A Comprehensive Research Review Regarding the Material Behavior of Concrete Filled Double Skin Tubes

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Abstract

The limited availability of land is a contributing factor necessitating the construction of multi-story buildings. Steel-concrete composite structures have emerged as a viable alternative construction material for buildings necessitating long-span constructions, including bridges, buildings with substantial intercolumn distances, and several other construction types. The utilization of composite steel enables the entire cross-section to effectively bear loads by leveraging the interaction between steel and concrete structural elements. Consequently, with a reduced cross-section, the load-bearing capacity and span length can be preserved at capacities comparable to those of ordinary reinforced concrete structures. This study provides a detailed investigation of the material behavior of Concrete-Filled Double-Skin Tubes (CFDST). The research primarily focuses on the development and examination of cross-sectional variations, stress-strain relationships in the materials, and their corresponding characteristics. The influence of various parameters on a variety of cross-sectional configurations have been recently examined in earlier research. Furthermore, this study discusses additional evaluations consisting of sandwiched concrete and the inner and outer steel components. Despite the substantial study conducted by CFDST, there is presently a lack of established guidelines or regulations pertaining to the design of composite structures. Consequently, it is imperative to acquire a comprehensive comprehension of the behavior exhibited by these materials. This understanding serves as essential for the development of design rules specific to CFDST composite structures. By performing consequently, the outcomes of this study can be effectively employed in the design, analysis, and optimization of the distinctive attributes associated with composite materials.

Keywords: *CFDST, composite material, cross-sectional variations, sandwiched concrete, steel material*

1. Introduction

The Northridge, California (1994) and Kobe, Japan (1995) earthquakes demonstrated that the collapse of steel structures at a particular moment was the result of joint failure. Therefore, it is essential to construct buildings that are resistant to earthquakes in order to substantially decrease the number of fatalities caused by these natural disasters. Following the earthquake, numerous studies on the structural connection design for earthquake-prone regions began to emerge, including the development of composite building materials.

The scarcity of land availability is a significant issue that justifies the need for the establishment of multi-story buildings. The strength and load-bearing capacity of a building increase proportionally with its height. Therefore, the duration of construction will also be enlarged. The utilization of composite steel enables the entire cross-section to effectively bear loads by leveraging the interaction between steel and concrete structural elements. This allows for the optimal utilization of the fundamental properties of each material. As a consequence, by decreasing the cross-sectional area, it is possible to maintain the load-bearing capacity and span length at levels that are comparable to the ones observed in ordinary reinforced concrete buildings.

Steel-concrete composite structures have become a feasible alternative construction material for buildings that require long-span constructions, such as bridges, buildings with significant intercolumn distances, and several other forms of construction. The combination of composite steel facilitates the distribution of loads throughout the full cross-section by relying on the mutually beneficial interaction between steel and concrete structural components. This interaction allows for the optimal utilization of the fundamental properties of each material, thereby enhancing structural performance and overall effectiveness. To enhance the load-bearing capacity and structural rigidity of the building. For the purpose of further improving structural performance and optimizing load capacity and stiffness in structures, the utilization of composite concrete structural parts may be regarded as an appropriate option.

Composite structures are extensively utilized in the construction of different types of structures such as buildings and bridges. In composite construction, resulting from the interaction between steel and concrete with their specific characteristics, the performance of the structure in terms of load capacity and building stiffness will be significantly improved.

There are a number of advantages to utilizing composite structural elements, including the following: (1) The cross-sectional capacity to withstand loads on composite materials is larger compared with conventional steel and concrete materials, allowing for the cross-sectional dimensions to be reduced; (2) Steel tubes in composite materials might be used as formwork for casting concrete; (3) Can reduce the probability of cross-sectional buckling because of its increased rigidity and inertia value. (4) Considering the combined capacity of steel and concrete, composite materials are appropriate for construction of high-rise buildings [1].

Steel Reinforced Concrete – SRC and Concrete Filled Tubes – CFT are the two forms of composite materials. The combination of steel and concrete will further improve the column's strength due to the confining effect of the steel tube and the presence of concrete will minimize the occurrence of local buckling of the steel tube [2], [3].

The CFT composite material has advantages that include (1) It has a greater carrying capacity as opposed to conventional steel and reinforced concrete material; (2) It has good resistance to fire and corrosion, due to the presence of a concrete cover as a heat conductor; and (3) It has high stiffness and inertia which ensures to prevent buckling in the cross-section [4].

