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A Critical Review of P–Delta Analysis and Stability Performance of Multistory Pre-Engineered Buildings

Sakshita A. Dukare[1], Sanket S. Sanghai[2] and Satish S. Raipure[3]
[1-2]Department of Civil Engineering, G H Raisoni College of Engineering, Nagpur, Maharashtra, India.
Email: dukaresakshita@gmail.com, sanket.sanghai@raisoni.net
[3]Structural Engineer, Vighnaharta Consulting Engineers, Nagpur, Maharashtra, India
Email: connect@vighnahartaengineers.com

***Abstract*— The trend of applying multistory pre-engineered buildings (PEBs) to industrial and commercial situations is on the rise, however, this has brought about some issues regarding stability and serviceability of the structures under lateral loading. Multistory cases are different from the conventional low-rise PEBs as they have increased slenderness, decreased lateral stiffness, and axial forces that interact significantly with lateral displacements which are in fact the governing design consideration for the second-order P–Delta effects. Usually, these effects are dealt with a simplified approach in present-day practice and this results in the potential underestimation of drift, member demand, and instability risk. The key goal of this review is to bring together and critically evaluate the existing studies on P–Delta analysis of multistory PEBs with a focus on analytical, numerical and case-study-based research. The review examines both linear and nonlinear analysis methods while evaluating performance metrics such as drift amplification and base shear reduction and member force interaction between structural elements. The research findings demonstrate that P-Delta effects must be studied because their absence creates inaccurate serviceability and ultimate performance forecasts that worsen under wind and seismic loading conditions. The nonlinear static and nonlinear dynamic methods provide accurate stability detection and displacement demand assessment throughout all assessment periods. The review has identified a lack of PEB-specific experiments and performance-based design frameworks which directs future research to establish safer multistory PEB systems that operate reliably.**

***Index Terms*— Geometric nonlinearity, Multistory buildings, P–Delta analysis, Pre-engineered buildings, Seismic performance, Structural stability.**

I. INTRODUCTION

A. Background and Motivation

Pre-engineered building development started as a solution which offered better cost efficiency compared to traditional steel construction methods used in designing low-rise industrial buildings and storage facilities. Their adoption increased due to standardized fabrication, reduced construction duration, efficient material utilization, and overall economic benefits [1].

Traditionally, PEBs comprised single-storey portal frames with large spans where first-order effects dominated structural performance.

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The past twenty years have seen increased urban development and decreased land availability and growing demand for flexible spaces which resulted in expanded PEB applications to both multistorey buildings and specific building types which include warehouses with mezzanine floors and industrial sheds and parking structures and mixed-use buildings [2],[3].

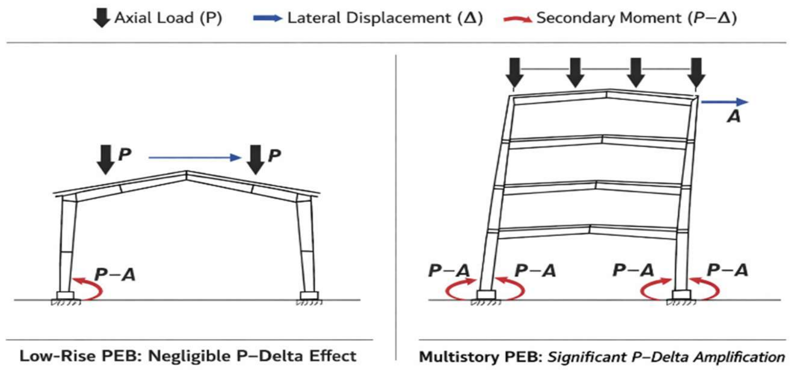

Figure 1. The diagram essentially sets a judicious comparison about a low rise PEB structure and a multi-story PEB structure.

The diagram shows how axial load (P) and lateral displacement (Δ) produce secondary moment (P–Δ) in both types of PEB structures

Second-order axial–lateral interaction effects become necessary for structural assessment because multistorey PEBs create three design challenges which include increased slenderness and decreased lateral stiffness and the high stiffness variation caused by tapered members [4],[5].

