BEHAVIOR OF SHORT RECTANGULAR CONCRETE-FILLED STAINLESS-STEEL TUBULAR COLUMN SUBJECTED TO AXIAL LOAD

Nabila Sultana[1], Md. Tanzil Hawlader*[2] and Mahbuba Begum[3]

[1] *Ph.D. Candidate, Department of CE, BUET, Bangladesh, e-mail: sultana.nabila.ce@gmail.com*
[2] *BSc Student, Department of CE, BUET, Bangladesh, e-mail: tanzil.ce.31@gmail.com*
[3] *Professor, BUET, Department of CE, Bangladesh, e-mail: mahbuba@ce.buet.ac.bd*

***Corresponding Author**

ABSTRACT

This research provides a comprehensive experimental exploration into the behaviour of columns made from concrete-filled Stainless Steel Tubes (CFSST) under axial loading conditions, with a focus on contrasting their composite performance against non-composite columns. The CFSST column seamlessly integrated the benefits of both stainless steel and concrete. Six specimens, including four composite and two steel-only sections, were tested to evaluate ultimate strength, stress-strain behaviour, lateral deflection behaviour, and failure mode.

The study demonstrated that concrete filling in stainless steel tubes significantly enhanced the column's strength and ductility compared to concrete concrete- or steel-only section. Transitioning from 2mm and 1.5mm steel-only section to steel-concrete composite configuration resulted in column capacity increases of 77% and 124%, respectively. The post-peak curve of steel-only sections shows a sharp decline, whereas composite CFSST sections can withstand force up to a long displacement without decline. Even post-peak force enhancement due to strain hardening can be observed for CFSST columns. The study demonstrated that thicker steel tubes are not much beneficial in the case of composite columns. Increasing the column plate slenderness from 50 to 67 led to a strength reduction from 73 MPa to 55.3 MPa. The stress-strain curve demonstrated an initial increase in stress with strain, followed by a gradual decline after reaching the ultimate strength. The experiment also analysed failure modes, revealing that thinner tubes does not exhibit a more abrupt failure compared to thicker steel tubes.

Keywords: *Concrete filled stainless steel tubular column, Slenderness ratio, Ductility, Tension Coupon test, Composite.*

1. INTRODUCTION

Concrete and steel stand as the predominant construction materials today, and their synergistic combination in composite structures reaps the benefits of both. Over recent decades, substantial portions of infrastructure have embraced steel-concrete composite structures, leveraging composite action for load-bearing capabilities. A proper bond between the steel section and the surrounding or filled concrete is crucial for the overall performance of these structures. A composite section, termed a "Concrete-Filled Steel Tube" (CFST), is created by placing concrete inside a hollow steel tube. When utilizing stainless steel as the outer shell, it is termed a "Concrete Filled Stainless-Steel Tube" (CFSST). The composite action of steel tubes and concrete enhances the strength of the CFST section, enabling it to withstand applied loads. This composite approach has gained recent popularity and finds application in diverse constructions such as buildings, bridges, and electrical towers. Researchers have conducted numerous studies on columns made of carbon steel tubes filled with normal and high-strength concrete, known as Concrete-Filled Steel Tubular (CFST) columns (Uy B 2008; Sakino et al. 2004; Liew et al. 2016; Kamil et al. 2018; Ahmed et al. 2018). These investigations have provided a thorough understanding of the behavior of CFST columns. It should be noted that stainless steels exhibit material behavior that is very different from carbon steels. However, research on the behavior of CFSST columns under varied loading circumstance has been quite limited. Due to better fire resistance incredibly high durability and resistance to corrosion of stainless-steel CFSST columns have grown research interest. It is necessary to research the behavior of CFSST sections to efficiently use the superior performance of stainless-steel.

The utilization of concrete-filled stainless-steel tubular (CFSST) columns in structural applications is on the rise, yet the existing body of research in this domain remains insufficient. Previous investigations into short columns composed of CFSST include works by Young & Ellobody, 2006; Lam & Gardner,2008; Uy B.,2008. Research involving laboratory testing of slender concrete-filled stainless-steel tubular (CFSST) columns was undertaken by Uy et al.,2009, Tao et al., 2016, Han et al. 2018, Zhu et al. 2023, Tang et al. 2023, Lin et al. 2023, Chen et al. 2023, Zhong et al 2024, Lai, et al 2024. A literature review has revealed a notable gap in research, indicating a lack of direct investigation into the influence of plate slenderness.

