Efficiency Assessment of Cruciform Steel Columns: Balancing Axial Capacity and Weight

Militia Keintjem
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, 11480, Indonesia
militia.marchella@binus.ac.id

Riza Suwondo
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, 11480, Indonesia
riza.suwondo@binus.ac.id (corresponding author)

Made Suangga
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, 11480, Indonesia
suangga@binus.ac.id

Received: 1 January 2025 | Revised: 24 January 2025 | Accepted: 5 February 2025

DOI: https://doi.org/10.48084/etasr.10107

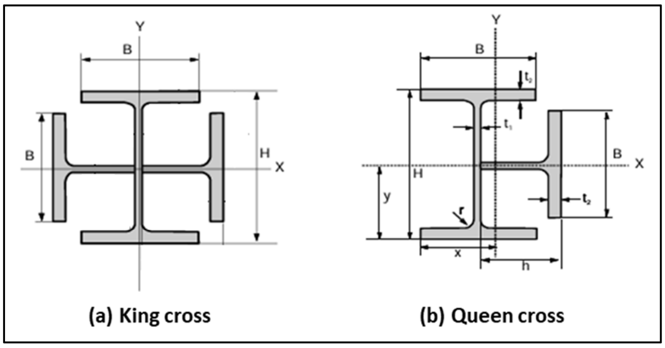
ABSTRACT

Cruciform steel columns, also known as king and queen cross sections, have gained attention in structural engineering for their ability to overcome the limitations of traditional I-sections and H-sections. These limitations include reduced stability due to slenderness effects and excessive material usage in tall columns. Designed to enhance axial load capacity while minimizing weight, cruciform sections offer a more efficient, cost-effective, and sustainable alternative for modern construction. This study assesses the efficiency of cruciform steel columns by comparing their design axial capacities to their unit weights. Having used AISC 360-16 provisions, single supported columns with heights of 2 m, 3 m, 4 m, and 5 m were analyzed. The results showed that all sections perform similarly for short columns (2 m), with efficiency differences of less than 8% due to the minimal impact of slenderness. However, at 3 m, the I-section is 20% less efficient than the H-section, and 30% less efficient than cruciform sections. For taller columns (4 m and 5 m), cruciform sections outperform conventional sections, with the king cross-section proving to be 30% more efficient than the H-section and superior to the queen cross-section. These findings highlight the structural and material advantages of cruciform sections, particularly in applications requiring tall columns with significant slenderness effects. By reducing material usage while maintaining high load-bearing capacity, cruciform sections enhance sustainability by lowering both carbon and construction costs. This study provides valuable insights for optimizing steel column designs to achieve more sustainable and cost-effective construction.

Keywords- cruciform steel section; king cross-section; queen cross-section; axial design efficiency; structural optimization

I. INTRODUCTION

Steel is a fundamental material used in modern construction and is valued for its strength, versatility, and efficiency. Advancements in steel section design have enabled the construction of increasingly complex and efficient structures, such as bridges, buildings, and towers, which play a pivotal role in contemporary economies [1-4]. These innovations are driven by the need for lightweight and structurally efficient solutions that optimize material usage and fabrication processes. The offsite manufacturing of steel components further enhances precision and reduces construction time, making steel an indispensable resource in the construction industry [5-7]. Among the various steel section profiles, the I-section is one of the most widely utilized owing to its high strength-to-weight ratio and ease of fabrication. However, conventional compression members, such as I-sections, are typically limited due to the flexural (Euler) buckling along their weak bending axes, which can lead to premature failure under axial loads, particularly in slender columns. Figure 1 illustrates the development of cruciform sections, commonly referred to as king and queen cross-sections to mitigate these limitations. These sections offer enhanced resistance to combined compression and bending owing to their symmetrical cross-sectional geometry, which redistributes the stresses more uniformly. Unlike conventional I-sections, in which failure is predominantly influenced by flexural instability, cruciform sections are governed by torsional buckling. This behavior provides improved stability in applications requiring slender members or where load eccentricities are common, making them particularly suitable for high-rise buildings, bridges, and seismic-resistant designs, where torsional effects constitute critical considerations [8-13]. Cruciform steel columns offer enhanced stiffness, higher axial load-carrying capacity, and reduced weight compared with the conventional columns [14]. Experimental studies have highlighted their excellent performance in terms of bearing capacity, ductility, and energy dissipation, provided that key design parameters, such as the flange width-to-thickness ratio, web depth-to-thickness ratio, and axial compression ratio, are appropriately configured [15, 16].