B. Significance of P–Delta Effects in Multistory PEBs

PDelta effects hold crucial importance for multistorey steel structures because structural responses to lateral loads increase when large axial forces combine with major lateral movements which create secondary rotational forces. The effects increase in multistorey PEBs because slender columns combine with semi-rigid connections and reduced stiffness that results from optimized tapered sections. The seismic actions create cyclic displacements which lead to second-order moment increases that cause inter-storey drift augmentation and internal force redistribution which may result in soft-storey mechanisms. Wind loading causes flexible frames to experience continuous deflections which heighten P–Delta moment amplification resulting in strength and serviceability limits that become controlling factors. The analysis results in non-conservative beliefs because the analysis fails to consider these effects which cause incorrect column moment calculations and thus mislead about stability predictions The analysis will result in non-conservative conclusions because it does not include all existing effects that lead to incorrect column moment calculations which subsequently affect stability prediction results [6]-[10].

II. Fundamentals Of P–Delta Analysis

A. Concept of Geometric Nonlinearity

Nonlinear geometrical behavior in structural systems takes place whenever equilibrium conditions come to be enforced in a deformed solid state rather than the initial state form. The effect shows its highest impact on multi-story steel buildings when combined axial loads and sideways building movements create additional internal bending moments which standard linear first-order analysis fails to detect. The global P-Delta effect represents the most widely accepted form which generates an overturning moment through total axial load distribution from a building's storey to its lateral displacement movement. The global P-Delta effect generates extra moment for each single storey of a multistory frame according to the following expression [11][12]:

$$M_{\Delta} = P \cdot \Delta$$

The axial load which all the columns of the storey support equals P while the storey displays lateral movement through Δ. The structural sway stability gets affected by this effect which causes interstory drift and increases column requirements. The P–δ effect which shows local geometric nonlinearity exhibits its existence at the member level while it causes global structural effects. This effect is associated with the curvature of individual columns subjected to axial compression and bending. The local second-order moment may be expressed as [13]:

$$M_\delta = P \cdot \delta$$

where δrepresents the local deflection of a member between its end supports. In multistory steel frames, both P–Δ and P–δ effects act simultaneously, where the former governs global stability while the latter governs member-level strength and buckling behavior. Accurate stability assessment therefore requires consideration of both components in advanced analysis procedures.

B. Code Provisions and Design Guidelines

Design standards address geometric nonlinearity either explicitly through nonlinear analysis or implicitly through amplification factors and stability coefficients. International standards such as AISC and Eurocode permit second-order analysis using geometric stiffness matrices, where equilibrium is solved iteratively on the deformed shape. In practice in India, incorporation of second-order effect is recommended by IS 800 when the stability index surpasses a specified threshold. Stability factor is usually determined as [15]:

$$\theta = \frac{P \cdot \Delta}{V \cdot h}$$

where V is the storey shear and $h$is the storey height. The first need for second-order analysis occurs when the value of theta exceeds predetermined limits. The established drift limits serve to prevent excessive lateral movement which indirectly limits P-Delta effect increases.

For simplified assessment, amplification of first-order moments may be performed using [16]:

$$M_u = \frac{M_1}{1 - \theta}$$

where M_1 the first order bending moment calculation must use the amplified design moment value which is denoted by Mu. The design process for steel frames uses these formulations as standard practice which proves essential for pre-engineered buildings that need fast assessment capabilities.

C. Relevance to Pre-Engineered Building Systems

The tapered built-up member design of pre-engineered building systems shows high member sensitivity to global and local P-Δ effects whenever they experience lateral loads [17],[18]. Semi-rigid beam–column connections further intensify this behaviour by reducing rotational restraint and increasing lateral flexibility, which amplifies displacements and associated P-Δ moments. The use of lightweight roof and wall panels decreases seismic mass yet results in increased drift sensitivity because they decrease building stiffness [19]. The combination of slender columns with semi-rigid joints and changing member shapes requires thorough geometric nonlinearity analysis to avoid force underestimation and multi-story PEB instability risks [20].

III. Structural Characteristics of Multistory Pre-Engineered Buildings

A. Structural Configuration and Load Path

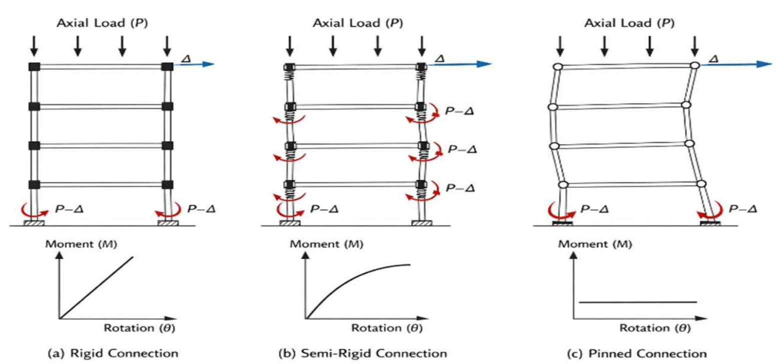

Figure 2. The schematic diagram shows three types of beam-column connections that include rigid connections, semi-rigid connections, and pinned connections in a multistory pre-engineered building structure

The diagram shows how these connections affect the building's lateral displacement patterns and the building's second-order P-Delta moment amplification.