According to Tao et al. (2016), the Circular Concrete-Filled Steel Tube (CFSST) column demonstrates exceptional fire-resistant capabilities. Han et al. (2018) conducted a comprehensive examination of CFSST column performance, specifically comparing carbon steel CFST columns with stainless steel CFSST columns. The study reveals that while bond strength is a weakness in CFSST, other properties exhibit significant improvements. Notably, hysteresis curves under cyclic loading illustrate adaptive behavior, indicating increased strength with higher strain in CFSST columns. Zhu et al. (2023) investigated the impact of tube thickness, temperature, duration of exposure to temperature, and concrete compressive strength. Zhong et al. (2024) performed eccentric compression tests on high-strength Circular Concrete-Filled Steel Tube (CFSST) columns. The analysis focused on ductility, strength, longitudinal strain development, and lateral deflection distribution. Results indicated that (i) higher concrete grades led to reduced ductility in HCFSST beam-columns, (ii) strength reduction factor decreased with initial loading eccentricity, (iii) the assumption of a plane section remaining plane held true for HCFSST sections under combined compression and bending, and (iv) lateral deflection distribution patterns exhibited approximately half-sine wave shapes in HCFSST beam-columns. Lai et al. (2024) compiled a database comprising 308 concentrically-loaded and 157 eccentrically-loaded Circular Concrete-Filled Steel Tube (CFSST) columns. The findings suggest that the strength enhancement resulting from a stainless steel tube is more pronounced compared to that of a carbon steel tube.

In light of the common occurrences of plate buckling or local buckling in columns, a recent series of tests was undertaken on six rectangular composite columns. The primary objective of these tests was to systematically examine the performance of thin-walled concrete-filled stainless-steel tubular (CFSST) columns. Additionally, a comparative analysis was conducted between thick-walled and thin-walled configurations, considering both CFSST and bare stainless steel (SS) tubes. The investigation aimed to discern distinct performance characteristics and behaviors under varying conditions, particularly in relation to plate buckling and local buckling phenomena. The American Institute of Steel Construction

(AISC) 2005 design code is applied for the anticipation of column strengths and subsequent comparison with the experimental test results.

2. EXPERIMENTAL PROGRAM

2.1 General

Six tests were performed, as shown in Table 1. All columns were constructed at a height of 2 feet. The steel tube wall thickness of three specimens was 1.5 mm, and that of the other three specimens was 2mm. Among the three specimens, one is steel-only, and the other two are filled with 4000 psi concrete. The global slenderness ratio was 12 for all 6 specimens. The concrete cylinder strength was 4000 psi. Stainless steel tube plate slenderness ratio (67 and 50) was the investigating parameter. The effect of composite action (steel-only section or concrete-filled section) was also another investigating parameter. The specimen IDs are assigned according to (1) whether composite or not (SS represents stainless steel steel-only columns, CS represents concrete filled stainless steel (CFSST) columns); (2) concrete strength ("A" represents concrete strength of 4000 psi); and (3) eccentricity ("E" is written initially if it is eccentrically loaded); (4) steel section thickness (the first digit = 1 represents tube thickness = 1.5mm, and 2 represents tube thickness = 2 mm). (5) Slenderness ratio (the second digit = 2 represents the height of the column, which is 2 feet (578mm to 618mm, varied unintentionally). The global or overall slenderness ratio can be defined as Le/k, where Le is the effective length of the column and k is the radius of gyration. But here in this paper, we will take L/d as the global slenderness ratio, where L is the total height of the specimen and d is the shortest dimension of the rectangular x-section. The plate slenderness ratio is defined as b/t, where b is the longest dimension of the x-section and t is the thickness of the steel tube.

