Journal of Civil Engineering Researchers

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Numerical Investigation of the Impact of Steel Profiles and Embedded Stiffeners in Circular and Square Concrete-Filled Steel Columns under Axial and Lateral Loading

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ABSTRACT

Concrete-filled steel tube (CFST) columns are widely used in high-rise buildings around the world due to their numerous structural advantages, including high load-bearing capacity, favorable inherent ductility, substantial energy absorption capabilities, and the elimination of the need for formwork. However, in Iran, these structures have not yet been widely implemented in practice, highlighting the need for further research in this area. Additionally, challenges such as buckling and local delamination between the concrete and steel under loading remain key issues for these columns. Research indicates that circular CFST columns provide the strongest confinement for concrete, whereas square CFST columns exhibit higher local buckling under loading. Furthermore, embedded steel profiles significantly enhance the overall performance of these columns. In this study, a finite element model of CFST columns with embedded cruciform profiles is validated using Abaqus software and subsequently analyzed parametrically. The objective of this study is to evaluate the seismic and axial performance of the "primary column cross-sections" and the "embedded steel profiles" with equivalent areas. The findings of this research demonstrate that filling the internal space of steel columns with concrete substantially improves axial and lateral performance, although it slightly reduces lateral ductility. Additionally, stress analysis reveals that the type of embedded steel profile directly influences the enhancement of load-bearing capacity and lateral performance. Results also show that square CFST columns outperform their circular counterparts in terms of axial strength and stiffness, though they exhibit lower axial ductility.

ARTICLE INFO

Received: December 26, 2024
Accepted: February 23, 2025

Keywords:
Numerical development
Concrete-filled steel columns
Axial performance
Lateral performance
Steel profiles embedded in concrete

DOI: 10.61186/JCER.7.1.22
DOR: 20.1001.1.22516530.1399.11.4.1.1

1. Introduction

Concrete-filled steel tube (CFST) columns represent a novel type of composite structural element, first introduced and studied by Tomi et al. in 1985. Subsequently, Xiao et al. in 1986 discussed the design methods for reinforced concrete columns confined with steel, thereby advancing the engineering applications of such structures. However, certain limitations in the application of CFST structures, such as the complexity of beam-to-column connections,

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local buckling of the steel tube, and poor fire resistance, have constrained their use in contemporary buildings [1].

In the past few decades, CFST structures have been widely adopted in modern buildings and bridges, even in seismically active regions [2,3]. These composite structures ideally combine the advantages of both steel and concrete columns—such as rapid construction and high strength. However, as span lengths and building heights increase, the cross-sectional area of these columns must often be significantly enlarged to provide the necessary load-bearing capacity. This has underscored the need for research aimed at improving the load-bearing capacity while reducing the cross-sectional dimensions of CFST columns [4]. As illustrated in Figure 1, steel columns can experience local buckling, which manifests as either inward or outward deformation. Shear failure is also evident in plain concrete columns, whereas outward buckling is primarily observed in CFST columns, with the internal concrete undergoing more ductile failure. Research has shown that the ultimate strength of CFST columns exceeds the combined strength of individual steel and reinforced concrete columns. Moreover, the ductility of CFST columns is significantly higher than that of steel or concrete columns alone [4].

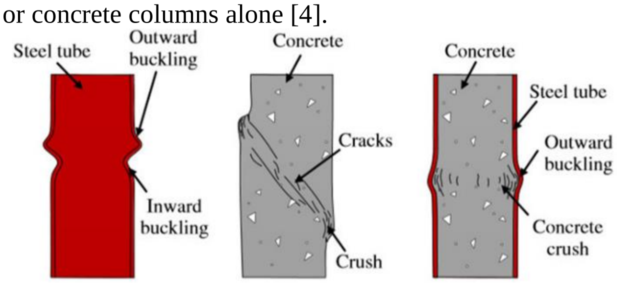

Figure 1: Schematic representation of failure modes for CFST columns, steel columns, and plain concrete columns [4]

Beyond conventional CFST columns, other variants have emerged, including CFST columns with embedded steel profiles and stiffeners. These have gained prominence in recent years due to their substantial enhancements in load-bearing and seismic performance. For example, Qing-Xiang Wang et al. [5] conducted experimental studies on the strength and ductility of 16 CFST columns with embedded cruciform steel profiles. They demonstrated that the embedded steel profile effectively prevents rapid propagation of shear cracks in concrete. Their results further revealed that increasing the structural steel index and confinement index improves the strength and ductility of the composite column. They also found that as the aspect ratio (length-to-diameter) increases, the composite column's strength decreases.

Meichun Zhu et al. [6] conducted experimental studies on square CFST columns filled with high-strength self-compacting concrete and reinforced with cruciform steel profiles under axial loading. Xu Chang et al. [7] performed numerical studies on the lateral strength of CFST columns with embedded cruciform profiles under combined axial and lateral loading, showing that the steel profile helps to bear lateral loads and reduces tensile stress in the concrete.

Numerical studies by Jingming Cai et al. [8,9] examined the mechanical behavior of circular and square CFST columns with embedded cruciform profiles under uniaxial compression, considering parameters such as steel tube ratio, embedded steel ratio, concrete strength, and steel yield strength. Fa-Xing Ding et al. [10] experimentally investigated the behavior of six square CFST columns with embedded cruciform steel profiles under axial loading, demonstrating that concrete strength and steel ratios influence ultimate load-bearing capacity and ductility.

Wang JZ et al. [11] studied the axial behavior and strength of 22 high-strength short concrete columns confined by steel tubes with embedded profiles through both experimental and numerical approaches, identifying the embedded steel profile's shape as a critical parameter in determining load-bearing capacity. Aizhu Zhu et al. [12] examined 30 cold-rolled square CFST columns with welded stiffeners along their inner surfaces. Moreover, Mizan Ahmed et al. [13] performed nonlinear analyses on short square CFST columns with embedded profiles, accounting for local buckling phenomena. Based on the reviewed literature, the most prominent finding regarding the axial and lateral performance of circular and square CFST columns with embedded profiles is the significant influence of cruciform embedded profiles on axial performance. Accordingly, this study proposes various circular and square CFST columns with different embedded steel profiles to evaluate their axial and lateral behavior. The results from axial and lateral loading tests on these proposed columns aim to enhance understanding and application in structural engineering, leading to the development of high-performance profiles with reduced cross-sectional areas. For validation, the experimental results of Tao Zhang et al. [14] on CFST columns with cruciform profiles will be analyzed using the finite element software ABAQUS [15]. Additionally, this study numerically investigates the impact of varying primary column cross-sections (circular/square) and embedded profiles. Axial and lateral performance criteria—including strength, stiffness, ductility, and deformation—are also examined comprehensively.