Aside from these benefits, CFT comes with drawbacks such as: (1) When the CFT material undergoes uniaxial loads (axial load and bending moment) at a specific perpendicular plane, the steel tube experiences a greater load than the concrete core considering its stiffness value becomes higher when composite action occurs; (2) The contribution of the section to the bending and torsion stresses at the center of the concrete core adjacent to the section's center of gravity is disregarded; (3) The presence of a concrete core dramatically raises the weight of the structure. Therefore, the most difficult aspect of designing earthquake-resistant structures is to optimize the strength-to-weight ratio (s/w) as the most important consideration [5].

The development of composite materials for Concrete Filled Tubes (CFT) has evolved in phases. Figure 1 demonstrates that the performance of Reinforced Concrete Filled Tubes (RCFT) is enhanced by the addition of reinforcement components. Due to the presence of transverse reinforcement as a binder to the concrete core, the inclusion of reinforcement elements to RCFT provides better performance compared to CFT under compressive axial loads and minimizes shear failure. According to the outcomes of the analysis, the constraining effect of reinforcement in the RCFT cross-section can increase capacity and ductility. However, due to the presence of reinforcement in RCFT, construction with this material requires careful consideration in terms of both in terms of construction erection and casting [6].

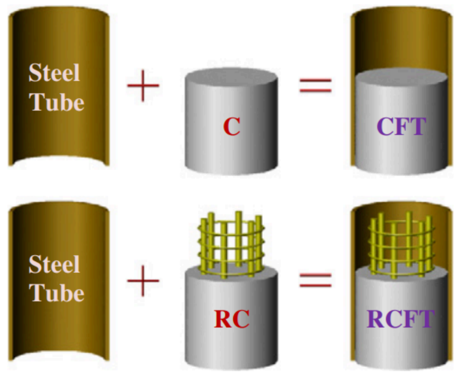

Figure 1. An illustration of CFT and RCFT (Xiamuxi & Hasegawa, 2012)

Concrete Filled Double Skin Tubular (CFDST) material analysis studies are beginning to develop due to the need for ease of construction. CFDST is a composite material comprised of an interior steel tube and an outer steel tube, both of which are filled with concrete [7]. The outer steel tubes behave as restraints for the concrete, while the inner steel tubes serve as binders for the concrete, potentially replacing the role of transverse reinforcing elements or the stirrups in Reinforced Concrete Filled Tubes (RCFT), which produces "stirrup effects" [8]. According to Hassanein et al. (2018) [9], the behavior of CFDST is preferable to that of CFT in terms of accepting cyclic loads. Additionally, CFDST exhibits a smaller structural weight while maintaining the same outer steel dimensions, which can be attributed to the presence of holes in the core of the inner steel tubes (Hassanein et al., 2018).

A study conducted in 1990 investigated the properties of the "CFDST" composite beam by Shakir-Khalil (1991) [10]. This beam design consisted of twelve columns of two concentric thin steel tubes, which were afterward filled with micro-concrete. As a result, the columns exhibited a sandwich-like configuration. The importance of conducting experimental investigations prior to undertaking composite column design in accordance with the British Standard BS5400 is emphasized in their research. The constant development is characterized by an increasing number of structural elements and varying types of loads. A predictive model was constructed to estimate the ultimate strength of Concrete-Filled Double-Skin Tubular (CFDST) members, wherein Square Hollow Sections (SHS) were utilized as both the inner and outer tubes. The diameters of the outer tubes were more extensive, and the width-to-thickness ratios were varied. The findings indicate a notable enhancement in ductility measurements, observed in both compression and bending, in comparison to ordinary hollow steel tubes. According to Zhao and Grzebieta (2002) [11], the utilization of inner tubes in CFDST has the potential to serve as a substitute for reinforcement in RCFT. The inclusion of inner tubes serves as a substitute for the function usually performed by transverse reinforcement. According to a study conducted by Han et al. in 2004 [12], the incorporation of steel tubes and sandwiched concrete in CFDST materials has been found to enhance their capacity and ductility.