Table 1: Details of specimens and test results

No.	Specimen Label	B×d×t (mm)	Length, L (mm)	B/t	L/d	f'_c (MPa)	f_y,Tension (MPa)	P (KN)	Δ_u (mm)	Δ_i (mm)	Δ_u-Δ_i	$\varepsilon_u = \frac{\Delta_u - \Delta_i}{L}$
1	SS12	50x100x1.5	612.0	67	12	28	221	126.75	5.8900	0.0076	5.8824	0.0096
2	SS22	50x100x2	578.5	50	12	28	221	213.15	6.0700	0.0000	6.0700	0.0105
3	ESS22	50x100x1.5	612.5	67	12	28	221	145.98	5.9100	0.0017	5.9083	0.0096
4	CSA12(1)	50x100x1.5	614.0	67	12	28	221	285.58	7.6100	0.0012	7.6088	0.0124
5	CSA12(2)	50x100x1.5	617.0	67	12	28	221	282.86	9.0800	0.0088	9.0713	0.0147
6	CSA22(1)	50x100x2	618.0	50	12	28	221	358.15	9.6400	0.0041	9.6359	0.0156
7	CSA22(2)	50x100x2	613.0	50	12	28	221	397.03	10.000	0.0013	9.9987	0.0163

2.2 Material Properties

Specimens were fabricated using 4"x2" (50mm x 100mm) rectangular tubes made of 306-grade stainless steel, emphasizing corrosion resistance and durability. Tubes with two thicknesses (t) were taken: 1.5mm and 2mm. Plate sections are extracted from the planar surfaces of a tube for the purpose of conducting a tension coupon test. This test is employed to quantify the material properties of stainless steel. The initial elastic modulus, E_o, and the yield strength, or 0.2% proof stress, are 105 GPa (may not be accurate) and 221 MPa, respectively. Concrete exhibiting a compressive strength of 21 MPa (3000 psi) at 28 days is employed to fill four hollow specimens. PCC cement was used to make the concrete. The average compressive strength on test day was 28MPa (4000 psi).

2.3 Specimen Preparation

The tubes made of 306-grade stainless steel were precisely cut into pieces measuring 610mm (2 feet) in length. Cutting Zig was used for it. The cut was not perfectly 610mm (2 feet); a few millimetres more or less in length resulted. Also, the cutting plane was not perfectly 90 degrees to the tube axis. That means the columns would not stand perfectly vertical. To cast the concrete, one end of the tube was sealed with polybags, tapes, and ropes to temporarily hold the fresh concrete. The tubes were kept standing, with the tied end at the bottom, using walls and other things to support the tubes. Concrete was freshly made with a mixture machine in the concrete laboratory. The concrete mix design was made such that the slump value would be high to make sure the concrete would fill the thin tubes well. The concrete was sequentially deposited in layers, followed by compaction by rodding.

Final compaction was achieved through the use of a vibrating machine. The specimens were positioned in an upright orientation. Curing was done for up to 28 days. Some specimens had a little gap between the steel tube and the concrete top layer, and some concrete surfaces were uneven. So, the concrete surface was not flushed with the steel tube. It was expected that rubber pads would be used during testing to account for the unevenness. To mitigate the potential for local failure at the ends of the specimen, two steel caps were manufactured, with the side plates measuring a height of 56mm. The caps were fabricated through the process of cutting and welding 12mm-thick recycled steel plates. These two caps were made removable and used for all testing. The caps were put at both ends, as shown in Figure 1. A geotextile layer was used between the column end and the cap. Geotextile was also used to fill the side gaps between the cap and specimen.

