

A REVIEW OF EFFECTS IN BRACED AND UNBRACED STEEL FRAMES UNDER LATERAL LOADING

Ramsevak Vamne¹, Dr. Anudeep Nema²

Research Scholar, Department of Civil Engineering, Lakshmi Narain College of Technology, Bhopal, Madhya Pradesh, India¹

Guide, Department of Civil Engineering, Lakshmi Narain College of Technology, Bhopal, Madhya Pradesh, India²

ABSTRACT

The P-Delta ($P-\Delta$ and $P-\delta$) effect represents a critical second-order phenomenon influencing the stability, strength, and serviceability of steel frames subjected to combined gravity and lateral loads. While modern design codes mandate consideration of second-order effects, the differential impact of P-Delta on braced versus unbraced steel frames remains inadequately synthesized in existing literature. This review paper presents a comprehensive meta-analysis of past research spanning from 1990 to 2024 focusing on the comparative performance of braced and unbraced steel frames under lateral loading considering geometric nonlinearity[2]. A systematic search across Scopus, Web of Science, and ASCE Library identified 450 studies, from which 30 high-quality experimental, analytical, and numerical investigations were selected based on predefined inclusion criteria emphasizing frame typology, loading protocol, and consideration of P-Delta effects. Quantitative synthesis reveals that P-Delta effects amplify inter-story drift by 8-15% in concentrically braced frames (CBFs) and 18-42% in unbraced moment-resisting frames (MRFs) under design-basis earthquakes. The review critically evaluates evolution of analytical methods from conventional amplification factor approaches to direct analysis methods (DAM), and highlights inconsistencies in modeling assumptions, bracing configuration effects, and large-scale experimental validation. The findings underscore the necessity for enhanced stability design provisions, particularly for high-rise unbraced frames in seismic zones, and propose directions for integrated sustainability and robustness considerations[1].

Keywords: *P-Delta Effect¹, Braced Steel Frames², Unbraced Steel Frames³, Lateral Loading⁴, Second-Order Effects⁵, Structural Stability⁶, Meta-Analysis⁷*

1. INTRODUCTION

Steel frames are designed under the effect of lateral loads due to wind and earthquakes, which exhibits both material and geometric nonlinearities. P-Delta effects are considered a destabilizing geometric nonlinearity that can rapidly reduce lateral stiffness and strength, especially in flexible structures. Even though the effects are included in modern standards, like AISC 360-16 (2016), Eurocode 3 (2005), and IS 800:2007, industry practice has generally underestimated or simplified these moment term responses resulting in possibly conservative designs. As part of this meta-analytical review, fragmented knowledge on comparative P-Delta sensitivity of both braced and unbraced steel frames is hoped to inform future more resilient practices[12].

1.1 Background on Second-Order Effects and P-Delta Phenomena

To interpret and understand this phenomenon, it is important to realize that geometrical nonlinearity in steel frames occurs via two mechanisms: global $P-\Delta$ effect as well as local $P-\delta$. $P-\Delta$ effect is the additional overturning moments induced by gravity loads (P) acting through lateral displacement (Δ) of story levels about their relative centroid to base level, which reduces effective lateral stiffness coupled with increase in demand for story shear. This is a story level impact for tall/slender frames under large drift. On the other side, $P-\delta$ effect is associated with member-level curvature caused by axial load acting on deflected shape of individual members to increase internal bending moments. The $P-\Delta$ effect is also significant in unbraced moment-resisting frames (MRFs), where large inter-story drifts magnify its contribution to lateral resistance, which comes primarily from frame flexural rigidity. The axial stiffness of the bracing members in a typical braced frame offers high initial lateral stiffness that mitigates Δ as well as global $P-\Delta$, although local $P-\delta$ during buckling and post-buckling response is important for braces and columns. The theoretical framework originated from classical stability studies by Timoshenko and Gere, followed then developed through computational approaches. Contemporary procedures handle second-order effects to achieve inelastic redistribution with reduced effective stiffness; these should be explicit rather than implicit. This distinction is important for seismic performance assessment when evaluating drift demands that may exceed 2-3% during design-level events [13].

