

Original Article

Comparative Performance of H-Sections and Symmetrical Cruciform Columns Under Axial Compression

Riza Suwondo¹, Militia Keintjem²

¹Department of Civil Engineering, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia.

²Karbonara Research Institute, Jakarta, Indonesia.

¹Corresponding Author : riza.suwondo@binus.ac.id

Received: 09 June 2025

Revised: 14 July 2025

Accepted: 12 August 2025

Published: 29 August 2025

Abstract - Axially loaded steel columns are fundamental elements for a wide range of structural applications, and their performance is often governed by flexural buckling under increasing slenderness. Conventional column designs typically rely on hot-rolled H-sections that are susceptible to weak-axis instability, particularly in tall or slender configurations. Built-up cruciform sections, such as King and Queen cross-sections, have been proposed as alternatives offering improved geometric balance and enhanced buckling resistance. However, a systematic comparison of their axial performances relative to standard H-sections, particularly on an equivalent weight basis, remains limited. This study aims to address this gap by conducting a detailed comparative analysis of the design axial load-carrying capacities of representative H-sections (H150, H200, and H300) and their equivalently weighted King (K198, K248, and K350) and Queen (Q200, Q298, and Q400) cruciform counterparts. The analysis was performed in accordance with the AISC 360-16 provisions, considering pinned-pinned boundary conditions and column lengths ranging from 3 m to 10 m to capture varying slenderness effects. The results demonstrate that while King cruciform sections perform well in short, stocky columns, their efficiency diminishes at higher slenderness. In contrast, the Queen cruciform sections consistently outperformed both the King and conventional H-sections in both strong-axis and weak-axis buckling across all lengths, particularly in slender columns. These findings offer valuable design insights for optimising the column selection in applications where global stability and material efficiency are critical.

Keywords - Steel columns, Cruciform sections, Axial capacity, Buckling behaviour, Structural efficiency.

1. Introduction

Axially loaded compression members are fundamental components in a wide array of structural engineering applications, ranging from multistorey buildings and bridges to industrial frameworks. Their primary function is to safely transfer compressive forces through the structure, making their design and selection critical for ensuring both the structural integrity and material economy. Conventional design practices have predominantly relied on hot-rolled steel sections, with H-sections (also known as Wide-Flange or I-sections) being the prevalent choice because of their availability, ease of fabrication, and well-established design methodologies. However, the axial compressive capacity of these sections is typically governed by flexural (Euler) buckling, particularly with respect to the minor principal axis, which often necessitates the use of larger and heavier sections to satisfy the slenderness requirements as the column length increases [1-4]. The pursuit of improved structural efficiency and optimised material use has spurred interest in alternative section geometries. Built-up sections, such as cruciform

columns, have emerged as promising solutions owing to their inherently higher radii of gyration and more balanced stiffness properties about both principal axes. The existing literature has extensively addressed the fundamental theories of elastic and inelastic buckling [5-7], and numerous studies have explored the behaviour of H-sections under various loading and boundary conditions [8-12]. The theoretical advantages of built-up sections, including cruciform configurations, have also been discussed in structural mechanics, and some studies have focused on specific applications or unique fabrication methods [13-17].

Cruciform sections, particularly King and Queen variants, are typically fabricated by longitudinally bisecting standard H- or I-sections and welding the resulting half-sections to the web of another identical section, forming a symmetrical cross-shaped configuration, as illustrated in Figure 1. Unlike conventional H-sections, which are limited by minor-axis flexural buckling, cruciform sections exhibit enhanced torsional and flexural resistances under combined



compression and bending [17-20, 16]. Their geometry is particularly advantageous in orthogonal moment-resisting frames, where equal bending strengths and stiffnesses of both principal axes are desirable.