2. Validation of the Simulation Model

In this section, numerical modeling of an experimental CFST column tested under axial compressive loading by Tao Zhang et al. [14] is conducted to validate the simulation process. The numerical analysis employs the Quasi-Static method, with nonlinear geometric configurations activated. All modeling steps, including part creation, assembly, and interactions, are accurately implemented in ABAQUS. In the loading module, the supports are modeled as fixed, and an incremental axial load is applied. For meshing, an optimal element size of 0.5 cm is utilized, ensuring precise meshing. Steel components are modeled with S4R shell elements, while concrete components use C3D8R solid elements with reduced integration to mitigate hourglass effects. Additionally, buckling modes are considered in the analysis. To evaluate the numerical model's performance, the axial displacement of the column's top section is considered as the displacement variable, while the reaction forces at the supports represent the load-bearing capacity. A load-displacement curve is extracted and compared with the experimental data from Tao Zhang et al. (Figure 2).

From Figure 2, a reasonably good agreement is observed between the finite element analysis (FEA) results and the experimental findings. The load-displacement curve from the ABAQUS model closely aligns with the experimental data, confirming the accuracy of the numerical modeling and the reliability of the simulation.

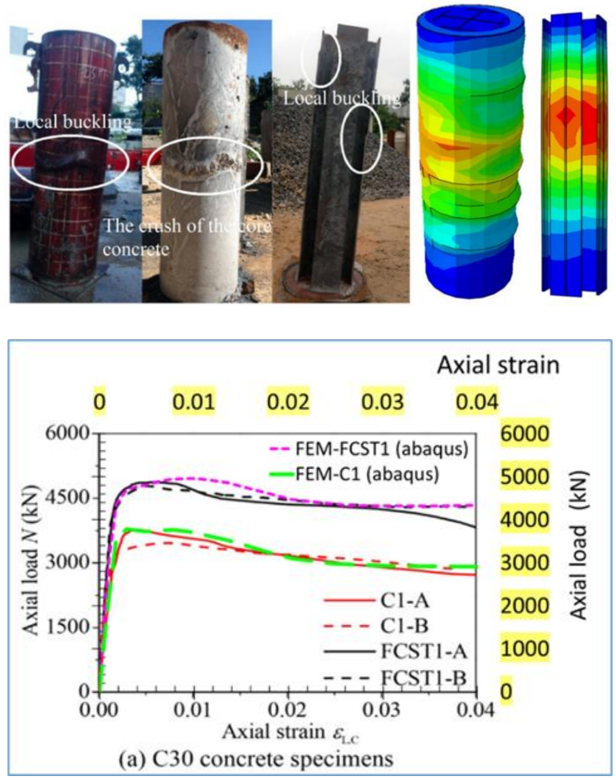

Figure 2: Comparison and validation between experimental load-displacement curve [14] and the numerical simulation results

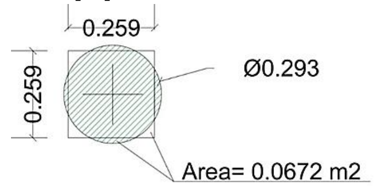

Figure 3: Equivalent dimensions of square and circular CFST columns with equal cross-sectional areas.

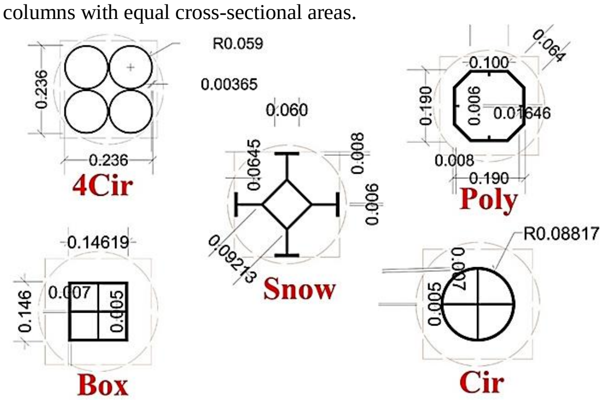

Figure 4: Proposed innovative profiles embedded in CFST columns (circular/square) with equivalent areas.

3. Analysis of Results

To extend the experimental work by Tao Zhang et al. [14], a parametric numerical analysis is conducted in this study. This includes examining the following scenarios:

a) Behavior without concrete: The seismic and axial performance of a circular CFST column with an embedded cruciform profile is studied without the presence of concrete.

b) Comparison of circular vs. square cross-sections: The study investigates how seismic and axial behavior changes when using a square CFST column with an equivalent cross-sectional area to the circular CFST column. Similar analysis is performed for cases without concrete.

c) Introduction of innovative profiles: Five new embedded profiles are proposed to replace the validated cruciform profile ("Plus") within circular and square CFST columns. These innovative profiles are designed to examine their impact on seismic and axial performance. Figures 3 and 4 illustrate the equivalent cross-sectional dimensions for circular and square columns, as well as the new embedded profiles.

From Figure 3, the cross-sectional area of the circular column is calculated as 0.0672 m², corresponding to a diameter of 0.293 m. For the square column, a side length of 0.259 m is determined to provide an equivalent area. These dimensions are used in numerical simulations.

Figure 4 shows the five new profiles, which include:

