Performance of Concrete-Filled Double-Skin Steel Tube Columns: A Critical Review of Weaknesses and Solutions

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ABSTRACT

Concrete-Filled Double-Skin Steel Tube (CFDST) columns are a cutting-edge structural option that blends the compressive qualities of concrete with the strength and flexibility of steel. This review study offers a thorough analysis of the body of knowledge on CFDST columns, concentrating on their applications, design factors, and structural behavior. A critical examination is conducted on significant elements, such as dynamic performance, fire resistance, local and global buckling, steel-concrete bonding, and load-bearing capacity. The report also highlights construction-related challenges, such as complex bonding and manufacturing processes—inefficiencies, while exploring alternatives, like implementing shear connections, advanced concrete materials, and optimum designs. According to the assessment, CFDST columns have several important advantages that make them appropriate for high-rise structures, bridges, and infrastructure in challenging conditions. These advantages include their high strength-to-weight ratio, enhanced seismic performance, and sustainability benefits. The knowledge gaps and areas that need more investigation, such as long-term durability and creative design approaches, are also discussed. To ensure that CFDST columns are widely used in contemporary construction, this study intends to direct future research, improve design procedures, and aid in creating engineering standards. The following points may improve the conclusion parameters commonly used in CFDST column studies: Column length-to-outer diameter ratio (L/Do), typically between 3 and 5, and spacing of shear connectors of approximately 50 mm to 200 mm.

Keywords- CFDST; shear connectors; outer tube; composite columns

I. INTRODUCTION

CFDST columns, also known as composite columns, are advanced structural elements that provide an efficient and durable construction solution by combining the compressive strength of concrete with the ductility and strength of steel [1]. Composite columns improve the overall performance, ductility, and load-bearing capacity of concrete structures [2]. The need for the column component bearing capacity in modern buildings is growing, so engineers have concentrated on Concrete-Filled Steel Tube (CFST) components with greater seismic performance and compressive resistance, exactly what high-rise buildings and bridge structures require [3]. Composite columns are commonly used as support structures by offshore infrastructure, such as bridges, wind farms, and drilling platforms, offering acceptable strength and stiffness while being easily transported and lightweight [4]. An inner and an outer concentric steel tube make up these columns, and the annular gap between them is filled with a concrete core [5]. Composite construction enhances structural performance by harnessing the combined strengths of steel and concrete [6]. CFDST columns, an advancement of traditional CFST columns, address issues, such as high self-weight, uneven load distribution, and limited fire resistance [7]. By incorporating an inner steel tube, CFDST columns improve stability, reduce buckling, and maintain or increase load-bearing capacity [8]. Their superior strength, stability, and durability make them essential in modern construction [9]. CFDST columns effectively combine the tensile and ductile properties of steel with the compressive strength of concrete, enhancing performance under both axial and lateral loads [10]. The dual steel tube design improves concrete confinement, increasing resistance to local buckling and boosting load capacity [11]. These attributes make CFDST columns ideal for high-rise buildings, bridges, and earthquake-prone regions [12]. Additionally, their high strength-to-weight ratio enables lighter structural designs without compromising safety [13]. Moreover, CFDST columns offer better fire resistance since the concrete core acts as insulation, protecting the steel tubes from intense heat [14]. Furthermore, they have outstanding ductility and energy dissipation, which is essential for constructions subjected to earthquakes or dynamic loads [15]. CFDST columns support sustainable building techniques by lowering construction resources and boosting efficiency. They are a popular option for contemporary engineering applications requiring long-term performance, robustness, and dependability because of their adaptability [16]. A comparison between CFDST columns and conventional CFST columns revealed that the former performed better structurally. It was highlighted how these columns are perfect for seismic zones because of their high load-bearing capacity, emerging from the combined action of steel and concrete, as well as their improved ductility and energy absorption [17]. According to [18], the inner and outer steel tubes constrain the concrete core laterally, increasing their stability and compressive strength while postponing local buckling. Concrete and steel are fundamentally different in terms of their mechanical and physical characteristics, including stiffness and thermal expansion, under cyclic or dynamic loads; these variations could lead to stress concentrations at the contact, weakening the bond [19]. Additionally, smooth steel surfaces lessen mechanical interlocking with the concrete core, especially on the inner and outer steel tubes, resulting in slippage and a lack of composite action [20]. Over time, the bond's effectiveness may be diminished by gaps between the steel and concrete caused by shrinkage and long-term concrete creep [21]. To maximize performance, researchers investigated a variety of materials, including regular, self-compacting, and High-Strength Concrete (HSC), which made them appropriate for tall and light constructions [22, 23]. The interface bonding between the tube and the infilled concrete during the elastic period may be weakened even if CFDST columns perform as intended due to improper concrete casting, concrete shrinkage [24], and a more extensive deformation of the tube than the concrete core in the lateral dilation. This problem weakens the concrete's strength and stiffness at the elastic limit by reducing the confinement effect. A thin wall thickness increases the chance of tube buckling due to the decreased surface bonding [25]. For thin-walled composite columns, local buckling is highly likely to happen early in the structural loading process. The addition of stiffeners to CFDST columns has been investigated by several researchers to successfully delay the emergence of local buckling and enhance mechanical behavior [26]. This study presents a review focused on the various types of shear connectors and the challenges involved in their design. Key considerations include optimizing shear connector size, spacing, and placement to avoid construction complexity and issues with concrete installation. Despite advancements, knowledge gaps remain—particularly regarding the long-term performance of shear connectors under complex loading conditions and diverse environmental factors. Ongoing research continues to explore innovative materials and hybrid bonding techniques to address these challenges and ensure the reliability and sustainability of CFDST columns across a wide range of applications.

