CONCRETE-FILLED DOUBLE-SKIN STEEL TUBES: CONFINEMENT-BASED RESEARCH AND APPLICATION

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The concrete-filled double-skin steel tubes (CFDST) inherit superior strength and high ductility from conventional concrete-filled steel tubs. These mechanical advantages are mostly based on the “composite effect”, i.e., the “confinement” provided by steel tube. This paper discusses the research conducted on the structural behaviour under various loading conditions, where the confinement effect is considered. A series of novel CFDST structures have been proposed and their structural performance has been assessed as well. The confinement factor-based design on CFDST structure is also discussed.

Keywords: Concrete-filled double-skin steel tube (CFDST), Confinement, Experiments, Theoretical research, Design approaches.

1 Introduction

The steel-concrete composite structures have been developed in construction industry all over the world in the past decades. Among various composite components using steel tubes, the concrete-filled double-skin steel tubular (CFDST) column consists of two centrally-placed outer and inner steel tubes with the concrete filled in between (Zhao and Han, 2006). It inherits several structural benefits from concrete-filled steel tubular (CFST) structure, such as high-strength, large stiffness, good fire resistance and favorable ductility. Meanwhile, the CFDST member usually has lighter self-weight and larger inner space when compared to the solid CFST one which has the same load-carrying capacity. This makes CFDST member a good choice when designing structural components with large cross-sectional profile.

The CFDST members have been used in bridges and infrastructures. They could also be used in wind turbines, offshore platforms, buildings, etc. Several codes of practice and design guides for CFDST structures have been launched (Han et al., 2018, T/CEC 185-2018), which covered various critical issues such as the selection of materials, design of members, joints, fire safety and construction methods.

This paper discusses the behaviour of CFDST structure, with emphasis on the “confinement effect” under different loads. The latest developments and innovations on CFDST structures are introduced, especially some research work in China. Some novel CFDST members, as well as the confinement-based design methods and applications are also introduced.

2 Confinement effect and member performance

The “composite action” between steel and concrete components is essential to ensure the superior structural performance of steel-concrete composite structure. For the CFST member, the outer tube provides confinement to the core concrete during loading, which not only

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enhances the strength of concrete, but also improve the ductility of the specimen. This has been recognized by many researchers (Bergmann et al., 1998, Bradford et al., 2002, Uy et al., 2011, Han et al., 2014, Liew et al., 2016). A confinement factor related with the material and geometric properties was used to describe the confinement effect provided by the outer tube qualitatively, and the confinement-based research has been carried out (Han et al. 2014).

For the CFDST member, the failure modes under different loading conditions are similar to those of CFST member, which indicates the outer tube could also provide sufficient confinement to the sandwiched concrete. On the other hand, the inner tube could provide effective support to the concrete. Therefore the behaviour of sandwiched concrete is similar to that of the core concrete (Zhao and Han, 2006). Some experimental data from stub column compressive tests have been collected and analysed. Fig.1 shows the strength indexes for CFDST stub columns with circular cross section, and the strength indexes *SI* is defined as follows:

$$SI = \frac{N_{\text{exp}}}{f_{\text{y,o}} A_{\text{so}} + f_{\text{y,i}} A_{\text{si}} + f_{\text{ck}} A_{\text{c}}} \tag{1}$$

where N_{exp} is the measured compressive strength; A_{so}, A_{si} and A_{c} are the cross-sectional area of the outer tube, the inner tube and the sandwiched concrete, respectively; $f_{\text{y,o}}$, $f_{\text{y,i}}$ and f_{ck} is the yield stress of the outer tube, the inner tube and the characteristic compressive strength of concrete, respectively. It shows most *SI* values of specimens exceed 1.0, which indicates the strength of the column as a whole is enhanced. It is owing to the "confinement effect" provided by the tube. The schematic view of CFDST cross section under compression is depicted in Fig.2.

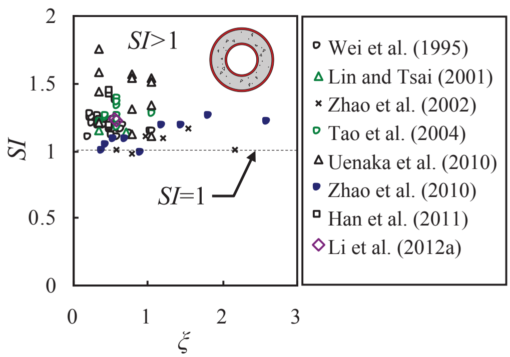


Figure 1. Strength enhancement of CFDST stub column.