(a) King cross (b) Queen cross

Fig. 1. Cruciform section.

The failure of cruciform columns is typically associated with local buckling instability and is often accompanied by sufficient plastic deformation [15]. Advanced finite element analysis techniques using ABAQUS software have been instrumental in examining the buckling, post-buckling behavior, and overall strength of cruciform columns [17]. Additionally, comparative studies indicate that standard cruciform sections generally outperform the modified versions in terms of load-bearing capacity. These findings suggest that cruciform steel columns are well-suited for use in seismic regions, where their ductility and energy dissipation properties are particularly beneficial. Their versatility also makes them valuable for applications in high-rise buildings and bridges, where structural efficiency is a critical consideration [16]. Recent studies [18, 19] have demonstrated that the load-carrying capacity is influenced not only by the global slenderness of the column, but also by the ratio of the elastic torsional–flexural buckling load to the elastic minor-axis flexural buckling load. These insights indicate that the existing design provisions, which rely solely on slenderness as the basis for resistance reduction factors, may be inadequate for cross-section columns prone to torsional buckling [20].

Building on the advantages of cruciform steel columns, researchers have also explored the geometric and material optimization of steel structures to further enhance efficiency and sustainability [21-25]. These studies focused on the member sizing, shape, and configuration factors to achieve optimal structural performance. Additionally, optimization efforts have been extended to consider load distribution, connection design, and material selection, to maximize structural capacity while minimizing material usage and environmental impact. Although cruciform steel columns, including the king cross and queen cross sections, have been extensively studied for their mechanical behavior, failure modes, and theoretical performance, few studies have evaluated their advantages in practical design scenarios. Specifically, there is a lack of comparative assessments tied to critical engineering parameters, such as axial capacity under realistic load combinations, structural weight in material-sensitive designs, and cost efficiency in large-scale applications. These practical considerations are essential for industries focusing on lightweight construction, such as aerospace, transportation infrastructure, and high-rise buildings in seismic regions, where material efficiency and ductility play pivotal roles in structural safety and sustainability. The present study seeks to bridge these gaps by assessing the design axial capacity of cruciform steel columns, specifically the king and queen cross-sections, and comparing their performance to conventional I-sections. Additionally, a weight-based assessment was incorporated to quantify the material efficiency of the cruciform sections. By examining these columns under realistic load combinations and design conditions, this study sought to provide insights into their potential applications in weight-sensitive, cost-efficient, and seismic-resistant structural designs.

II. MATERIALS AND METHODS

The current study examined the structural performance of cruciform steel columns by evaluating their design axial capacities under various conditions. A comparative analysis was performed to assess the effectiveness of the king cross and queen cross-sections against conventional I-sections and H-sections. The columns were modeled as simply supported, as displayed in Figure 2, with varying clear heights to account for the effects of slenderness and stability. This configuration represents an idealized condition commonly used in structural analysis to establish baseline performance, as it minimizes the external restraints and focuses on the intrinsic behavior of the column under axial loading. To investigate the impact of slenderness on stability, the study analyzed columns with clear heights of 2, 3, 4, and 5 m. These specific heights were chosen to represent a range of practical scenarios encompassing short, medium, and long columns typically found in common building structural applications. The employed steel material was JIS G 3101 SS400 with a yield strength (F_y) of 245 MPa, chosen for its widespread availability in Indonesia. This ensures that the study reflects practical construction practices while addressing cost efficiency and ease of procurement. Although JIS G 3101 SS400 was used, the findings are not limited to this material and can be applied to other commonly utilized structural steel to adjust material properties and certify this study's relevance beyond regional constraints.