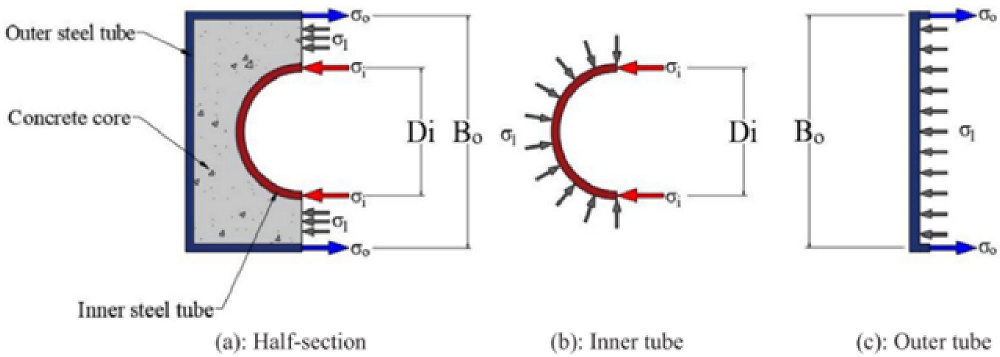

Figure 2. Free-body diagram of CFDST in S-C section (Ayough et al., 2020)

In the instance that the inner steel tubes undergo yielding prior to other components, their function as a binder for the sandwiched concrete becomes less effective, leading to a decrease in ductility values. Obtaining optimal performance is contingent on the outer steel tubes undergoing yielding prior to the inner steel tubes, a phenomenon that is regulated by the thickness ratio of these two components. The identification of critical thicknesses at which yield failure and buckling failure occur enables the control of premature failure. The determination of the thickness ratio can be conducted by applying the force balance equation and utilizing a free-body diagram, as seen in Figure 2. The analysis pertains to a CFDST column featuring a cross-sectional configuration consisting of square outer and circular inner tubes, commonly referred to as S-C [13].

In recent years, there has been a notable surge in research pertaining to earthquake engineering utilizing CFDST (Concrete-Filled Double Skin Tubes) materials. There have been progressive differences in the development of precise designs for beam-column connections utilizing the Concrete Filled Double Skin Tubes (CFDST) composite material. According to Fang et al. (2020) [14], the utilization of galvanized corrugated tubes in CFDST columns offers notable benefits in terms of corrosion resistance. Furthermore, the study demonstrates that these columns are both economically feasible and competitive in terms of their resistance to local failure and ductility. A research investigation was conducted to examine the behavior of a CFDST column featuring an octagonal cross-sectional shape. According to Alqawzai et al. (2020) [15], the inclusion of stiffeners between the inner tubes and outer tubes has been found to have a notable impact on enhancing the "stirrup effect" and mitigating the incidence of elastic-plastic local buckling in the outer tubes. The objective of the forthcoming research is to reduce corrosion by employing stainless steel material for SHS outer tubes and carbon steel for CHS inner tubes. The stress interaction within the outer cross-section of stainless steel and concrete (f_{i1}) exhibits inconsistent behavior and concentrates at the corners. According to a study conducted by Lama et al. (2022), the interaction stress induced by the outer stainless steel SHS tubes on concrete (f_{i1}) is much higher compared to the interaction stress generated by the inner carbon steel CHS tubes on concrete (f_{i2}).

In spite of all the CFDST research, there are currently no guidelines or regulations regarding the design of these composite structures; therefore, a thorough comprehension of the behavior of these materials is absolutely necessary for the development of composite structure design regulations.

2. The investigation of cross-sectional variations

2.1. Circular outer – circular inner tubes (C-C)

The aforementioned cross-sectional form is the predominant shape employed in experimental tests, as evidenced by its inclusion in 12 published studies and a cumulative sample size of 152 specimens.

In the year 1994, a total of 26 cross-sectional test specimens were utilized in the CFDST experiment. These specimens were subjected to both quasi-static loading and cyclic compression. The experiment comprised modifying the ratios of diameter to thickness for both the outer tubes (Do/to) and the inner tubes (Di/ti). The range of ratios for the outside tubes was from 43 to 169, while for the inner tubes, it was from 51 to 146. Buckling failure was observed in both the inner and outer tubes. The observed phenomenon can be attributed to the elevated ratio of diameter to thickness (D/t) and the occurrence of premature buckling within the outer tubes. Nevertheless, the presence of concrete in CFDST structures serves to enhance the cross-sectional capacity and mitigate buckling effects until the material reaches its maximum strength. The findings of the study conducted by Wei et al. (1994) [16] indicate that CFDST composite materials have a notable enhancement in their capacity, ranging from 10% to 30%, when subjected to compressive axial loads. Additionally, these materials exhibit an increase in axial strain, which ranges from around 0.5% to 1%.

