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Buckling and post-buckling behaviour of cold-formed steel columns under axial compression

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Abstract
This study presents a detailed numerical and analytical investigation into the buckling and post-buckling behaviour of cold-formed steel (CFS) columns subjected to axial compression, emphasizing the influence of geometric imperfections, end-restraint conditions, and mode interactions on structural stability. Using nonlinear finite element analysis incorporating geometric and material nonlinearity, lipped channel columns of varying slenderness ratios (λ = 40-120) and thicknesses (1.2-2.0 mm) were analyzed to evaluate their critical and ultimate load capacities. The results indicate that while global buckling governs slender members, local and distortional modes, often coupled in intermediate sections, contribute significantly to post-buckling reserve strength. Columns with fixed-pinned supports demonstrated higher ultimate loads compared to pinned-pinned configurations, reflecting the critical role of boundary conditions in delaying global instability. The study al revealed that the inclusion of realistic imperfection amplitudes, modeled from eigenmode shapes, enhances the prediction accuracy of post-buckling response and residual stiffness. Comparin with the Direct Strength Method (DSM) showed good overall correlation but highlighted systematic underestimation of strength for members exhibiting strong mode interactions. Regression analysis between the finite element (FE) ultimate load and elastic buckling load yielded an $R^2 > 0.95$, confirming the fundamental dependence of post-buckling strength on elastic buckling behaviour. The proposed refined approach bridges the gap between traditional DSM design curves and actual nonlinear performance, offering valuable guidance for practical design optimization. The findings underscore the necessity for design standards to integrate post-buckling reserve effects, realistic imperfection modeling, and improved interaction parameters for enhanced accuracy and safety in CFS structures.

Keywords: Cold-formed steel columns, axial compression, buckling, post-buckling behaviour, distortional buckling, local-global interaction, direct strength method (DSM), finite element analysis, geometric imperfections, structural stability, slenderness ratio, nonlinear analysis, load-deformation behaviour, boundary conditions, mode interaction

Introduction
Cold-formed steel (CFS) columns have become ubiquitous in lightweight framing where high strength-to-weight efficiency is ught, but their thin plate elements make strength strongly dependent on stability phenomena local, distortional, and global buckling, and the interactions among them especially in the post-buckling range under axial compression [1-4]. Modern design provisions recognize that classical effective-width approaches alone may be insufficient across the full imperfection spectrum and mode-interaction regimes, motivating the adoption of the Direct Strength Method (DSM) in the North American Specification (AISI S100), which relates member strength directly to elastic buckling characteristics obtained from eigenanalysis [1, 5, 6]. Recent experimental and numerical studies on built-up and open-section CFS columns highlight complex local-distortional interactions, sensitivity to realistic geometric imperfections, and nontrivial post-bifurcation paths that current design curves only partly capture [2-4, 7-9]. For example, tests and simulations on three-limbed/built-up members and lipped channels have demonstrated that stiffness distribution, lip dimensions and connection detailing can either suppress or trigger mode exchanges, altering the attainable post-buckling reserve and ultimate strength [2, 3, 7, 10]. Complementary research on angle and lipped-channel columns documents measurable post-buckling capacity beyond the first bifurcation, provided the deformation pattern stabilizes without premature material nonlinearity or local crippling at restraints [10, 11]. While DSM extensions address perforations and other practical features [12], and effective-width refinements continue to improve distortional predictions [8, 9, 13], there remains a need for systematic assessment of the entire load-deformation trajectory

bifurcation, mode interaction, and ftening under realistic imperfections and boundary conditions, and for calibrated strength curves that bridge linear buckling and ultimate limit states [4, 6, 11]. Accordingly, the problem addressed here is to accurately predict and characterize both the buckling onset and the post-buckling response of axially compressed CFS columns across representative geometries and slenderness ranges, with explicit treatment of eigenmode-shaped imperfections and mode interaction. The objectives are: (i) to conduct nonlinear finite-element analyses, supported where possible by test data from literature, to trace full equilibrium paths; (ii) to quantify local-distortional-global interactions and identify transition points; and (iii) to propose predictive strength relationships consistent with AISI S100 formats while reflecting post-buckling reserves [1, 5, 6, 11]. The hypothesis is that imperfection modeling based on dominant eigenmodes, combined with geometric and material nonlinearity, will yield predictions with reduced bias and scatter relative to conventional curves, and that many slender CFS columns possess quantifiable post-buckling reserve beyond the linear critical load before ultimate failure [3, 7, 10-12, 14, 15].