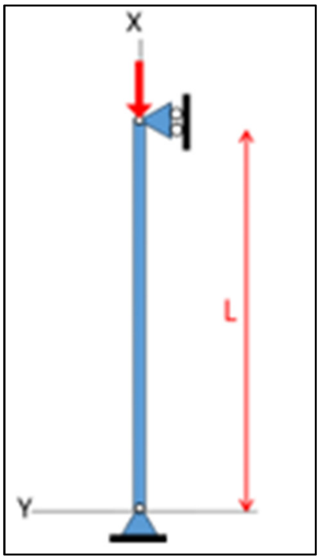


Fig. 2. Simply supported column.

The steel profiles used in this study are presented in Table I. These profiles were selected to reflect common structural elements in the Indonesian construction industry. Their geometric properties were carefully considered to ensure a representative analysis of the cruciform column configurations. It is noted that the H-sections have wider and more equal flanges, whereas the I-sections have narrower flanges and a taller web. Only compact elements were included in the analysis, which was determined based on the compact criteria specified in:

$$\frac{b_f}{2t_f} = 0.56\sqrt{\frac{E}{F_y}} \text{ and } \frac{h}{t_w} = 1.49\sqrt{\frac{E}{F_y}} \quad (1)$$

where E represents the modulus of elasticity, b_f is the flange width, t_f is the flange thickness, h is the clear distance between flanges less than the fillet or corner radius at each flange, and t_w is the web thickness.

The analysis and design of the columns adhere to the AISC 360-16 design code [26], a widely recognized standard for steel structure design. The design axial capacity (ϕP_n) was determined using the critical stress (F_{cr}) and gross cross-sectional area (A_g), given by:

$$\phi P_n = 0.9F_{cr}A_g \quad (2)$$

The critical stress (F_{cr}) depends on the slenderness ratio (KL/r) of the column, which captures the relationship between the effective length (KL) and the radius of gyration (r):

$$F_{cr} = \left(0.658^{\frac{F_y}{F_e}}\right)F_y \text{ when } \frac{KL}{r} \leq 4.71\sqrt{\frac{E}{F_y}} \quad (3)$$

$$F_{cr} = 0.887F_e \text{ when } \frac{KL}{r} > 4.71\sqrt{\frac{E}{F_y}} \quad (4)$$

where F_e denotes the elastic buckling stress, which is determined by:

$$F_e = \frac{\pi^2 E}{(KL/r)^2} \quad (5)$$

where E represents the modulus of elasticity of steel (200.000 MPa).

These equations account for the buckling behavior of the column, which varies based on its geometry, material properties, and support conditions. The present study provides a new perspective by including weight-based comparisons to evaluate the structural efficiency of cruciform steel columns. Unlike previous studies that focused mainly on axial capacity or mechanical behavior, this study assessed the ratio of axial capacity to column weight, thus offering a clearer insight into the balance between strength and material usage, which is crucial for cost- and weight-efficient design.

TABLE I. STEEL PROFILE USED IN THIS STUDY

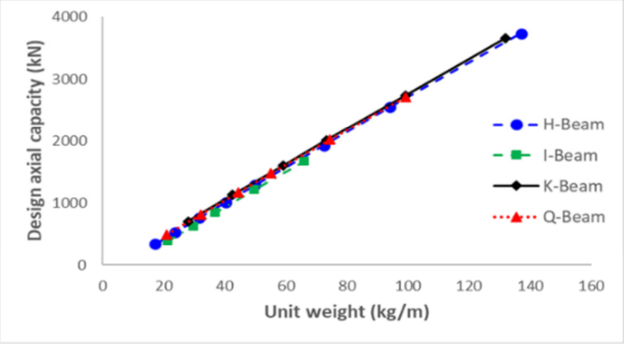
Type	**Profile**	**H (mm)**	**B (mm)**	**A_g (mm^2)**	**r_x (mm)**	**r_y (mm)**
H-Beam	H-100	100	100	2190	41.8	24.7
	H-125	125	125	3031	52.9	31.1
	H-150	150	150	4014	63.9	37.5
	H-175	175	175	5121	75.0	43.8
	H-200	200	200	6353	86.2	50.2
	H-250	250	250	9218	108.0	62.9
	H-300	300	300	11980	131.0	75.1
	H-350	350	350	17390	152.0	88.4
I-Beam	I-200	200	100	2716	82	22.2
	I-250	250	125	3766	104	27.9
	I-300	300	150	4678	124	32.9
	I-350	350	175	6314	147	39.5
	I-400	400	200	8410	168	45.4
King cross	K-150	150	75	3570	44.8	46.4
	K-200	200	100	5432	60.3	62.1
	K-250	250	125	7532	75.9	77.5
	K-300	300	150	9356	90.8	92.9
	K-350	350	175	12628	107.5	109.5
	K-400	400	200	16824	123	125.5
Queen cross	Q-150	150	75	2678	50.8	34
	Q-200	200	100	4074	68.4	45.6
	Q-250	250	125	5649	68.2	57.1
	Q-300	300	150	7017	103.1	68.2
	Q-350	350	175	9471	122.0	80.2
	Q-400	400	200	12618	139.5	91.9

