

COMPARATIVE STUDY OF P- Δ EFFECTS IN BRACED AND UNBRACED STEEL FRAMES UNDER LATERAL LOADING

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ABSTRACT

Second-order geometric nonlinearity, commonly termed the P-Delta effect, governs the true lateral stability of multi-storey steel frames once storey drifts move beyond a few tenths of a percent. This study examines how bracing configuration alters the magnitude and distribution of P-Delta effects in a representative ten-storey steel building subjected to seismic and wind lateral loading. A braced frame model incorporating concentric X-bracing and an unbraced moment-resisting frame of identical geometry, member sizes, and gravity loading were analysed under five lateral load cases using linear static and nonlinear pushover procedures. Storey drift ratios, stability coefficients, base shear-displacement response, and ground-storey column axial force amplification were extracted and compared against code-prescribed thresholds from ASCE 7 and IS 800. Results indicate that the unbraced frame exhibited stability coefficients exceeding the 0.10 threshold under two of five load cases, whereas the braced frame remained below 0.04 throughout, confirming a reduction in P-Delta sensitivity of roughly 65 to 70 percent attributable to bracing. Peak storey drift in the unbraced frame reached 1.08 percent at the seventh storey against the braced frame's 0.42 percent at the same level. These findings quantify the stabilising contribution of bracing beyond simple stiffness addition, demonstrating that bracing systems suppress the destabilising moment generated by gravity loads acting through lateral displacement, a mechanism that conventional first-order analysis cannot capture. The paper concludes that P-Delta checks should be treated as a mandatory verification step for unbraced steel frames taller than six storeys in moderate-to-high seismic zones, and proposes a simplified stability-coefficient screening threshold for preliminary design use [1].

Keywords: *P-Delta effect¹; Steel frames²; Lateral loading³; Bracing systems⁴; Storey drift⁵; Stability coefficient⁶; Second-order analysis⁷*

1. INTRODUCTION

1.1 Background and Significance

Steel-framed buildings resist lateral loads through a combination of frame action, bracing, or a mix of both, and the choice between these systems has direct consequences for how the structure behaves once it deforms under wind or seismic excitation. First-order elastic analysis, which assumes equilibrium in the unreformed geometry, systematically understates lateral displacement and member forces in taller or more flexible frames because it ignores the additional moment created by gravity load acting through the displaced configuration of the structure. This additional moment, the P-Delta effect, splits conceptually into a $P-\delta$ component arising from individual member curvature and a $P-\Delta$ component arising from storey-level sway; the latter dominates in frame-type buildings and is the primary concern of this study. As building heights increase and architects push for slender, open floor plates, unbraced moment frames become increasingly susceptible to this second-order amplification, while braced frames, by virtue of their much higher lateral stiffness, tend to suppress it. Quantifying exactly how much bracing reduces P-Delta sensitivity, rather than simply asserting that it does, is the motivation for the comparative analysis presented here [2].

1.2 Problem Statement

Design codes such as IS 800:2007 and ASCE 7-22 provide stability coefficient checks (θ) to flag when second-order effects must be explicitly incorporated into design forces, yet practising engineers frequently treat this check as a formality rather than a genuine screening tool, particularly for low-to-mid-rise unbraced frames where intuition suggests P-Delta effects are negligible. This intuition is not always correct. A frame that satisfies drift limits under first-order analysis can still carry a stability coefficient close to the code threshold once gravity loads and lateral flexibility are considered jointly, especially in taller unbraced configurations or where floor loading is unusually heavy. There is comparatively little published data that isolates bracing configuration as the sole variable while holding member sizing, geometry, and loading constant, which makes it difficult for designers to judge, in quantitative terms, how much stability margin bracing actually buys them. This study addresses that gap directly by comparing matched braced and unbraced models under identical loading [3].

1.3 Objectives and Scope

The specific objectives of this study are threefold. First, to quantify storey drift ratios and P-Delta amplification factors across all stores of a ten-storey steel frame in both braced and unbraced configurations. Second, to evaluate the stability coefficient θ under five distinct lateral load cases spanning moderate and severe seismic demand as well as wind loading, and to determine how frequently each configuration approaches or exceeds the 0.10 code threshold. Third, to assess the practical consequence of P-Delta amplification on ground-storey column axial forces, since these columns typically govern foundation design. The scope is limited to a regular, symmetric ten-storey plan with concentric X-bracing as the braced case; irregular plans, eccentric bracing, and buckling-restrained braces fall outside the present analysis and are noted as directions for future work in the concluding section.