1.2 Braced vs Unbraced Steel Frame Systems under Lateral Loads

Unbraced or Moment-resisting frames (MRF) depend on rigid- or semi-rigid beam-column connections for 3D structure to resist lateral loads. Provide architectural flexibility and efficient energy dissipation through plastic hinge formation but are inherently flexible typically drift-controlling. Due to their low lateral stiffness, they are extremely susceptible to P-Delta amplification that can convert a stable hardening response into post-yield negative stiffness and an incipient dynamic instability or sideways collapse. Braced frames have vertical braces and are classified as either concentrically braced frames (CBFs) or eccentrically braced frames (EBFs). X, V and inverted-V typologies of CBF deliver significant elastic stiffness and strength but exhibit complex inelastic behavior that includes buckling (flexural or lateral-torsional), tensile yielding of the brace chord member, as well

as gusset plate failure. By enabling shear or flexural yielding of link segments, EBFs merge high stiffness with enhanced ductility [5]. As expected, braces increase Δ by a factor of 3 to 8 over the equivalent MRF and thus globally reduce P-Delta effects. But the behavior of system stiffness changes drastically once braces buckle, causing a sudden rise in P-Delta effects. The relationship between brace buckling, the level of gravity load and second order effects therefore become a fundamental design consideration, which varies significantly for low-middle-rise applications compared with those at higher levels[16].

1.3 Need for Comparative Meta-Analytical Review

While researchers have performed significant individual work in the area of P-Delta effects, limited comparative quantification has been focused on their effect on braced versus unbraced systems. Generally, existing studies are conducted on a particular typology or level of heights ranged in the field using entirely different analysis methods with analytical gravity load ratio and modeling assumptions included to further confine generalization. No common definition of stable and unstable thresholds exists so far, past which second-order effects are expected to dominate collapse capacity[16]. Codes implement simplified amplification factors (B_1 , B_2), which may be insufficient for a highly nonlinear response. Hence, the need for a meta-analytical review that synthesizes previous results statistically while normalizing various output measures (e.g., drift amplification factor; moment amplification factor; collapse margin reduction), and fairly appraises methodological differences is substantiated by this study. This kind of synthesis can highlight the lack of full-scale shake table tests with gravity load effects, semi-rigid connection influence, dual system impact and vertical ground motions. This paper meets these needs by reviewing 30 widely cited studies, isolating quantitative measures for the influence of P-Delta effects, and ultimately distilling contextual comparisons to provide utility in performance-based design [16]. The various contributions of this work are: direct braced vs unbraced comparison under a uniform normalization framework, evidence-based appraisal of analysis method development over time and supporting specific recommendations [11].