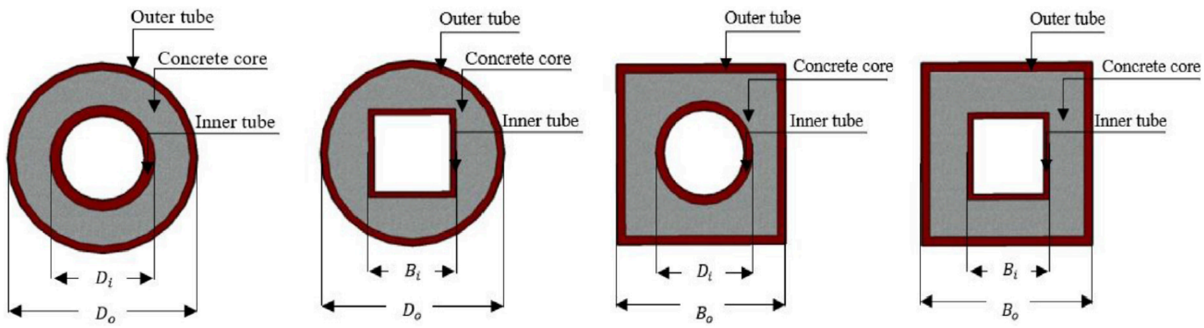

Figure 3. Details configuration of CFDST columns (Ayough et al., 2020)

The most recent study on C-C cross-sections was conducted in 2020 with a total of 23 specimens. The specimen consists of outer tubes fabricated from stainless steel and inner tubes made from high-strength carbon steel. Variables ranging from 48 to 57 are utilized for the variable "Do/to," whereas the variable "Di/ti" encompasses a range of 5 to 23. The behavior of the specimen is determined qualitatively by the type of concrete material and its ultimate capacity, which is further influenced by a rise in concrete strength. Nevertheless, differences in cross-sectional slenderness among specimens serve as the determining factor or underlying cause for these various behavioral characteristics [17].

2.2 Circular outer – square inner tubes (C-S)

Three experimental investigations have been carried out to examine the cross sections of CFDST using different types of C-S steel tubes. The test consisted of a total of 25 specimens.

In 2002, a total of eight columns were selected for experimental testing. These columns were characterized by a C-S section and have Do/to ratios ranging from 19 to 56, as well as Bi/ti values ranging from 22 to 26. The square-section inner tubes do not effectively enhance the structural integrity of the cross-sectional area. The primary variables in this experiment, specifically the slenderness of the outer tubes, have a significant impact on the determination of ductility and energy dissipation values. These values will deteriorate as the slenderness of the outer tubes increases [18].

In a study conducted in 2016, the researchers observed a range of values for the variable Do/to, which ranged between 70 and 160. Additionally, the ratio between the variables Bi/ti was found to vary between 12 and 80. The observed failure mechanism involves an outward buckle in the outer tubes and an inward buckle in the interior tubes. At the maximum ratio, specifically when Do/to = 160 and Bi/ti = 80, the ultimate strength of the CFDST specimen surpasses approximately 22% of the ultimate strength of the cross-section. It is important to note that this percentage value is affected by the Bi/Do value, as stated by Uenaka (2016) [8].

2.3. Square outer – circular inner tubes (S-C)

The cross-sectional form under consideration is the second most common, following the C-C shape, in the experimental test conducted on CFDST structures. A combined total of 30 specimens were included throughout four interrelated studies.

In 2002, a number of experiments were conducted on S-C sections. These sections were characterized by a range of values for the ratio of cross-sectional width to outer tube thickness (Bo/to), ranging from 16 to 43. Additionally, the cross-sectional diameter to inner tube thickness (Di/ti) varied from 16 to 20, and the hollowness ratio (Di/Bo) ranged from 0.48 to 0.6. The observed phenomenon involved the occurrence of local buckling in both steel tubes. The outside tubes exhibit an outward buckle, characterized by bending towards the exterior. Conversely, the inner tubes undergo both outward and inward buckling, which is occasionally referred to as *"distorted diamond"* buckling due to its resemblance to the shape of a diamond. According to a study conducted by Zhao et al. in 2002 [11], it was observed that the mechanical properties of CFDST specimens, including ductility and energy absorption, exhibited notable improvements in comparison with conventional steel tube structures.