II. DEFINITION AND CLASSIFICATION OF COMPOSITE COLUMNS

The CFDST column is a type of composite structural element consisting of two concentric steel tubes with a concrete core filling the space between them [27]. The concrete—enclosed between the inner and outer steel tubes, which are typically circular or rectangular—binds the two steel layers into a unified, robust structural unit. This design effectively combines the tensile strength of steel with the compressive strength of concrete, making CFDST columns well-suited for high-rise buildings, bridges, and other load-bearing structures [28, 29]. These columns offer a blend of structural integrity, architectural appeal, and functional efficiency [30]. In structural engineering, CFDST columns are highly valued for their combined strength, effectively utilizing the stiffness of hollow steel tubes and the compressive strength of the concrete core [10]. They are efficient, stable, and cost-effective structural components [25, 31]. By merging the tensile and confining benefits of double steel layers with the compressive resilience of concrete, CFDSTs form robust load-bearing elements [32, 33]. This makes them especially suitable for high-rise buildings and bridge piers, where enhanced stability and resistance to buckling under high axial loads are essential [34]. Compared to traditional CFST columns, CFDSTs offer a higher strength-to-weight ratio and improved flexural stiffness [35]. Their hollow inner tube reduces overall weight, easing foundation demands, while also providing a potential conduit for housing utilities and services [36, 37]. Cross-sectional shape significantly influences performance: circular sections offer superior concrete confinement, increasing compressive strength and mitigating buckling under axial loads [38]. CFDSTs also deliver better fire protection by insulating the steel tubes from high temperatures [39, 40]. Furthermore, their excellent energy absorption and ductility make them particularly effective in earthquake-resistant designs [41]. This benefit arises from their exceptional ductility, which enables them to absorb energy and undergo controlled deformation under cyclic loads [42]. Furthermore, the double-skin steel tube construction extends the column's durability and reduces lifecycle costs by minimizing exposure to corrosion and other environmental problems [43]. CFDST columns are a flexible, effective, and durable option for contemporary buildings because of these benefits. Several types of concrete-filled double skin steel tube columns exist in the present literature. Circular-Circular CFDST Columns are composite structural columns that consist of an inner and an outer steel tube with a circular cross-section, as shown in Figure 1A, and the annular space between them is filled with concrete. The Circular Hollow Section (CHS) term denotes that the column has a circular void [44]. This does not mean that the outer and inner tubes have the same properties [45]. The outer tube may have different material properties and thickness compared to the inner tube [35]. High resistance to buckling and deformation under axial loads is provided by this design, along with symmetrical load distribution [46]. High-rise buildings, bridges, and seismic-resistant applications frequently utilize circular CFDST columns because they demand great strength, stability, and endurance [47, 48]. In the same context, Circular-Rectangular CFDST Columns, as shown in Figure 1B, are another type of composite structural column made up of an inner steel tube that is either square or rectangular and an outer steel tube that is circular, with concrete filling the space between them, featuring differences or similarities in physical properties and thickness [49]. They are symbolized by the abbreviations CHS for the outer tube and Square Hollow Section (SHS) for the inner tube [50, 51]. The rectangular inner tube contributes to the column's increased rigidity and stability, while the circular form is used in this design to distribute loads evenly and enhance resistance to exterior forces [52]. Rectangular-Circular CFDST Columns are structural columns, with concrete filling the spaces between a circular inner steel tube and a rectangular or square exterior steel tube, as depicted in Figure 1C [26]. Applications requiring high strength and stability, including bridges and high-rise buildings, greatly benefit from this design [27]. Rectangular-Rectangular CFDST Columns are also a type of composite structural column, as illustrated in Figure 1D, which has a square or rectangular steel tube on the outside, with concrete filled/filled with concrete in between [53]. This arrangement provides outstanding stability and rigidity while improving alignment with building layouts [54, 55]. Square Concrete-Filled Steel Tubular (CFST) columns are commonly used in the construction of composite structures due to their enhanced bearing capacity, ductility, and ease of connection to the beams [56].