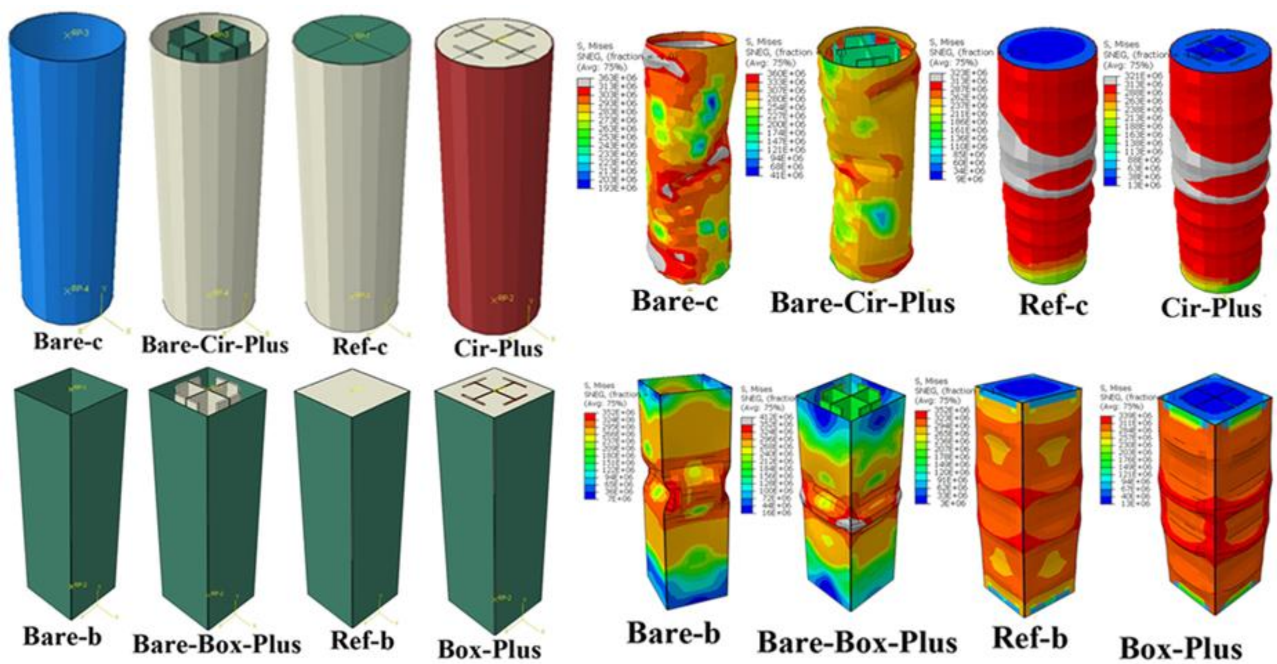

Figure 5: Modeling, Naming, and Axial Loading of Circular and Square CFST Columns (With and Without Concrete).

- 4Cir: Four circular segments.
- Poly: Polygonal profile.
- Snow: Snowflake-shaped profile.
- Box: Reinforced square profile.
- Cir: Reinforced circular profile.

These profiles are designed with areas equivalent to the validated cruciform profile ("Plus") and are analyzed for their influence on seismic and axial performance in CFST columns.

Classification of Profiles

The proposed profiles are categorized based on mass concentration:

- Centralized profiles: Profiles with mass concentrated at the center (e.g., Box and Cir).
- Peripheral profiles: Profiles with mass concentrated around the perimeter (e.g., Snow and 4Cir).
- Intermediate profiles: Profiles with mass distributed between the center and perimeter (e.g., Plus and Poly).

Further numerical simulations will explore the impact of these profiles on the behavior of circular and square CFST columns, aiming to identify high-performance designs with optimized cross-sectional areas.

3.1. The Effect of Concrete in Concrete-Filled Steel Tubes with Cross-Sectional Inserts

This section examines the axial and lateral behavior of circular concrete-filled steel tube (CFST) columns validated in the second part of this study when the concrete is removed. Similarly, the axial and lateral behavior of square steel tube columns without concrete is analyzed. Figure 5 illustrates the modeling and naming conventions for circular and square CFST columns, both with and without concrete. According to Figure 5, the "Bare" model represents hollow steel columns (without concrete), while the "Ref" model denotes reference steel columns (with concrete but without internal inserts). The second subscript "c" and "b" correspond to circular and square cross-sections, respectively. The "Cir-Plus" and "Box-Plus" models represent circular and square CFST columns with cross-shaped inserts, respectively.

Furthermore, Figure 5 shows the von Mises stress distribution and deformations under axial loading. The results indicate that stresses are primarily concentrated in the outer shell, and buckling deformations in the outer shell are evident in the hollow "Bare" models.

Under lateral loading, additional results are obtained. By aggregating these results into load-displacement curves and employing bilinear approximation using an equivalent energy approach, the axial and lateral performance of the models can be assessed. Figure 6 presents the load-displacement curves for the tested columns. Table 1 summarizes the axial and lateral performance metrics derived from analyzing the bilinearized load-displacement curves.

In Table 1:

- Δy and Vy indicate the displacement and load at the yield point, respectively.
- Δu represents the maximum effective displacement experienced by the columns.
- The maximum load sustained, denoted as P, serves as the resistance criterion.
- The initial stiffness, K, is obtained by dividing Vy by Δy, while ductility, μ, is calculated by dividing Δu by Δy.

The subscripts "ax" and "sh" in Table 1 represent axial and lateral performance, respectively. By comparing these performance metrics with the "Bare" circular and square models, the relative axial and lateral performance of CFST columns (with concrete) compared to hollow steel columns (without concrete) can be determined. These results are presented in Figure 7.