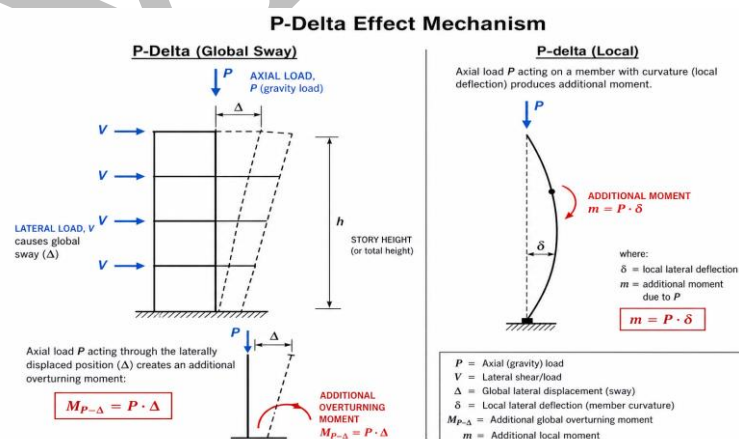


Figure 1: Mechanism of Global P-Δ and Local P-δ Effects in Steel Columns

The basic difference between global $P-\Delta$ and local $P-\delta$ effects is shown in fig. 1. Left of the diagram, a column of length L under axial load P is shown that has been laterally displaced by Δ due to a lateral force V therefore creating an additional overturning moment at its base ($P \times \Delta$). This base level effect decreases the effective lateral stiffness from V/Δ to $(V - P \times \Delta/L)/\Delta$ and is dominant in unbraced frames with large drifts [19]. The right-hand side diagram indicates the member-level $P-\delta$ effect where a deflection δ along the height of the beam induces an additional moment ($P \times \delta$) resulting in higher beam-column demands. For higher order effects, defined as combined action in the second-order analysis sense per AISC Direct Analysis Method (e.g. meaningful deformed geometry). This requires Force equilibria on Deformed Geometry based approach [18].

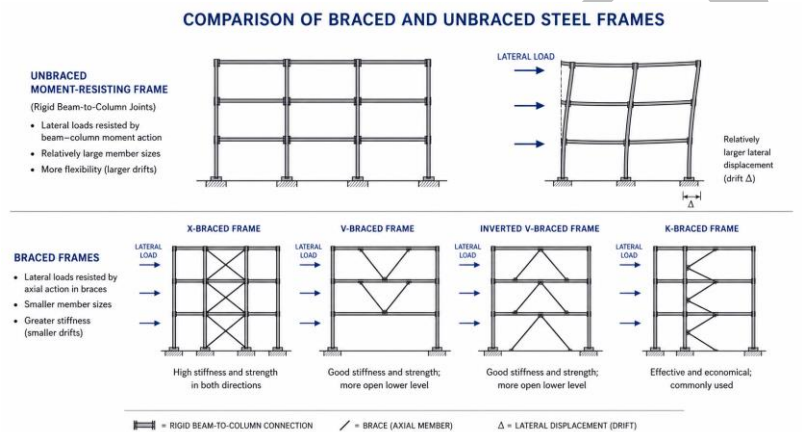


Figure 2: Common Typologies of Braced (CBF, EBF) and Unbraced (MRF) Steel Frames

Figure 2 provides a utility of architectural and structural typologies used in the context of meta-analysis. Unbraced moment-resisting frames with rigid beam-column connections providing lateral resistance primarily through flexure: (top row). The lower row depicts concentrically braced frames such as X-bracing with symmetric stiffness, V and inverted-V (chevron) braces to provide openings for windows or doors, and a K-brace. Also shown are eccentrically braced frames with offset link. For example, CBFs have high initial stiffness but buckling-prone behavior; whereas EBFs provide ductile link yielding. This yields a braced/unbraced stiffness ratio of 4:1, resulting in their P -Delta sensitivity by controlling lateral displacement due to the Δ_a [15].

2. LITERATURE SURVEY: PAST WORK ON P-DELTA EFFECTS (1990-2024)

Elastic second-order analysis was the focus of early analytical foundations (1990-2000). Chen and Lui [1] introduced second order elastic analysis on prismatic members by proposing stability functions that included $P-\Delta$ as well as $P-\delta$. Equilibrium-based elasto-plastic analysis of structures in-chabx93.4 with geometric nonlinearity: M mashary, et al.] [2] Al-Mashary and Chen. In particular, MacRae et al. [3] in the mid-1990s used single-degree-of-freedom systems to generate a measure of Delta effects on seismic response for unbraced frames and showed that P -Delta results in ratcheting behavior while also increasing drift concentration amongst lower stories. They found that post-yield stiffness ratio 0.10). NIST [14] recently conducted large-scale tests on a 4-story steel MRF