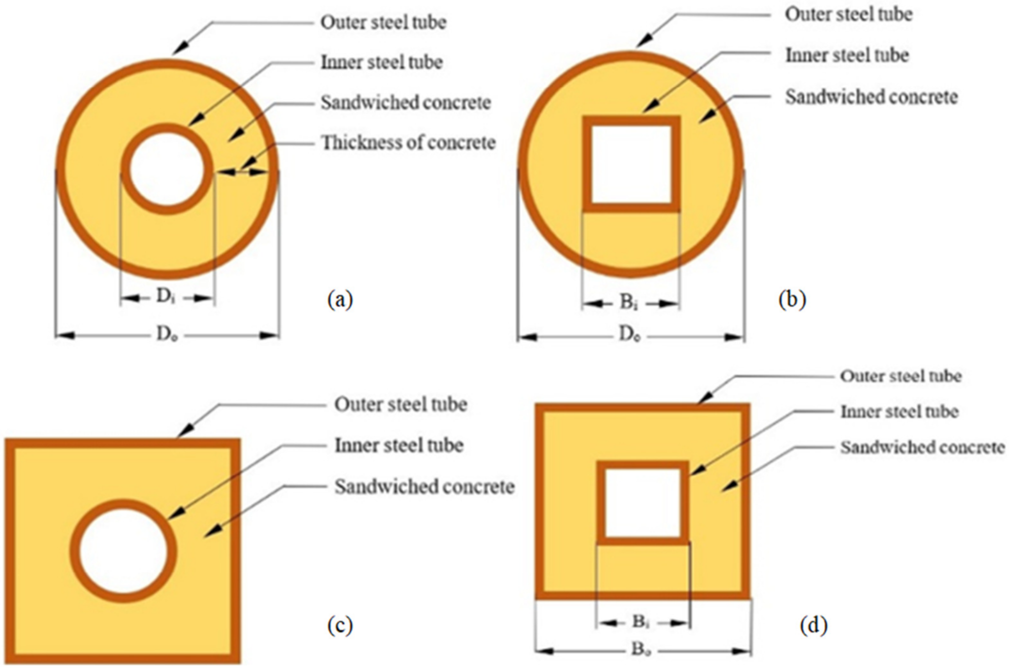

Fig. 1. (a) Circular-circular, b) circular-rectangular, c) square-circular, and d) rectangular-rectangular.