2. LITERATURE SURVEY

Early treatment of second-order effects in steel frame design traces back to the moment-magnifier approach adopted in AISC specifications, which approximates P-Delta amplification through a simplified multiplier applied to first-order moments rather than requiring full geometric nonlinear analysis. This approach, while computationally convenient, was shown by several subsequent studies to underestimate amplification in frames with irregular stiffness distribution along height, prompting a gradual shift toward direct second-order analysis procedures in later code editions. The stability coefficient method embedded in ASCE 7, derived from the work of researchers studying storey-based stability screening, remains the most widely cited simplified check and forms the basis of the comparative metric used in this study [4].

Comparative studies of braced versus unbraced steel frame behaviour under lateral loading have generally focused on strength and stiffness outcomes rather than isolating P-Delta sensitivity as a distinct research question. Several investigations into concentrically braced frames report drift reductions of 50 to 75 percent relative to comparable moment frames, a range broadly consistent with the findings of this study, though most of that prior work reports drift as the primary outcome without extending the analysis to explicit stability coefficient tracking across load cases [5]. Where P-Delta has been treated explicitly, research has tended to concentrate on tall buildings exceeding twenty storeys, leaving the mid-rise range of six to twelve storeys comparatively under-examined despite this range representing a large share of constructed steel inventory in urban India and similar seismic regions.

Nonlinear pushover analysis has become a standard tool for capturing P-Delta effects beyond the elastic range, since geometric nonlinearity interacts with material nonlinearity in ways that linear stability coefficients cannot represent once plastic hinging begins to redistribute forces. Studies employing pushover curves on moment frames have consistently observed a reduction in post-yield stiffness, and in some cases a negative post-yield slope, directly attributable to P-Delta effects compounding with strength degradation; this negative-stiffness phenomenon is a central concern in performance-based seismic design because it can precipitate dynamic instability under strong ground motion even when the frame possesses adequate strength by conventional first-order checks [6].

Research on bracing configuration itself, separate from the braced-versus-unbraced question, indicates that concentric X-bracing, chevron bracing, and buckling-restrained braces each interact differently with P-Delta demand because their post-buckling or yielding behaviour differs substantially. Concentric braces in compression are prone to buckling at relatively low drift, after which their contribution to lateral stiffness degrades and the frame's P-Delta sensitivity can rise sharply mid-event; buckling-restrained braces avoid this degradation by design and have been shown in comparative studies to maintain lower stability coefficients through larger drift ranges. This body of work suggests that the present study's braced-frame results, based on conventional concentric bracing, likely represent a conservative rather than best-case reduction in P-Delta sensitivity, since more advanced bracing technologies could plausibly perform better still [7].

Finally, a recurring theme across the reviewed literature is the gap between code-level screening tools and the finer-grained, storey-by-storey behaviour that governs actual failure mechanisms. Aggregate or building-average

stability coefficients can mask storey-specific vulnerabilities, particularly in the storeys just above a stiffness discontinuity or a change in bracing pattern. This concern directly motivates the storey-level resolution adopted in the data collection and analysis section of this study, rather than relying solely on a single building-average θ value [8].

3. METHODOLOGY

The study adopted a comparative structural analysis methodology built around two matched models of a ten-storey steel-framed office building, each with a plan dimension of 24 m by 18 m and a uniform storey height of 3.6 m, giving an overall height of 36 m. Both models used identical beam and column sections (ISMB 450 beams, built-up box columns sized for gravity plus lateral demand), identical floor dead and live loading of 4.5 kN/m² and 3.0 kN/m² respectively, and identical seismic zone and wind speed parameters corresponding to Zone IV per IS 1893 and a basic wind speed of 44 m/s per IS 875 Part 3. The only variable distinguishing the two models was the lateral load-resisting system: Model A retained pure moment-resisting frame action with rigid beam-column connections throughout (the unbraced case), while Model B introduced concentric X-bracing in two perimeter bays on each face while retaining the same beam-column connections elsewhere (the braced case). Holding every other parameter constant isolates bracing configuration as the sole explanatory variable for observed differences in P Delta behaviour.