III. RESULTS AND DISCUSSION

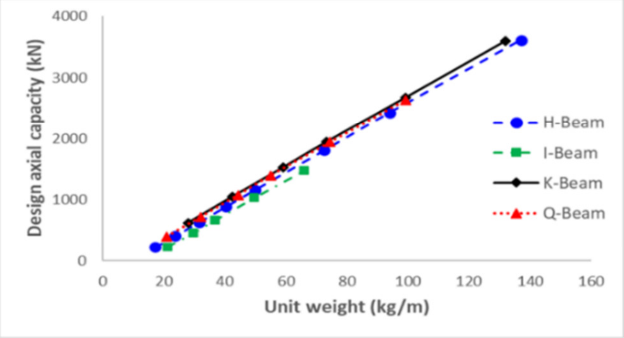
This section provides a detailed evaluation of the structural efficiency of cruciform steel columns (king and queen cross-sections) compared to standard I-sections and H-sections. The efficiency of each column type was assessed by analyzing the ratio of axial design capacity to self-weight, which reflects the balance between strength and material usage. The analysis considered columns with clear heights ranging from 2 m to 5 m to examine the impact of slenderness on performance. The results highlight the relationship between axial design capacity and unit weight across different column heights, as portrayed in Figure 3. For shorter columns (2 m), the axial capacities of the I-section, H-section, king cross-section, and queen cross-section vary minimally, with efficiency differences of less than 8%. At this height, the slenderness effects are negligible, so axial performance is primarily determined by the gross sectional area. Failure occurs due to material yielding rather than instability. As a result, the choice of section type has little impact on efficiency, as shown by the nearly identical capacity-to-weight ratios across all sections.

As the column height increased to 3 m, differences in efficiency emerged. The axial capacity-to-weight ratio of the I-section was 20% lower than that of the H-section and 30% lower than that of the cruciform section. This reduction highlights the higher susceptibility of the I-section to instability with an increasing slenderness. In contrast, the H-section and cruciform sections maintained consistent efficiency. This can be attributed to their geometric configurations, which provide better lateral stability and load distribution. The symmetric geometry of cruciform sections allows for a more uniform stress distribution, improving their ability to resist axial loads, even as the slenderness effects become more pronounced. The advantages of cruciform sections are more evident for columns with heights of 4 m. In this case, the failure primarily occurred due to elastic bulking because of the high value of the slenderness ratio. King and queen cross-sections outperform the I-section and H-section in terms of efficiency. The efficiency of the King Cross section surpasses that of the H-section by 30%, whereas the Queen Cross section is 20% more efficient than the H-section. The enhanced performance of cruciform sections can be linked to their optimized geometry, which ensures effective material utilization and improved stability under axial loads. This result highlights the potential of cruciform designs for applications that require taller columns, where the balance between strength and weight is critical.