Multistory pre-engineered buildings select their structural systems based on their operational requirements and requirements for lateral force handling and their construction process. Moment-resisting frames become the preferred solution for architectural designs that require open spaces because these frames use their beam and column systems to withstand lateral impacts. The vertical loads of these buildings transfer from beams to columns and then to the foundation base, while the horizontal forces create storey shears that the frames can counter through their bending movements. The moment frames in PEBs exhibit considerable lateral movement because their tapered members and semi-rigid joints create flexible structures.

In multistory PEB structures, beam-column connections may be rigid, semi-rigid, or pinned, each exhibiting distinct moment–rotation characteristics that govern lateral displacement response and are widely referenced in stability assessments of steel frames [22],[23]. Braced-frame systems use braces to create effective load paths which enable buildings to withstand wind and seismic forces while maintaining their structural integrity. The hybrid system uses moment-resisting frames as its primary vertical load system while braces handle lateral loads which results in a perfect blend of structural strength and adaptable material utilization. The system's second-order behavior depends on three main factors which include axial force dominance and moderate bending capacity and vertical load to lateral load ratio [24],[25].

B. Material and Sectional Properties

Tapered built-up sections in PEB systems are the design characteristic par excellence. These members are designed with variable depth along their length to match bending moment demand, which results in material savings but also introduces non-uniform stiffness. The flexural rigidity of a tapered member varies as [26]:

$$EI(x) = E \cdot I(x)$$

where $I(x)$ is the moment of inertia that varies along the length of the member. This variation results in a decrease of the stiffness region by the smaller depth and the increase of the buckling and P–Delta effect being more prone to occur.

Modern steel grades with high strength are used more frequently to minimize member dimensions and weight. Though, the larger yield strength boosts axial power, it is not so much a case of proportional increase in stiffness which is mainly a function of the modulus of elasticity. As a result, slenderness ratios tend to increase, which adversely affects global stability in multistory frames [27][28].

Table 1 summarizes typical material and sectional characteristics of multistory PEBs and their influence on stability behavior.

TABLE I: STRUCTURAL CHARACTERISTICS OF MULTISTORY PEB SYSTEMS AND STABILITY IMPLICATIONS

Parameter	Typical PEB Practice	Influence on P–Delta Behavior
Column section	Tapered built-up I-section	Variable stiffness increases drift sensitivity
Steel grade	High-strength steel	Higher capacity but unchanged stiffness
Roof and floor system	Lightweight steel decking	Reduced mass but lower lateral stiffness
Column slenderness	Moderate to high	Increased second-order moment amplification

C. Connection Behavior and Its Influence on P–Delta Effects

Connection behavior is a main factor that will determine how lateral load will be absorbed by the multistory PEBs. Rigid connections allow for large rotation and significantly lower lateral displacement due to the increased frame stiffness. But still, these kinds of connections are not common practice in PEB because of their complicated fabrication and high costs.

Semi-rigid connections are becoming more common in applications where joint rotational stiffness is in between that of full rigidity and that of pinned conditions. The moment rotation relationship can be simplistically represented as [29]:

$$M = k_\theta \cdot \theta$$

where k_θ is the rotational stiffness of the connection and θ is the joint rotation. Reduced rotational stiffness leads to increased frame flexibility, which amplifies storey displacement and consequently P–Delta effects.

Pinned connections are highly effective in transferring gravity loads, however, they provide very little resistance to lateral forces and thus cannot be considered as the main lateral systems in multistory PEBs. Kinematic studies have repeatedly confirmed that the modeling of semi-rigid joint behavior is a must in order not to underestimate drift and second-order moments, particularly in the case of seismic loading [30].

IV. Literature Review on P–Delta Analysis of Multistory PEBs

A. Analytical Studies

Analytical approaches to P–Delta behavior in multistory steel frames have progressed from simplified moment-amplification methods to rigorous second-order iterative analyses. Earlier code-based amplification factors approximate geometric nonlinearity but may underpredict demands in flexible or semi-rigid systems [31,32]. Advanced nonlinear static and time-history analyses show that P–Delta effects significantly increase interstory drifts, alter yielding sequences, and reduce collapse margins, emphasizing the necessity of second-order analysis for performance-based design of slender multistory frames [33,34].