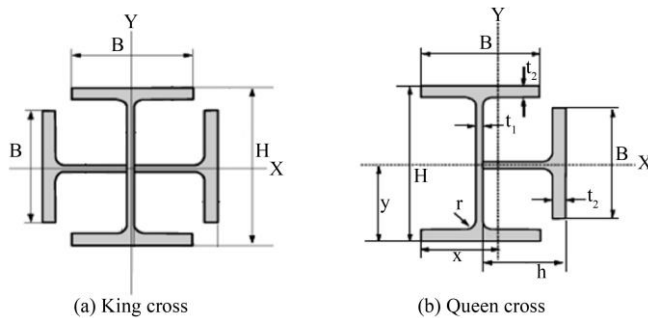


Fig. 1 Cruciform section

Experimental studies have demonstrated that cruciform columns offer an increased axial capacity, ductility, and energy dissipation under cyclic loading, making them suitable for seismic applications [21]. Finite element analyses further confirmed that cruciform columns can outperform conventional sections in terms of their load-bearing capacity and overall structural efficiency [15]. Moreover, the behaviour of cruciform column panel zones has been systematically investigated with regard to flange thickness, web thickness, and continuity plate detailing [22]. These findings highlight the potential advantages of cruciform configurations in modern structural designs, particularly in stability-critical applications.

However, despite this growing body of research, there is a notable lack of comprehensive and systematic comparative studies that evaluate the axial compression performance of cruciform columns, particularly the King and Queen configurations, relative to conventional H-sections on an equivalent weight basis. Prior comparisons have typically been limited in scope, focusing either on idealised models or on isolated geometric conditions, without accounting for equivalent cross-sectional area or practical slenderness effects. Consequently, there is insufficient empirical evidence to guide structural engineers in selecting the most structurally efficient and materially economical section type for axially loaded steel columns.

Understanding the relative performance of conventional and alternative column configurations is not only of academic interest but also of practical importance for structural engineers. With growing demands for material efficiency, cost optimisation, and enhanced performance under loading, particularly in seismic-prone regions, engineers are increasingly seeking column solutions that provide stability without unnecessary material use. Cruciform sections, particularly those fabricated from standard profiles, offer the opportunity to achieve more uniform stiffness and improved

buckling resistance, potentially enabling lighter and more efficient structural systems. However, their adoption in practice remains limited because of the absence of systematic, design-oriented comparisons and the lack of code-based guidance.

This study aims to address this critical gap by conducting a detailed comparative analysis of the design axial load-carrying capacities of representative H-sections (H150, H200, and H300) and their equivalently weighted King (K198, K248, and K350) and Queen (Q200, Q298, and Q400) cruciform counterparts. The investigation followed the AISC 360-16 standards and looked at column lengths from 3 to 10 m to cover a range of slenderness ratios. The main goal was to assess the buckling performance and structural efficiency of these sections under axial compression. This study provides useful insights for choosing columns. The results offer practical design advice and establish a scientific foundation for improving section selection in steel structures, where axial capacity and overall stability are important design factors.

2. Methodology

This study used a comparative analytical approach to assess the axial load-carrying capacities of selected H-sections and their equivalent King (K-series) and Queen (Q-series) cruciform shapes. The analysis followed established structural steel design principles and the relevant sections of AISC 360-16: Specification for Structural Steel Buildings [23]. The steel material used was JIS G 3101 SS400, which has a yield strength (F_y) of 245 MPa and a modulus of elasticity (E) of 200,000 MPa.

All columns were modelled as simply supported (pinned-pinned condition), with varying clear heights to capture the influence of slenderness and overall stability on axial performance. This boundary condition reflects practical column applications in which end rotations are permitted, and is commonly adopted in buckling studies as a baseline assumption. This allows for a consistent and standardised comparison of different section geometries while avoiding the complexity of partial or full rotational restraints. The effective length factor was taken as $K = 1.0$, in both principal axes, as per AISC 360-16. While actual boundary conditions may vary in practice (e.g. fixed or partially restrained), the pinned-pinned assumption offers a conservative and widely accepted reference point. The column lengths ranged from 3 m to 10 m, enabling systematic assessment across a representative range of slenderness ratios typically encountered in design practice.

To ensure a meaningful and unbiased comparison based on material efficiency, the selected steel sections were designed to have approximately equal cross-sectional areas and similar weights per unit length. Three hot-rolled H-sections (H150, H200, and H300), which are widely used in structural engineering practice for columns in low- to mid-rise

buildings, were chosen to represent the small, medium, and large section groups. For each of these baseline H-sections, the corresponding King and Queen cruciform sections were developed by recombining the bisected wide-flange profiles in a symmetrical configuration. The cruciform sections K198, K248, and K350 (King), and Q200, Q298, and Q400 (Queen), were selected to match the weight of their H-section counterparts as closely as possible. This equivalence enables a direct evaluation of the geometric effects on buckling and axial performance while eliminating mass-related bias. The section pairings used for the analysis are summarised as follows.