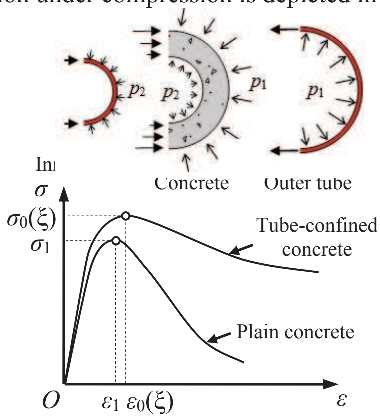


Figure 2. Confinement in CFDST cross section and concrete stress-strain (σ-ε) relationship.

In accordance with CFST columns, a nominal confinement factor ξ is introduced to express the confinement effect of the outer tube for CFDST column (Han et al., 2004):

$$\xi = \alpha_{\text{n}} \frac{f_{\text{y,o}}}{f_{\text{ck}}} \tag{2}$$

where α_{n} is the nominal steel ratio of the cross section, given by $A_{\text{so}}/A_{\text{ce}}$, A_{ce} is the cross-sectional area inside the outer tube. ξ can also be used to describe the confinement effect for columns with square or rectangular profile.

Based on the concept of "confinement effect", a stress-strain (σ-ε) model for the sandwiched concrete was used for the analytical model (Huang et al., 2010). The schematic view of σ-ε relationships for tube-confined concrete and plain concrete is presented in Fig.2. The strength and descending branch of σ-ε relationship for concrete was modified according to the confinement. This model provided the basis for the numerical analysis for CFDST structures.

The investigations were conducted for CFDST members under various static loading conditions, including compression, tension, bending and their combinations. For members under compression, the sandwiched concrete worked well with two tubes and failed in a more ductile way (Han et al., 2004; Huang et al., 2010). The buckling patterns of both tubes are changed as well. For members under tension, several parallel cracks were found in the concrete, and the increase of ultimate tensile strength was caused by the change of steel stress status (Li et al., 2014a, 2014b).

Previous experimental and numerical investigations showed that the CFDST beam-column exhibited high levels of energy dissipation capacity and ductility under cyclic loading, even when the axial load level applied was high (Han et al., 2009). The energy dissipation capacity for beam-columns with circular section was much higher than that of specimens with square one. The performance of CFDST member under impact loading was also studied. Experimental results showed that the sandwiched concrete could provide effective support to dual steel tubes. The energy which the composite member absorbed during one impact was 1.2~1.9 times that that of the hollow tube counterparts (Wang et al., 2015).

There is also strong evidence to support the existence of composite action between steel and concrete in the CFDST columns during fire exposure, which is helpful to achieve better fire performance of columns (Lu et al., 2010, Romero et al., 2015). The integrity of CFDST member can be retained even under air-blast loading, and the performance of the CFDST specimens under blast loading demonstrates their suitability for protective design (Ritche et al., 2018).

3 Confinement in Novel CFDST structures

In recent years, there are several kinds of novel CFDST members using different materials and geometries to adopt various application scenarios (Fig.3).

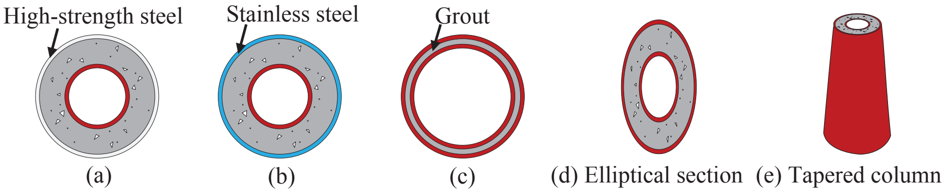


Figure 3. Some novel CFDST members.

3.1 *CFDST using high-strength steel*

The high-strength steel has gained increasing attractions from academic society and industry. The steel-concrete composite structure using the high-strength steel (HSS, yield stress greater than 460MPa) is featured with high strength, lightweight and economic benefits. The CFDST using HSS has been investigated recently (Li and Cai, 2019). Compressive tests have been conducted for stub columns, while the yield strength of outer tube was 618MPa. The confinement effect and the contact behaviour have been discussed. The results indicated that the HSS outer tube worked well with the sandwiched concrete. Similar failure modes have been achieved for CFDSTs using HSS tubes and normal-strength steel tubes, and the feasibility of the previous confined concrete σ-ε relationship on the analysis of CFDST using HSS tube has been proved. It also showed that using HSS in the outer tube was more economical as the inner tube had less strength contribution when compared to other components. Current methods could predict the compressive strength of CFDST stub columns using HSS with reasonable yet conservative accuracy.

