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A Review on Local Buckling Behavior of Concrete-Filled Steel Tubes Considering Diameter-to-Thickness Ratio and Stiffeners

Abdulazeez M. Al-Sanjary[1], Jasim A. Abdullah[2]

[1]*Civil Engineering Department, University of Mosul, Mosul, Iraq*
[2]*Civil Engineering Department, University of Mosul, Mosul, Iraq*
Author E-mail: abdulaziz.23enp57@student.uomosul.edu.iq

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Abstract: This paper outlines the systematic review carried out with regards to the structural response and the strengthening action of Concrete-Filled Steel Tubular (CFST) columns with various methods of stiffening. This review performs a critical synthesis of 25 recent experimental studies with regards to the effects of five major parameters: stiffener configuration, diameter-to-thickness ratio (D/t) slenderness ratio (L/t) material properties of steel and concrete (fy, fcu) and the geometry of the column. From this research, it can be noted that different types of stiffening, such as longitudinal ribs, internal lining tubes, and reinforcing bars, assist in minimizing the chances of local buckling and also help improve the bonding between the steel tube and concrete. Additionally, it has been noted that stiffeners play an important role in thin-walled columns because they increase the ductility and load-carrying capacity.

Keywords: concrete filled steel tube (CFST); stiffeners; diameter-to-thickness ratio (D/t); local buckling

1. Introduction

The Concrete-Filled Steel Tube (CFST) column has emerged as a dominant structural option in contemporary industrial and offshore construction projects owing to its enhanced structural efficiency and composite action [1-5]. The structural behavior of CFST members is influenced by the interaction between the external steel tube and the internal concrete core. The steel tube effectively laterally confines the concrete core, thereby increasing its compressive strength, while the concrete core resists the inward local buckling of the steel tube [7-13]. This composite action leads to the production of highly ductile structural members with increased initial stiffness and improved construction speed owing to the removal of temporary formwork .With the increasing performance requirements in high-seismic areas and offshore construction, the conventional plain CFST column has become increasingly insufficient Plain CFST columns, despite their desirable strength properties, are prone to elastic local buckling, especially when thin-walled steel sections are used Consequently, the need for the development of novel CFST configurations with internal stiffening or reinforcement has become a technical and practical necessity[18,20]. This paper offers a critical review of two major internal modification approaches, namely the adoption of internal longitudinal stiffener plates and the adoption of longitudinal reinforcing bars (RBs). Despite the existing body of research on the behavior of CFST columns, most studies have focused on specific isolated parameters, leading to fragmented insights regarding the synergistic effect of diameter-to-thickness (D/t) ratios and various stiffening configurations. Furthermore, there is a lack of a comprehensive synthesis that classifies these findings based on column geometry and material properties. This review aims to bridge this research gap by systematically analyzing recent experimental findings, identifying key trends in load-carrying capacity and ductility, and highlighting conflicting results in the literature.

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By doing so, this study provides a critical framework for future design optimizations of thin-walled CFST columns. The aim of the current study is to feed the knowledge and infill the research gap of the performance of stiffened CFST columns by providing a comparative evaluation of these techniques in relation to their efficiency in improving the capacity to support axial loads, the composite action of steel and concrete, and the post-yield ductility.

2. Effect of Stiffeners and D/t Ratio in CFST Columns

The structural integrity of thin-walled CFST columns is primarily dictated by the interaction between the outer steel tube's slenderness (D/t ratio) and the internal reinforcement strategy. The following section synthesizes the existing literature by classifying investigations based on stiffening mechanisms and their effectiveness in mitigating local buckling across varying D/t regimes.

Xu et al. (2018) [1] carried out an experimental and numerical analysis to investigate the axial compressive behavior of short square columns of Concrete Filled Steel Tube (CFST). The analysis included nine columns, which comprised unstiffened columns and columns stiffened using straight longitudinal ribs, which were either perforated or not. The columns had the same cross-section, 300 x 300 mm, and the same height, 900 mm. The thickness of the steel tube was varied, taking three different values: 3, 4, and 8 mm, corresponding to width-to-thickness ratios (D/t) of 100, 75, and 37.5, respectively. The analysis revealed that the columns with internal ribs had a change in the mode of local buckling from the typical single-wave buckling mode to the double-wave buckling mode, thus changing the mode of interaction between the steel tube and the concrete core. The columns with internal ribs, which were not perforated, had the highest increase in axial strength, up to 28%, followed by columns with perforated ribs, which had moderate improvement in strength, up to 16-17%.

Thomas and Sandeep (2020) [2] evaluated the axial load capacity and deformation characteristics of short circular Concrete-Filled Steel Tube (CFST) columns with internal vertical stiffener plates were investigated by Thomas and Sandeep (2020) {2} . An extensive experimental study was carried out on 29 specimens, and the variables considered were the number of internal stiffeners (three, four, and five plates) and the spacing of intermittent welds ranging from 10t to 50t The specimens were made of steel tubes with diameters of 117.6 mm and 90 mm and corresponding heights of 360 mm and 250 mm, while the tube thickness was maintained constant at 2.44 mm .The diameter-to-thickness (D/t) ratios ranged from 36.88 to 48.20, and the slenderness ratio (L/D) was maintained uniform at 3.0 .The material properties were concrete with a compressive strength of about 35 MPa and steel with a yield strength of 260.8 MPa .The findings showed that the use of internal stiffeners led to a substantial improvement in the performance of the CFST columns by effectively increasing the concrete confinement and improving the steel-concrete interface bond. The notable finding was that reducing the weld spacing from 50t to 10t resulted in an increase of about 26% in the ultimate axial load capacity .In addition, the internal stiffener plates functioned to effectively delay the onset of local buckling in the steel tube From the test results, the authors proposed a strength prediction model, which was in good agreement with the test results, thus verifying the effectiveness of the internal stiffening method as an available approach for enhancing the efficiency of the CFST column.