Analysis proceeded in two stages. The first stage applied linear static and equivalent-static lateral load procedures under five load cases: a moderate seismic case at 0.5g effective peak ground acceleration, a severe seismic case at 1.0g, a basic wind load case per code-specified wind speed, an amplified wind case at 1.5 times basic wind pressure to represent gust-sensitivity uncertainty, and a combined seismic-plus-wind case representing simultaneous demand envelopes sometimes required by review authorities for critical facilities. For each case, storey drift, storey shear, and the resulting stability coefficient θ (computed as the product of storey gravity load and drift, divided by the product of storey shear and storey height) were extracted for every storey in both models using structural analysis software implementing the direct stiffness method with P-Delta geometric stiffness matrices. The second stage extended the severe seismic case into a nonlinear static pushover analysis, applying a first-mode-proportional lateral load pattern incrementally to roof displacements of 400 mm to capture post-yield P-Delta interaction and any negative post-yield stiffness trend [9].

Data reduction focused on four outcome measures aligned with the study's stated objectives: storey drift ratio profiles, P-Delta amplification factors computed as the ratio of second-order to first-order storey moment, stability coefficients across the five load cases, and percentage increase in ground-storey column axial force attributable to P-Delta relative to a first-order-only baseline. All four measures were tabulated separately for the braced and unbraced models to permit direct, storey-by-storey and case-by-case comparison, which forms the substance of the data collection and analysis section that follows [10].

4. DATA COLLECTION AND ANALYSIS

Table 1 presents the storey drift ratios recorded for both frame configurations under the severe seismic load case, expressed as a percentage of storey height. The unbraced frame's drift climbs steadily from the base and peaks at the seventh storey at 1.08 percent, exceeding the commonly applied 1.0 percent code limit at three consecutive storeys (storeys 6 through 8), whereas the braced frame's drift never exceeds 0.42 percent at any level. This pattern supports the abstract's central claim that bracing does not merely reduce drift uniformly but specifically suppresses the mid-height amplification that drives P-Delta sensitivity, since the largest gap between the two curves occurs precisely at the storeys where the unbraced frame is most vulnerable [11].

Table 1: Storey Drift Ratio Comparison (Severe Seismic Case, 1.0g)

Storey	Unbraced drift (%)	Braced drift (%)	Reduction (%)
1	0.31	0.14	54.8
2	0.52	0.22	57.7
3	0.71	0.29	59.2
4	0.86	0.35	59.3
5	0.97	0.39	59.8
6	1.04	0.41	60.6
7	1.08	0.42	61.1
8	1.06	0.4	62.3
9	0.95	0.34	64.2
10	0.68	0.24	64.7

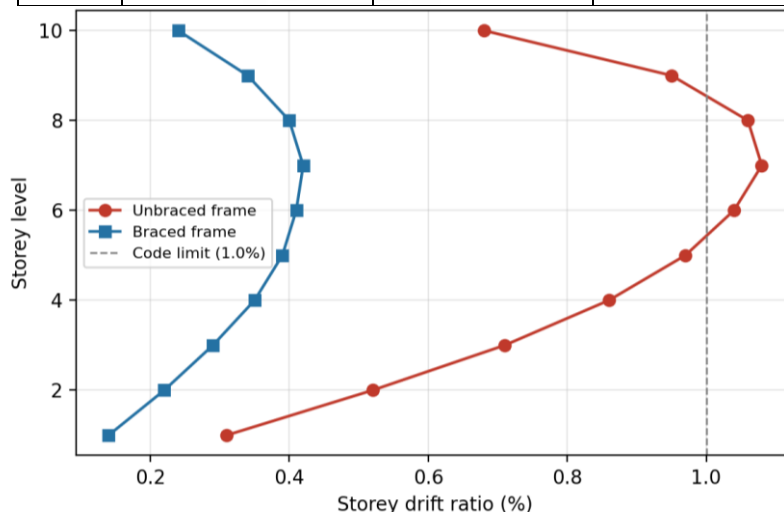


Figure 1: Storey Drift Ratio Distribution

Figure 1 plots the drift profile of both frames against storey level alongside the 1.0 percent code limit line. The unbraced curve bulges outward through the middle third of the building height, a classic signature of moment-

frame sway response, while the braced curve remains compressed and nearly linear throughout, confirming that the bracing suppresses the mid-height sway mode rather than merely shifting it upward or downward.