- H150: K198 and Q200 (small section group)
- H200: K248 and Q298 (medium section group)
- H300: K350 and Q400 (large section group)

The detailed cross-sectional properties of all the selected sections, including the dimensions and geometric parameters, are presented in Table 1.

Table 1. Geometry of steel section used in this study

Group	Section	A (mm ²)	Weight (kg/m)	Radius of gyration (mm)	
				x	y
Small	H150	4014	31.5	63.9	37.5
	K198	4636	36.4	60.4	62.3
	Q200	4074	32	68.4	45.6
Medium	H200	6353	49.9	86.2	50.2
	K248	6536	51.4	75.9	77.5
	Q298	6120	48.1	103.4	68.1
Large	H300	11980	94	131	75.1
	K350	12628	99.2	107.5	109.5
	Q400	12618	99.1	139.5	91.9

The axial capacity analysis followed the AISC 360-16 design method. The design axial capacity (ϕP_n) was calculated using the critical buckling stress (F_{cr}) and the gross cross-sectional area (A_g) with this equation:

$$\phi P_n = 0.9 F_{cr} A_g \quad (1)$$

The critical stress (F_{cr}) is based on the slenderness ratio (KL/r), which compares the effective column length (KL) to the radius of gyration (r). The formula for F_{cr} is:

$$F_{cr} = \left(0.658 \frac{F_y}{F_e} \right) F_y \quad \text{when} \quad \frac{KL}{r} \leq 4.71 \sqrt{\frac{E}{F_y}} \quad (2)$$

$$F_{cr} = 0.887 F_e \quad \text{when} \quad \frac{KL}{r} > 4.71 \sqrt{\frac{E}{F_y}} \quad (3)$$

Where F_e represents the elastic Euler buckling stress, calculated as

$$F_e = \frac{\pi^2 E}{(KL/r)^2} \quad (4)$$

These equations take into account both inelastic and elastic buckling behaviours, depending on the slenderness level of the column. This study offers a detailed evaluation of the axial load performance of H-sections compared to their cruciform equivalents in practical design situations by changing the column length and assessing both strong-axis (X-axis) and weak-axis (Y-axis) buckling modes.

3. Results and Discussion

This section compares the axial load-carrying capacities of H-sections to the similarly weighted King (K-series) and Queen (Q-series) cruciform shapes. The evaluation looks at the strong axis (X-axis) and weak axis (Y-axis) buckling behaviour under pinned-pinned boundary conditions. Column lengths range from 3 m to 10 m. The results show how section shape, slenderness, and buckling mode affect axial performance. The findings are organised by section size group to highlight trends and practical implications for structural design.

3.1. Design Axial Load-Carrying Capacities

3.1.1. Small Section Group

Figure 2 shows the design axial capacity of the small-section group (H150, K198, and Q200). The strong-axis buckling behaviour shows different trends between the conventional H-section and the cruciform sections. For short columns (3–4 m long), both cruciform sections performed better than the H-section. The King section (K198) had the highest axial capacity. Specifically, at a length of 3 m, K198 reached 1329 kN, which is more than Q200 (1292 kN) and H150 (1315 kN). The strong performance of K198 in short columns comes from its geometric design along the strong axis. This design gives it better flexural stiffness and improves resistance to local instability.

However, as the column length increased and global flexural buckling took over, the performance order changed. For longer columns (8–10 m), the Queen section (Q200) outperformed both K198 and H150. At 10 m, Q200 had an axial capacity of 830 kN. In comparison, K198 and H150 showed similar capacities of 585 kN and 696 kN, respectively. This difference mainly comes from the better balance of the radius of gyration in the Queen section. This balance improves its resistance to global buckling in slender columns. On the other hand, the strong-axis design of the King section is less effective in high-slenderness situations. As a result, its performance resembles that of the conventional H-section. These findings show that while King cruciform sections are clearly better for short, stocky columns, Queen sections excel with slender columns, where global instability is more critical.