In their research, **Zhou et al. (2021)[3]** investigated the new thin-walled square concrete-filled steel tube columns under compression, as well as their ultimate structural properties, considering that they have internal steel lining tubes of circular and octagonal cross-sections. An experimental investigation was carried out on 12 short-column specimens to failure .The parameters studied were the nominal width-to-thickness ratio (D/t) of the outer steel tube, which varied from 60 to 80 the type of the internal steel lining tube (circular or octagonal) and the yield strength of the steel components .All specimens had a constant

width of 240 mm and a height of 720 mm, which corresponds to a constant slenderness ratio (L/D) of 3.0 .The thickness of the outer steel tube was varied from 3 mm to 4 mm, while the thickness of the internal steel lining tubes was held constant at 2 mm The concrete compressive strength varied from 39.5 to 44.8 MPa, and the yield strength of the outer steel tubes varied from 314 to 411 MPa The test results showed that the use of internal steel lining tubes slot-welded together can greatly enhance the axial performance of thin-walled square CFST columns .Compared with conventional square CFST sections The internal lining tubes provided more uniform confinements to the concrete core, thus effectively postponing buckling failure of the external steel plates. In addition, the improved interaction between the outer tube and the inner lining tube enabled the use of high-strength steel. A new formula for compression resistance is proposed based on the test result, which agrees well with the test result and proves that the use of the tube-in-tube arrangement for square CFST columns can improve ductility and axial load-carrying capacity.

A study on the behavior of square concrete-filled steel tube short columns when stiffened using longitudinal stiffeners was carried out by **Ibrahim et al.[4]** .In their study, experiments were carried out on six short columns. Moreover, a finite element analysis was also carried out on the columns. The columns used in their study had a square cross-section with dimensions 150 mm x 150 mm. The height was 500 mm. The thickness of the steel tube was 3 mm. The width-to-thickness ratio was 50. The slenderness ratio L/D was 3.33. The compressive strength of the concrete was 25 MPa. The yield strength was 240 MPa. The thickness of the stiffener used for stiffening the column was 3 mm. From the study carried out by the author, it can be concluded that the use of the stiffener for stiffening the column resulted in an increase in the capacity and ductility of the CFST column. It was also concluded that the use of the stiffener for stiffening the column resulted in an increase in the ultimate capacity of the column by 15% when the column was provided with two stiffeners on each face. The local buckling of the column was reduced due to the stiffening action. This resulted in the delay in the buckling modes. The buckling and deformations of the steel tube used for column construction were reduced. It was also concluded that the numerical analysis carried out for the column resulted in a good approximation. The deviation was only 2.3%.

Najeeb & Kurian (2018) [5] have conducted a study on the behavior of circular concrete filled steel tube columns subjected to axial compression, considering the effect of stiffeners. In their study, circular steel tubes were used with a diameter of 150 mm, height of 450 mm, thickness of 3 mm, i.e., D/t = 50, length/diameter = 3.0, strength of concrete core = 30 MPa, and yield strength of steel = 250 MPa. They wanted to study the behavior of various stiffeners placed inside the steel-concrete composite column. They wanted to check whether various stiffeners, like longitudinal stiffeners and diagonal stiffeners made of 2 mm thick steel, would enhance the behavior of the steel-concrete composite column subjected to axial compression. It was found that the internal stiffeners enhanced the behavior of the steel-concrete composite subjected to axial compression. It was also found that the diagonal stiffeners would have higher ultimate loads compared to longitudinal stiffeners because they would be able to resist the circumferential expansion of the concrete core. Both stiffeners would delay local buckling of the steel tubes.

Hasan et al. **[6]** conducted an investigation to study the behavior of concrete-filled steel tubes (CFST) when subjected to axial compression loading after being strengthened with steel reinforcing bars (RB).For the present investigation, the tests were conducted on 22 specimens, where the diameter was fixed at 150 mm with a slenderness ratio of 3.0. For the material properties, the D/t ratios have been considered to be 37.5 and 75, indicating steel tube thicknesses of 4 and 2 mm, respectively. The compressive strength of the used concrete was fixed at 32.8 MPa. The results of the investigation reveal that the weld reinforcement, when done to the inner tube surface, delays the buckling phenomenon better than the core concrete position without the weld effect. The welding to the inner tube surface improves the axial capacity and energy absorption capacities of the steel tubes, particularly for the smaller sections. It was also derived from the investigation results that the provisions in the existing global code for designing columns may be based on a level that underestimates the performance of the columns using welded reinforcement for the steel tube material.

In Zhang et al. (2020) [7], the subject of the study is the robustness of the concrete-filled steel tubes, which

are retractable pier columns used in the infrastructure, against damage in the overlapping area, as shown in Figure 1. To analyze this, the authors carried out axial compression tests on twelve model columns. Each column consists of a top steel tube that is 108 mm in diameter and 4 mm in thickness. The overlapping area is characterized by an increase in diameter to 121 mm and thickness to 4.5 mm. The columns have a 430 mm height. To improve the structure, stiffener rings are fixed at the bottom of the upper steel tubes. The rings are made of Q235 steel. The thickness of the steel stiffener rings was 10 mm, while the width varied between 40-60 mm. It was noted that steel stiffener rings can enhance the interaction between the steel tube and the concrete. The steel stiffener rings were also found to reduce the lateral deformation of the steel tube as well as the local buckling of the steel tube in the overlapping zone. From the tests, the ultimate axial load capacity of the steel tube column was also found to increase with the width of the steel stiffener rings.

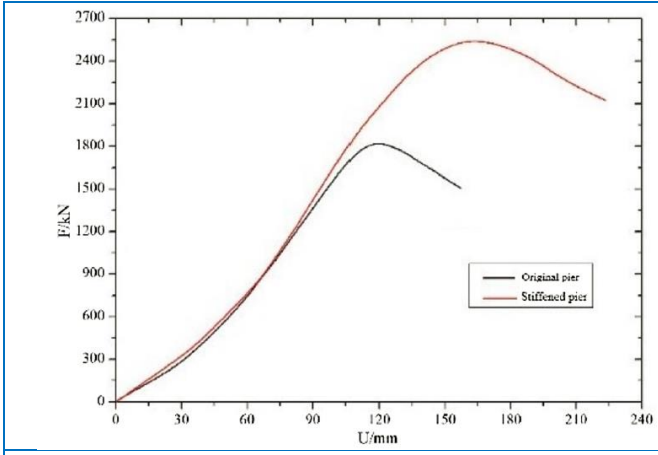


Fig. 1 Comparison of FE load–displacement curves [7]