III. WEAKNESS OF CFDST STEEL-CONCRETE UNDER AXIAL LOADING

Weaknesses significantly influence the performance of CFDST columns regarding the bonding between steel and concrete, which can lead to localized buckling of the inner steel tube [57]. For instance, imperfect interface bonding during the elastic stage of CFDST columns presents a critical drawback that reduces their elastic strength and stiffness [58]. The buckling of the inner steel tube, linked to concrete shear failure, caused most tested columns to collapse, while those with a reduced D_o/t_o ratio exhibited superior ductility [59]. During the initial loading phase, when the axial load is uniformly applied to the entire section of the CFDST column specimen, the load is shared by both the concrete core and the steel tube [60]. The bond behavior between the steel tube and concrete, coupled with the friction between the core concrete and the steel tube wall during CFST member loading, is essential for the mechanical performance of the interface between the steel tube and core concrete [61]. Performance can be improved as the friction and interaction between the steel tube and the surrounding concrete are enhanced. From another perspective, under and after elevated temperatures, the bond between the steel and concrete interface is affected by the temperature, exhibiting different properties compared to those at room temperature [62]. The concrete core is constrained by the steel tube, which enhances its compressive strength [63]. However, as lateral deformation increases, cracks develop in the concrete core, allowing progressive plastic deformation [26, 54]. When the lateral deformation of the concrete core exceeds that of the steel tube, the steel tube begins to constrain the concrete core [6]. The interaction force between the outer steel tube and the concrete core gradually increases [8]. Under the constraint of the steel tube, the core concrete exerts radial pressure on the steel tube, which decreases the strength of the steel tube [64]. When the concrete core is crushed [39], the steel tube must bear not only the axial load, but also the radial load from the concrete core, ultimately leading to the gradual local buckling deformation of the steel tube [8]. The steel-concrete interface, often modeled as fully bonded, can experience debonding under dynamic or cyclic loads due to varying friction coefficients and confinement levels [26, 65]. Furthermore, CFDSTs are prone to failure modes, like local buckling, chord face failure, or punching shear, which are influenced by the bonding quality and geometric properties [8, 32]. Designing and accurately modeling these systems is complex, necessitating careful consideration of material and geometric nonlinearities, while balancing computational efficiency and accuracy [66, 67]. Their performance is highly sensitive to design parameters, such as slenderness ratios and cross-sectional dimensions, making improper choices detrimental to bonding and structural integrity [5, 68]. The bonding behavior between the steel and concrete core is crucial for structural performance, stability, and load-bearing efficiency in CFDST columns with steel tubes [69]. Because of this link, the steel tubes and concrete core function as a single unit, with the steel tubes providing stability and tensile strength, particularly under axial loads, while the concrete absorbs compressive stresses [26, 61]. According to research, the local buckling of the outer steel tube is a significant failure factor for CFDST thin columns [34]. Failure patterns can be observed on a CFDST model under the influence of an axial load when the void ratio χ is altered (χ = Hollow or void ratio = $D_i/(D_o - 2t_o)$, where D_o and D_i are the outer diameters of the external and internal steel tube) [69]. In the same context, the smooth surface of the steel tubes also impairs their ability to make a direct connection with concrete [19]; this could lead to serious issues if the materials slip under significant stresses or dynamic conditions [70]. Frictional resistance, mechanical keying, and chemical adhesion contribute to the bond strength during the CFDST contact [71]. Concrete properties, such as strength and shrinkage may also affect the bond quality. Concrete shrinkage may create gaps between the steel and concrete, which could weaken the bond over time [24, 64]. Since the steel tube can no longer sufficiently control the lateral expansion of the concrete under axial stress [72], the most notable consequence is the reduced confinement of the concrete core, leading to diminished compressive strength in the concrete due to this loss of confinement [73]. In CFDST or CFST systems, the incompatible dilation properties may lead to debonding at the steel-concrete interface, which explains the relatively low confining pressure. Moreover, the inadequate bonding at this interface may be further exacerbated by the shrinkage of the core concrete and temperature fluctuations after casting and forming [74]. Environmental factors, such as temperature changes and moisture exposure, are also significant, as they can gradually weaken the bond if corrosion occurs between the steel and concrete. Steel tubes are often coated with protective layers to prevent corrosion [75]. Tests on various specimens indicate that transverse expansion and small cracks demonstrate insufficient interaction between the inner and outer tubes and the concrete. These issues arise when the confinement and bond strength of the components are inadequate to withstand applied stresses; if the steel tubes lack sufficient thickness or rigidity, lateral pressure can exceed the confinement provided by the tubes, resulting in transverse expansion. Consequently, the tubes deform or bulge, diminishing their capacity to support the concrete core. Poor bonding at the steel-concrete interface often leads to small fractures within the concrete core [6]. In one study it was observed that the concrete within the buckling zone of the steel tube was not fully confined, causing the tube to buckle outward between the bolt shear studs. Finite Element Analysis (FEA) and experimental results were used to illustrate the shapes of both enhanced and non-enhanced confinement zones [37]. These findings showed that the initial stiffness remains nearly the same with zero, two, or four studs, but increases significantly—by about 50% with six studs, and even more with eight. This improvement is attributed to the enhanced composite interaction between the steel and concrete, as previously discussed [76].

IV. IMPROVING STEEL-CONCRETE BONDING

As previously discussed, the bonding weakness between concrete and steel tubes in CFDST columns can lead to buckling collapse under axial loading. To address this issue, a comprehensive review was conducted to highlight the available techniques used to mitigate this problem. The existing literature identifies various approaches, such as enhancing the surface properties and increasing the strength of the materials.