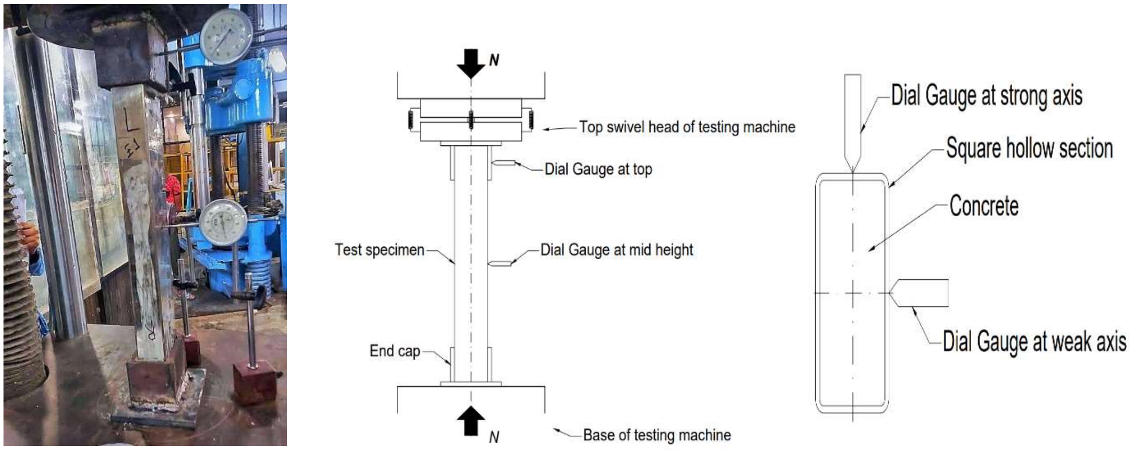


Figure 1: Test setup

2.4 Instrumentation and loading setup

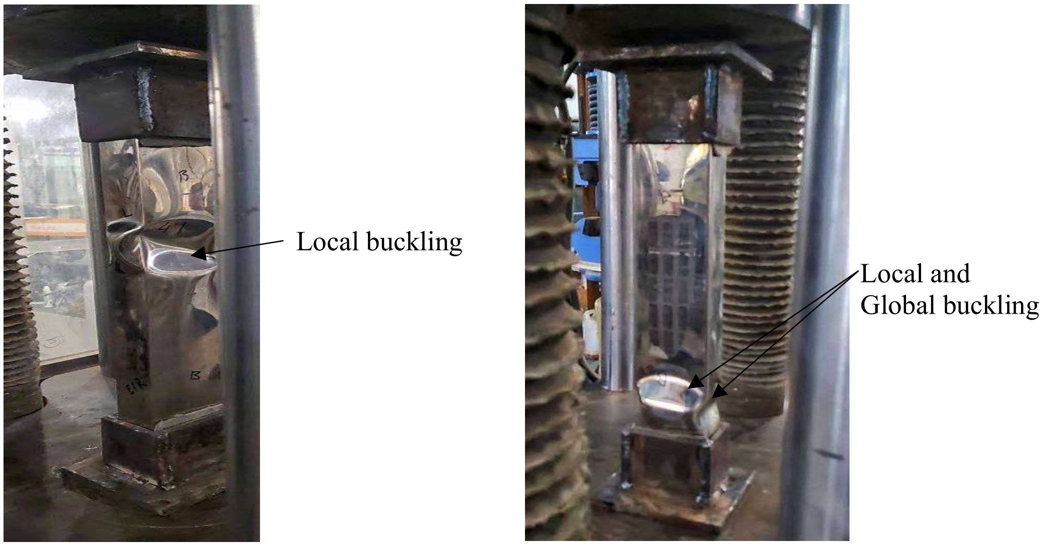
The loading tests were conducted employing a universal testing machine with a capacity of 2000 KN. The testing machine has a swivel head, which can accommodate the problem if the sample is not perfectly vertical. Also, it simulates pin-ended top support. The bottom support is a plane base; no measures were taken to simulate a pin support, so the bottom end of the specimen may act like a fixed support. The setup is shown in Figure 1. To measure lateral deflections at both top height and mid height and along the strong axis and weak axis, four dial gauges were used.

3. TEST RESULTS AND DISCUSSIONS

3.1 Test observations

Specimens were fabricated using 50mm x 100mm (4"x2") rectangular tubes composed of 306-grade stainless steel. Figure 2 shows a view of specimens after testing. It was observed that hollow steel-only sections failed in a similar mode and composite sections failed in another mode. The failure of composite sections may be characterized by either axial compression or a typical flexural mode, where substantial lateral deflections are induced due to global buckling.