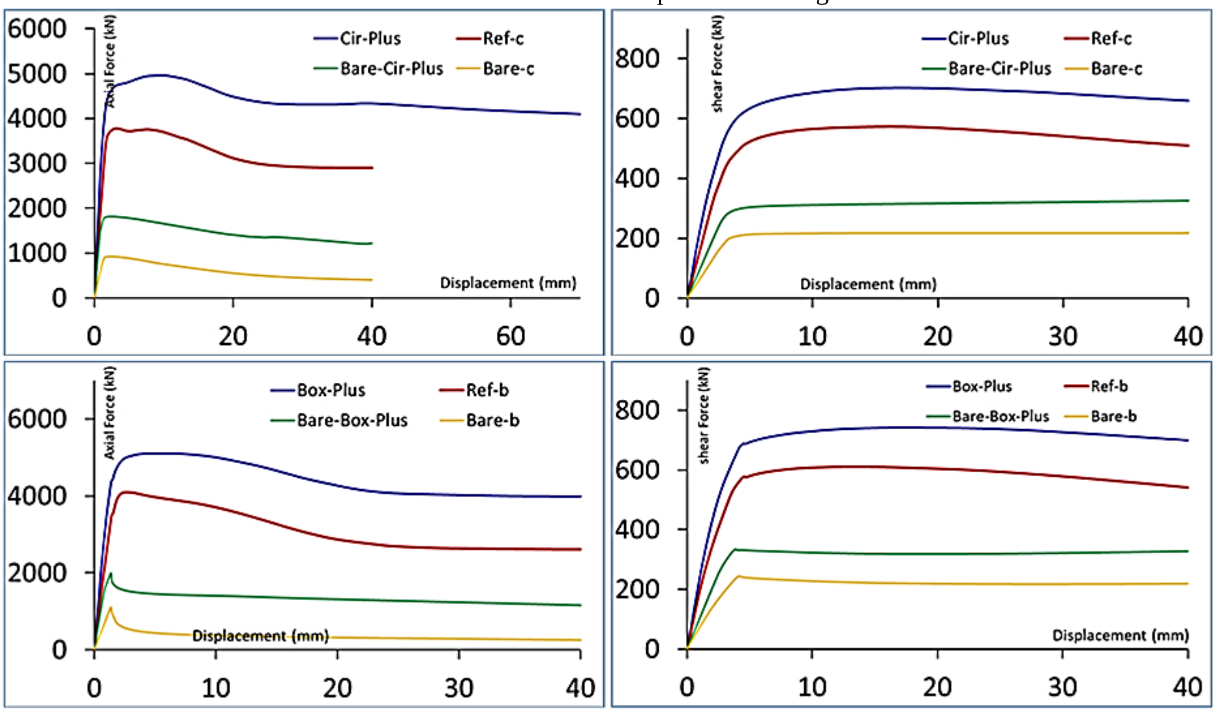

Figure 6: Load-Displacement Curves for Axial and Lateral Loading of Circular and Square CFST Columns (With and Without Concrete).

Table 1

Axial and Lateral Performance Metrics of Circular and Square CFST Columns (With and Without Concrete).

Spectrum	Δy (mm)	Vy (kN)	Δu (mm)	P_{ax} (kN)	K_{ax} (kN/mm)	μ_{ax}
Bare-c	1.22	829	12.94	929	680	10.6
Bare-Cir-Plus	0.94	1592	23.49	1811	1697	25.0
Ref-c	1.45	3245	40	3781	2246	27.7
Cir-Plus	1.45	4553	40	4961	3147	27.7

Spectrum	Δy (mm)	Vy (kN)	Δu (mm)	P_{sh} (kN)	K_{sh} (kN/mm)	μ_{sh}
Bare-c	3.39	216	40.00	217	64	11.8
Bare-Cir-Plus	3.30	315	40.00	325	96	12.1
Ref-c	3.47	547	40	572	158	11.5
Cir-Plus	3.42	679	40	702	199	11.7

Spectrum	Δy (mm)	Vy (kN)	Δu (mm)	P_{ax} (kN)	K_{ax} (kN/mm)	μ_{ax}
Bare-b	1.21	985	1.64	1106	817	1.4
Bare-Box-Plus	0.89	1625	3.49	1991	1833	3.9
Ref-b	1.43	3674	17	4093	2563	12.0
Box-Plus	1.26	4419	40	5102	3508	31.8

Spectrum	Δy (mm)	Vy (kN)	Δu (mm)	P_{sh} (kN)	K_{sh} (kN/mm)	μ_{sh}
Bare-b	3.21	222	40.00	241	69	12.5
Bare-Box-Plus	3.19	322	40.00	334	101	12.5
Ref-b	3.43	587	40	611	171	11.7
Box-Plus	3.46	723	40	741	209	11.6

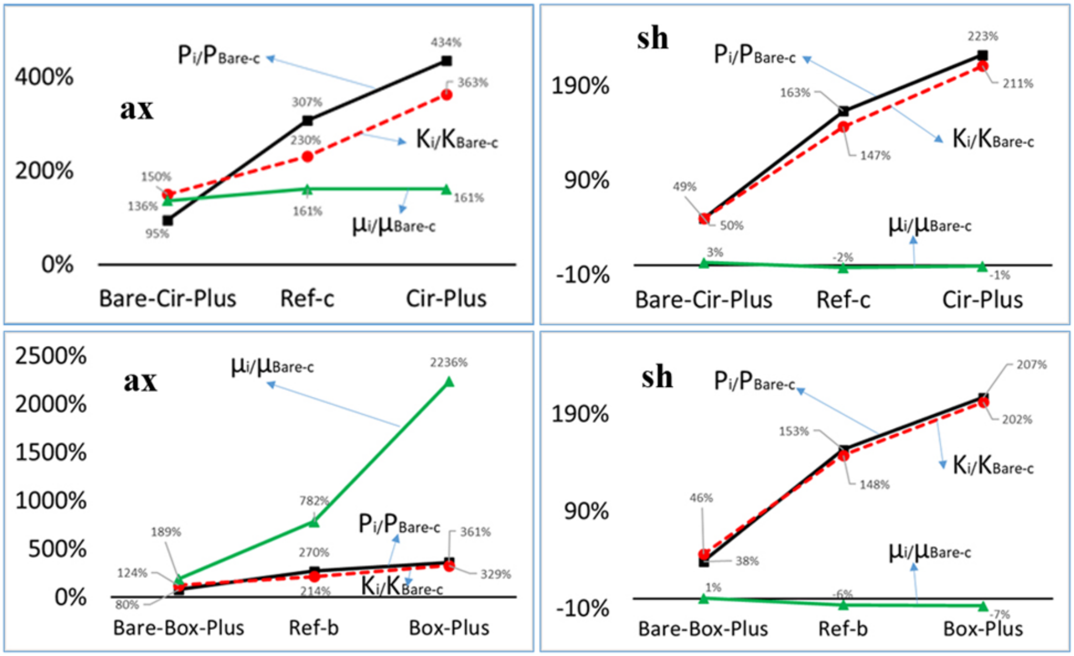

Figure 7: Relative Axial and Lateral Performance of Circular and Square CFST Columns Compared to Hollow Steel Columns.