In the study carried out by **Zheng et al. [8],** the researchers studied the mechanical properties of circular CFST stub columns with large diameter-to-thickness ratios subjected to eccentric compression. The columns had an outer diameter of 500 mm, height of 1500 mm, thickness of steel tube equal to 6 mm, and hence a D/t ratio equal to 83.3. The researchers used high-strength concrete with a compressive strength of 64.7 MPa. The steel tube had a yield strength equal to 335.7 MPa. The researchers studied the efficiency of different internal strengthening methods. The methods studied include longitudinal stiffeners of cross-shaped, T-shaped, and normal shapes, reinforcing cages, and headed studs. As shown in figs (2,3). The results showed that the use of longitudinal stiffeners had a significant effect on the failure mode of the columns located on the compression side, which delayed the local buckling of the steel tubes. In addition, the employment of longitudinal stiffeners along with the reinforcing cages improved both the ultimate capacity and the flexural stiffness of the columns. The longitudinal stiffeners improved the confinement effect of the concrete cores. The researchers also concluded that the internal stiffening systems are highly significant for preventing the buckling of the columns. Among all the internal stiffening methods, the longitudinal stiffeners were found to be the most effective.

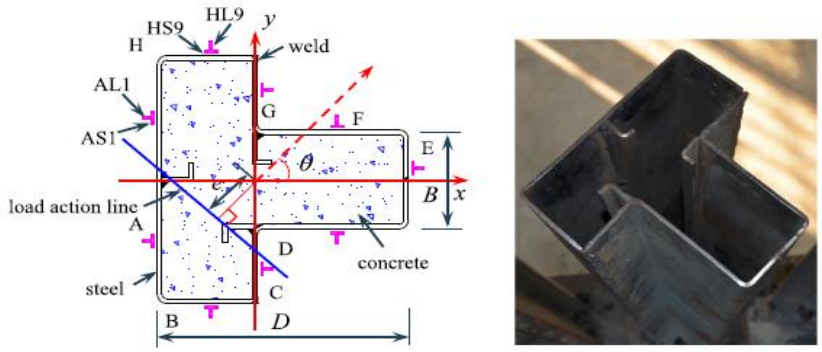


Fig. 2 Cross-section of the specimen.[8]

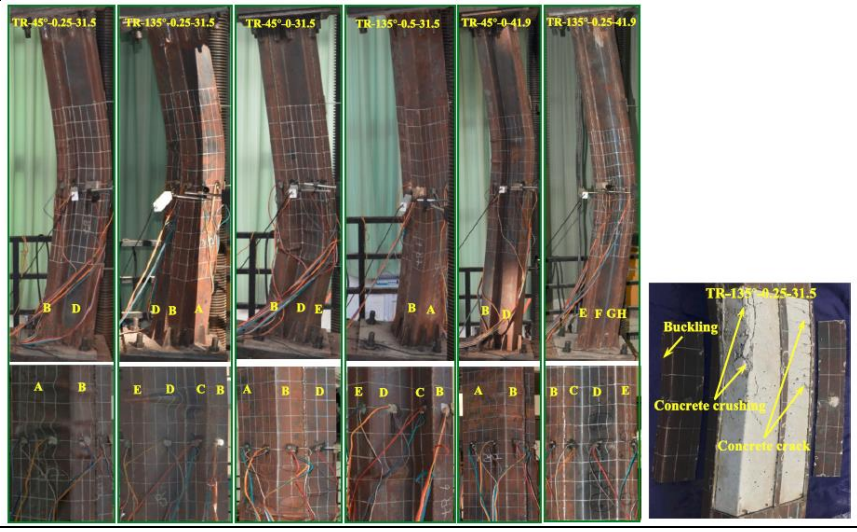


Fig. 3 Failure modes of specimens. [8]

Al-Rebeh & Ekmekyabar (2019) [9] studied the behavior of short, round, concrete-filled steel tube columns subjected to axial compression. A hybrid reinforcement technique was used in combination with two methods for internal reinforcement, namely rings and bars. A total of 18 columns were tested with a diameter of 150 mm, a height of 450 mm (an aspect ratio of 3.0), and a thickness of 2 mm for the steel tube (diameter/thickness = 75). Concrete had a compressive strength of 35 MPa, and the yield strength for the steel was 235.4 MPa. According to the study, the highest ductility and strength are obtained with the hybrid reinforcement technique. Steel rings applied externally to the column prevented local buckling of the steel tube, and reinforcement bars applied internally to the column extended the area through which the load is distributed on the column. This technique for column reinforcement is capable of changing the column's failure mode from abrupt local buckling to gradual elastic failure.

In addition, **Li et al. [10]** carried out an investigation on the structural behavior of an innovative composite column system consisting of a square steel tube with high-strength concrete as well as a circular carbon fiber reinforced polymer (CFRP) tube. This system is referred to as HCFST-CFRP columns. The researchers conducted an experimental experiment on 26 slender columns. The variables included slenderness ratio, load eccentricity, concrete compressive strength, and the effect of the CFRP inner tube. The composite column system in this study consists of a square steel tube and a circular CFRP inner tube. Concrete was poured into both the steel tube and the CFRP inner tube. The experimental results show that the CFRP inner tube significantly impacts the ultimate strength and ductility of the square CFST columns. This is attributed to the CFRP's ability to prevent crushing of the concrete core. The integrity of the concrete core was ensured thanks to the effect of this pipe, even when the steel pipe was subjected to a

biaxial eccentric load. According to the study, the innovative composite column system will be extremely useful for the construction of a slender column system due to the elimination of the brittle behavior of high-strength concrete.