Two years afterward, in 2004, 12 specimens with Bo/to, Di/ti, and Di/Bo exhibited varying values within specific ranges: the first combination ranged from 40 to 100, the second combination ranged from 11 to 55, and the third combination ranged from 0.27 to 0.75. In 2004, a total of 12 specimens were examined, each possessing the genetic combinations Bo/to, Di/ti, and Di/Bo. These specimens exhibited varying values within specific ranges: the first combination ranged from 40 to 100, the second combination ranged from 11 to 55, and the third combination ranged from 0.27 to 0.75. The results of the examination indicate that there are considerable improvements in the performance of CFDST in comparison to ordinary steel tubes. According to Han et al. (2004) [12], the outer tube exhibited a failure known as outer buckle type failure, however, the inner tube did not experience the typical *"elephant's foot buckling"* failure commonly observed in conventional steel tube elements. Instead, the inner tube experienced both outward and interior buckling.

In 2011, an additional study was conducted on columns using cross-sectional configurations denoted as C-C and S-C. Obviously, the experimental setup also incorporated conventional steel tubes in order to facilitate a comparative analysis. Similar to the findings of prior studies, the cross-sectional elements of the outer tubes exhibited outer buckling, whereas the cross-sectional elements of the inner tubes demonstrated "distorted diamond" buckling. These buckling phenomena were observed in the upper part of the cross-sectional area and were accompanied by the collapse of the concrete material. According to a study conducted by Han et al. in 2010 [7], the S-C specimen has more strength compared to the C-C section. However, it demonstrates lower performance when subjected to “stirrup effects”, as seen by the comparatively small circumferential strain values observed in the outer tubes.

2.4. Square outer – square inner tubes (S-S)

Extensive research has been conducted on the cross-sectional form in consideration. A combined total of 29 specimens were included throughout four related studies.

In the year 2009, a total of eight specimens were selected for analysis. These specimens exhibited Bo/to ratios ranging from 60 to 80, and Bi/ti ratios ranging from 20 to 40. The specimens were then subjected to axial compression stresses for further investigation. The behavior of the S-S section exhibits similarities to that of the S-C section, wherein the latter demonstrates enhanced ductility compared to normal steel tubes, as evidenced by a failure strain value of 0.6% [11].

The predominant form of plastic deformation is longitudinally distributed, with a relatively minor amount occurring in the upper region. This phenomenon may arise due to the comparatively reduced efficiency of the “stirrup effects”, in square inner tubes as compared to circular ones. In the context of CFDST structures with C-C sections, the hollowness ratio is a significant parameter. This ratio represents the relationship between the cross-sectional area of the concrete and the cross-sectional area subjected to loading, and it exerts a comparable influence on the structural behavior. Nevertheless, it has been observed that CFDST components featuring a cross-sectional configuration comprising square inner and outer tubes (referred to as S-S) exhibit lower cross-sectional capacity and ductility when compared to cross-sections consisting of circular inner and outer tubes (referred to as C-C) [19].

Table 1. The development of cross-sectional variations

No.	Proposed Design	References	Research Results
1.	Circular outer – circular inner tubes (C-C)	Wei et al., 1994	A comprehensive examination was conducted on a set of 26 cross-sectional test specimens, wherein these were exposed to both quasi-static loading and cyclic compression. The observed behavior can be explained by the increased ratio of diameter to thickness (D/t) and the onset of premature buckling in the outer tubes.
		Ayough et al., 2020	The experimental results of a sample size of 23 specimens were analyzed. These specimens were comprised of exterior tubes constructed from stainless steel and interior tubes composed of high-strength carbon steel. The behavior of the specimen is influenced by both the specific type of concrete material and its ultimate capacity.
2.	Circular outer – square inner tubes (C-S)	Elchakani et al., 2002	A total of eight columns were examined for experimental testing. The important variables in this experiment, namely the slenderness of the outer tubes, exhibit a substantial influence on the assessment of