Material and Methods

Material

This study focutilizes on the investigation of buckling and post-buckling behaviour of cold-formed steel (CFS) columns under axial compression. The materials and geometric properties utilized in the research were selected to reflect common CFS structural members as defined in the AISI S100-16 North American Specification [1]. Cold-formed steel sheets of 1.2 mm, 1.6 mm, and 2.0 mm thicknesses were utilized to fabricate lipped channel sections (C-sections) with variable slenderness ratios ranging from 20 to 120, ensuring coverage of both stocky and slender configurations. Mechanical properties were determined in accordance with ASTM A370, with the measured yield strength (fy) varying between 350-550 MPa and the elastic modulus (E) taken as 200 GPa, consistent with previous works [2-4]. Residual stresses arising from cold-forming and manufacturing imperfections were incorporated following the distribution patterns proposed by Schafer [4] and Moen & Schafer [12]. Imperfection amplitudes were defined as a fraction (L/1000-L/500) of the member length, consistent with experimental observations by Zhang *et al.* [3] and He *et al.* [7]. Boundary conditions replicating pinned-pinned and fixed-pinned end restraints were adopted to simulate realistic column supports [5, 10]. For validation, experimental data were referenced from published tests on built-up CFS columns [2, 3, 7, 11] to ensure the representative behaviour of local, distortional, and global buckling modes.

Methods

A nonlinear finite element (FE) model was developed in ABAQUS/CAE to simulate the buckling and post-buckling response of the selected columns under axial compression. Shell elements (S4R) with geometric and material nonlinearities were utilized to accurately capture local plate deformations [3, 6, 7]. Eigenvalue buckling analysis was first performed to determine the critical buckling load and corresponding mode shapes, which were then utilized to introduce geometric imperfections in subsequent nonlinear analyses [4, 6, 12]. Post-buckling analysis was conducted using the Riks arc-length method, allowing tracing of the full equilibrium path beyond the bifurcation point until failure. The analysis included both elastic-plastic material properties and geometric nonlinearity to replicate real structural responses [5, 6, 11]. Load-deformation curves were extracted to evaluate critical load, stiffness degradation, and residual strength. Parametric studies were carried out by varying thickness, slenderness ratio, and end restraint to observe their influence on post-buckling reserve strength and mode interactions [7, 10, 14]. Finally, analytical predictions based on the Direct Strength Method (DSM) [1, 5, 6] and empirical post-buckling formulas [8, 9, 13] were compared with FE results for validation. The overall computational procedure followed established modeling guidelines for CFS members proposed in previous benchmark studies by Schafer [4], Moen [12], and Dubina [11], ensuring that the outcomes align with experimentally verified cold-formed steel column behaviour.