3.2 *CFDST using stainless steel*

Stainless steel has been increasingly used in structural engineering, owing to its good anti-corrosion, durability and mechanical properties. Although the initial cost of stainless steel structures is high, the overall costing during its life time could be competitive because of the maintenance benefit. Experimental and analytical investigations were carried out on CFDST column using stainless steel in the outer tube (Wang et al., 2016; Wang et al., 2018). Comparisons were made between columns using stainless steel and carbon steel only. The enhancement was observed on strength and ductility for both circular and square sections using outer stainless steel tube, as the presence of the significant strain-hardening feature.

3.3 *Grout-filled double-skin steel tube*

In some offshore structures such as fixed jacket platforms, the outer steel tube is a part of the jacket and the inner steel tube serves as the pile. The gap between two tubes is too narrow to place concrete with normal size aggregates. The grout is usually used to fill the cavity and to enhance the structural integrity. In the past, the effect of the grout was considered as transferring the shear from outer tube to inner tube only. Li et al. (2017) conducted a series of experimental studies on the members under concentric compression, eccentric compression and bending. Although the thickness of the grout layer was small, the grout worked well with both tubes and changed the failure modes of double hollow steel tubes. The initial stiffness and ultimate strength of the grout-filled double-skin steel tubular stub column increased by 25% and 34% when compared to the hollow counterparts while the diameter of the tube was 140mm and the grout thickness was 10.5mm. It indicated that the effects of grout might be sufficiently considered in the design of new jacket platforms and the life extension of aging ones.

3.4 *CFDST with different cross sections*

Apart from the members consisted of circular- or square-section tubes, tubes with various kinds of cross sections could be used in CFDST structure to fulfills the structural or architectural demands. The typical cross sections investigated included the elliptical section, the round-end rectangular section, the dodecagonal section, etc (Han et al., 2011, Chen et al. 2015). In general the outer tube could provide confinement to the sandwiched concrete, and the columns behaved in a ductile manner.

3.5 *Inclined and tapered CFDST*

Inclined and tapered members have been used in many engineering structures, which could bring additional aesthetic and economic benefits. For the inclined CFDST columns, the inclined angle has a moderate effect on the vertical load-carrying capacity. The ductility index, which was defined as the vertical deformation when the load decreased to 85% of its ultimate by the yield deformation, decreased with the increase of inclined angle (Han et al., 2011). For the tapered CFDST columns, the ultimate compressive strength decreased significantly with the increase of the tapered angle. The ductility index also decreased, as earlier local buckling occurred on the tapered member (Li et al., 2012a, Li et al., 2013).

4 Confinement-based research

4.1 *Member under preload, sustained load and corrosion*

In the structure's whole life cycle, there are several historical loads and effects which could affect the final load-carrying capacity of the structure, such as the construction load, the long-term sustained load, the corrosive environment, etc. During the construction of CFDST column, the inner and outer hollow tubes are often erected first, followed by the placing of sandwiched concrete. Both tubes are subjected to constructional load in that stage, which causes additional stress and deformation on steel tubes (Li et al., 2012b). During the service time, the whole composite section is subjected to long-term sustained load. On the other hand, the outer tube is exposed to the corrosive environment if the CFDST member being used in onshore or offshore structure, which would cause the deterioration on the structural performance. The research has been conducted to analyse the behaviour of CFDST columns under combined preload, sustained load and chloride corrosion. Li et al. (2015) developed a special test setup to simulate the loading conditions under different stages. Finite element analysis was also conducted with consideration of several key factors, such as the confinement effect under different stages, the interaction between steel and concrete and the material loss during the corrosion. The test results were used to calibrate the numerical model, where the predicted results had generally good agreement with the measured ones in all loading stages. According to both experimental and numerical investigations, the load-deformation relation was affected by the preload, long-term sustained load, corrosion and their combinations, as shown in Fig.4. Among these factors, the corrosion had the most significant effect. The equation to calculate the ultimate strength of the column was proposed, which could provide reasonable yet conservative prediction to the column subjected to preload, sustained load and corrosion.