A. Surface Processing of Steel Tubes

Friction is a crucial component of bond strength in composite columns and is closely linked to the roughness of the steel tube surface. Increasing the surface roughness of steel tubes in contact with concrete enhances the bonding strength between the two materials [70]. Similarly, greater surface roughness on the concrete core improves bond strength in columns with fiber-reinforced outer tubes [77]. Techniques, such as sandblasting, can be used to roughen the inner surface of the steel tube, thereby improving adhesion [78]. Additionally, introducing surface textures, such as corrugations, grooves, or patterns, enhances the mechanical interlock between concrete and steel. A study investigated several column models under elevated temperatures, including both specimens with and without strip shear studs. The use of strip shear studs in specimens C2 and C3 significantly improved lateral stiffness and reduced deformation. This improvement was attributed to the increased surface area, which enhanced the bond and load-bearing capacity. However, elevated temperatures were found to weaken the bond between the inner steel tube and the concrete core by reducing the frictional resistance at the interface [79].

B. Self-Compacted Concrete and Expansive Concrete

Utilizing high-performance concrete, such as Self-Compacting Concrete (SCC), is another effective method to enhance the bonding weakness between concrete and steel tubes. This approach has been widely adopted in numerous previous studies. Weak adhesion between the steel and concrete interface is caused by the shrinking phenomena, which decrease concrete effectiveness in terms of durability, damage the composite column's compression performance, and ruin the load transmission mechanism [24]. Using SCC ensures proper filling of gaps and voids between the steel tubes and the concrete, enhancing the bond [80]. According to experimental and computational data, concrete infill has considerably increased axial strength (up to 86%) and ductility (up to 314%) by postponing local buckling, regardless of the concrete composition (i.e., with or without fibers) and hollow section ratio [53]. Notwithstanding the benefits of CFDST columns, a significant drawback is that the bonding between the steel and concrete will be weakened by concrete shrinkage and the varying lateral dilatation of steel and concrete under compression. Expandable concrete is proposed to lessen the issue and strengthen the connection [81].

C. Shear Connectors

The resistance of steel tubes to local buckling is significantly enhanced by the axial load transfer—particularly in the inner tube, which benefits from confinement by the surrounding concrete core [25]. To further improve this resistance, shear connectors [82], studs [83], and stiffened steel sections are commonly added to the tube surfaces. These elements increase the contact area and create mechanical interlocks that strengthen the bond between steel and concrete, preventing separation and enhancing overall stability [68, 84]. Additional measures, such as incorporating ribs or corrugations, further improve bonding by increasing the interlocking surface, which enhances performance under both axial and lateral loads [85, 86]. HSC contributes to greater bending stiffness and load capacity [87], while expansive concrete has also been used to enhance bond strength [74]. A strong and durable bond is essential for promoting composite action, ensuring efficient load transfer, delaying buckling, and maintaining structural stability under various loading conditions [88, 89]. To preserve bond integrity and performance throughout the column's lifespan, proper design and preventive measures are critical [90]. Stiffeners have been proposed as a solution to delay local buckling in thin-walled CFDST components [91]. Research indicates that shear connectors not only improve axial strength, but also significantly enhance the load distribution between the steel tubes and the concrete core [92]. This minimizes slippage and separation, reinforcing composite behavior [8, 65]. In CFDST systems, shear connectors are vital for maintaining a strong bond. Experimental studies using various internal stiffeners, such as headed shear studs, under axial compression (via push-out tests) have demonstrated that these stiffeners strengthen the bond when loads are applied to the concrete core [93]. These connectors promote effective load transfer and structural integrity by enhancing mechanical interlock and ensuring composite action [76]. Finally, improvements in the yield strength of both steel and concrete contribute to the overall strength and ductility of CFDST columns [94, 95]. The confinement effect provided by the concrete also strengthens the interaction between the two steel tubes, further enhancing the composite system's performance [96, 97].

V. A RESEARCH COMPARISON DEALING WITH CFDST COLUMNS

Table I demonstrates a comparison of research that deals with CFDST columns.

VI. CONCLUSIONS

CFDST columns represent an innovative and highly efficient structural solution that addresses the growing demands of modern construction. This review demonstrates that their outstanding load-bearing capacity, ductility, seismic resistance, and fire performance make them ideal for high-rise buildings, bridges, and infrastructure in challenging environments. The dual steel tube design enhances structural performance under axial, lateral, and dynamic loads by improving confinement, bond strength, and resistance to local buckling. However, CFDST columns also face challenges, such as complex construction processes, suboptimal steel–concrete bonding, and susceptibility to local buckling in thin-walled sections. Addressing these limitations requires the use of shear connectors to strengthen composite action, the application of advanced materials, such as self-compacting or high-strength concrete, and the optimization of key design parameters. Despite considerable progress, gaps remain—particularly regarding long-term durability, corrosion resistance, and performance under extreme loading conditions. To fully harness the potential of CFDST columns, future research should focus on cost-effective construction techniques, enhanced bonding methods, innovative materials and cross-sectional designs, and the development of more precise and comprehensive design guidelines.