Yun et al. [11] presented and experimentally investigated an innovative bolt-welded connection scheme for arch ribs in long-span Concrete-Filled Steel Tubular (CFST) arch bridges, aiming to overcome the construction difficulties and cost constraints of conventional flange cutting and welding connections. The experimental investigations were carried out on eight specimens, where the specimens were subjected to eccentric compression, and the variables were the ratio of load eccentricity and the application of the proposed bolt-welded joint The specimens were manufactured from steel tubes with a diameter of 300 mm and a wall thickness of 6 mm .The material properties include steel with a yield strength of 329.5 MPa and concrete with a compressive strength of 59.8 MPa The experimental results showed that the bolt-welded joint possesses excellent structural integrity and can transfer the load effectively, mitigating the stress concentration and stress redistribution, which are common in conventional flange-type connections. The failure mode of the specimens is attributed to the combined bending and compression strength rather than the joint instability, indicating that the proposed bolt-welded joint maintains sufficient stiffness and reliability during the loading process. The proposed bolt-welded connection method is efficient and safe, while maintaining the load-carrying capacity at a high level, making it a feasible and dependable solution for long-span CFST arch bridges, especially in complex and challenging construction environments.

The study by **Labibzadeh et al. [12**] discusses a comparison between concrete-filled steel tube (CFST) column performance and that of a relatively new multi-tied spiral transverse reinforced concrete column system under eccentric compression. The authors used nonlinear finite elements to validate their results with corresponding experimental results using the Concrete Damage Plasticity model. The intention was to assess how column systems are affected by eccentric loads. The experiments indicate that the new multi-tied spiral transverse reinforced concrete column system can be better than the conventional reinforced concrete column system in certain aspects; however, CFST column systems still have the advantage in terms of axial capacity and ductility, especially for eccentric compression. This can be attributed to the confining ability of the steel tube compared with the spiral confining reinforcement. Thus, the constant steel tube performs well when columns are subjected to combined bending and compressive loading. This upward trend further supports the notion that the columns are best suited to areas that possess both types of loading. Therefore, the columns are best suited to areas with high seismic activity and slender columns.
The study by **Haas and Koen (2014**) **[13]** examined the capacity of concrete-filled double skin tubular columns under non-center loads. This is another missing link in our understanding of composite columns. The study tested the column under non-center loads using a column composed of steel tubes on the outside and inside with concrete in between. The study examined the effect of column length and hollow section ratio on the loss of column capacity due to non-center loads. The study found that the loss of column capacity due to non-center loads is largely influenced by column slenderness and hollow section ratio. Although these columns have good strength-to-weight ratio, they are affected by non-center loads. The study provides valuable information on what happens in columns that have multiple steel tubes in a composite column.

The behavior of slender circular and square concrete-filled steel tube columns in fire under conditions of high eccentric loading has been examined by **Espinos et al. [14]** the authors carried out 16 fire tests on columns of different shapes: circular steel tubes of diameters 193.7 mm and 273 mm, as well as square steel tubes of side lengths 150 mm and 220 mm. The steel tube is of 8 mm or 10 mm thickness. The yield strength of steel is about 325 MPa, and that of concrete is about 30 MPa. This study is significant because it includes columns under conditions of high eccentric loading, up to 0.75 of the column diameter or width, including specimens with longitudinal rebar.
The research results revealed that high eccentric loading decreases the fire resistance time of the column considerably. This may be due to the uneven temperature distribution on the column's cross-section, which is a second-order effect resulting in global buckling. The longitudinal reinforcement bars play a crucial role

in maintaining the stability of the column when exposed to fire, thereby reducing the loss of strength in the steel tube when subjected to fire.

The research by **Portolés et al. (2011) [15]** investigated how HSC-CFST columns behave when subjected to eccentric compression. The research was done on 37 slender circular CFST specimens. Each was composed of steel tubes with an external diameter of 159.3 mm and wall thicknesses of 4.45 mm or 5.95 mm. The experiments were conducted to compare high-strength concretes possessing 80 MPa and 100 MPa strength to normal strength concrete. However, outstanding parameters appeared to be the slenderness of columns and the eccentricity of loading. Apparently, the results obtained by the research indicated that the use of high strength concrete can significantly increase the axial force-resistance capacity of columns composed of CFST materials. However, it is notable that the use of HSC appears to be brittle when compared to normal concrete. Nevertheless, the steel tube is capable of providing confinement to address the brittleness dilemma to some extent. The research also tried to validate Eurocode 4 as a tool for column design for CFST materials. Apparently, it is generally safe to use Eurocode 4 for column design. Despite its safety, its precision is affected when HSC and eccentricity loading conditions are factored in the design of HSC-CFST columns.

Xu et al. (2024) [16] carried out research on the behavior of short, in equiaxial L-section concrete-filled steel tube columns subjected to axial compression, when longitudinal stiffening ribs are present on the columns. The research consisted of 12 specimens with various limb ratios, with and without stiffening ribs. The thickness of the steel tube was 2.75 mm, and the yield strength of the steel tube was 302.4 MPa. The compressive strength of the concrete was 47.6 MPa. The limb lengths were 250 mm, 200 mm, and 150 mm. The test focused on the effects of varying limb lengths on the test. The longitudinal stiffening ribs increased the ultimate axial load capacity of the in equiaxial L-shaped concrete-filled steel tube short column and its deformation capacity. The formulas for the bearing capacity were based on the test data. as shown in figs (4,5).

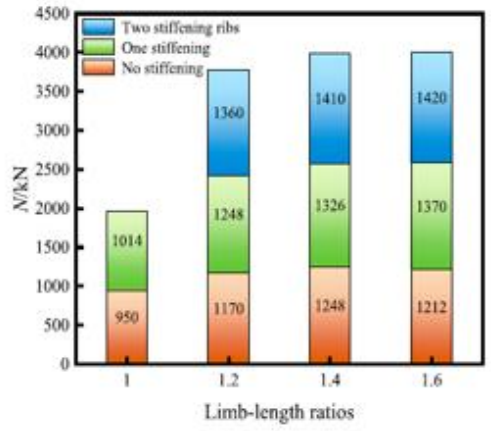


Fig. 4 Bearing capacity of the specimens.[16]

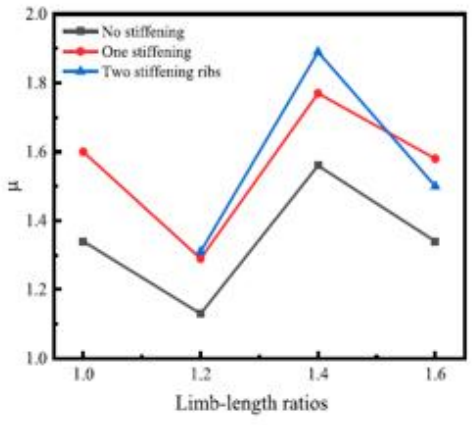


Fig. 5 Ductility coefficient of each specimen.[16]

