analysis is essential for accurate response prediction in taller commercial buildings of this type.

8. CONCLUSION

- A three-dimensional ETABS model of the commercial building was successfully developed and analysed for 10, 15, 20 and 25 storeys under dead, live, wind, seismic and temperature loads as per relevant Indian Standard codes, demonstrating ETABS as an efficient platform for analysis and design of multi-storey buildings.
- Expansion joints effectively divided the building into independent structural blocks, allowing free thermal movement, reducing stress concentration and improving serviceability and durability by minimizing cracking risk.
- Structures without expansion joints experienced significantly higher displacement under temperature loading than structures with expansion joints, confirming that expansion joints are essential for large commercial buildings subject to considerable temperature variation.

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- P-Delta analysis produced higher storey displacement and drift than first-order analysis, with the effect of geometric nonlinearity becoming more pronounced as building height increased; the influence was most significant for the 20- and 25-storey models, demonstrating that neglecting P-Delta effects can lead to underestimation of structural response.
- Storey displacement increased progressively with the number of storeys for all models, with maximum values in the 25-storey configuration; storey drift increased with height but remained within IS 1893 permissible limits throughout.
- All structural models satisfied the strength and serviceability requirements of IS 456:2000, IS 875 and IS 1893, with the use of expansion joints reducing unnecessary thermal stress and contributing to a more efficient and economical structural system.
- The combined consideration of P-Delta effects and expansion joints provides a more realistic representation of actual structural behaviour: expansion joints improve thermal performance and reduce stress concentration, while P-Delta analysis accurately captures second-order effects. Both should therefore be incorporated in the structural analysis and design of multi-storey commercial buildings to ensure safety, serviceability, durability and overall performance.

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