No.	Proposed Design	References	Research Results
			ductility and energy dissipation measurements. The degradation of these values is expected with the escalation of the slenderness of the outer tubes.
		Uenaka et al., 2016	The failure mechanism of the outer tubes was observed to be an outward buckle, while the inside tubes exhibited an inward buckle. The experimental findings indicate that the ultimate strength of the CFDST specimen exceeds roughly 22% of the ultimate strength of its cross-section. It is essential to acknowledge that the aforementioned proportion is influenced by the Bi/Do value.
3.	Square outer – circular inner tubes (S-C)	Zhao et al., 2002	The performance was assessed across a variety of values for the ratio of cross-sectional width to outer tube thickness (Bo/to), ranging from 16 to 43. The outside tubes demonstrate an outward deformation, characterized by bending in the direction away from the center point. On the other hand, the inner tubes experience a combination of outward and inward buckling, commonly known as "distorted diamond" buckling.
		Han et al., 2004	A collective count of twelve specimens was obtained. The examination results reveal that the outside tube demonstrated a failure characterized as outer buckle type failure. Conversely, the inner tube did not manifest the conventional "elephant's foot buckling" failure.
		Han et al., 2010	An experimental investigation was carried out to investigate the behavior of columns with various cross-sectional designs. The outside tubes displayed outward buckling in their cross-sectional elements, whereas the cross-sectional elements of the inner tubes exhibited a buckling configuration referred to as "distorted diamond."
4.	Square outer – square inner tubes (S-S)	Zhao and Grzebieta, 2009	A total of eight specimens were selected for the purpose of analysis. The issue of interest pertains to stresses caused by axial compression. The behavior of the S-S section displays resemblances to that of the S-C section, where the latter showcases increased ductility in comparison to conventional steel tubes.
		Yang et al., 2012	The primary mode of plastic deformation was investigated, with a very small proportion observed in the higher region. However, it has been noted that CFDST components with a cross-sectional design consisting of square inner and outer tubes, known as S-S, have reduced cross-sectional capacity and ductility in comparison to cross-sections composed of circular inner and outer tubes.

3. Stress-strain relationships in materials

3.1. Sandwiched concrete materials

When the CFDST column experiences an external axial load (σ_1), the concrete core undergoes volumetric expansion in the lateral direction. In contrast, the presence of two steel tubes, namely the inner and outer steel tubes, serves to restrict the lateral displacement of the concrete sandwiched between them. As a result, the concrete experiences compression (σ_3). Furthermore, the flexural deformation resulting from the sandwiched concrete generates circumferential stress (σ_2). Consequently, the concrete experiences a triaxial compression, as illustrated in Figure 4. The phenomenon of confinement resulting from the presence of steel tubes is commonly referred to as "passive confinement." This term is used to describe the gradual rise in pressure due to compression, which is dependent on the increase in strain in the lateral direction. Meanwhile, during the loading process, the concept of "active confinement" emerges when the pressure consistently rises [20].

The “stirrup effect” enhances the performance of CFDST columns by increasing their ultimate strength, stiffness, ductility, and energy dissipation capabilities within the concrete core. The “stirrup effect” can dramatically enhance the strength of concrete by introducing pressure, leading to more pronounced improvements in concrete with lower compressive strength compared to high strength concrete [7], [21], [22].

The behavior of CFDST columns is hardly affected by steel, however, the selection of concrete model and material significantly impacts the outcomes. The researchers endeavored to construct a numerical model with the aim of predicting the stress-strain characteristics of sandwiched concrete.

This was achieved by making the assumption that the stress applied on lateral restraints remains constant during the loading process.

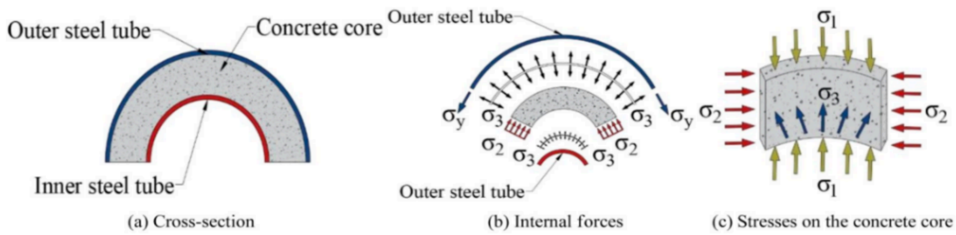

Figure 4. Free-body diagram of CFDST in C-C section (Ayough et al., 2020)

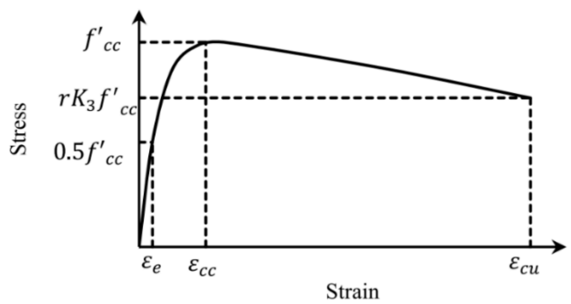

Figure 5. Stress-strain relationship of sandwiched concrete (Pagoulatou, 2014)