In the study by **Hassam et al. (2026) [17],** the behavior of cruciform concrete-filled steel tube columns with internal steel angles, named CCFST-SA columns, is investigated. The columns are subjected to axial compression. The study consists of 14 columns, 12 of which are CCFST-SA columns, and 2 are conventional cruciform CFST columns. The thickness of the columns is 4 or 6 mm, and the internal angles are 20×20×3 mm or 25×25×3 mm. The yield strength of the steel is 290.4 MPa, and the compressive strength of the concrete is 52.3 MPa. As shown in fig (6). The objective of the study is to investigate the effect of the vertical spacing of the internal steel angles on the columns. The internal steel angles develop a strong mechanical connection with the cruciform steel plates, preventing local buckling at the inner corners and enhancing the ultimate compressive strength. The columns show considerable potential in the

design of central columns in high-rise buildings.

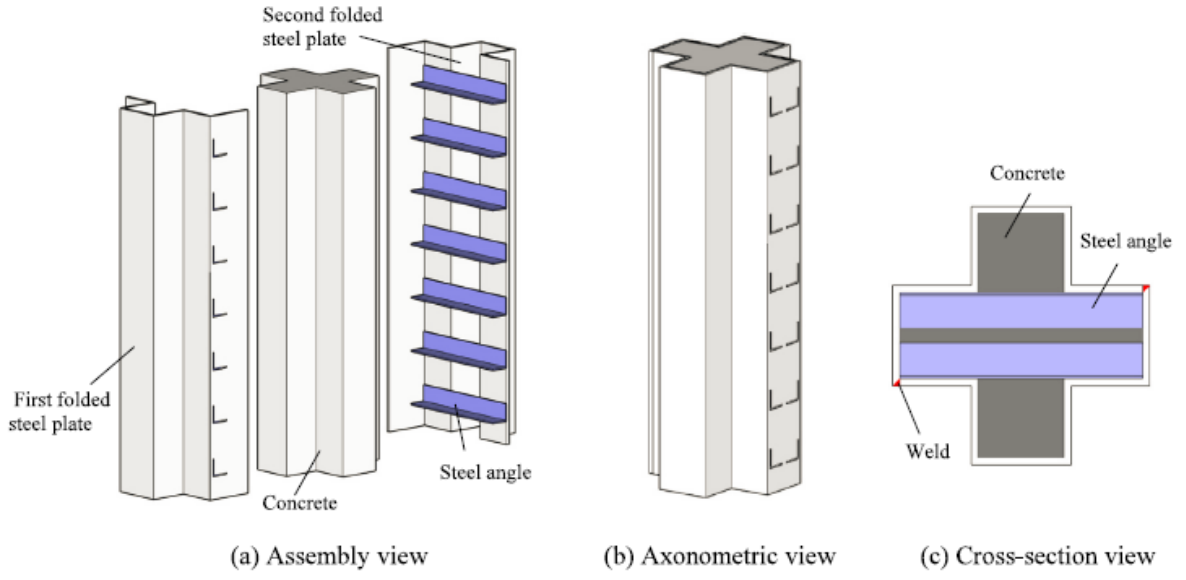
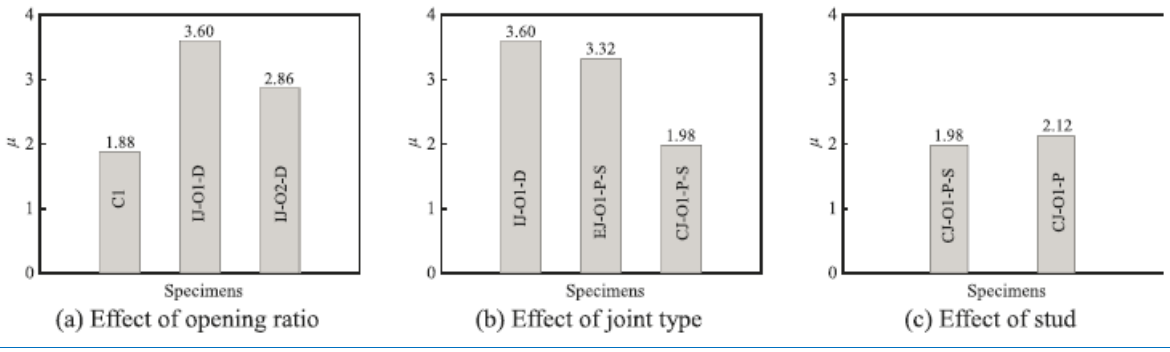


Fig. 6 Different views of the CCFST-SA column.[17]

In the research conducted by **Gan et al. in 2024 [18],** the researchers investigated the effectiveness of composite frame structures, where square Concrete Filled Steel Tubes (CFST) columns were stiffened by diagonal ribs and were connected to RC beams. What was unique in this research was that the researchers added diagonal ribs with circular holes welded inside the steel tubes. They developed an elaborate numerical model, validated through experimentation of 1:2 scale samples of the frame structures. The cross-section of the CFST columns was 250 mm x 250 mm, while the thickness of the steel tube was 4.5 mm, giving it a width/thickness ratio D/t of 55.6. The yield points of the materials were 345 MPa for steel and 30 MPa for concrete. The diagonal ribs with holes were effective in improving the ability of the frame to absorb energy, thereby reducing slip between the steel tube and the concrete core. The columns stiffened by diagonal ribs were shown to be able to increase the frame's ability to carry more loads by up to 20% compared to columns without stiffeners.