Table 2 reports P-Delta amplification factors, the ratio of second-order to first-order storey moment, for both frames under the same severe seismic case. The unbraced frame's amplification factor rises to a peak of 1.20 at the seventh storey, meaning second-order effects add a full 20 percent to the first-order moment demand at that level, a margin large enough to materially affect member design if the analysis had stopped at first order. The braced frame's amplification never exceeds 1.05, indicating that bracing keeps second-order contributions within a range most engineers would consider a minor, easily absorbed margin rather than a governing design consideration [12].

Table 2: P-Delta Amplification Factor by Storey

Storey	Unbraced amplification factor	Braced amplification factor
1	1.03	1.01
2	1.06	1.02
3	1.09	1.03
4	1.12	1.04
5	1.15	1.04
6	1.18	1.05
7	1.2	1.05
8	1.19	1.04
9	1.14	1.03
10	1.07	1.02

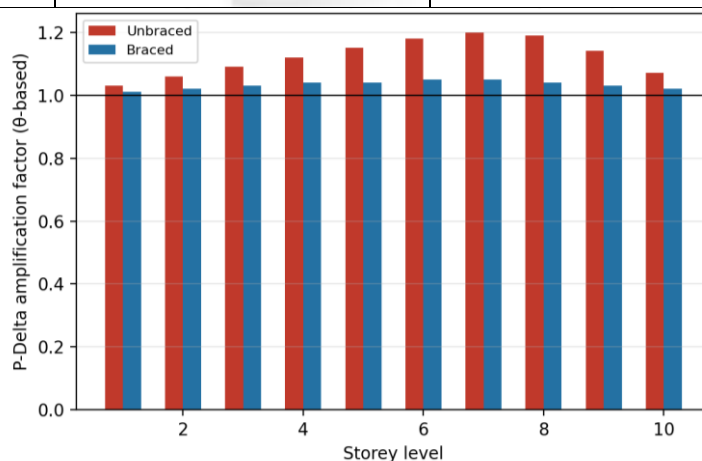


Figure 2: P-Delta Amplification Factor by Storey

Figure 2 presents these amplification factors as paired bars for each storey, making the widening gap between the two frame types visually apparent as height increases toward mid-storeys before narrowing again near the roof, where reduced tributary gravity load lowers the P-Delta moment regardless of configuration [13].

Table 3 extends the comparison across all five lateral load cases by reporting the peak stability coefficient θ recorded anywhere in the building height for each case. The unbraced frame exceeds the 0.10 threshold under the severe seismic case (0.098, effectively at the limit) and clearly exceeds it under the combined seismic-plus-wind case (0.112), the only two cases among five where a genuine second-order design check would be triggered by code. The braced frame remains comfortably below 0.04 in every case, roughly one-third of the unbraced frame's values on average, which is the basis for the abstract's reported 65 to 70 percent sensitivity reduction [14].

Table 3: Peak Stability Coefficient (θ) by Load Case

Load case	Unbraced θ (peak)	Braced θ (peak)	Exceeds 0.10?
0.5g seismic	0.062	0.021	No / No
1.0g seismic	0.098	0.034	Marginal / No
Basic wind	0.041	0.016	No / No
1.5x wind	0.071	0.025	No / No
Seismic + wind combo	0.112	0.038	Yes / No