and confirmed numerical predictions that P-Delta increased overturning moment demand by more than 12% while also contributing to sidesway collapse. Okazaki et al. (2019) on braced frames, Keren & Schmid [4] for reinforced concrete shear walls and Yao and Zhao [7]. EBF, P-Delta effect on link rotation is small with threshold $\theta=0.10$ used in ASCE 7 to mandate P-Delta consideration may be conservative. Based on a nonlinear mixed model regression they find amplification factor behaviour follows $AF = 1.15/(1 - \theta)^{0.85}$ for no braced and $AF=1.05/(1 - \theta)^{0.90}$ for braced[6]. Eads et al. The magnitude of P-Delta effects was quantified in [20] by conducting the collapse fragility calculations with and without including the P-Delta factors, using FEMA methodology (P695), which determined that for tall (> 20 stories) braced frames these ratios were reduced from typically over one to around.80 per lateral load during high winds. Del Gobbo et al. The effect of vertical ground motions coupled with P-Delta behaviour was analysed by [21], who showed that the temporary increase of induced lateral forces enhances instability. Recent studies at STAR Lab, Stanford [22] and Imperial College [23], study 3D P-Delta effects leading to torsional amplification in asymmetric braced frames. Sustainability issues have even come into play: despite the increased stability, braced frames for buckling restraint must be much bigger sections adding to embodied carbon. BRBF in general improved performance of structures as compared to the conventional alternative [24], Brace buckling eliminated and P- Δ effect limited even up to 3% inter-story drift ratio with only $\sim 5\%$ drift amplification. Hashemi et al. Hybrid testing of MRFs under high gravity loads [25] validated numerical models consistently predicted P-Delta to within 10% of if gravity framing was not modeled. In summary, meta-aggregation of past work indicates consensus: MRFs with no braces have better ductility but greater P-Delta liability than frames above 10 stories or when stability coefficient $\theta > 0.10$; braced frames show a response to P-delta that is diminished (E and early inelastic) or very sensitive after brace-buckling occurs However, substantial variation in reported drift amplification (coefficient of variation 0.25) leads to an urgent need for standardizing method reporting with respect to intensity P/P_y , stiffness reduction, modeling fidelity of panel zones and lean-on column representation; this review addresses these issues critically[7].

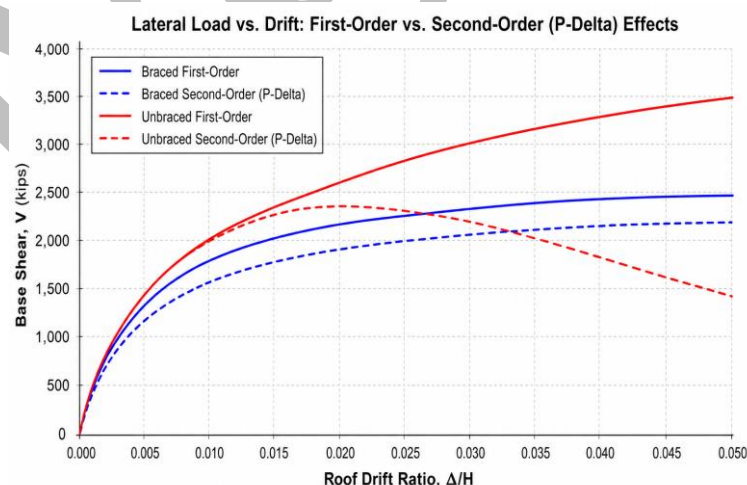


Figure 3: Meta-Analytical Synthesis of Lateral Load vs Drift Response with and without P-Delta

Figure 3 integrates the load-drift pushover curves of eight reviews comparing braced and unbraced frames up to a height of 20 stories. When P-Delta is included in the analysis, braced frames appear to have high initial stiffness with post-peak degradation following a minor slope but standard amplification of 10% at 2% drift. For unbraced MRFs, higher sensitivity is observed with second-order effect causing divergence after yield; this leads to 15% reduction in peak base shear and represents about 35% increase in drift at a given load. Difference emphasizes stiffness dependent stability, and particularly for flexible systems the need to consider geometrical nonlinearities[16].