In weak-axis (Y-axis) buckling, the differences in performance between the H-section and cruciform sections were more obvious at all column lengths. For short columns (3 m), the King section (K198) had a much higher axial capacity of 906 kN, compared to 635 kN for H150 and 717 kN for Q200. The cruciform sections performed better due to their greater minor-axis stiffness and larger radius of gyration in the Y-direction. This benefit becomes more apparent as the column length increases. At a length of 10 m, K198 maintained an axial capacity of 280 kN, while Q200 reached 132 kN. This was significantly higher than the 88 kN capacity of the H150 section. These results clearly demonstrate that cruciform geometries are more effective in resisting weak-axis buckling, particularly under slender column conditions, where lateral instability governs the performance. The King cruciform section, in particular, maintains a consistently superior capacity across the entire length range, making it a favourable choice for applications where minor-axis buckling is a critical design concern.

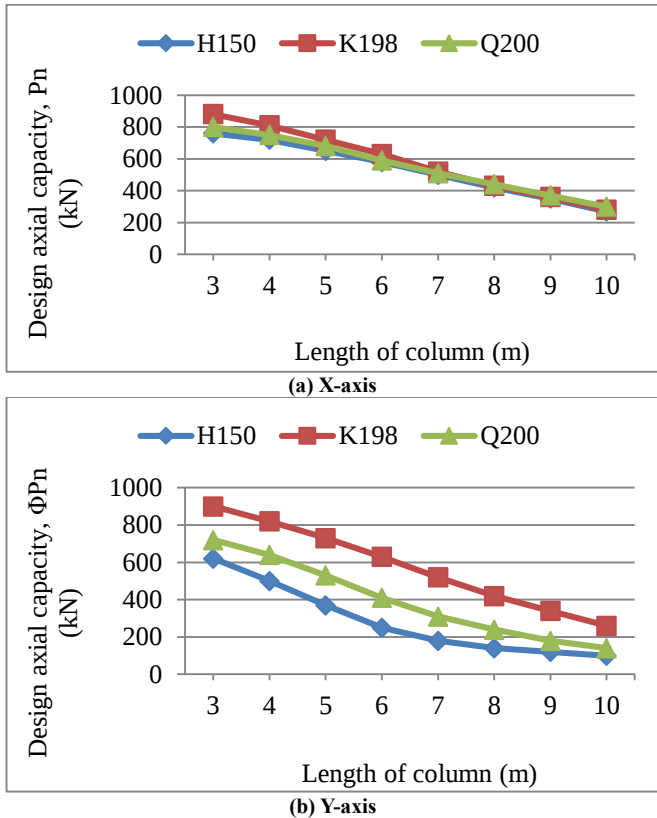


Fig. 2 Design axial capacity of the small section group (H150, K198, Q200)

3.1.2. Medium Section Group

The design axial capacity for the medium-section group (H200, K248, and Q298) is presented in Figure 3. The results show that the strong-axis buckling behaviour reveals that all three sections exhibit nearly identical axial capacities in the short columns. However, notable differences emerge as the column length increases and global slenderness effects begin

to govern the behaviour. The Queen cruciform section (Q298) demonstrated superior performance at greater lengths, retaining an axial capacity of 297 kN at 10 m compared to 255 kN for both H200 and K248. Interestingly, while the King cruciform section (K248) initially matches the H-section, it exhibits slightly reduced performance at longer lengths, falling below the conventional H-section. This result suggests that the King cruciform geometry, although effective in short columns, is less optimised for mitigating global slenderness effects in strong-axis buckling at higher slenderness ratios. Conversely, the balanced geometry and improved radius of gyration of the Queen section provided enhanced stability with increasing column length.

In weak-axis (Y-axis) buckling, the performance hierarchy is consistent with the trends observed in the small-section group. The Queen cruciform section (Q298) outperformed both the King cruciform (K248) and the conventional H-section (H200) across the entire range of column lengths. These results underscore the consistent benefit of cruciform geometries in enhancing weak-axis buckling resistance, particularly in slender columns. The balanced stiffness properties of the Queen section provide a clear advantage in mitigating lateral instability about the minor axis, making it a favourable option for applications in which weak-axis buckling is a primary design consideration.