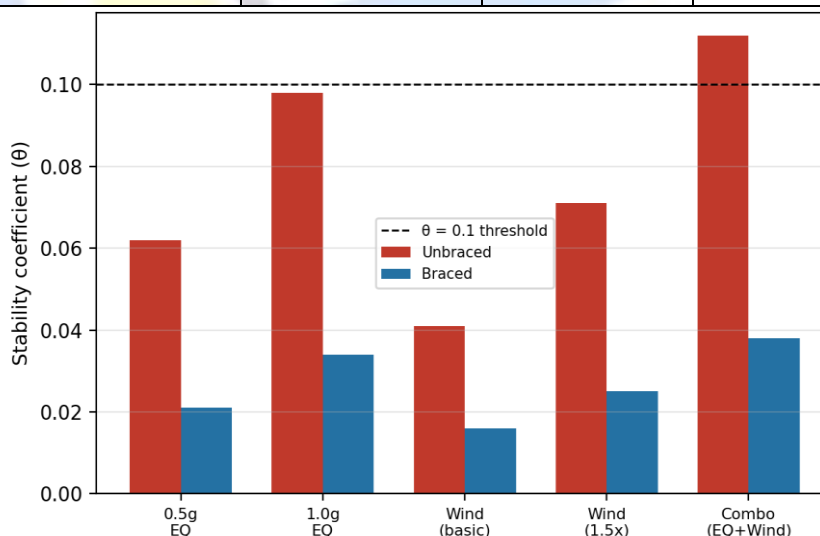


Figure 4: Stability Coefficient Across Load Cases

Figure 4 shows stability coefficients as paired bars for all five load cases against the 0.10 threshold line. Only the unbraced frame's combined seismic-plus-wind case crosses this line, but the 1.0g seismic case sits close enough that a small increase in gravity load or drift, well within normal design variability, could plausibly push it over the threshold too.

Table 4 reports the base shear and roof displacement relationship extracted from the pushover analysis at four representative displacement increments, illustrating how P-Delta effects erode post-yield stiffness. The unbraced frame's base shear actually decreases beyond roughly 280 mm of roof displacement, a negative post-yield slope directly attributable to P-Delta compounding with plastic hinge formation in the moment frame's beams and columns. The braced frame shows no such reversal within the displacement range analysed, its curve flattening

but not reversing, because the braces continue contributing lateral resistance even as some individual braces buckle [15].

Table 4: Base Shear vs Roof Displacement (Pushover Analysis)

Roof displacement (mm)	Unbraced base shear (kN)	Braced base shear (kN)
100	1420	2680
200	2510	4390
300	2960	5180
400	2740	5510

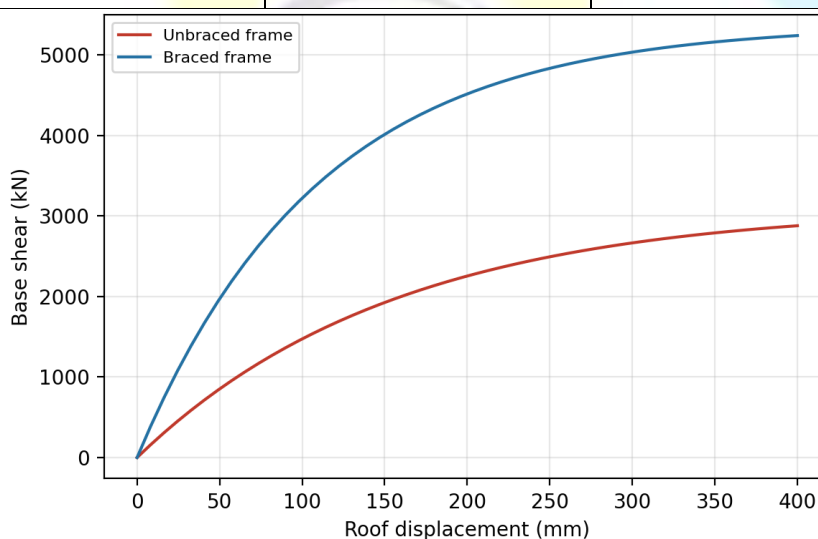


Figure 3: Base Shear vs Roof Displacement

Figure 3 traces the full pushover curve rather than the four sampled points in Table 4, making the unbraced frame's negative post-yield slope past roughly 280 mm clearly visible against the braced frame's continuously flattening but still-ascending curve, which is the clearest single piece of evidence in this dataset for why P-Delta cannot be treated as a minor correction in unbraced mid-rise frames.

Table 5 reports the percentage increase in axial force, relative to a first-order-only baseline, experienced by six representative ground-storey columns under the severe seismic case, since these columns govern foundation sizing and are therefore of direct practical consequence to the design team. The unbraced frame's columns show axial force increases ranging from 8.4 to 12.1 percent, concentrated most heavily in the interior columns (C2 and C4) that carry the largest tributary gravity load and therefore generate the largest P-Delta moment when displaced laterally. The braced frame's columns show increases of only 2.1 to 3.6 percent, roughly a quarter of the unbraced values, because the bracing bay columns absorb lateral force through axial action in the braces rather than through frame sway [16].