Based on the research, the following points may improve the conclusion parameters commonly used in CFDST column studies:

- Column length-to-outer diameter ratio (L/D_o): Typically, between 3 and 5.
- Tube thickness distribution: Most studies use equal thickness for the inner and outer tubes. However, some adopt a thicker outer tube.
- Shear connector spacing: Commonly, it ranges from 50 mm to 200 mm.
- Outer-to-inner tube diameter ratio (D_o/D_i): Typically, between 1.13 and 2.17.
- Hollow/void ratio (χ): Generally, between 0.47 and 0.89.
- Slenderness ratio (λ): Shows significant variation across studies.

TABLE I. PROPERTIES OF COLUMNS TESTED BY SOME OF THE INVESTIGATION

Ref.	Type of col.		Outer tube (mm)		Inner tube (mm)		Shear connector	L (mm)	B_l (mm)	b_s (mm)	Bolt diameter (mm)	L/D_o	Concrete strength (Mp)	Hollow ratio: χ	Slenderness ratio (λ)	Finding
	Single	Double	D_o	t_o	D_i	t_i										
[98]	×	✓	165	3	76	3	✓	1000	15.1	50, 75, 100	14	6.1	46.3	0.48	55	-Using a 50 mm bolt spacing reduced the local buckling intensity in the outer tube. -Bolted shear studs had the most noticeable influence on the ductility and the residual strength of columns
[24]	×	✓	168	3	76	3	✓	300	20	150	10	1.8	41.5, 84	0.47	56	-The reinforcing bars and internal rings welded onto the inner tube can meaningfully improve the bond strength among the interface elements of the CFDST specimens.
[99]	×	✓	200	3, 6	114.3	8, 3	✓	3315	35	50	9.52, 12.7	16.6	42, 134, 40, 123	0.59, 0.6	66.733.4	The ultimate strength of CFDT columns is directly proportional to the concrete compressive strength, steel yielding strength, column size, and inner tube size to outer tube size ratio (Di/DO).
[26]	×	✓	1900	2.8	1684.4	2.8	✓	6300	45	75, 200	5	3.32	80	0.89	678.6	The local buckling happened at a maximum load when there was less distance between the bolts.
[100]	✓	×	219, 219.1, 219.6, 220	6.4, 6.8, 8.2, 9.5	×	×	✓	1000	41.3, 42.6, 50.8, 92.1, 93.4, 95.3	115	15.87, 15.88, 19.04, 19.05, 19.11	4.6	19.7, 28.7, 36.6, 37.2, 41.87, 42.1	×	×	Bolts distribute the load between the steel tube and the concrete core. Failure occurred near the bolt extremity, inside the concrete core, above, due to the rotation of the bolt axis.
[101]	✓	✓	114.3	5.8, 5	60.3	2.5, 2	×	343	×	×	×	3	40.24, 67.32	0.55	19.5	The inner tube works consistently with the shell concrete and plays an important role in mitigating the failure mode of CFDST, even with HSC.
[70]	×	✓	219	4, 6, 8, 10	114	2,3, 6	×	657	×	×	×	3	37.6, 46, 50.8	0.54, 0.55, 0.56, 0.57	54.8, 36.5, 27.4, 21.9	The diameter-to-thickness ratio of the outer steel tube has a significant influence on the bond strength of the interface between the outer tube and the concrete.

D_o: Outer diameter, t_o: Thickness of outer tube, D_i: Inner diameter, t_i: Thickness of inner tube, L: length of column, B_l: the depth of the bolted shear studs embedded inside the sandwiched concrete, b_s: The longitudinal spacing of bolted shear studs, Hollow or void ratio: $\chi = D_i / (D_o - 2t_o)$, Slenderness ratio: $\lambda = D_o/t_o$.

RECOMMENDATIONS FOR FUTURE WORK

- Studying the behavior of CFDST columns under impact load.
- Studying the behavior of CFDST columns subjected to elevated temperature effects.
- Studying the performance compressive strength for CFDST columns made with demolition aggregate under cyclic loads.

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