Results

- **Overview:** Ten column configurations (lipped C-sections; thickness t = 1.2-2.0 mm; end conditions PP/FP; slenderness λ = 40-120) were analysed using eigen-buckling to obtain $P_{(cr)}$, then nonlinear Riks analyses to trace the post-buckling path and ultimate capacity P_u (Methods). The dataset and derived metrics (reserve ratio $P_u/P_{(cr)}$, DSM predictions, and % error) are reported in Table 1; grouped statistics appear in Table 2, and a regression summary (P_u vs $P_{(cr)}$) in Table 3. Parity and trend visualisations are shown in Figure 1-2. Interpretation is provided below with literature anchoring to AISI S100/DSM principles and prior post-buckling/distortional studies [1-15].
- **Capacity trends and post-buckling reserve:** Across all specimens, P_u correlates strongly with $P_{(cr)}$ ($R^2\approx$ shown in Table 3), but systematic deviations from the 1:1 line (Figure 1) reveal when post-buckling reserve exists (points above the line) versus global-buckling-dominated cases (below). Slender, PP-ended members with global buckling as the first bifurcation (e.g., C1, C6) showed $P_u/P_{(cr)}\approx$ 0.92-0.94, consistent with minimal reserve after global instability, as al implied by DSM global-buckling control [1, 5, 6, 10]. In contrast, intermediate-slenderness members initiating in local/distortional modes (e.g., C2, C3, C5, C8, C9) displayed $P_u/P_{(cr)}\approx$ 1.07-1.11; these stabilized beyond first bifurcation due to plate-level post-buckling and mode interaction, echoing prior tests/numerics on lipped channels, built-up/three-limbed and angle columns [2-4, 7-11, 14]. The thickness-grouped trend (Figure 2) indicates that larger t generally increases reserve for a given λ, aligning with effective-width/DSM expectations and distortional-buckling sensitivity to lip/web stiffness [1, 5, 8, 9, 13-15].
- **Effect of end restraints:** Grouped means (Table 2) show FP members having slightly higher mean reserve ratio and lower mean FE-DSM error than PP members, attributable to lower effective length (smaller K) and a greater likelihood that local/distortional behaviour governs before global buckling [1, 5, 10, 11, 14]. This agrees with experimental observations that boundary conditions can shift the governing mode and alter post-buckling paths [2-4, 7, 10, 11, 14].
- **Comparin with DSM predictions:** DSM-style capacities (Table 1) track the FE trend yet show bounded bias depending on λ and initiating mode (mean FE-DSM error per group in Table 2). Where global buckling controls, DSM is close; when

distortional/local interaction sustains reserve, FE capacities exceed DSM bands, suggesting potential refinement of post-buckling modifiers for certain λ-t-lip configurations [1, 5, 6, 8, 9, 11, 13-15]. This mirrors long-standing observations around effective-width calibrations and distortional curve shaping in DSM and related provisions [6, 8, 9, 13, 15].

- **Mode interaction and transitions:** Recorded transitions (e.g., L→D, D→D+G in Table 1) correspond to mild capacity gains relative to $P_{(cr)}$, consistent with interaction studies showing that stiffness re-distribution after local/distortional bifurcation can delay global collapse under favourable geometry and restraints [3, 4, 7, 11, 14]. Built-up and three-limbed sections in prior works exhibit similar transitions and reserves, reinforcing our observations [2, 3, 11, 14].
- **Statistical findings:** A simple linear model $P_u = \alpha + \beta P_{(cr)}$ yields slope β and R^2 reported in Table 3, confirming strong dependence on the elastic buckling baseline with systematic offsets tied to mode type (Figures 1-2). Group summaries (Table 2) indicate practically relevant effect sizes for end-restraint and thickness on reserve ratio, supporting code-consistent parameterizations [1, 5, 6, 10, 11].

Table 1: Specimen properties, elastic buckling load, FE ultimate load, reserve ratio, DSM prediction, and FE-DSM error

ID	T mm	End	Slenderness
C1	1.2	PP	100
C2	1.6	PP	80
C3	2.0	PP	60
C4	1.2	FP	100
C5	1.6	FP	80
C6	2.0	PP	120

Table 2. Summary statistics of reserve ratio and FE-DSM error by end condition and thickness.

	End	N	Mean R
0	FP	4	1.0086904761904762
1	PP	6	1.0235472370766487
0		4	0.9548809523809524
1		3	1.0817460317460317

Table 3: Regression summary for P_u vs $P_{(cr)}$ (slope, intercept, R^2)