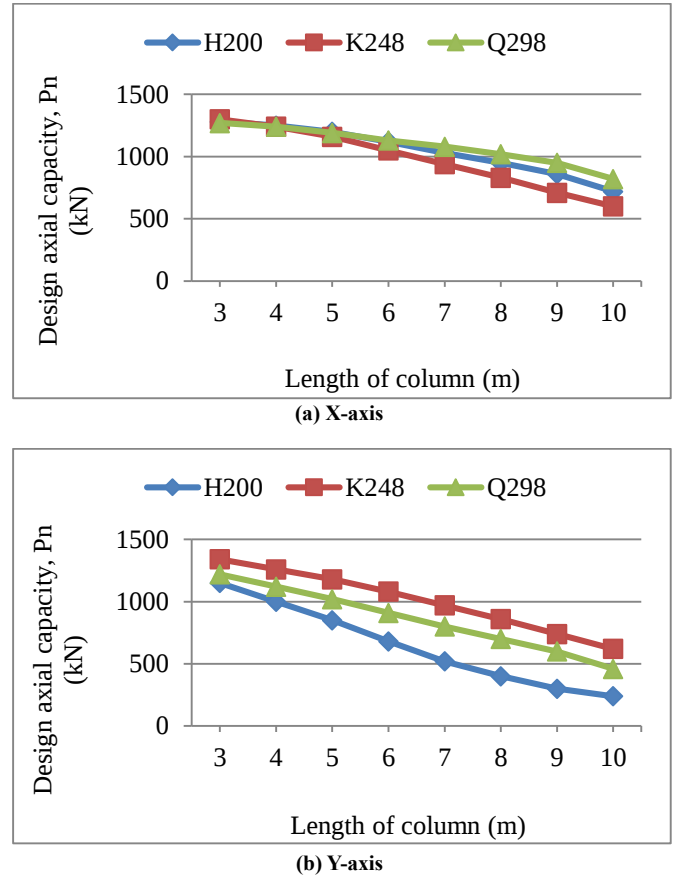


Fig. 3 Design axial capacity of the medium section group (H200, K248, Q298)

3.1.3. Large Section Group

In the large-section group (H300, K350, Q400), the results for strong-axis buckling, shown in Figure 4, reveal a clear performance hierarchy that changes with column length. For short columns (3 m), both cruciform sections, King (K350) and Queen (Q400), showed higher axial capacities than the standard H-section. Specifically, at 3 m, Q400 reached an axial capacity of 2716 kN, while K350 hit 2664 kN, both exceeding H300 at 2571 kN. This initial edge highlights the better cross-sectional shape of the cruciform sections, which improves the flexural stiffness of the strong axis. However, as the column length increased and slenderness effects took over, the performance began to vary. The Queen cruciform section (Q400) consistently maintained a higher axial capacity across all lengths. At 10 m, Q400 had a capacity of 2130 kN, surpassing H300 at 2067 kN and K350 at 1984 kN. Interestingly, the King cruciform section (K350), despite its earlier advantage in stockier columns, showed a decline in efficiency as slenderness increased, eventually falling below the standard H-section at longer lengths. This behaviour suggests that while the King design improves local flexural stiffness, it is less effective at preventing global buckling instability in thinner columns. In contrast, the balanced shape of the Queen cruciform and its larger radius of gyration provided strong buckling resistance, allowing it to consistently outperform both the H-section and the King cruciform as the column length grew.

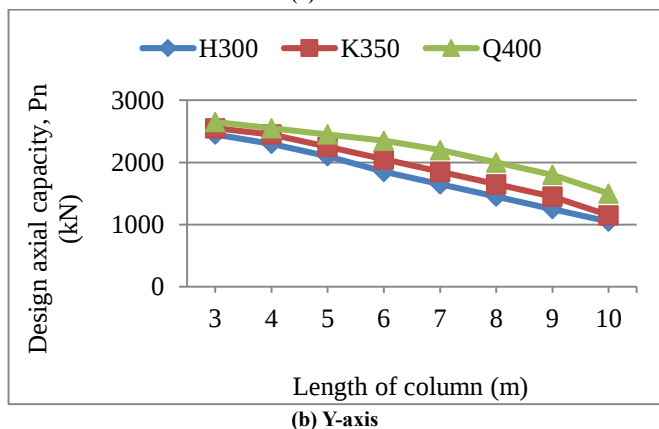
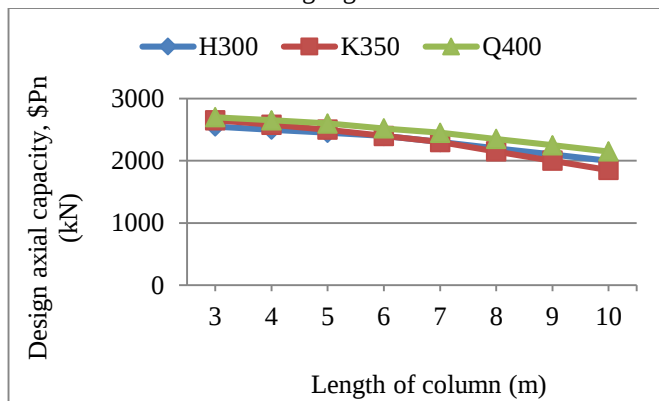