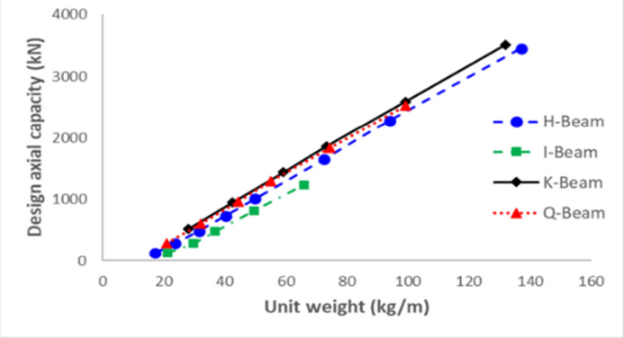
This trend continued when the column height reached 5 m, with the efficiency of the cruciform sections becoming increasingly evident. Notably, the king cross-section exhibited superior efficiency compared to the queen cross-section, attributed to its optimized geometry. The king cross-section benefits from a more effective flange-web interaction, which enhances its axial load-bearing capacity and stability. The broader flanges and symmetrical configuration distribute stress more uniformly, reducing localized stress concentrations and improving resistance to lateral-torsional buckling. Additionally, the king cross-section exhibited higher torsional rigidity than the queen cross-section. This increased rigidity mitigated torsional deformation under eccentric or combined loading, further contributing to its enhanced efficiency. In contrast, the queen cross-section, which is still effective, has slightly less optimized geometric proportions, resulting in marginally lower axial resistance and stability. This performance gap stresses the importance of geometric optimization in cruciform designs, particularly in balancing the flange and web dimensions to achieve superior structural efficiency. For conventional column sections, these findings align with those of previous research [14], where it was concluded that flanged cruciform columns support greater axial loads while simultaneously reducing the total weight and expense of the structure. The optimized geometry of cruciform sections, particularly the king cross-section, increases the load-bearing capacity while improving material efficiency, making it a cost-effective alternative to traditional I-sections and H-sections. This synergy between load efficiency and reduced material usage underscores the practical advantages of cruciform sections in modern construction applications, particularly in weight-sensitive and cost-efficient designs.



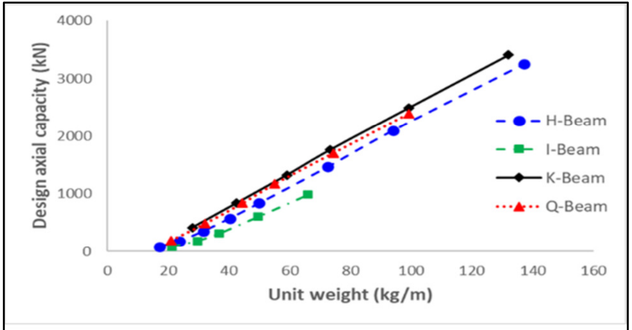
(a) Column height 2 m



(b) Column height 3 m



(c) Column height 4 m



(d) Column height 5 m

Fig. 3. The axial design capacity and the unit weight of the steel sections.

The findings indicate that cruciform sections, especially the king cross-section, are well-suited for tall and very tall columns, where material efficiency and stability are crucial. Their superior performance compared to I-sections and H-sections, renders them an excellent choice for high-rise buildings, industrial structures, and other applications that prioritize minimizing weight while maximizing load capacity. From a sustainability perspective, cruciform sections optimize material usage by providing higher axial capacity with less steel. This reduction in material consumption directly lowers the embodied carbon from steel production, a significant contributor to greenhouse gas emissions. Additionally, their lighter weight reduces transportation and handling energy, improving the overall construction efficiency and environmental impact. For shorter columns, where efficiency differences between section types are minimal, cost and ease of fabrication may play a more significant role in section selection. Overall, these findings offer a practical approach to using cruciform sections to enhance structural efficiency while supporting sustainability objectives.

IV. CONCLUSIONS

This study assessed the efficiency of cruciform steel columns (king and queen cross-sections) compared to standard I- and H-sections, focusing on the relationship between axial design capacity and column weight at different heights. According to the findings, cruciform sections are efficient structural solutions, particularly for applications requiring material optimization and enhanced stability in taller columns. The results indicate that for short columns (2 m), all steel sections exhibit similar performance because the impact of slenderness is minimal. However, as column height increases, the advantages of cruciform sections become more apparent. For medium-height columns (3 m), cruciform sections maintain their efficiency compared to H-sections, while I-sections show reduced performance. For taller columns (4 m and 5 m), the king cross-section outperforms both the queen cross-section and standard sections due to its optimized geometry, which enhances load-bearing capacity and resistance to buckling. These findings emphasize the importance of geometric optimization in improving material efficiency and stability, especially in slender column designs.