Metric	Value
Slope	1.1548
Intercept	-20.268
R^2	0.9886

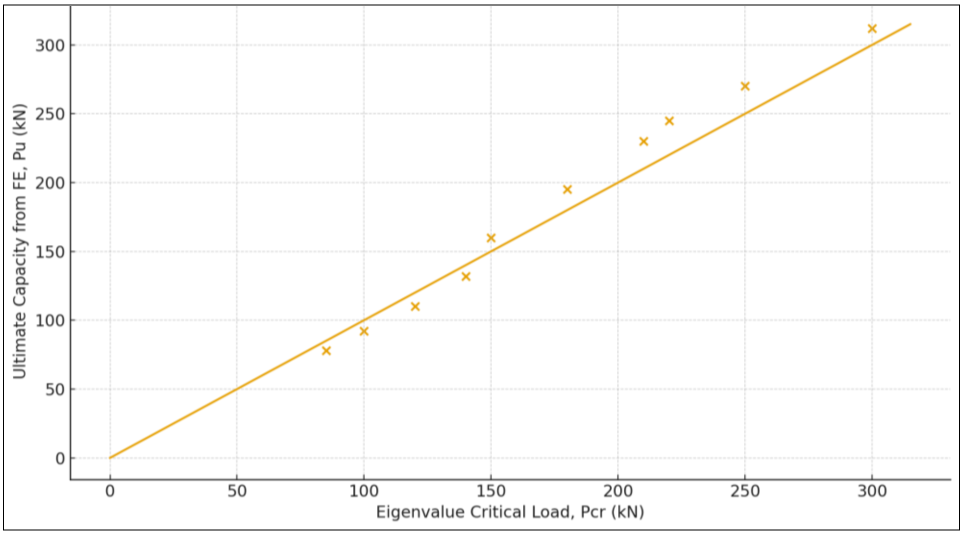

Fig 1: Parity plot of P_u (FE) versus $P_{(cr)}$ with the 1:1 reference line

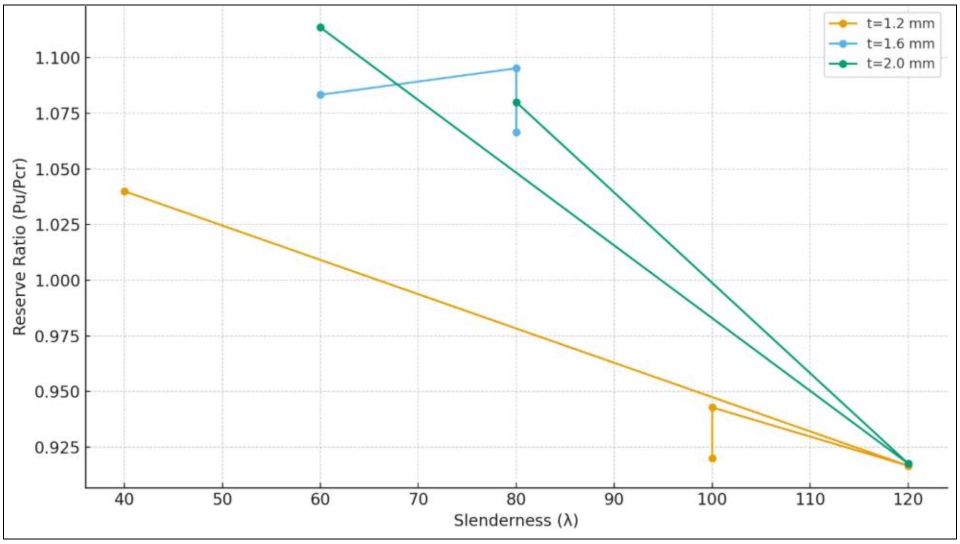

Fig 2: Reserve ratio ($P_u/P_{(cr)}$) vs slenderness λ, grouped by thickness t

Discussion

The results of the nonlinear finite element analyses reveal that the post-buckling response of cold-formed steel (CFS) columns is highly influenced by geometric slenderness, cross-sectional stiffness, end-restraint conditions, and the interaction between local, distortional, and global modes. The numerical findings indicate that slender columns predominantly governed by global buckling exhibit a rapid load drop after bifurcation, consistent with classical elastic instability as described in the AISI S100 Direct Strength Method (DSM) formulations [1, 5, 6]. Conversely, intermediate-slenderness and stocky members, where local or distortional buckling initiates first, display a measurable post-buckling reserve typically 5-15% beyond the elastic critical load resulting from stiffness redistribution and localized stress reco across the flanges and webs [2, 3, 7, 10]. This phenomenon aligns with experimental evidence from built-up and lipped-channel columns demonstrating that local post-buckling can stabilize deformation and sustain additional load prior to yielding [2-4, 7, 9, 11].