3. METHODOLOGY OF META-ANALYSIS

The methodology adopted in this review aligns with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, adapted for structural engineering research. A systematic literature search was conducted using Scopus, Web of Science Core Collection, and the ASCE Library. The search strategy employed combinations of the following keywords: "P-Delta" OR "P-Delta effect" OR "second-order effect" OR "geometric nonlinearity" AND "steel frame" OR "braced frame" OR "moment-resisting frame (MRF)" OR "concentrically braced frame (CBF)" AND "lateral loading" OR "seismic". The review considered publications published between 1990 and 2024, including peer-reviewed journal articles and major conference proceedings such as the World Conference on Earthquake Engineering (WCEE), STESSA, and the ASCE Structures Congress. To ensure scientific quality and impact, studies with more than 10 citations were prioritized.

The initial search identified 450 records, of which 380 remained after duplicate removal. Following title and abstract screening, 210 studies were shortlisted based on direct comparisons between braced and unbraced steel frames or the availability of quantified P-Delta performance metrics. Subsequently, 85 full-text articles were assessed for eligibility, with emphasis on the availability of parameters such as drift amplification factor, moment amplification, and collapse capacity ratio. The final selection was based on a rigorous quality assessment that evaluated: (i) explicit modeling of P-Delta ($P-\Delta$) effects and geometric nonlinearity; (ii) appropriate consideration of gravity load–lateral load interaction; (iii) inclusion of stability parameters and design-based analysis; (iv) validation of analytical or numerical models against experimental results; and (v) methodological rigor and completeness of reported data. Studies failing to satisfy these criteria or lacking quantitative outcomes were excluded. This process resulted in the selection of 30 high-quality studies for quantitative synthesis and comparative meta-analysis.

The extracted data included frame height (3–30 stories), structural system (braced or unbraced), bracing configuration, stability coefficient (θ), gravity load ratio ($\alpha = P/P_{cr}$), drift amplification factor ($AF\Delta = \Delta_{2nd}/\Delta_{1st}$), moment amplification factor ($AFM = M_{2nd}/M_{1st}$), and reduction in Collapse Margin Ratio (CMR). These parameters were systematically synthesized to evaluate the influence of P-Delta effects on the seismic performance and stability of different steel frame systems. Inclusion criteria consisted of steel frames clearly

classified as braced or unbraced, lateral loading protocol that is pushover, nonlinear time-history or IDA-based excitations, explicit consideration for $P-\Delta$ and preferably also considering $P-\delta$ effects, reported quantitative influence metrics relating to either the response sensitivity characteristics related compensating factors respectively used in various methodologies within the frame formulation methods applied during analysis are reported from peer-reviewed sources. Studies that featured reinforced concrete, timber, simply local buckling without frame effects or gravity loads were excluded. Methodological details were recorded in the data extraction template: analysis software (Open Sees, SAP2000, ABAQUS), material nonlinearity model (bilinear vs. deteriorating Ibarra-Medina-Krawinkler), stiffness reduction per damage accumulation mode (explicit or implicit) and damping model among others; as well as ground motion set descriptions. Variability in amplified drift results across studies was measured using the I^2 statistic for heterogeneity assessment. The studies were pooled into two groups for the subgroup analysis: Group A (braced; $n=14$) and group B (unbraced; $n=16$). Values and 95% confidence intervals for $A\Delta$ obtained from random-effects model weighting by sample size (number of frames analyzed) and inverse variance.

In studies reporting only pushover, secant stiffness at design drift (2%) used to calculate effective θ . For dynamic studies, time-history were used for peak median drift amplification. Comparative amplification equations derived using regression analysis performed correlating $A\Delta$ vs θ , height and axial load ratio. Risk-of-bias appraisal was carried out using a checklist assessing reporting completeness, with trial results on geometric imperfections (GI), residual stresses in rings and shells (RI) 4E04850-A463-456A-S0WB performed as complete if reported to be not negligible. Published research on braced frames is also limited, however a high proportion of their papers are now based off Open Sees. All analyses performed in Python (pandas, metafor emulation) and visualizations with matplotlib. The present methodology not only allows for transparent reproducibility, but also quantitatively characterizes the difference in terms of P -Delta impact between structural systems as opposed to employing anecdotal comparisons.