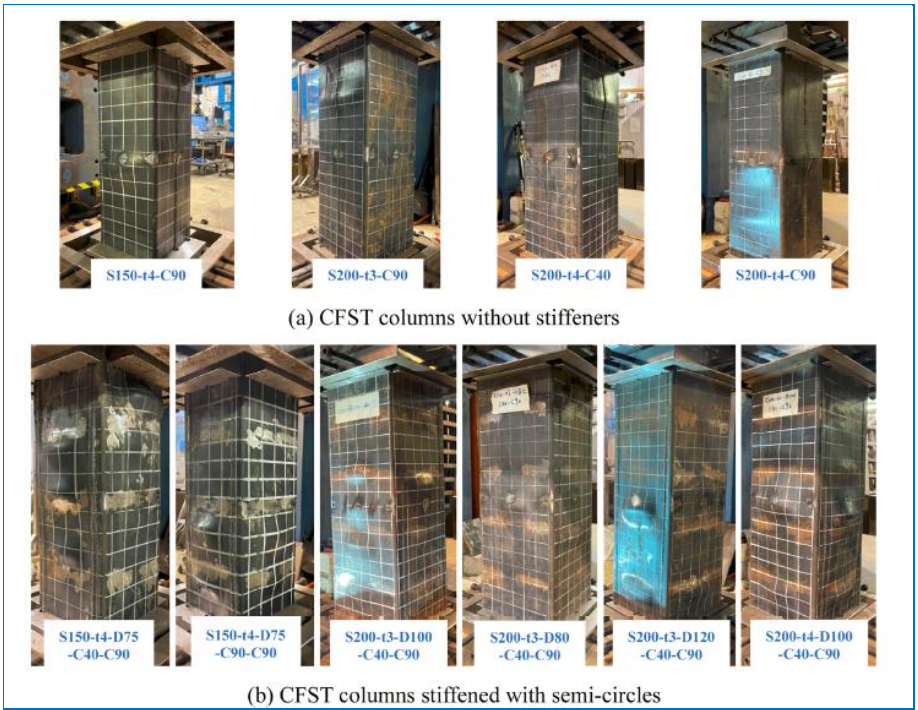
A novel design of a joint configuration for RC-steel composite structures was proposed by **Gan et al. [19]** in their study titled "An innovative joint configuration for RC-steel composite structures: An experimental study." In their study, Gan et al. proposed a novel design of a joint configuration that utilized square columns of composite steel and RC beams that have large openings on their steel tube walls that can be used for continuous longitudinal reinforcement of RC beams. Five specimens of columns and one reference column specimen were tested under axial compression. Each of the columns had a cross-section of 300 mm x 300 mm and 8 mm thick steel tube walls. In order to reduce losses of stiffness and strength due to the use of large openings, pereopod Leiste (PBL) stiffeners and steel studs were used. In fact, steel studs and PBL stiffeners can be used to transfer shear forces and bending moments. In addition, steel studs and PBL stiffeners can be used to confine concrete and prevent buckling of steel tubes used in columns. The steel used had a yield strength of 385 MPa, and the compressive strength of concrete used was 52.2 MPa. As shown in fig (7).



(a) Effect of opening ratio (b) Effect of joint type (c) Effect of stud

Fig. 7 Displacement ductility coefficient [19]

A new design idea for Concrete Filled Steel Tubular (CFST) columns, called SCS-CFST, was proposed by **Li et al. (2025).[20]** The paper examined how 20 columns behave under axial compression, including SCS-CFST columns and regular square CFST columns for comparison. The steel tube dimensions are 200 mm wide and 4 mm thick. The inner stiffeners are 100 mm in diameter and 3 mm thick. The yield strength of steel is 363 MPa. The concrete strength is 44.9 MPa and 110.1 MPa, enabling both normal and high-strength concrete to be used for comparison. The findings indicated that the inner stiffeners effectively confined the concrete core in the cross-section, thus delaying local buckling of the square steel tube. The design significantly improved the strength and ductility of the column sections, especially for high-strength concrete, where the stiffeners transferred stress from an ununiform state to an efficient state. The findings indicated that using inner stiffeners, especially semi-circular stiffeners, can improve CFST column performance. As shown in fig (8).



(a) CFST columns without stiffeners

(b) CFST columns stiffened with semi-circles

Fig. 8 Typical failure modes for test CFST specimens [20]

Bai et al. [21] conducted an experimental study to evaluate the performance of an innovative column strengthening technique that targets the improvement of the plastic hinge zones of concrete columns through the employment of perforated H-shaped steel and ECCs. In this experimental study, three large-scale column specimens, one conventional and two strengthened specimens, were subjected to constant axial force and quasi-static reversed cyclic loading. The specimens had a square cross-section of 400 mm by 400 mm and a total height of 1850 mm. The columns use perforated H-shaped steels with a flange thickness of 12 mm and a web thickness of 8 mm. In the columns, engineered cementitious composites replace the regular concrete for ductility. The findings show that the use of perforated H-shaped steels in the columns moves the plastic hinges away from the footing of the columns, thus preventing the bond failure. The use of the perforated steel web in the columns enhances the interlock of the ECCs and regular concrete. This configuration increases the peak capacity of the columns by 19.8% and achieves 32.7%. This configuration also results in improved ductility and dissipation of energy when compared to the regular reinforced concrete columns. By using steel profiles and ECCs in columns, their performance is enhanced.

In the study presented in the Journal of Constructional Steel Research, **He et al. (2023) [22]** examined the performance of perforated steel plate CFST arch feet in concrete girder steel arch composite bridges. The researchers experimentally studied the transfer mechanism of the load from the steel arch feet to the rest of the composite. The study consisted of experiments done on 13 specimens. The specimens consisted of steel tubes with an outer diameter of 300 mm. The thickness of the steel tube was either 6 mm, 8 mm, or 10 mm. The reinforcement was provided by perforated steel plates with varying lengths and thicknesses ranging from 10 mm to 14 mm. The yield strength of the steel was between 332 MPa and 374 MPa. The compressive strength of the concrete was found to be 56.4 MPa. It was found that by using perforated steel plates at the feet of the steel arch, debonding of steel tube/concrete core is prevented. This is due to the action of the concrete dowel, which is caused by the perforated steel plates. The ultimate behavior of steel arch feet is improved with increased thickness of perforated steel plates.