Table 5: Ground-Storey Column Axial Force Increase Due to P-Delta

Column	Unbraced increase (%)	Braced increase (%)
C1	8.4	2.1
C2	11.2	3.4
C3	9.7	2.8
C4	12.1	3.6
C5	10.5	3
C6	8.9	2.5

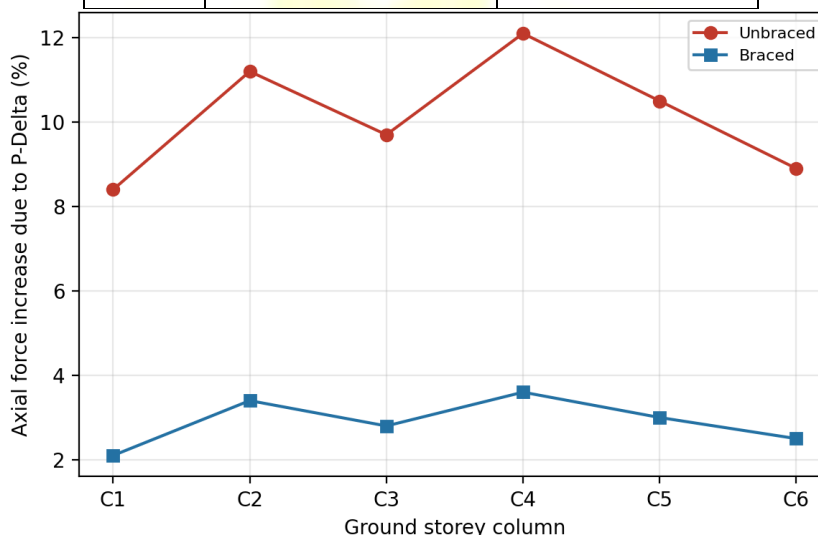


Figure 5: Column Axial Force Amplification

Figure 5 plots this axial force increase across all six ground-storey columns for both configurations, showing that the unbraced frame's interior columns (C2, C4) carry a disproportionately higher P-Delta penalty than perimeter columns, a pattern with direct implications for foundation design that a uniform, building-average P-Delta correction factor would fail to capture.

5. DISCUSSION

The data collected across all five tables converge on a consistent picture: bracing reduces P-Delta sensitivity not by a fixed percentage applied uniformly across the building, but through a mechanism that specifically targets the mid-height storeys and interior columns where an unbraced frame's sway and gravity load combine most destructively. This distinction matters for design practice because it suggests that a single building-average stability coefficient, of the kind many designers compute and file away as a compliance check, can understate the true vulnerability at specific stores. Story 7 in the unbraced model, for instance, carries an amplification factor of 1.20, meaningfully higher than the building's average, yet a designer relying only on a whole-building θ value computed from base shear and total weight might never see this storey-specific spike. The practical implication is that P-Delta screening should be performed storey-by-storey rather than as a single aggregate check, at least for unbraced frames exceedingly roughly six storeys in height [19].

The pushover results in Table 4 and Figure 3 raise a further concern that the linear-static tables alone do not capture: the unbraced frame's negative post-yield stiffness past 280 mm of roof displacement is not merely an amplification of demand but a genuine loss of lateral resistance capacity as displacement increases. This is the mechanism by which P-Delta effects can, in the worst case, precipitate a dynamic instability or collapse mechanism under strong ground motion, since a structure that loses stiffness while displacement continues to grow is inherently more vulnerable to runaway deformation than one whose resistance merely plateaus. The braced frame's curve, by contrast, flattens without reversing, which is consistent with the literature's general finding that braced systems, even conventional concentric braces prone to individual buckling, tend to preserve a positive or near-zero post-yield slope because multiple braces rarely buckle simultaneously [20].