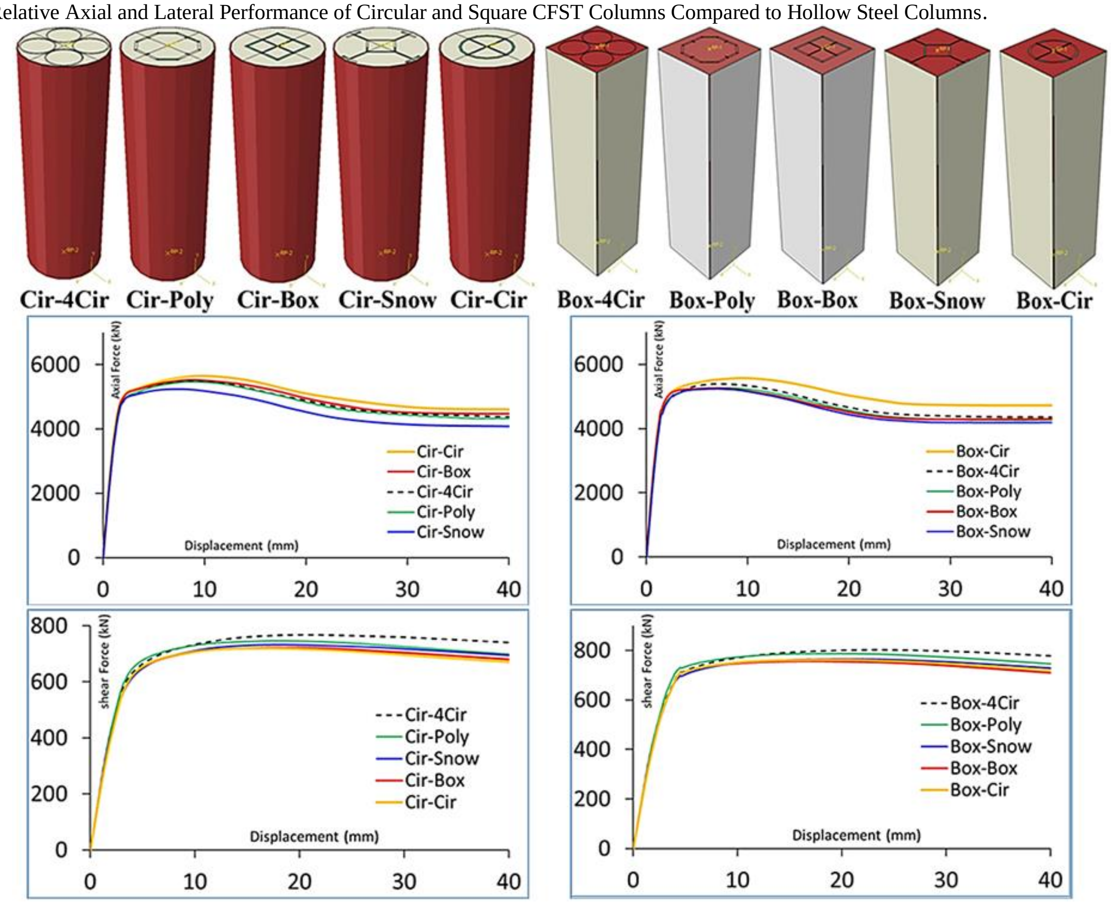

Figure 8: Modeling, naming, and axial and lateral load-displacement curves of circular and square concrete-filled steel columns with new internal sections.

Key findings from Figure 7 include the following:

- The axial resistance of the reference circular column filled with concrete ("Ref-c") is 307%

higher than the hollow circular column ("Bare-c"). Additionally, axial stiffness and ductility increase by 230% and 161%, respectively. The axial performance of the hollow circular column with a cross-shaped insert ("Bare-Cir-Plus") and the CFST column with the same insert ("Cir-Plus") shows improvement compared to the hollow column ("Bare-c").

- The lateral resistance of the reference circular column filled with concrete ("Ref-c") is 163% higher than the hollow circular column ("Bare-c"), with stiffness increasing by 147% and ductility decreasing slightly by 2%. For models with cross-shaped inserts, "Bare-Cir-Plus" and "Cir-Plus" exhibit enhanced lateral resistance and stiffness but reduced ductility compared to "Bare-c."
- The axial resistance of the reference square column filled with concrete ("Ref-b") is 270% higher than the hollow square column ("Bare-b"), with stiffness and ductility increasing by 214% and 782%, respectively. The axial performance of the hollow square column with a cross-shaped insert ("Bare-Box-Plus") and the CFST column with the same insert ("Box-Plus") also improves compared to "Bare-b."
- The lateral resistance of the reference square column filled with concrete ("Ref-b") is 153% higher than the hollow square column ("Bare-b"), with stiffness increasing by 148% and ductility decreasing slightly by 6%. The lateral performance of "Bare-Box-Plus" and "Box-Plus" shows increased resistance and stiffness but reduced ductility compared to "Bare-b."
- In the hollow circular column ("Bare-c"), the column collapses inward and slightly outward after loading. A similar behavior is observed in "Bare-Cir-Plus." However, when filled with concrete, stress and deformation are primarily concentrated in the outer shell, with outward buckling only.
- In the hollow square column ("Bare-b"), the column collapses inward and slightly outward at mid-height after loading. This behavior is also seen in "Bare-Box-Plus." When filled with concrete, stress and deformation are concentrated in the outer shell, with outward buckling only at mid-height.
- Stress and deformation patterns under lateral loading are generally similar across all tested models.
- In axial loading, hollow steel columns exhibit sudden drops in the load-displacement curves due to buckling and distortion. This behavior limits their effective axial performance, reducing ultimate load and ductility significantly.
- Concrete-filled columns, on the other hand, demonstrate significantly improved ductility due to the absence of severe buckling, particularly in axial loading. However, this improvement is less pronounced under lateral loading.

4. The Effect of Internal Sections on Circular and Square Concrete-Filled Steel Columns

This section investigates how axial and lateral performance changes when alternative internal sections (as depicted in Figure 4) are used in circular and square concrete-filled steel columns, replacing the cross-shaped section while maintaining the same cross-sectional area. Figure 8 illustrates the modeling of circular and square concrete-filled steel columns with new internal sections and their corresponding load-displacement curves for axial and lateral loading. Additionally, Table 2 presents the axial and lateral performance of these columns based on the bilinear analysis of the load-displacement curves.

4.1. Axial Performance of Circular and Square Concrete-Filled Steel Columns

By consolidating the axial performance data of circular and square concrete-filled steel columns, it is possible to compare these two shapes at different reinforcement levels. Figure 9 demonstrates the comparative axial performance of circular and square columns in terms of strength, stiffness, and ductility.

The following key findings are derived from Figure 9:

- Adding internal sections to circular or square concrete-filled steel columns enhances axial and lateral performance in terms of strength and stiffness. However, the impact on ductility is less definitive, as discussed below.
- Upon completion of axial loading tests, the numerical analysis reveals the axial performance of concrete-filled steel columns with various internal sections and stiffeners. Given the equal cross-sectional areas of the steel and concrete for both circular and square samples, these two shapes can be directly compared at each level of reinforcement.
- The square column exhibits higher axial strength than the circular column in both the bare and reference specimens. After reinforcement with internal steel sections, the circular column outperforms the square column in axial strength, except in the cross-shaped section ("Plus") where

Table 2
Axial and lateral performance of circular and square concrete-filled steel columns with new internal sections.