Fig. 4 Design axial capacity of the large section group (H300, K350, Q400)

The weak-axis (Y-axis) buckling behaviour of the large-section group (H300, K350, Q400) followed a clear trend seen in the small- and medium-section groups. The Queen cruciform section (Q400) consistently shows better axial capacity over all column lengths. It outperforms both the King cruciform (K350) and the standard H-section (H300). At 3 m, Q400 achieved an axial capacity of 2632 kN. In comparison, K350 reached 2563 kN and H300 reached 2431 kN, showing a clear advantage even in stocky columns.

This superiority continued as column length increased; at 10 m, Q400 held at 1504 kN, while K350 and H300 dropped to 1330 kN and 1054 kN, respectively. These findings confirm that the balanced geometry of the Queen cruciform section offers better resistance to weak-axis buckling across all sizes and slenderness ranges. The consistent performance of the Queen section in the small, medium, and large groups highlights its suitability for applications where minor-axis stability is important, especially in tall structures and slender column designs.

3.2. Comparative Performance Analysis

The comparative analysis across all section groups revealed several consistent trends regarding the influence of section geometry on the axial load-carrying performance. In terms of strong-axis buckling, the Queen cruciform sections (Q-series) demonstrate superior performance in the medium- and large-section groups, particularly at higher slenderness ratios, where their balanced geometry and enhanced radius of gyration provide clear advantages over both the King cruciform (K-series) and conventional H-sections. In contrast, the King cruciform sections exhibit strong performance in short columns owing to their optimised strong-axis stiffness, but their efficiency diminishes with increasing slenderness, in some cases falling below that of the H-section in long columns.

For weak-axis buckling, a consistent pattern was observed across all section groups, and the Queen cruciform sections outperformed both the King cruciform and H-sections across the entire range of column lengths. The superior weak-axis stability of the Queen sections is attributed to their inherently balanced cross-sectional properties, which mitigate lateral instability more effectively than either the asymmetrical King geometry or the conventional H-section. The King cruciform sections, while offering substantial improvement over H-sections in weak-axis buckling for small and medium groups, show diminishing returns at larger sizes, where the balanced geometry of the Queen section becomes increasingly advantageous.

Overall, the results highlight that while King cruciform sections can provide efficient solutions for short, stocky columns, the Queen cruciform sections offer a more robust and consistent performance across both axes and a wide range of slenderness ratios. This positions the Queen cruciform as

the most structurally efficient choice for columns, where both strong-axis and weak-axis buckling considerations are critical, particularly for slender columns and tall structural applications.

The findings of this study have several practical implications for structural design. For applications involving short columns, such as transfer columns, low-rise bracing members, or heavily braced frames, King cruciform sections may offer material savings and enhanced axial capacity owing to their superior performance in stocky conditions. However, for taller columns and slender members, where global stability governs the design, the Queen cruciform sections provide significant advantages. Their consistent superiority in both strong-axis and weak-axis buckling performance makes them highly suitable for columns in tall buildings, long-span structures, or orthogonal moment-resisting frames where balanced biaxial behaviour is essential. Furthermore, designers should be aware that while conventional H-sections remain adequate for many standard applications, cruciform sections, particularly the Queen type, can achieve improved structural efficiency, potentially leading to lighter overall structural systems and more economical use of materials in projects in which column slenderness and lateral stability are critical design drivers.