The stress-strain model proposed by Mander et al. (1989) [23] is capable of analyzing the pre-peak and post-peak response of sandwiched concrete subjected to compressive stresses. Mander employs the equation (1) established by Popovics (1973) [24] to establish the compressive strength of sandwiched concrete (f'_{cc}). Furthermore, the correlation between strain (ε'_{cc}) and f'_{cc} can be anticipated using equation (2). Pagoulatou et al. (2014) [25] present recommendations related to the stress-strain relationship in sandwiched concrete on CFDST columns, as depicted in Figure 5. The present model commonly employs Hooke's Law within the limits of linear elasticity, namely up to 50% of the compressive strength. The prediction of the non-linear behavior of concrete can be achieved through the utilization of equation (3) established by Saenz (1964). In this formula, the post-peak region ($\varepsilon'_{cc} \leq \varepsilon_c \leq \varepsilon_u$) is considered to exhibit a descending linear characteristic. In the Mander equation [23], the values of f'cc and εcc are utilized, with K_1 and K_2 having respective values of 4.1 and 20.5.

$$f'_{cc} = f'_c + K_1 f_1 \varepsilon'_{cc} = \varepsilon'_c\left(1 + \frac{K_2 f_1}{f'_c}\right) \tag{1}$$

$$\sigma_c = \frac{f'_{cc}\lambda\left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)}{\lambda - 1 + \left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)^{\gamma}}, \ with\ \lambda = \frac{E_c}{E_c - \left(\frac{f'_{cc}}{\varepsilon'_{cc}}\right)} \tag{2}$$

$$f_c = \frac{E_c \varepsilon_c}{1 + \left(R + R_E - 2\right)\left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right) - (2R-1)\left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)^2 + R\left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)^3}, \ with\ 0.5\,\varepsilon'_{cc} \leq \varepsilon_c \leq \varepsilon'_{cc} \tag{3}$$

3.2. Steel materials

Despite its simplicity in utilizing only two variables, namely elastic modulus (E_s) and yield strength (f_y), the elastic-plastic model is considered unsuitable for implementation in the design of strain-based continuous strength method (CSM), particularly in the instance of carbon steel tubes possessing significant thickness. Figure 6(b) demonstrates the phenomenon of linear strain hardening, wherein the slope of the strain hardening modulus (E_{sh}) remains constant within the region containing the yield strength and ultimate strength. According to Appendix C.6 in Eurocode 3 for limit state design, this model utilizes E_{sh}, which is equal to 1% of E_s. According to Boeraeve et al. (1993) [26], it is recommended to use a strain hardening modulus value of E_{sh} = 2% E_s. This suggestion is based on the assessment results obtained from many experimental stress-strain tests conducted on mild steel with a yield strength ranging from 235 MPa to 460 MPa. It is worth noting that this recommendation aligns with the one provided in the ECCS publication. The utilization of mild steel as a material model in the numerical analysis of composite columns employing carbon steel is not acceptable due to the presence of a plateau in its stress-strain curve. Conversely, high-strength steel commonly exhibits strain-hardening behavior in the absence of a yielding state plateau. According to this perspective, a number of scholars, including L. H. Han et al. (2007) [27], Khanouki et al. (2016) [28], Li and Cai (2019) [29], and Pagoulatou et al. (2014) [25], have taken advantage of a bilinear material model in their finite element simulations of CFT and CFDST columns using high-strength steel tubes.