Spectrum	Δy (mm)	Vy (kN)	Δu (mm)	P_{ax} (kN)	K_{ax} (kN/mm)	μ_{ax}
Cir-4Cir	1.45	4878	40	5487	3366	27.6
Cir-Poly	1.42	4844	40	5465	3411	28.2
Cir-Box	1.39	4934	40	5528	3538	28.7
Cir-Snow	1.35	4586	40	5234	3398	29.6
Cir-Cir	1.43	5075	40	5646	3542	27.9
Box-4Cir	1.32	4755	40	5393	3595	30.2
Box-Poly	1.32	4659	40	5265	3542	30.4
Box-Box	1.24	4652	40	5262	3748	32.2
Box-Snow	1.28	4580	40	5236	3564	31.1
Box-Cir	1.38	5061	40	5573	3660	28.9

Spectrum	Δy (mm)	Vy (kN)	Δu (mm)	P_{sh} (kN)	K_{sh} (kN/mm)	μ_{sh}
Cir-4Cir	3.47	743	40	767	214	11.5
Cir-Poly	3.35	722	40	746	215	11.9
Cir-Box	3.55	702	40	723	198	11.3
Cir-Snow	3.44	710	40	733	207	11.6
Cir-Cir	3.47	697	40	721	201	11.5
Box-4Cir	3.54	782	40	803	221	11.3
Box-Poly	3.43	769	40	788	224	11.7
Box-Box	3.52	738	40	756	210	11.4
Box-Snow	3.46	747	40	765	216	11.6
Box-Cir	3.46	747	40	761	216	11.6

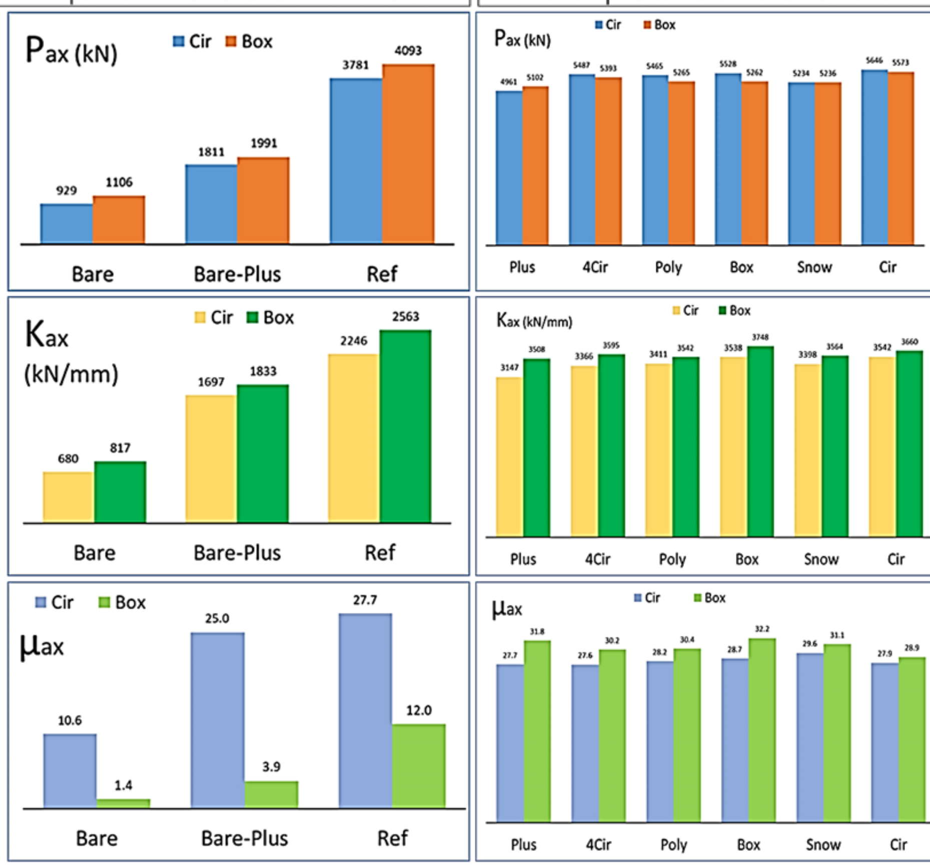

Figure 9: Comparative axial strength, stiffness, and ductility performance of circular and square columns in this study.

- the square column demonstrates superior axial strength.
- The square column shows higher axial stiffness than the circular column in both bare and reference specimens. Following reinforcement, the square concrete-filled steel column continues to exhibit greater axial stiffness compared to its circular counterpart.
- The square column has lower axial ductility compared to the circular column in both bare and reference specimens. After reinforcement, the circular column exhibits even lower axial ductility than the square column. In bare columns, the ductility difference is particularly pronounced due to the sudden axial strength drop caused by buckling in the square specimens.

- Under axial loading, bare square columns experience severe strength drops due to sudden buckling, which significantly reduces ductility. This phenomenon is mitigated in concrete-filled columns, where the increased ductility of circular and square columns becomes evident.
- Unlike axial performance, buckling does not have a pronounced effect on lateral loading, as abrupt instability is less likely in such scenarios. Thus, lateral performance trends differ from those observed under axial loading.

4.2. Lateral Performance of Circular and Square Concrete-Filled Steel Columns

By consolidating the data related to the lateral performance of circular and square concrete-filled steel columns, their lateral performance can be compared across various reinforcement levels. Figure 10 illustrates the comparison of lateral strength, stiffness, and ductility for circular and square columns investigated in this study.

From Figure 10, the following significant findings are derived:

- Square columns exhibit higher lateral strength than circular columns in both bare and reference specimens. After reinforcement with internal steel sections, square columns continue to show superior lateral strength compared to circular columns.
- Square columns demonstrate greater lateral stiffness than circular columns in both bare and reference specimens. This trend remains consistent after reinforcing the concrete-filled steel columns with internal sections.
- In bare and reference specimens, square columns display higher lateral ductility than circular columns. After reinforcement, circular columns generally achieve higher lateral ductility than square columns. However, in the reinforced samples, lateral ductility of circular and square columns becomes nearly equivalent.