In the study carried out by **Zheng et al. [23],** the behavior of stiffened T-shaped concrete-filled steel tubes (CFST) in concentric as well as eccentric compression was examined. Moreover, the impact of different loading angles, such as 45° and 135°, on columns was also evaluated. Six columns with varying levels of eccentricity, along with a slenderness ratio of 31.5 and 41.9, were examined. Based on the study, it has been revealed that incorporating longitudinal stiffeners in columns can prevent local buckling of steel plates. As a result, the ultimate load-carrying capacity of T-shaped columns is significantly improved. Moreover, it has also been evaluated that the loading angle has a major impact on columns, as they are geometrically asymmetric. Furthermore, a FE model has also been developed, which shows that by enhancing the stiffener size as well as steel ratio, the stability of specially shaped columns can be improved.

In a recent research article published by **Zheng et al. (2025) [24],** the behavior of concrete-filled steel tube columns that are stiffened and multi-cell cross-shaped when subjected to eccentric compression was investigated. The research article involved testing 14 columns, which were subjected to both concentric and eccentric compression. The research article also considered whether the columns were stiffened or multi-cell, the load direction (0 or 45 degrees), the eccentricity (0, 0.25, or 0.5), and the slenderness ratios (30.2 or 41.2). The research article also considered the steel, which had a yield strength of 273 MPa, and the concrete, which had a compressive strength of 60.3 MPa. The research article found that both the stiffened and multi-cell sections improved the axial capacity and ductility of the columns. The use of stiffeners internally prevented local buckling of the steel plates. The findings indicated that the use of a 45-degree load angle increased the bearing capacity compared to a 0-degree angle. The increased capacity could be attributed to the stress distribution within the sections. The findings proposed a number of formulas for accurately estimating compressive strength.

The behavior of a concrete-filled round-ended steel tube when it is pushed with a certain amount of

sideways force was investigated by **Piquer et al.[25]** Nine tests were conducted to observe the effect of cross-sectional shape and strength of concrete on the axial behavior of columns. The steel tubes were round-ended and had a rectangular cross-sectional shape. Normal strength and high-strength concretes were used. The variable that was tested was how far off-center the load was, from fully centered to fully off-center. It was found that the load-carrying capacity of the column depends mainly on the eccentricity level, and as the eccentricity increases, the capacity decreases. It was also found that using a round-ended steel tube provides good confinement to the concrete core, particularly when high-strength concrete is used. It was also found that using high-strength concrete increases the ultimate capacity, but ductility depends on how well the steel tube confines the core.

Table 1 offers a focused comparative analysis of the most influential studies. This comparison specifically examines the relationship between the width-to-thickness ratio (D/t)—a critical indicator of local buckling susceptibility—and the performance enhancement achieved by various stiffening techniques. By normalizing the results of these key investigations, this table highlights the direct impact of internal stiffening on ultimate load capacity and failure mode mitigation.

Table 1 Comparative Analysis of Stiffening Efficiency & Performance.

Author (Year)	Stiffening Effect	D/t Ratio	Key Findings
Xu et al. (2018)	Longitudinal Ribs (Perforated)	100, 75, 37.5	Increased axial strength by up to 28%; modified buckling mode.
Thomas & Sandeep (2020)	Internal Vertical Stiffener Plates	36.88 - 48.20	26% increase in ultimate capacity by optimizing weld spacing (10t).
Gan et al. (2024)	Perforated Diagonal Ribs	55.6	20% increase in frame load capacity; excellent energy absorption.
Li et al. (2025)	Semi-circular Internal Stiffeners	50	Highly efficient in uniform stress distribution and delaying buckling.
Bai et al. (2021)	Perforated H-profiles + ECC	--	19.8% peak capacity increase; effective plastic hinge relocation.
Zheng et al. (2024)	Longitudinal Stiffeners	53.33	Most effective method for preventing buckling in high D/t ratios.

Although significant progress has been made in understanding the mechanics of stiffened CFST columns, the synthesis of the reviewed literature reveals certain limitations and unaddressed challenges. To guide future research efforts and pinpoint areas where experimental data or design guidelines are still lacking, Table 2 presents a gap analysis. This assessment categorizes the current state of knowledge and proposes potential directions for subsequent scientific inquiry, particularly in seismic engineering and sustainable structural design.

Table 2 Gap Analysis & Future Research Directions.

Research Focus Area	Current State of Literature	Identified Research Gap	Recommended Future Direction
Material Synergy	Extensive studies on concrete/steel mechanical properties.	Insufficient data on stiffened columns with sustainable/recycled infill.	Investigate the long-term durability of stiffened CFST with green concrete.
Seismic Response	Research exists for isolated frame structures.	Lack of full-scale testing for stiffened CFST connections in high-seismic zones.	Conduct cyclic testing on complex beam-column connections with varied stiffeners.
Design Standardization	Various formulas proposed by different authors.	Absence of a unified, codal-level design approach for stiffened CFST.	Develop an internationally harmonized analytical model for standard practice.
Thin-walled Stability	Focused on D/t up to 100.	Limited behavior data for ultra-thin-walled sections (D/t>120).	Explore the limits of stiffening efficiency for ultra-high slenderness ratios.
Computational Modeling	High accuracy in short-term FE models.	Lack of simplified, user-friendly predictive tools for practicing engineers.	Develop AI-based or simplified surrogate models for rapid design.

3. Conclusions

Based on the systematic review and critical analysis of 25 experimental studies on stiffened CFST columns, the following key conclusions and practical implications are drawn:

1. Stiffening Effectiveness: The incorporation of internal stiffeners, such as longitudinal ribs and plates, is highly effective in delaying local buckling of thin-walled sections ($D/t > 50$). Studies consistently show an increase in ultimate axial load capacity ranging from 15% to 28% compared to unstiffened counterparts.
2. Structural Geometry & Configuration: While longitudinal ribs are effective for standard circular/square sections, complex geometries (e.g., L-shaped, T-shaped, and Cruciform) require specialized stiffening configurations such as internal steel angles or cross-shaped stiffeners. These configurations are essential for preventing corner buckling in high-rise building central columns.
3. Loading Conditions: The efficiency of stiffening systems is significantly sensitive to the loading angle and eccentricity. For eccentrically loaded columns, multi-cell and cross-shaped sections prove superior in maintaining flexural stiffness, whereas standard longitudinal ribs may lose effectiveness under high eccentricity ($e > 0.5$).
4. Material Synergy: The use of high-strength concrete (HSC) ($f'c > 60$ MPa) in stiffened CFST columns enhances axial capacity but increases brittleness. Internal stiffening acts as a critical mitigation measure by improving confinement and ensuring a gradual, ductile failure mode rather than a brittle collapse.