However, some limitations should be considered when interpreting these results. The study focuses exclusively on support columns, which may not fully represent real-world boundary conditions. Additionally, the findings rely on computational analysis without experimental validation, highlighting the need for future experimental studies to confirm these results. Despite these limitations, this study demonstrates the practical benefits of cruciform steel columns for high-rise and long-span structures, particularly in weight- and cost-sensitive designs. Future research could explore the dynamic behavior, economic impact, and performance of cruciform sections under different boundary conditions and material properties to better understand their applications in structural engineering.

ACKNOWLEDGMENT

The authors express their sincere gratitude to the Karbonara Research Institute for the invaluable support and resources provided throughout this research. Special thanks to the Civil Engineering Department of BINUS University for their continuous guidance, encouragement, and access to necessary facilities and equipment.

DATA AVAILABILITY

The utilized data can be found at: https://zenodo.org/records/14542225.

REFERENCES

[1] E. Ching and J. V. Carstensen, "Truss topology optimization of timber–steel structures for reduced embodied carbon design," *Engineering Structures*, vol. 252, Feb. 2022, Art. no. 113540, https://doi.org/10.1016/j.engstruct.2021.113540.

[2] A. A. Abbood and N. Oukaili, "Behavior of Axially Loaded Concrete Columns Reinforced with Steel Tubes Infilled with Cementitious Grouting Material," *Civil Engineering Journal*, vol. 10, no. 2, pp. 599–613, Feb. 2024, https://doi.org/10.28991/CEJ-2024-010-02-017.

[3] A. A. Abbood and N. Oukaili, "A study on interactional behaviors of concrete-encased cementitious grouting mortar-filled steel tube columns under combined loading," *Journal of Constructional Steel Research*, vol. 220, Sep. 2024, Art. no. 108810, https://doi.org/10.1016/j.jcsr.2024.108810.

[4] Y. Sun, Y. Liang, and O. Zhao, "Testing, numerical modelling and design of S690 high strength steel welded I-section stub columns," *Journal of Constructional Steel Research*, vol. 159, pp. 521–533, Aug. 2019, https://doi.org/10.1016/j.jcsr.2019.05.014.

[5] P. Foraboschi, "Predictive Formulation for the Ultimate Combinations of Axial Force and Bending Moment Attainable by Steel Members," *International Journal of Steel Structures*, vol. 20, no. 2, pp. 705–724, Apr. 2020, https://doi.org/10.1007/s13296-020-00316-6.

[6] A. Toktarova, I. Karlsson, J. Rootzén, L. Göransson, M. Odenberger, and F. Johnsson, "Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study," *Energies*, vol. 13, no. 15, Jan. 2020, Art. no. 3840, https://doi.org/10.3390/en13153840.

[7] *UK structural steelwork: 2050 decarbonisation roadmap*. UK: British Constructional Steelwork Association, 2021.

[8] E. A. Smith, "Buckling of Four Equal-Leg Angle Cruciform Columns," *Journal of Structural Engineering*, vol. 109, no. 2, pp. 439–450, Feb. 1983, https://doi.org/10.1061/(ASCE)0733-9445(1983)109:2(439).

[9] M. Motallebi Nasrabadi, S. Torabian, and S. R. Mirghaderi, "Panel zone modelling of Flanged Cruciform Columns: An analytical and numerical approach," *Engineering Structures*, vol. 49, pp. 491–507, Apr. 2013, https://doi.org/10.1016/j.engstruct.2012.11.029.

[10] N. Harris and G. Urgessa, "Strength of Flanged and Plain Cruciform Members," *Advances in Civil Engineering*, vol. 2018, no. 1, Feb. 2018, Art. no. 8417208, https://doi.org/10.1155/2018/8417208.

[11] R. Dai, B. Behzadi-Sofiani, S. Buhagiar, M. A. Wadee, and L. Gardner, "Behaviour, finite element modelling and design of flanged cruciform section steel columns," *Thin-Walled Structures*, vol. 204, Nov. 2024, Art. no. 112268, https://doi.org/10.1016/j.tws.2024.112268.

[12] H. Ran, Z. Tang, Y. Wang, X. Chen, Z. Chen, and Y. Sun, "Testing, modelling and design of laser-welded stainless steel slender I-section beam-column members under combined compression and major-axis bending," *Thin-Walled Structures*, vol. 203, Oct. 2024, Art. no. 112238, https://doi.org/10.1016/j.tws.2024.112238.