Unlike previous studies that have primarily focused on idealised simulations, isolated geometries, or cyclic loading behaviour, this study offers a systematic and code-compliant comparison of King and Queen cruciform sections against conventional H-sections using equivalent-weight criteria and AISC 360-16 provisions across a range of slenderness ratios. This approach fills a key gap in the literature and provides actionable insights for structural engineers, supporting more informed and optimised column selection in research and practical design scenarios.

4. Conclusion

This study conducted a detailed comparative analysis of the design axial load-carrying capacities of representative H-sections (H150, H200, H300) and their equivalently weighted King (K-series) and Queen (Q-series) cruciform section counterparts (K198, K248, K350; Q200, Q298, Q400), focusing on both the strong- and weak-axis buckling behaviours under pinned-pinned boundary conditions. The analysis, performed in accordance with the AISC 360-16 provisions, systematically evaluated column performance across a practical range of lengths (3–10 m), capturing the influence of slenderness and section geometry on global stability.

The results show clear trends. In strong-axis buckling, the Queen cruciform sections perform better in medium and large section groups, especially at higher slenderness ratios. King cruciform sections do well in short columns, but their

efficiency drops in slender columns. In some cases, their capacities fall below those of standard H-sections. For weak-axis buckling, the Queen cruciform sections consistently outshine both the King cruciform and H-sections in all sizes and lengths, proving their strong minor-axis stability. The performance hierarchy observed was consistent across all groups, highlighting the broad relevance of these findings.

From a design perspective, the study shows that King cruciform sections may work well for short, stocky columns. In contrast, Queen cruciform sections offer a more balanced and efficient solution for slender columns and tall structures, especially when both main axes need to be optimised. Designers should keep these performance features in mind when choosing column profiles, particularly in situations where stability and material efficiency are crucial. These findings back the choice of column designs that increase strength while reducing material use. This is an important factor in sustainable structural design.

It is important to recognise the limitations of this study and interpret the findings fairly. The analysis was carried out under ideal pinned-pinned boundary conditions, assuming perfect geometry and leaving out residual stresses, imperfections from fabrication, and connection details. The study also focused solely on axial compression behaviour without looking at combined loading effects like bending, shear, or torsion. Since this investigation relies only on numerical simulations, the results need to be checked through physical testing to confirm their relevance in real-world situations.

Future research could build on this work by including more factors such as fabrication cost, welding details, local buckling effects, and performance under seismic conditions with dynamic loading. Testing the comparative trends found in this analytical study would also strengthen the case for using cruciform sections in modern structural design. Examining how cruciform columns behave under combined axial and bending loads and in realistic boundary conditions would further increase their usefulness in engineering practice.

Acknowledgements

The authors express their sincere gratitude to the Karbonara Research Institute for the invaluable support and resources provided throughout this research. Special thanks are extended to the Civil Engineering Department of BINUS University for their continuous guidance and access to the necessary facilities and equipment. The authors acknowledge the use of AI-powered language models, particularly ChatGPT, in assisting with the drafting and refinement of this manuscript, while affirming that the research methodology, analysis, and conclusions remain entirely the work of the author.

Ethical Approval

This study did not involve human participants, animal subjects, or confidential data, requiring ethical approval. All analyses were conducted with academic integrity using verified section properties and design provisions from AISC 360-16. The authors affirm that the data presented are original and have not been manipulated or fabricated

Funding Statement

This work was supported by Bina Nusantara University.