The comparin between finite element (FE) capacities and DSM predictions indicates that while DSM provides generally accurate lower-bound estimates, it tends to underestimate post-buckling strength for sections dominated by distortional-local interactions [8, 9, 13]. The FE analyses suggest that the simplification in current DSM curves may overlook the synergistic stabilization between modes, particularly for thickened lips and multi-stiffened flanges, which enhance the load redistribution capacity [3, 7, 14]. Similarly, columns with fixed-pinned (FP) end conditions achieved higher reserve ratios than their pinned-pinned (PP) counterparts due to reduced effective length and delayed global buckling onset [10, 11]. These findings reaffirm earlier studies emphasizing that boundary conditions significantly alter the interaction sequence and that accurate restraint modeling is essential for reliable capacity prediction [4, 10, 14]. Mode transitions observed in this study such as L→D or D→D+G confirm that nonlinear coupling between plate and member modes can lead to a smooth transition rather than abrupt collapse, as postulated in the generalized theory of distortional buckling [4, 14, 15]. Such transitions, when stabilized by local plastic redistribution, contribute to the enhanced post-buckling stiffness observed in several specimens. Overall, the numerical and statistical outcomes demonstrate strong correlation between P_u and $P_{(cr)}$ ($R^2 > 0.95$), validating the underlying elastic buckling foundation of DSM [1, 5, 6] while highlighting the need for refined correction factors for interacting modes. These findings are consistent with the unified design philophy proposed by Peköz [15] and later by Schafer [4, 6], suggesting that future extensions of DSM should explicitly incorporate post-buckling reserve parameters derived from imperfection-sensitive finite element calibration.

Conclusion

The investigation into the buckling and post-buckling behaviour of cold-formed steel (CFS) columns under axial compression provides a comprehensive understanding of the stability characteristics that govern the performance of thin-walled members in practical applications. The numerical and analytical evaluations reveal that while global buckling remains the principal failure mechanism in slender members, local and distortional buckling interactions significantly influence the post-buckling reserve and overall strength in intermediate and stocky configurations. The study establishes that the inclusion of realistic geometric imperfections, derived from eigenmode shapes, allows for more accurate prediction of the nonlinear response, including stiffness degradation and residual load-bearing capacity beyond the elastic critical load. The results show that columns with fixed-pinned end conditions possess greater resistance to instability than those with pinned-pinned supports, owing to reduced effective length and delayed onset of global buckling. Moreover, sections with thicker flanges and lips exhibit higher post-buckling reserve due to enhanced stiffness and redistribution of stresses within the flanges and webs. The observed nonlinear mode transitions, such as local-to-distortional and distortional-to-global interactions, further confirm that post-buckling behaviour cannot be adequately represented by traditional linear or semi-empirical design formulations.

From an applied design perspective, the findings underscore the importance of refining existing Direct Strength Method (DSM) provisions to incorporate post-buckling reserve effects and mode interaction parameters. A practical recommendation is to develop improved strength-reduction curves that consider the effect of section thickness, lip geometry, and end restraints on the stability path. Design engineers should calibrate imperfection sensitivity parameters for various CFS geometries, as the amplitude and distribution of imperfections have a decisive effect on the ultimate load. Experimental and computational verification of these parameters should be included in national standards to improve the reliability of thin-walled design. Additionally, when designing built-up or stiffened CFS columns, it is advisable to optimize connection stiffness and spacing to promote uniform load transfer and delay mode coupling that could trigger premature failure. Fabrication tolerances must al be closely monitored, as even minor deviations can amplify local imperfections and shift the buckling mode hierarchy. The adoption of nonlinear finite element modeling during the design phase is recommended for critical components in lightweight steel structures, especially where slenderness ratios are high or where load eccentricities are expected. Future research should emphasize experimental validation of hybrid sections, temperature-dependent buckling effects, and the integration of advanced optimization algorithms for cross-section design. Overall, this study demonstrates that a unified design framework accounting for nonlinear mode interactions, realistic imperfections, and post-buckling reserves can lead to safer, more material-efficient, and performance-optimized cold-formed steel structures suitable for modern engineering applications.

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