B. Numerical and Finite Element-Based Studies

Researchers have achieved better understanding of P-δ interactions at local levels and P-Δ amplification effects at global levels through their second-order analytical methods and nonlinear finite-element research. The advanced beam–column formulations which combine geometric stiffness and large-displacement behaviour and inelasticity control mechanisms prevent engineers from making false stability predictions. The analyses show new failure mechanisms which local buckling and axial-force redistribution and ground-motion spectral effects create because they have a critical impact on P-Δ amplification [35–37]. Tapered members together with semi-rigid joints in pre-engineered buildings produce non-uniform curvature which leads to amplified local P-δ effects while making changes to overall moments and building displacement patterns. The P-Δ FE methods which use iterative calculations maintain their accuracy through proper joint depiction and element size distribution [38],[39].

C. Experimental and Validation Studies

Designing concepts have to improve their seismic vulnerability evaluations in elaboration with good analysis of structural and nonstructural elements by concentrating on achieving the target realization under possible constraints and plentiful degrees of freedom. Recently, full-scale and sub assemblage studies conducted on modular frames and hybrid self-centering systems have reported enhanced inter-story drifts, changed hinge patterns, and impacted residual stability during sequential loading, therefore, it is necessary to carry out specific PEB testing [40],[41].

D. Key Findings and Limitations in Existing Literature

TABLE II: SUMMARY OF LITERATURE ON P–DELTA ANALYSIS RELEVANT TO MULTISTORY PEBs

Author (Year)	Methods / Key Findings	Limitations / Research Gap
Kim (2018) [42]	Nonlinear static analysis showed drift amplification due to P–Delta	Limited to prismatic steel frames
Chen (2018) [43]	Stability indices validated for tall steel frames	No PEB-specific modeling
Zandonini (2019) [44]	Semi-rigid joints increased second-order effects	Experimental scale limitations
Xu (2019) [45]	Numerical study on connection stiffness influence	No seismic loading considered
Kwon (2020) [46]	Nonlinear dynamic analysis under earthquakes	Conventional steel frames only
Park (2020) [47]	P–Delta impact on collapse margin	No tapered members
Shi (2020) [48]	FE-based geometric nonlinearity modeling	High computational demand
Li (2021) [49]	Wind-induced P–Delta amplification in flexible frames	Low-rise focus
Barbosa (2021) [50]	Advanced FE modeling of steel frames	No validation
Nguyen (2021) [51]	Drift control with second-order analysis	Simplified connections
AlHamaydeh (2022) [52]	Seismic P–Delta sensitivity assessment	Generic steel buildings
Wang (2022) [53]	Tapered section stiffness effects	Limited height range
Das (2022) [54]	Indian code-based P–Delta evaluation	Approximate methods only
Zhang (2023) [55]	Nonlinear pushover with P–Delta	No experimental comparison
Lee (2023) [56]	Hybrid braced frame stability study	Not PEB-oriented
Kumar (2023) [57	Parametric study on axial load ratio	Simplified geometry
Ahmed (2024) [58]	Numerical validation with field data	Single case study
Silva (2024) [59]	Large displacement FE analysis	High modeling complexity
Choudhary (2024) [60]	Multistory steel frame seismic stability	No PEB optimization
Rao (2025) [61]	Comparative study of analysis methods	Lack of experimental data

The combination of the studies reviewed indicates that the P–Delta phenomena result in a considerable enhancement of the internal moments and inter-storey drifts in multistorey pre-engineered buildings (PEB), particularly in cases involving heavy axial loads, tall and slender columns, and flexible joints. Innovations in second-order numerical methods make it possible to get precise predictions, whereas the traditional method of increasing the loads prescribed by code may prove to be optimistic. Nevertheless, the fewer number of tests, unrealistic connections, simple section designs, and lack of SSI-coupled studies underscore the requirement for thorough studies that are validated [42–50]