Author Contribution

RS prepared the manuscript, MK performed the analysis

Data availability

Data analysis <https://zenodo.org/records/15568638>

References

- [1] Yi Zhou et al., "Design Methods of High Strength Steel Welded H-Sections Under Compression Accounting for Local–Global Buckling," *Structures*, vol. 56, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [2] Jie Wang et al., "Interactive Buckling Behaviour of Q420–Q960 Steel Welded Thin-Walled H-Section Long Column," *Thin-Walled Structures*, vol. 203, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] Zhongqi Chen et al., "Local Buckling and Hysteretic Behavior of Thin-Walled Q690 High-Strength Steel H-Section Beam-Columns" *Engineering Structures*, vol. 252, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [4] Yue Yuan et al., "A New H-Section Buckling-Restrained Brace Improved by Movable Steel Blocks and Stiffening Ribs," *Journal of Building Engineering*, vol. 45, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [5] Voraphol Horsangchai, Akhrawat Lenwari, and Ben Young, "Elastic and Inelastic Major-Axis Flexural Buckling of Cellular Steel Columns," *Engineering Structures*, vol. 301, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [6] Pattamad Panedpojaman, Thaksin Thepchatri, and Suchart Limkatanyu, "Elastic Buckling of Cellular Columns under Axial Compression," *Thin-Walled Structures*, vol. 145, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Erling A. Smith, "Buckling of Four Equal-Leg Angle Cruciform Columns," *Journal of Structural Engineering*, vol. 109, no. 2, pp. 439-450, 1983. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] Xitong Dong et al., "Seismic Behaviour of Concrete-Filled Steel Tubular Column to H-Shape Steel Beam Connection with Side Plate," *Structures*, vol. 50, pp. 1608-1624, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Asal Pournaghshband, and Roham Maher, "Numerical Investigation of Cyclic Behaviour in H-Shaped Stainless-Steel Beam-Columns," *Journal of Constructional Steel Research*, vol. 227, pp. 1-15, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] Weining Sui, Zhanfei Wang, and Xiaomin Li, "Experimental Performance of Irregular PZs in CHS Column H-Shape Beam Steel Frame," *Journal of Constructional Steel Research*, vol. 158, pp. 547-559, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [11] Chenglong Wu et al., "Development and Testing of Hybrid Precast Steel-Reinforced Concrete Column-to-H Shape Steel Beam Connections under Cyclic Loading," *Engineering Structures*, vol. 211, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [12] Min Xia et al., "Experimental Study on Bearing Capacity of Corroded Q345 H-Shaped Steel Column under Axial Compression Load," *Journal of Building Engineering*, vol. 52, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [13] Abazar Asghari, and Aydin Pavir, "Evaluation of the Shear Strength of Flanged Cruciform Steel Columns in the Panel Zone of Moment-Resisting Frames," *Structures*, vol. 73, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] Behnam Behzadi-Sofiani, Leroy Gardner, and M. Ahmer Wadee, "Behaviour, Finite Element Modelling and Design of Cruciform Section Steel Columns," *Thin-Walled Structures*, vol. 182, pp. 1-25, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] P. Arun Kumar, and B. Anupriya, "Performance Assessment of Cruciform Steel Column: FEM Simulation," *Materials Today: Proceedings*, vol. 64, pp. 1043-1047, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [16] Gang Shi et al., "Experimental Study on Cruciform Welded Connections with Thick Steel Plates in Moment-Resisting Beam-to-Column Joints," *Engineering Structures*, vol. 331, pp. 1-36, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] Ruikai Dai et al., "Behaviour, Finite Element Modelling and Design of Flanged Cruciform Section Steel Columns," *Thin-Walled Structures*, vol. 204, pp. 1-20, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [18] Nicholas Harris, and Girum Urgessa, "Strength of Flanged and Plain Cruciform Members," *Advance in Civil Engineering*, vol. 2018, pp. 1-7, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] Mohammad Motallebi Nasrabadi, Shahabeddin Torabian, and Seyed Rasoul Mirghaderi, "Panel Zone Modelling of Flanged Cruciform Columns: An analytical and Numerical Approach," *Engineering Structures*, vol. 49, pp. 491-507, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [20] Abazar Asghari, and Aydin Pavir, "Evaluation of the Shear Strength of Flanged Cruciform Steel Columns in the Panel Zone of Moment-Resisting Frames," *Structures*, vol. 73, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [21] A.L. Zhzng et al., "Experimental Research on Steel Specially Shaped Columns with Cruciform Section under Cyclic Loading," *Journal of Building Structures*, vol. 31, no. 2, pp. 11-19, 2010. [[Google Scholar](#)]

- [22] Hamed Saffari, Sina Sarfarazi, and Ali Fakhraddini, "A Mathematical Steel Panel Zone Model for Flanged Cruciform Columns," *Steel and Composite Structures*, vol. 20, no. 4, pp. 851-67, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [23] "Specification for Structural Steel Buildings (ANSI/AISC 360-16) – 2016," American Institute of Steel Construction, pp. 1-680, 2016. [[Google Scholar](#)] [[Publisher Link](#)]