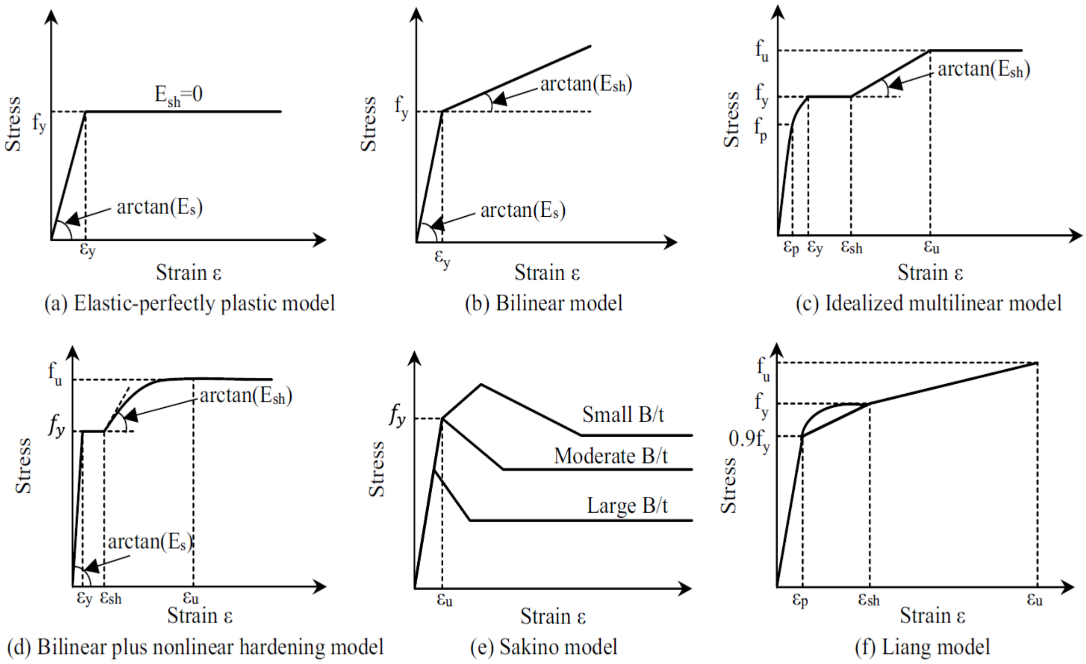

Figure 6. Schematic representation of the steel stress-strain model (Ayough, 2020)

The subsequent component is the stress-strain curve employing a multilinear model, which incorporates the presence of a yield plateau and strain hardening phenomena within the steel material. In their study, Han et al. (2011) [30] proposed a multilinear model for carbon steel in a concrete-filled tubes (CFT) column. The model comprises five different phases, as illustrated in Figure 6(c). In the present model, the steel exhibits elastic behavior beyond its limit, particularly when the applied stress (f_p) exceeds 0.8 times the yield stress (f_y). Additionally, the initial strain (ε_{sh}) associated with the onset of strain hardening is ten times greater than the yield strain (ε_y), which aligns with the recommendations provided in the ECCS publication. The aforementioned model has been employed by several researchers in their respective studies, including L. H. Han et al. (2007) [27], Li and Cai (2019) [29], Tao et al. (2011) [21], and F. C. Wang and Han (2019) [17].

Identical to the bilinear model, the multilinear model assumes a constant value for the strain hardening modulus. Nevertheless, empirical findings from steel testing indicate a gradual non-linear decline in stiffness. Consequently, Mander [23] substitutes the linear component of strain hardening with a curved response, as illustrated in Figure 6(d). In this model, a continuous hardening strain modulus is implemented, following the guidelines outlined in ECCS publications.

4. Conclusion

In accordance with the aforementioned discussions, it is possible to draw the following conclusions and present recommendations as follows.

1. The parameters examined in this study encompassed the dimensions of the outer and inner steel tubes, including their respective diameters and thicknesses. Additionally, the investigation encompassed the strength of the concrete utilized as an infill material between the steel tubes, along with the yield strength for both steel tubes. The cross-sectional capacity and ductility of square inner and outer tubes, also known as S-S, are lower in comparison to cross-sections of circular inner and outer tubes, denoted as C-C.
2. Confined concrete has much greater strength when compared to unconfined concrete. This phenomenon can be attributed to the fact that the strength exhibited by the CFDST column surpasses the combined strength of the individual components, namely the inner tube, outer tube, and concrete. The control of the strength and ductility of the concrete in the CFDST column can be achieved by adjusting both the thickness of the inner tube and the thickness of the outer tube. The thickness of the inner tube has to satisfy the minimum standard to ensure the safety of the column. In order to optimize the buckling strength of the inner tube while minimizing material usage, a potential approach is the implementation of a corrugated inner tube.
3. Considering numerous studies being undertaken regarding CFDST materials, there has recently been a lack of recognized standards or regulations regarding their design. Consequently, it is fundamental to possess a comprehensive understanding of the mechanical behavior shown by these materials in order to improve the development of design regulations for composite structures.
4. One of the factors to be taken into account considering opting for composites instead of ordinary concrete reinforcement in structural applications is the prevention of structures with excessively enormous dimensions. The capacity of the entire structure can be enhanced, and its structural behavior is more likely to accommodate higher flexural stresses due to an increased rigidity point, despite its reduced dimensions. The compressive strength of the steel was significantly enhanced by the presence of concrete encasement, according to the steel's confinement mechanism. This can potentially lead to improvements and necessitate further investigation into the requirement for viable alternative materials for building structures that require long-span constructions.

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