Additionally, evident bending deformation emerged towards the conclusion of the testing phase, attributable to the sustained application of loads intended to induce collapse. Local buckling-induced failure was visible in hollow steel sections. Local buckling of steel tubes predominantly occurred in the vicinity of the mid-height of the specimen or in proximity to either the top or bottom end cap. Measurements of lateral deflections were conducted along the entire height of the column. The calculated capacity was divided into 10 intervals. At each interval, the loading was paused for a few seconds to read the dial gauges. Lateral deflections could not be taken at and after the peak load, as the dial gauges were removed after the 11th interval.



(a) SS12 (b) SS22

(c) CSA22(2) (d) CSA12(1) (e) CSA12(2)

Figure 2: Failure behaviour of the Test Specimens

3.2 Effect of Plate Slenderness Ratio

Figure 3 illustrates the impact of the plate slenderness ratio on the axial load versus axial shortening curves. 1.5mm thickness tubes have a plate slenderness ratio of b/t = 67, and for 2mm thickness tubes, the plate slenderness ratio is 50. As anticipated, it is evident that an increase in the slenderness ratio corresponds to a decrease in the peak load. Both steel-only sections and composites show the moderate effect. But the post-peak curves do not show a difference for thick or thin sections.

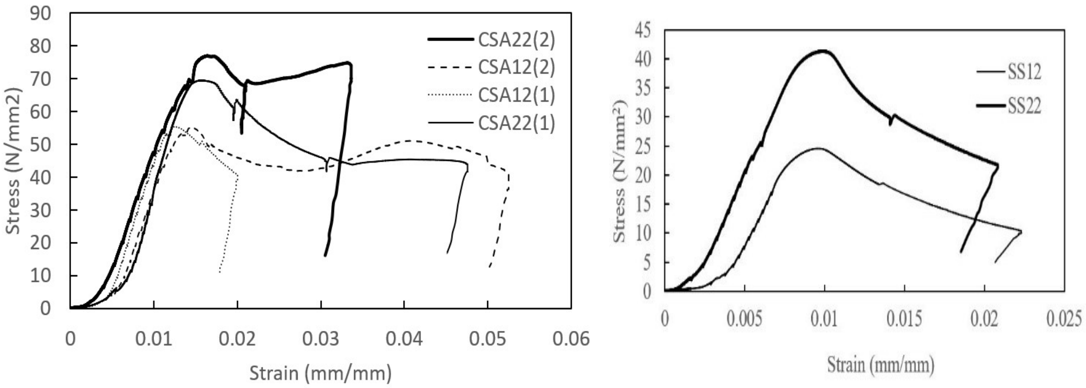


Figure 3: Effect of plate slenderness on axial load-normalized axial shortening curves

3.3 Comparison between steel-only and composite section

Two composite specimens with the same properties were prepared to ensure confidence in the results. For composites with a 1.5mm thickness, CSA12(1) and CSA12(2), the strengths were 285.58 kN and 282.86 kN, respectively, differing by less than 1% (0.96%). Similarly, for composites with a 2mm thickness, CSA22(1) and CSA22(2), the strengths were 358.15 KN and 397.03 KN, showing a difference of more than 10%. The strength increases for 1.5-mm-thick composites ranged from 123% to 125%, ranging from 126.75 to 282.86. In the case of 2mm-thick composites, the strength increase was 68% to 86%, ranging from 213.15 to 358.15. From these results, it can be concluded that making composites with a thinner section would be more efficient in terms of cost. Figure 4 shows the comparison of strength and post-peak behavior. All these behaviours improve greatly.

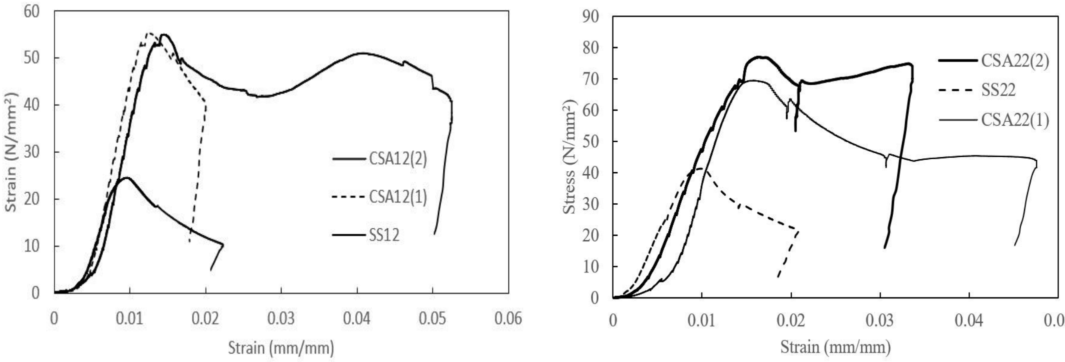


Figure 4: Effect of concrete filling on axial stress- normalized axial shortening curves