V. Comparative Analysis of P–Delta Modeling Approaches

A. Linear Static vs Nonlinear Static Analysis

Linear static (first-order) analysis is performed considering equilibrium on the structure in its original shape only, and therefore it disregards both geometric stiffness and the second-order amplification effects, which is the reason why such analysis is characterized with being conservative and low-cost making it suitable for preliminary design [61]. On the other hand, Nonlinear static (second-order, P–Delta) analysis fully embraces geometric nonlinearity by incorporating MΔ = PΔ in the iterative equilibrium formulation, which leads to more accurate capturing of stability effects overall [52]:

$$K_t(u)\, u = F$$

The tangent stiffness Kt consists of geometric stiffness terms that vary with the displacement vector uu. Nonlinear static methods such as second-order elastic analysis or pushover analysis with geometric stiffness yield higher accuracy for flexible multistorey frames where P–Δ effects are significant [52],[53]. The advantages of this system apply most effectively to PEB structures that have a tall and slender design and which undergo substantial drifts and axial-flexural interaction [54],[55]. Even though nonlinear static analysis needs several iterations for the equilibrium solutions, it still turns out to be more efficient than nonlinear dynamic time-history analysis in terms of computation [56],[57]. It is also widely used in design when second-order effects are the primary consideration [51],[58].

B. Nonlinear Static vs Nonlinear Dynamic Analysis

Nonlinear dynamic (time-history) analysis resolves the full dynamic response under specified ground motions or wind time series. It captures rate effects, mode coupling, higher-mode contribution, and cumulative damage under cyclic loading. The governing equation is [58]:

$$M\ddot{u}(t) + C\dot{u}(t) + K_t(u)u(t) = F(t)$$

Even though nonlinear dynamic (time-history) analysis is still the most reliable method for evaluating seismic performance and collapse, especially in the case of structural response affected by higher-mode effects, strong nonlinearity, or near-fault pulses; it is still a computation-intensive method and very sensitive to the choice of input motion [55],[59]-[61]. Nonlinear static (pushover) analysis at the same time presents a much simpler and straightforward capacity–displacement evaluation which is mainly working for regular, low-to-mid-rise structures that are first mode dominated. So adaptive and multi-modal pushover approaches are to an extent limiting the necessity of dynamic analysis for collapse margin estimation making method selection dependent on the context [52],[56],[60],[62],[64].

C. Software-based Implementation Strategies

TABLE III: Comparative Analysis of Literatures

Author (Year)	Method / Focus
Bhandari (2018) [62]	Assessment of proposed lateral load patterns in pushover
Rooshenas (2020) [63]	Comparison of adaptive pushover methods vs time history
Bruschi (2021) [64]	Effects of modelling choices in concentrated plasticity
Di Re (2022) [65]	Simple numerical pushover procedure for slender members
Cheng (2022) [66]	P–Delta effects under near-fault and far-fault motions
Kuria (2023) [67]	Review of pushover methods limitations and improvements
Abd-Elhamed (2023) [68]	Pushover vs time history for RC high-rise comparison
AlHamaydeh (2023) [69]	INSPECT-SPSW OpenSees package for nonlinear analyses
Shabani (2023) [70]	Review of OpenSees GUIs and modelling workflows
Rodríguez (2024) [71]	Comparative evaluation of static and dynamic methods

Commercial packages (ETABS, SAP2000, STAAD.Pro) typically provide convenient second-order elastic analysis and pushover modules that include geometric stiffness options which are straightforward to use for routine PEB models [65],[53]. Open-source platforms such as OpenSees permit flexible modelling of distributed plasticity, geometric nonlinearity and custom hysteretic laws which is essential for research, parametric studies, and high-fidelity PEB simulation [61],[59]. Finite element choices (lumped versus distributed plasticity), element formulation (large-displacement versus small-displacement), and connection models (rigid, semi-rigid spring elements, or detailed bolted/welded contact models) strongly influence P–Delta predictions; distributed plasticity and large-displacement formulations give the most physically consistent results for tall, slender PEBs but at higher computational expense [53],[61],[66]. Practically a hybrid workflow is effective: use commercial FE tools for rapid parametric studies and OpenSees or research FE codes for detailed verification and fragility assessment [61],[66],[64].