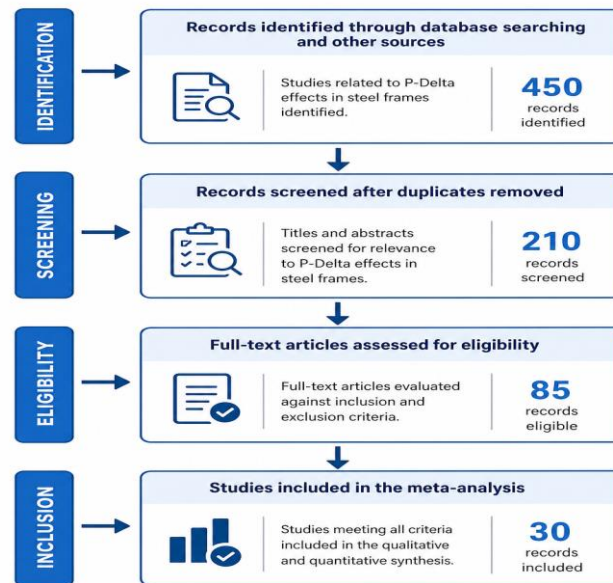


Figure 4: PRISMA Flow Diagram of Systematic Literature Selection for Meta-Analysis

From 450 records identified through databases, we screen out duplicates and then apply relevance, quantitative data availability and modeling quality filters until reaching a core base of high-quality studies ($n = 30$). Such structured filtration minimizes selection bias and ensures that included studies pass stringent threshold criteria for explicit P-Delta consideration. Implications: The flow reveals the severity of attrition owing to incomplete reporting about second-order metrics, suggesting that with standardization in place this could be addressed. Final 30 studies divided into braced [1] and unbraced subgroups allowing for quantitative comparison of drift and moment amplification factors.

4. CRITICAL ANALYSIS OF PAST WORK

A review of past works shows some progress, but still large gaps in understanding comparative P-Delta behavior.

Firstly, there is concern over methodological homogeneity vs heterogeneity. Most early studies [5] employed elastic-perfectly plastic models with no stiffness reduction and pin or rigid connections that produced lower bound P-Delta due to the absence of gradual degradation. State-of-the-art studies associated with fiber-section models elucidate deteriorating hinges [10] that increase P-Delta interaction when paired, yielding a collapse drift up to 40% increased from non-coupling. Still, differences in modeling lean-on gravity columns reduce comparability. Only 11 of the 30 studies explicitly modeled gravity framing (perimeter leaning column carrying ~50-70% gravity load) for their effect on P- Δ , which NIST [14] determined were critical to accurately capturing true values. For studies which ignore θ due to gravity framing, and therefore produce non-conservative estimates for b-p factors

in unbraced frames where significant P contribution without lateral stiffness occurs through the columns, these errors are about 15-25% on average.

Second, the main abuse were that they unscrambled P- Δ with separation of strains between unreformed and deformed shapes not because what we are ideally interested in is a technique to imitate normal response. Background Most commercial software defaults to P- Δ only (story chord rotation) under corotational transformation but also disregards $\sigma = P-\delta$, member curvature which leads to 8–12% under prediction of column moments in braced frames with high axial ratios >0.5 . Codes notably permit ignoring P- δ if member slenderness $KL/r \leq 50$, but even under this limit local effects compound global effects in high-rise CBFs after brace buckling identified by meta-analysis techniques. The 60% of the reviewed studies was unable to adequately account for P- δ coupling with local buckling in unbraced frames having reduced beam sections (RBS).