[13] H. Ran, Z. Chen, Y. Ma, E. OBrien, and Y. Sun, "Experimental and numerical study of laser-welded stainless steel slender I-section beam-columns," *Engineering Structures*, vol. 286, Jul. 2023, Art. no. 116128, https://doi.org/10.1016/j.engstruct.2023.116128.

[14] P. A. Kumar and B. Anupriya, "Performance assessment of Cruciform steel column: FEM simulation," *Materials Today: Proceedings*, vol. 64, pp. 1043–1047, Jan. 2022, https://doi.org/10.1016/j.matpr.2022.05.099.

[15] L. Huijun, "Experimental research on steel specially shaped columns with cruciform section under cyclic loading," *Journal of Building Structures*, 2010, [Online]. Available: https://www.semanticscholar.org/paper/Experimental-research-on-steel-specially-shaped-Huijun/83e03dc3191c723b880da35d2d2abd593d760801.

[16] D. M. U. Rani, P. S. Kiran, and J. M. Jenifer, "Experimental Study on Behaviour of Cruciform and Modified Cruciform Steel Section," *International Journal of Civil Engineering*, vol. 5, no. 7, pp. 1–4, Jan. 2019, https://doi.org/10.14445/23488352/IJCE-V5I7P101.

[17] D. Camotim and P. B. Dimis, "Buckling, Post-Buckling and Strength of Cruciform Columns," *American Institute of Steel Construction*, May 2011.

[18] B. Behzadi-Sofiani, L. Gardner, M. A. Wadee, P. B. Dinis, and D. Camotim, "Behaviour and design of fixed-ended steel equal-leg angle section columns," *Journal of Constructional Steel Research*, vol. 182, Jul. 2021, Art. no. 106649, https://doi.org/10.1016/j.jcsr.2021.106649.

[19] B. Behzadi-Sofiani, L. Gardner, and M. A. Wadee, "Stability and design of fixed-ended stainless steel equal-leg angle section compression members," *Engineering Structures*, vol. 249, Dec. 2021, Art. no. 113281, https://doi.org/10.1016/j.engstruct.2021.113281.

[20] B. Behzadi-Sofiani, L. Gardner, and M. A. Wadee, "Behaviour, finite element modelling and design of cruciform section steel columns," *Thin-Walled Structures*, vol. 182, Jan. 2023, Art. no. 110124, https://doi.org/10.1016/j.tws.2022.110124.

[21] R. McKinstray, J. B. P. Lim, T. T. Tanyimboh, D. T. Phan, and W. Sha, "Optimal design of long-span steel portal frames using fabricated beams," *Journal of Constructional Steel Research*, vol. 104, pp. 104–114, Jan. 2015, https://doi.org/10.1016/j.jcsr.2014.10.010.

[22] A. Kaveh, V. R. Mahdavi, and M. Kamalinejad, "Optimal design of pitched roof frames with tapered members using ECBO algorithm," *Smart Structures and Systems*, vol. 19, no. 6, pp. 643–652, 2017, https://doi.org/10.12989/sss.2017.19.6.643.

[23] A. Kaveh and M. H. Ghafari, "Geometry and Sizing Optimization of Steel Pitched Roof Frames with Tapered Members Using Nine Metaheuristics," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, vol. 43, no. 1, pp. 1–8, Mar. 2019, https://doi.org/10.1007/s40996-018-0132-1.

[24] A. Kaveh, M. Z. Kabir, and M. Bohlool, "Optimal Design of Multi-Span Pitched Roof Frames with Tapered Members," *Periodica Polytechnica Civil Engineering*, vol. 63, no. 1, pp. 77–86, 2019, https://doi.org/10.3311/PPci.13107.

[25] N. W. Bishay-Girges, "Improved Steel Beam-Column Connections in Industrial Structures," *Engineering, Technology & Applied Science Research*, vol. 10, no. 1, pp. 5126–5131, Feb. 2020, https://doi.org/10.48084/etasr.3248.

[26] *Specification for Structural Steel Buildings*. USA: American Institute of Steel Construction, 2016.