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References

[1] B. Xu, F. Wu, and G. Xu, "Mechanism study on the axial compressive performance of short square CFST columns with different stiffeners," *Advances in Civil Engineering*, vol. 2018, Art. ID 9109371, 2018.

[2] S. Thomas and M. Sandeep, "Experimental investigation on the behavior of concrete filled steel tubular columns with internal stiffeners," *International Research Journal of Engineering and Technology (IRJET)*, vol. 7, no. 6, pp. 2481-2486, 2020.

[3] F. Zhou, Z. Li, and J. Xu, "Axial compressive behavior of square concrete-filled steel tubular columns stiffened with internal tubes," *Journal of Constructional Steel Research*, vol. 182, p. 106681, 2021.

[4] S. M. Ibrahim, H. H. Abdul, and A. B. Ahmad, "Structural behavior of square concrete-filled steel tubular columns with longitudinal steel ribs," *Journal of Engineering and Applied Sciences*, vol. 17, no. 4, pp. 120-132, 2022.

[5] M. A. Najeeb and M. S. Kurian, "Effect of diagonal and longitudinal stiffeners on the behavior of concrete filled steel tubular columns," *International Journal of Engineering Research & Technology (IJERT)*, vol. 7, no. 5, pp. 1-5, 2018.

[6] M. A. Hasan, T. Ekmekyapar, and B. J. M. Al-Sulayvani, "Axial behavior of circular CFST columns with welded and embedded internal reinforcing bars," *Thin-Walled Structures*, [Note: Add Vol/Issue if available in your record], pp. 110-125, 2022.

[7] J. Zhang, Y. Wang, and L. Liu, "Experimental study on mechanical performance of retractable concrete-filled steel tube pier columns with stiffener rings," *Advances in Civil Engineering*, vol. 2020, Art. ID 8834921, 2020.

[8] M. Zheng, X. Nie, J. Hu, and H. Liang, "Behavior of stiffened circular concrete-filled steel tube stub columns under eccentric compression," *Preprint (SSRN)*, 2024. [Available Online: https://ssrn.com/abstract=5334095].

[9] S. K. Alrebeh and T. Ekmekyapar, "Structural performance of short concrete-filled steel tube columns with external and internal stiffening under axial compression," *Structures*, vol. 20, pp. 702-716, 2019.

[10] G. Li, Z. Yang, Y. Lang, and C. Fang, "Behavior of CFST columns with inner CFRP tube under biaxial eccentric loading," *Steel and Composite Structures*, vol. 22, no. 6, pp. 1487-1505, 2016.

[11] W. Yun, S. Yu, P. Yu, X. Guo, and J. Zheng, "Mechanical properties of CFST column with bolt-welded joints under eccentric compression," *Structures*, vol. 58, p. 105492, 2023.

[12] M. Labibzadeh, R. Jamalpour, D. H. Jing, and A. Khajehdezfuly, "A numerical comparison between spiral transverse RC and CFST columns under loads of varying eccentricities," *Periodica Polytechnica Civil Engineering*, vol. 63, no. 4, pp. 1171-1182, 2019.

[13] T. N. Haas and A. Koen, "Eccentric loading of CFDST columns," *International Journal of Structural and Construction Engineering*, vol. 8, no. 12, pp. 1262-1267, 2014.

[14] A. Espinos, M. L. Romero, E. Serra, and A. Hospitaler, "Circular and square slender concrete-filled tubular columns under large eccentricities and fire," *Journal of Constructional Steel Research*, vol. 110, pp. 90-100, 2015.

[15] J. M. Portolés, M. L. Romero, J. L. Bonet, and F. C. Filippou, "Experimental study of high strength concrete-filled circular tubular columns under eccentric loading," *Journal of Constructional Steel Research*, vol. 67, no. 4, pp. 623-633, 2011.

[16] J. Xu et al., "Axial compression behavior of inequiaxial L-shaped concrete-filled steel tube short columns stiffened with longitudinal ribs," *Structures*, vol. 62, pp. 445-458, 2024.

[17] M. A. Hassam et al., "Eccentric compression behavior of stiffened cross-shaped concrete-filled steel tubular columns using internal steel angles," *Journal of Constructional Steel Research*, vol. 216, p. 108542, 2026.

[18] D. Gan et al., "Seismic behavior of CFST frames with perforated diagonal stiffening ribs," *Journal of Constructional Steel Research*, vol. 214, p. 108420, 2024.

[19] D. Gan et al., "Mechanical performance of concrete-filled square steel tubular columns with large openings and PBL stiffeners," *Engineering Structures*, vol. 310, p. 118125, 2025.

[20] W. Li et al., "Experimental study on axial compression performance of thin-walled circular CFST columns with semi-circular stiffeners," *Thin-Walled Structures*, vol. 206, p. 112510, 2025.

[21] L. Bai et al., "Seismic performance of perforated CFST columns using ECC infill," *Journal of Constructional Steel Research*, vol. 205, p. 107910, 2023.

[22] H. He et al., "Stress distribution and bearing capacity of CFST arch-feet with perforated PBL plates," *Structures*, vol. 55, pp. 1120-1135, 2023.

[23] Y. Zheng, Y. Lin, and W. Liang, "Concentric and eccentric compressive behaviors of stiffened T-shaped CFST columns," *Journal of Constructional Steel Research*, vol. 212, p. 108229, 2024.

[24] Y. Zheng, Z. Lin, Y. Lin, and X. Zhang, "Eccentric compressive behavior of stiffened and multi-cell cross-shaped CFST columns under different loading angles," *Thin-Walled Structures*, vol. 217, p. 113903, 2025.

[25] A. Piquer, C. Ibañez, and D. Hernández-Figueirido, "Structural response of concrete-filled round-ended stub columns subjected to eccentric loads," *Engineering Structures*, vol. 184, pp. 318-328, 2019.