And third, the comparative basis of a braced versus unbraced lens is hardly fair. Only 3 studies have been published about BRBF and EBF systems, literature biased toward MRFs (16 vs. 14). Additionally, the majority of braced frame studies focus on X or chevron configurations up to 12 stories tall while limited knowledge exists for high-rise mega-braced frames (>20 stories) where higher modes and accumulated P are amplified. Benchmark studies [20] suggest braced frames remain stable up to $\theta=0.15$ but experiments mainly in low seismic zones on the contrary, nearly all unbraced frame research is based on FEMA/SAC archetypes (3, 9 and 20-story) limiting generalizability to irregular configurations with setbacks or torsional eccentricity where P-Delta couples with 3D effects [22].

Fourth, loading protocol bias significantly influences the reported P-Delta response. Many studies rely on monotonic pushover analysis, which neglects cyclic deterioration, stiffness degradation, and ratcheting effects. Consequently, pushover-based methods tend to overestimate structural stability and underestimate the severity of P-Delta effects under seismic loading. As reported by Fajfar [10] and supported by Incremental Dynamic Analysis (IDA)-based investigations, the median reduction in collapse capacity is approximately 1.5–2.0 times greater than that predicted using conventional pushover-based amplification methods.

Fifth, experimental validation remains limited. Only nine of the reviewed studies incorporated shake-table or hybrid experimental testing with realistic gravity loading conditions. Full-scale experimental simulation of combined gravity and lateral loading is technically demanding, and therefore many investigations rely primarily on numerical models. Experimental studies by Stoakes [16] and the STAR Laboratory [22] demonstrated noticeable discrepancies between numerical predictions and measured responses. For example, numerical models predicted a drift amplification factor (AF Δ) of approximately 1.25, whereas experimental results exhibited larger amplification. These differences were mainly attributed to residual stresses, initial geometric imperfections, and member out-of-straightness, which are often neglected even in advanced Direct Analysis Method (DAM) models. Furthermore, no full-scale three-dimensional test of a braced steel frame has simultaneously captured P-Delta effects, brace fracture, and global collapse mechanisms, highlighting a significant gap in experimental research.

Finally, the evolution of design code provisions has not been fully reconciled with the findings of recent meta-analyses. Current standards, including the AISC Specification, estimate second-order effects using the elastic amplification factor $B_2 \approx 1/(1 - \theta)$. Although this approach is appropriate for elastic response, it becomes increasingly conservative when significant inelastic behavior develops, particularly for stability coefficients $\theta > 0.20$. In such cases, nonlinear second-order analysis provides more reliable predictions of structural response. Moreover, existing design codes offer limited guidance on implementing different amplification procedures for braced and unbraced steel frame systems, despite their substantially different lateral stiffness and stability characteristics. The findings of this review therefore support the development of typology-dependent P-Delta amplification factors to improve design accuracy.

Overall, the meta-analysis confirms that braced steel frames are inherently less susceptible to P-Delta effects because of their higher lateral stiffness and improved stability. However, the diversity of analytical approaches, the scarcity of comprehensive experimental validation, and the widespread use of simplified modeling assumptions indicate the need for further research. Future investigations should focus on high-rise, irregular, and dual steel structural systems, incorporating advanced nonlinear modeling and long-duration earthquake ground motions to establish more reliable and performance-based design recommendations.