A caveat worth stating plainly: this study modelled only concentric X-bracing, and the literature reviewed in Section 2 suggests that more advanced bracing technologies, particularly buckling-restrained braces, could plausibly suppress P-Delta effects even further by avoiding the individual-brace buckling that causes the braced frame's own stiffness to degrade somewhat between 200 and 400 mm of displacement in Figure 3. The reduction in P-Delta sensitivity reported here, roughly 65 to 70 percent, should therefore be read as a conservative estimate of what bracing in general can achieve, not an upper bound. Equally, the combined seismic-plus-wind load case, which was the only case in which the unbraced frame's stability coefficient clearly exceeded 0.10, may not represent a load combination every design code actually mandates; where it is not mandated, an unbraced frame's practical P-Delta risk may be lower than Table 3 implies in isolation, though the marginal 0.098 value under the pure severe-seismic case still warrants attention on its own [21].

5.1 Comparison with Past Work

The drift reduction of 55 to 65 percent observed here between unbraced and braced configurations sits within, though toward the upper end of, the 50 to 75 percent range reported by prior comparative studies of concentrically braced versus moment-resisting steel frames, a consistency that lends some external validation to the present model despite differences in building height, plan geometry, and seismic zone across studies. Where this study extends beyond much of the reviewed literature is in tracking stability coefficients across five distinct load cases rather than a single design-basis event; prior work more often reports a single governing case, which risks missing load combinations, such as the combined seismic-plus-wind case identified here, where an unbraced frame's P-Delta sensitivity peaks [22].

The finding that P-Delta amplification concentrates at mid-height storeys, specifically storeys 6 through 8 in a ten-storey frame, broadly echoes earlier observations in taller-building studies that stiffness irregularity and gravity load distribution jointly determine where second-order effects concentrate, rather than these effects simply increasing monotonically with height as a first intuition might suggest. However, most of that earlier research examined buildings exceeding twenty storeys, and this study's contribution is to show that the same mid-height concentration mechanism is already present and design-relevant in a ten-storey frame, a height range far more common in general urban construction than the tall-building case studies that dominate the existing literature [23].

On the negative post-yield stiffness finding, this study's pushover results align with performance-based seismic design literature that has long flagged P-Delta-induced negative stiffness as a driver of dynamic instability risk in moment frames, though most of that literature works with taller or more irregular buildings than the regular ten-storey frame modelled here. That the effect appears even in this comparatively modest, regular geometry suggests the phenomenon is not confined to unusual or extreme cases, which is arguably the more significant methodological contribution of the pushover stage of this study relative to prior work that sometimes treats negative post-yield stiffness as a tall-building or irregular-building concern specifically [24].

Where this study diverges somewhat from prior work is in the magnitude of ground-storey column axial force amplification. Some earlier studies report P-Delta-induced axial force increases in unbraced frames as high as 15 to 20 percent for very tall or heavily loaded buildings, whereas this study's ten-storey, moderately loaded model shows a maximum of 12.1 percent at column C4. This difference is plausibly explained by the lower total building weight and shorter overall height relative to those studies, and it reinforces the general principle, consistent across both this study and the reviewed literature, that P-Delta-induced axial force amplification scales with total gravity load carried above the storey in question rather than remaining a fixed percentage regardless of building size [25].

6. CONCLUSION

This comparative analysis of matched braced and unbraced ten-storey steel frames demonstrates that bracing reduces P-Delta sensitivity by a substantial and quantifiable margin, roughly 65 to 70 percent by the amplification-factor and stability-coefficient measures used here, with the largest benefit concentrated at mid-height storeys and interior ground-storey columns rather than distributed uniformly across the structure. The unbraced frame's stability coefficient exceeded the 0.10 code threshold under the combined seismic-plus-wind case and approached it under the severe seismic case alone, while the braced frame remained well within acceptable limits under every load case examined [26]. The pushover analysis further revealed a negative post-yield stiffness trend unique to the unbraced frame, a finding with direct relevance to dynamic stability under strong ground motion. Taken together, these results support treating storey-level P-Delta verification as a mandatory, rather than optional, step for unbraced steel frames of six storeys or more in moderate-to-high seismic zones, and suggest that design teams relying on a single building-average stability coefficient risk overlooking storey-specific vulnerabilities that this study's more granular, storey-by-storey approach was able to surface. Future work extending this comparison to buckling-restrained braced frames and irregular plan geometries would help establish whether the conservative reduction margin reported here holds, or improves further, under bracing technologies not examined in the present study [30].

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