VI. Performance Analysis Parameters

A. Lateral Displacement and Interstory Drift

P–Delta amplification directly increases lateral displacements and interstory drift in multistory frames as axial forces act through the laterally displaced geometry. For a storey with total axial column load $P$and lateral storey displacement Δ, the incremental second-order moment is $M_\Delta = P\Delta$. When applied to the overall storey equilibrium the amplified moment demand may be approximated as [66]:

$$M_u = \frac{M_1}{1-\theta}, \theta = \frac{P\Delta}{Vh}$$

where $M_1$is the first-order moment, $V$is storey shear and $h$is storey height, which yields a stability coefficient θused commonly in code checks [65],[66]. Drift amplification ratio (DAR) is commonly reported as [67]:

$$\text{DAR} = \frac{\Delta_{\text{2nd}}}{\Delta_{\text{1st}}}$$

and is sensitive to axial load ratio $\alpha = P/(A_g f_y)$, connection rotational stiffness k_θ, and member slenderness [68],[69]. Empirical and numerical studies show DAR increases nonlinearly with $\alpha$and with reduced rotational restraint, which has serviceability implications such as cladding damage, door/window misalignment and occupant discomfort [70],[71]. Under seismic cycles P–Delta interacts with material nonlinearity which can produce larger residual drifts when catenary or buckling mechanisms develop [72]. Designers should therefore evaluate both peak and residual drift demands in performance assessments.

B. Base Shear, Overturning Moment, and Stability Indices

The second-order effects create changes to global force requirements because they produce greater overturning moments which decrease the capacity to resist lateral forces. The global equilibrium including P–Delta contributions can be written as [73]:

$$\sum M = M_{\text{applied}} + \sum P_i \Delta_i = 0$$

The base shear needed for target displacement increases when P-Delta moments are added to the calculations. The first-order analysis method needs less base shear according to several comparative studies although this approach proves unsafe for tall flexible PEBs [74],[75].

Stability indices such as the story stability coefficient θor the column slenderness factor KL/rare effective screening parameters. Performance design requires practitioners to verify that θstays below code limits or they need to conduct second-order analysis. The structure becomes unstable at θvalues close to one because it leads to progressive mechanisms of failure [76],[77]. Parametric studies demonstrate that higher diaphragmatic flexibility and lower brace stiffness result in increased overturning moment amplification while reducing the available instability margin [78].

C. Member Demand Amplification and Failure Modes

P–Delta effects intensify member demands by amplifying bending–axial interaction, accelerating local buckling and plastic hinge formation in columns, typically represented through M–N interaction diagrams where second-order moments shift demand toward buckling limits. Effective design therefore incorporates amplified moments Meff =M1+MΔ in member checks [79].

Studies identify three dominant failure modes in PEB frames: local elastic buckling, hinge-induced soft-storey mechanisms, and global sway collapse, particularly with low redundancy [80],[81]. Nonlinear analyses demonstrate that capacity decreases through their use of imperfections and they show that systems will fail at an earlier time period. The drift-based assessment method shows how connection stiffness affects the system's ability to amplify signals [72],[73].

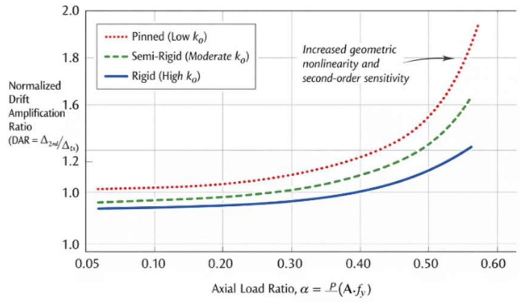

Figure 3. The drift amplification normalizer with the ratio of the axial load is available for each of the connection's stiffness cases, namely, rigid, semi-rigid, and pinned. The plot highlights nonlinear growth of DAR with αand reduced k_θ.

TABLE IV: PERFORMANCE ANALYSIS OF THE LITERATURES

Author (Year)	Case / Metric reported
De Francesco (2022) [77]	DAR vs period, reported DAR up to 1.6
Burgos (2023) [78]	Column M–N shift due to (M \Delta)
Khan (2024) [80]	Residual drift increase under near-fault motions
Ibrahim (2021) [79]	Effective buckling length charts for tapered columns
Silva (2024) [59]	Large displacement FE: 10% capacity loss
El-Zanaty (2021) [2]	Overturning amplification under variable bracing

VII. CONCLUSIONS

The assessment examines how P-Delta effects impact the structural evaluation and design process of multistorey pre-engineered buildings. All three study methods that included analytical work and numerical testing and comparative analysis showed that second-order effects produced larger increases in lateral movements and inter-storey drift and required higher member force demand. The design of PEBs with tapered members and semi-rigid connections and their reduced lateral stiffness makes them vulnerable to geometric nonlinearity during wind and seismic testing. The assessment shows that disregarding P-Delta effects creates risks for safety and stability and serviceability of the system. First-order analysis methods have limitations which the review establishes while showing that experimental testing and PEB design standards need to be developed to achieve accurate performance predictions for contemporary tall building systems.

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