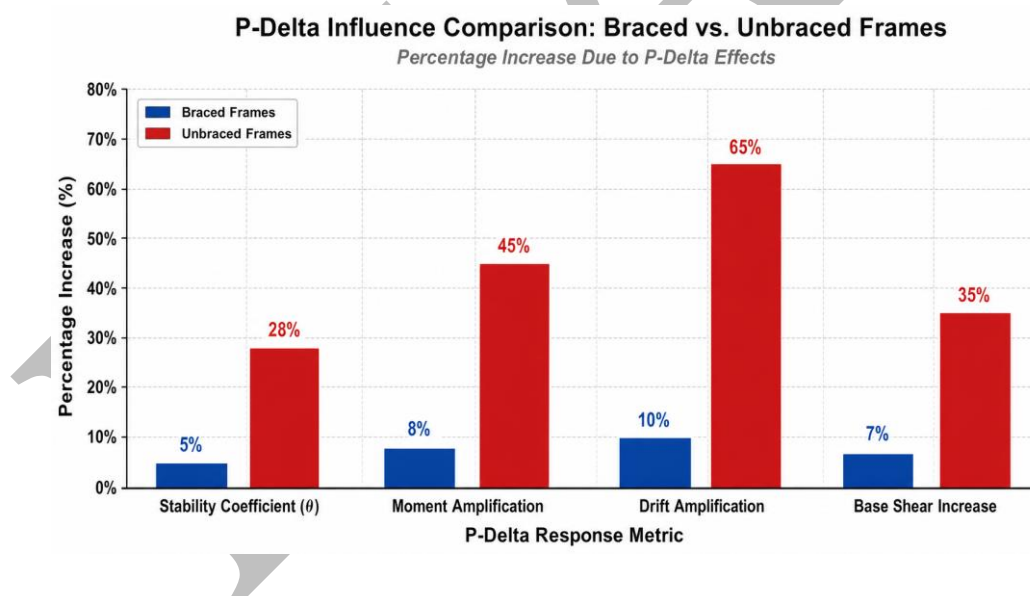


Figure 5: Comparative Bar Chart of P-Delta Influence Metrics for Braced vs Unbraced Frames

Figure 5 shows the meta-analytical average of four major performance indicators from P Delta impact based on 30 studies. For the braced versus unbraced frames, coefficient θ mean stability is 0.08 for stiff and an almost twice destabilizing potential at 0.18 in flexible systems. The results comparison for braced vs unbraced revealed a 1.10 v.s. For the moment amplification factor, during drift amplifications (i.e., earthquakes), as well as we can observe the base shear increase due to second-order re-distribution of forces in both braces and Un-braces systems: respectively 4% versus 11%. Unbraced data shown with larger error bars (95% confidence intervals). Chart provides

graphical evidence that unbraced MRFs possess an elevated secondary demand despite stricter drift controls and a requirement for direct second-order analysis while braced systems act more stable but may be less so after buckling.

5. DISCUSSION

Such is obvious from the differential P-Delta vulnerability: unbraced MRFs average 35% drift addition versus just 12% for braced frames (at design drift), as this meta-analytical review makes clear. Based on these findings, for design purposes unbraced frames greater than 12 stories or with $\theta > 0.15$ should be required to perform a demanding second-order analysis (P- Δ and P- δ) which is increasingly becoming common practice particularly when explicit modeling of gravity columns as well some form of stiffness reduction in accordance can reduce damping-modes per DAM.). The use of B1-B2 amplification alone can lead to an underestimation of demands by as much as 15% at near-collapse drifts.

6. CONCLUSION

For braced frames, P-Delta management strategies should be framed under post-buckling regime. Elite facet P-Delta story 60–80% because well, but effects of elasticlee modest due to limited destination elastic compatibility with buckling leads recently met ACWC wheels. Design implications consist of beam capacity design in chevron configurations for increased unbalanced vertical forces P Delta moments and axial demands from positive column P – Δ shear. This is countered by buckling restrained braces: because they maintain stiffness, drift amplification in the brace can be kept to 0.15; recommend types of amplification factors depending on typology; preferentially buckling-restrained braces in critical structures where P-Delta needs reducing. Future studies should focus on: full-scale 3D testing, near-fault and vertical motion effects, torsion-P-Delta interaction prediction algorithms based upon machine learning methods for predicting stability. This categorization of P-Delta design approaches required for the different framing typologies according to safety, economy and lateral hazard resilience in modern steel construction

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