4. COMPARISION BETWEEN THEORETICAL AND EXPERIMENTAL ANALYSIS

Numerous national standards or recommendations have been established to address the design considerations for carbon steel concrete-filled steel tube (CFST) columns, such as American code AISC (American Institute of Steel Construction, 2005), Eurocode, and Australian Standard. The code AISC is used to predict the column strength to compare with the test results presented in this paper. This comparison will evaluate the applicability of the CFT formula of AISC in calculating the strength of CFSST columns. The outcomes of this comparison between the code predictions and the corresponding test results are presented in Table 2. Table 2 also presents the acquired average values along with their respective standard deviations for the parameters under consideration. The code is conservative and underestimates the column strength.

Table 2: Code predictions and test results

No.	Specimen Label	N (KN)	N_{AISC}	N_{exp}/N_{AISC}
1	SS12	126.75	90	1.4083
2	SS22	213.15	120	1.7763
3	CSA12(1)	285.58	211	1.3535
4	CSA12(2)	282.86	211	1.3406
5	CSA22(1)	358.15	241	1.4861
6	CSA22(2)	397.03	241	1.6474
μ				1.502023123
σ				0.175221417

Table 2 shows the comparison between experimental capacity and code-predicted capacity in AISC (2010). It has been shown that the code prediction capacity and experimental capacity varied from 1.34 to 1.65, with an average value of 1.5 and a standard deviation of 0.175. The composite sections are found to be higher, and the code capacities for CFSST columns are found to be highly conservative for concrete-filled stainless steel tubular columns. So, modifications are required for the current in the current CFSST column to be applied to stainless steel tubes.

A similar study has been performed by Tao et al. 2008 for the CFST column. The comparison results presented by Tao et al. (2008) for conventional CFST columns are: the average of N_{exp}/N_{AISC} is 1.13 with a standard deviation of 0.133. This study involved the comparison of 234 test results. It's worth noting that a substantial portion of these tests were performed on specimens characterised by square sections.

5. CONCLUSIONS

Six rectangular stainless-steel columns underwent axial compression testing to assess the impact of concrete filling and plate slenderness on their behaviour and performance. The study also involved a comparison of the test results with an established design method, AISC (2010) applicable to conventional carbon steel concrete-filled steel tube (CFST) columns. Within the limitations of this investigation, the following conclusions can be drawn:

(1) The Load-deformation curve obtained from the axial loading tests provide insights into the structural performance of CFSST columns. The curves demonstrate the characteristic stages of loading, including initial linear elastic response, ultimate load and residual capacity behaviour.

The thickness was noted to influence the load-carrying capacity of the CFSST columns..

(2) The code underestimates the strength of concrete-filled stainless-steel tubular (CFSST) columns by approximately 50%. In comparison to concrete-filled steel tube (CFST) columns, the predictions are more conservative.

(3) It can be concluded from (2) that stainless steel with the same strength and thickness can withstand a higher load than carbon steel.

(4) There is no significant difference in the post-peak behaviour between the thick-walled and thin-walled CFSST columns. A thin-walled stainless-steel section with concrete filling would be a better option in terms of cost, ductility, and safety.

ACKNOWLEDGEMENTS

The authors express their gratitude to Professor Dr. Mahbuba Begum. Additionally, the contributions of the officials and workers in the SM Lab, Concrete Lab, Machine Shop, and Welding Shop of BUET are sincerely acknowledged. The Ph.D. research grant from BUET is also gratefully recognized.

REFERENCES

Abdella, K., Thannon, R. A., Mehri, A. I., and Alshaikh, F. A., (2011). Inversion of three-stage stress-strain relation for stainless steel in tension and compression. Journal of construction steel Research, 67(5), pp. 826-832.