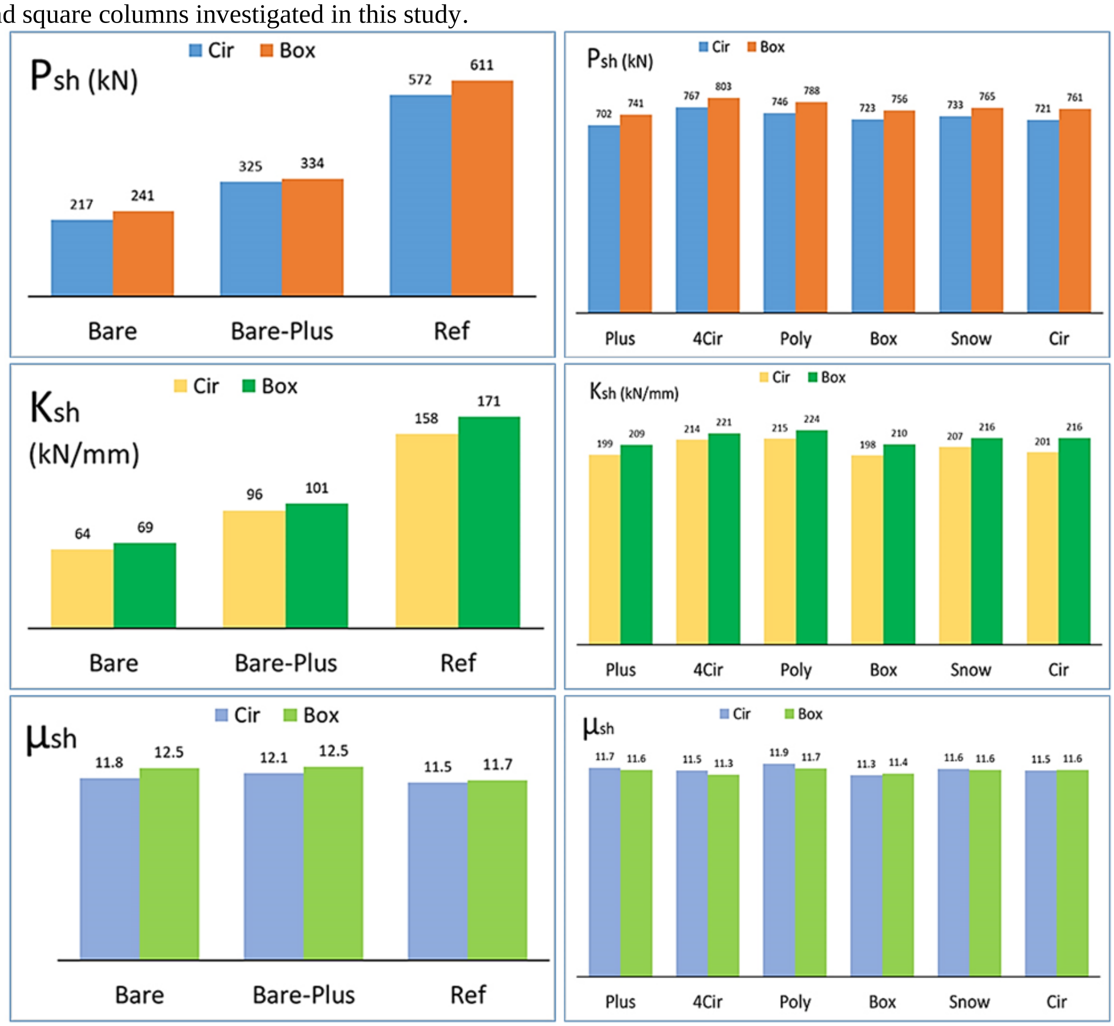

Figure 10: Comparison of lateral strength, stiffness, and ductility for circular and square columns in this study.

4.3. Comparative Relative Performance of Circular and Square Concrete-Filled Steel Columns

This section compares the relative performance of circular and square concrete-filled steel columns with various embedded steel sections and stiffeners. By expressing the relative axial and lateral performance in terms of percentage increase or decrease (sorted systematically), the overall behavior of these columns can be better understood. Relative performance is defined as the performance of each sample compared to its own reference case, i.e., the performance of circular samples relative to the circular reference column ("Ref-c") and square samples relative to the square reference column ("Ref-b"). Figure 11 presents the comparative relative axial and lateral performance of circular and square concrete-filled steel columns.

From Figure 11, the following major conclusions are drawn:

- "Cir-Cir" and "Cir-Box" samples show the highest increase in axial strength, with 49% and 46%, respectively. "Box-Plus" and "Box-Snow" samples exhibit the lowest increase in axial strength, with 25% and 28%, respectively. Overall, circular concrete-filled steel columns with embedded steel sections demonstrate higher relative axial strength compared to square columns.
- "Cir-Cir" and "Cir-Box" samples jointly achieve the highest increase in axial stiffness at 58%. "Box-Plus" and "Box-Poly" samples show the lowest increase in axial stiffness, with 37% and 38%, respectively. Circular concrete-filled steel columns exhibit superior relative axial stiffness compared to square columns.
- Square concrete-filled steel columns with embedded steel sections have significantly higher relative axial ductility than circular columns. This is due to the sudden buckling observed in bare square columns, which substantially reduces their axial ductility. Among square samples, "Box-Box" achieves the highest increase in relative axial ductility (169%), while "Box-Cir" has the lowest (141%). Among circular samples, "Cir-Snow" shows the highest increase in relative axial ductility (7%), while "Cir-4Cir" has the lowest (-0.3%).