Ahmed, M., Liang, Q. Q., Patel, V. I., & Hadi, M. N. (2018). Nonlinear analysis of rectangular concrete-filled double steel tubular short columns incorporating local buckling. Engineering Structures, 175, 13-26.

ANSI/AISC 360-05. (2005). *Specification for Structural Steel Buildings.* American Institute of Steel Construction, Chicago, Illinois, USA.

Chen, J., Shi, H., Li, J., Guo, M., Ding, F., Shao, Z., & Xiang, P. (2023). Mechanical properties of CFSST with steel reinforcement cage under biaxial eccentric compression. Journal of Constructional Steel Research, 204, 107853.

Han, L. H., Ren, Q.X., Li, W., (2018). Tests on stub stainless steel-concrete-carbon Tubular (CFSST) columns and joints: Summary of recent research. Journal of Constructional Steel Research, vol. 152, pp. 117-131.

Ibanez,C., Hernandez-Figuirido, D., and Piquer, A., (2018). Shape effect on axially loaded high strength CFST stub columns. Journal of Construction Steel Research, 147, pp. 247-256.

Kamil, G. M., Liang, Q. Q., & Hadi, M. N. (2018). Local buckling of steel plates in concrete-filled steel tubular columns at elevated temperatures. Engineering Structures, 168, 108-118.

Lai, B. L., Zheng, X. F., Fan, S. G., & Chang, Z. Q. (2024). Behavior and design of concrete filled stainless steel tubular columns under concentric and eccentric compressive loading. Journal of Constructional Steel Research, 213, 108319.

Lam, D., Gardner, L. (2008). Structural design of stainless-steel concrete filled columns. *Journal of Constructional Steel Research*, 64(11), 1275-1282

Liew, J. R., Xiong, M., & Xiong, D. (2016, November). Design of concrete filled tubular beam-columns with high strength steel and concrete. In Structures (Vol. 8, pp. 213-226).

Lin, Y., Zhao, Z., Gao, X., Wang, Z., & Qu, S. (2023). Behavior of concrete-filled U-shaped steel beam to CFSST column connections. Buildings, 13(2), 517.

Sakino, k., Nakaharam H., Morino, S., and Nishiyamam, I., (2004). Behavior of centrally loaded concrete filled steel-tuve short columns, Journal of Structural Engineering, ASCE,130, pp. 180-188.

Tang, H., Hou, L., Yuan, Z., Jia, Y., & Wang, Y. (2023, September). Eccentric compressive behavior of square concrete-filled stainless-steel tube (CFSST) stub columns. In Structures (Vol. 55, pp. 1920-1935).

Tao, Z., Ghannam, M., Song, T.Y., & Han, L.H (2016). Experimental and numerical investigation of concrete-filled stainless-steel columns exposed to fire. Journal of Construction Steel Research, 118,120-134.

Tao, Z., Uy, B., Han, L. H., He, S. H. (2008). Design of concrete-filled steel tubular member according to the Australian Standard AS 5100 model and calibration. *Australian Journal of Structural Engineering*, 8(3), 197-214.

Uy, B. (2008). Stability and ductility of high-performance steel sections with concrete infill. *Journal of Constructional Steel Research*, 64(7-8), 748-754.

Uy, B., Tao, Z., Liao, F. Y., & Han, L.H. (2009). Behaviour of slender square concrete-filled stainless-steel columns subjected to axial load.

Young, B., Ellobody, E. (2006). Experimental investigation of concrete filled cold-formed high strength stainless steel tube columns. *Journal of Constructional Steel Research*, 62(5), 484-492

Zhong, Y., Liu, A., Fu, J., & Zhao, O. (2024). Structural behaviour and resistances of high strength concrete-filled stainless steel tube (HCFSST) beam-columns. Engineering Structures, 301, 117273.

Zhu, Y., Cai, S., Xu, Y., Xiong, C., Zhang, C., Chen, Y., ... & Lin, X. (2023, November). Experimental research on axial mechanical properties of circular CFSST columns after exposure to temperature and sliding. In Structures (Vol. 57, p. 105210)