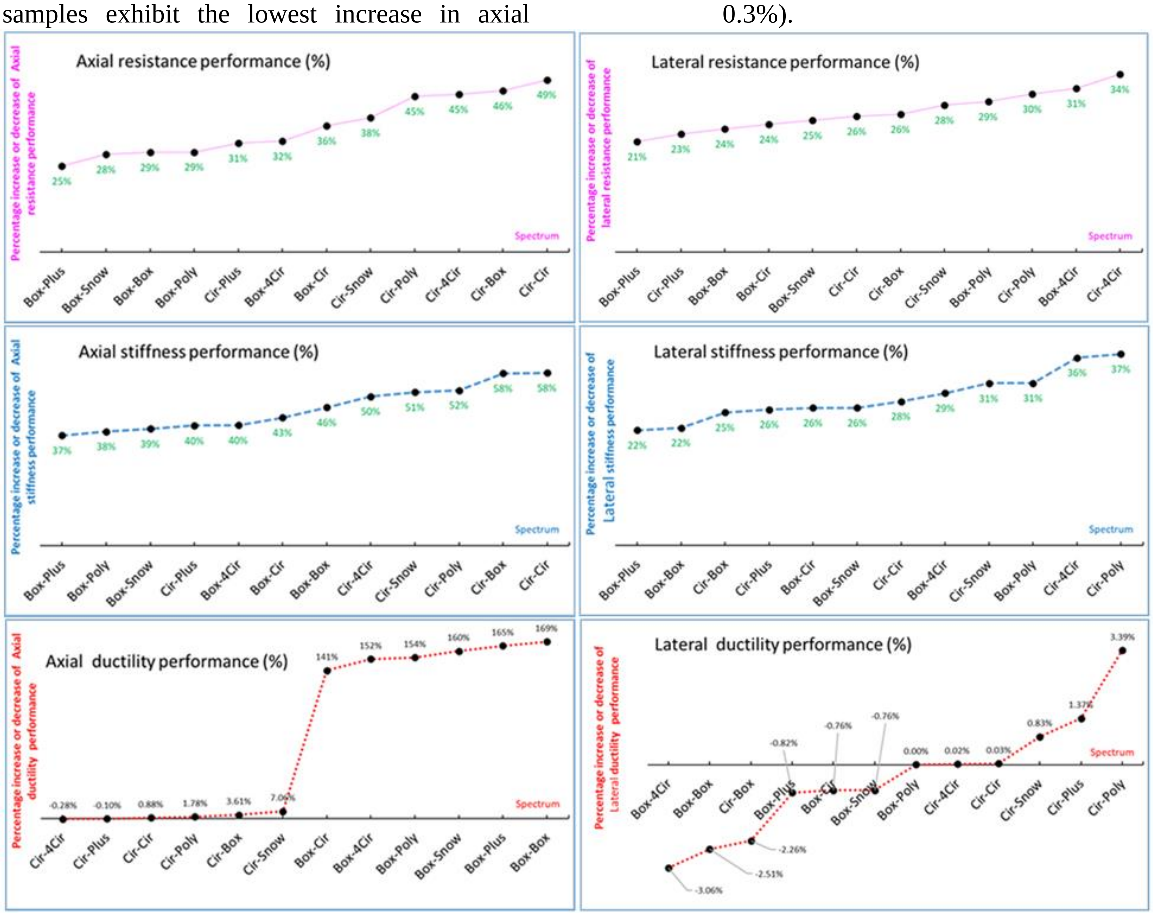

Figure 11: Comparative relative axial and lateral performance of circular and square concrete-filled steel columns.

- "4Cir-Cir" and "4Cir-Box" samples show the highest increase in lateral strength, with 34% and 31%, respectively. "Box-Plus" and "Cir-Plus" samples exhibit the lowest increase in lateral strength, with 21% and 23%, respectively. Overall, steel sections with profiles such as "4Cir" and "Poly" exhibit the highest relative lateral strength, while "Plus" profiles demonstrate the lowest.
- "Poly-Cir" and "4Cir-Cir" samples achieve the highest increase in lateral stiffness, with 37% and 36%, respectively. "Box-Plus" and "Box-Box" samples show the lowest increase in lateral stiffness, both at 22%.
- "Poly-Cir" and "Plus-Cir" samples achieve the highest increase in lateral ductility, with 3.4% and 1.4%, respectively. "Box-4Cir" and "Box-Box" samples exhibit the greatest reduction in lateral ductility, with -3.1% and -2.5%, respectively. Circular concrete-filled steel columns tend to demonstrate higher relative lateral ductility, while square columns are inclined toward lower relative lateral ductility.

In conclusion, circular concrete-filled steel columns generally outperform square columns in terms of ductility and stiffness, whereas square columns exhibit superior strength under certain conditions.

5. Conclusion

This research numerically analyzed the effects of steel sections and stiffeners embedded within circular and square steel columns filled with concrete under axial and lateral loading. The findings demonstrated that the incorporation of steel sections inside concrete-filled steel columns significantly enhances their axial and lateral performance. The numerical results closely aligned with experimental findings. Key conclusions based on the six types of internal embedded sections and two main steel column cross-sections are as follows:

- Filling the interior space of steel columns with concrete greatly improves axial performance (in terms of strength, stiffness, and ductility) and significantly enhances lateral performance (in terms of strength and stiffness). However, lateral ductility slightly decreases.
- The significant improvement in axial ductility due to concrete filling can be attributed to the prevention of premature distortion and buckling. In bare steel columns (without concrete), distortion and early buckling occur upon reaching yield strength under axial loading, reducing their effective ultimate displacement (ΔU). This issue is mitigated in concrete-filled steel columns, leading to higher axial ductility.
- Axial ductility improvement for square concrete-filled steel columns is 782%, and for circular ones, 161% compared to their bare counterparts. Conversely, since severe buckling does not occur under lateral loading, the lateral ductility of concrete-filled steel columns does not improve and may decrease slightly due to increased stiffness and yield points in strengthened samples.
- Stress distribution analysis showed that, under axial loading, the internal stiffener, outer shell, and concrete take the most load transfer responsibility in descending order. Under lateral loading, the outer shell, internal stiffener, and concrete take the most load in descending order, emphasizing the significant role of internal stiffeners in load transfer.
- Square concrete-filled steel columns outperform circular ones in axial strength and stiffness but have lower axial ductility.
- Reinforced square concrete-filled steel columns show higher axial stiffness and ductility than circular ones, albeit with lower axial strength.
- Square concrete-filled steel columns have superior lateral strength, stiffness, and ductility compared to circular columns in all cases (bare, reference, and reinforced).
- Reinforced square concrete-filled steel columns exhibit greater lateral stiffness and strength than circular ones but lower lateral ductility.
- Sections with centralized mass distribution (e.g., Box and Cir profiles) provide higher axial strength, stiffness, and ductility, while sections with distributed mass along the perimeter (e.g., Snow profiles) have the lowest axial performance metrics.
- Sections with mass concentrated near the perimeter (e.g., Cir4 and Poly profiles) enhance lateral strength and stiffness, while sections like Plus exhibit the lowest lateral strength and stiffness.
- Intermediate profiles (e.g., Plus and Poly) achieve the highest lateral ductility. Generally, circular columns have the highest relative lateral ductility and tend to increase lateral performance, while square columns exhibit the lowest relative lateral ductility and tend to decrease in this regard.

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