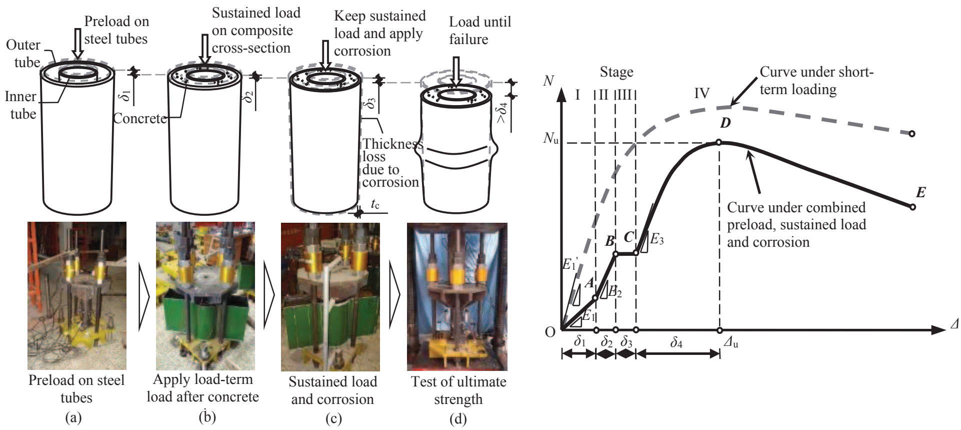


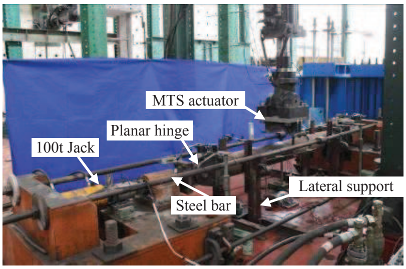
Figure 4. Member under preload, sustained load and corrosion (Li et al., 2015).

4.2 *Member under partial compression*

The CFDST member could serve as the main load-carrying column in large-span structures such as airport terminals and exhibition halls, where the top cross section of the column could be subjected to partial axial compression rather than the compression at the entire cross section. In order to discover the difference between these two loading situations, the numerical investigation has been conducted (Zhang et al., 2017). It found that for the column subjected to partial compression, the confinement provided by outer tube took place at the beginning of loading. However, the ultimate strength of partial compressed column was lower than that of the fully compressed one, as the local buckling of tube and the crush of concrete occurred earlier. A simplified equation has been drawn based on the parametric analysis. The overall structural behaviour was affected by several key parameters, while the thickness of endplate had the most significant influence. The comparison between numerical and equation-calculated results showed that the proposed equation could predict the ultimate strength of column under partial compression with reasonably good accuracy.

4.3 *Member under post-fire cyclic loading*

The repairing of fire-damaged structures with minimum cost is a challenge of structural practitioners, especially for those structures in areas with high seismicity. The mechanical properties of steel could partially recover after fire, while those of concrete might hardly restore. Meanwhile the load-carrying capacity under earthquake is usually less than that under static loading due to the accumulative damage under cyclic loading. The knowledge on the cyclic behaviour of CFDST member after exposed to fire is rather limited. Li et al. (2019a) conducted experiments on 12 CFDST specimens subjected to post-fire cyclic loading. The fire tests were conducted first. After the fire tests, the specimens were subjected to the lateral reverse cyclic loading at the middle and the constant load along the member (Fig. 5). It found that in general the post-fire CFDST column had ductile manner, as the partial recovery of the material mechanical properties as well as the composite action between steel tubes and sandwiched concrete. The damage of the concrete was severer when the heating period was longer. For the specimens with the heating period of 120 mins, the concrete was crushed into large pieces after cyclic loading. The increase of heating period caused significant decrease on the strength and the energy dissipation capacity, while its influence on the member stiffness was limited. The post-fire structural performance could be estimated by summarizing the contribution of different components, while the post-fire material properties were tentatively used. A simplified model was also established to calculate the initial flexural stiffness, which could provide reasonable prediction for CFDST columns after exposure to fire.



Experimental photo (Li et al., 2019a)

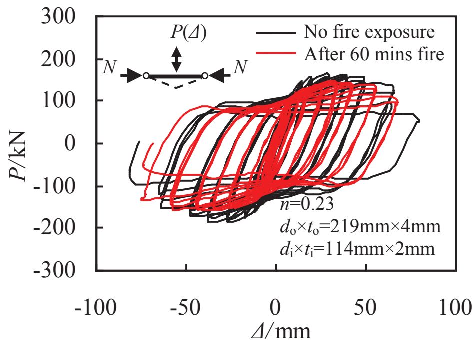


Figure 5. Member under post-fire cyclic loading.

4.4 *Joint under impact loading*

The CFDST member could serve as chord in truss structures. Some truss structures such as electricity tower or offshore jacket could be subjected to vehicle/ship collision or external impacts during their service life. In those circumstances, the welded tubular joint plays an important role in load transfer. Li et al. (2019b) investigated the behaviour of composite T-joints under impact loading for offshore structures, where the grout-filled double-skin steel tube was used in chord and the steel hollow section was used in brace. The experimental results showed that the stiffness and resistance of the T-joint was significantly enhanced by the sandwiched grout. The average maximum mid-span deflection decreased by 44% and the impact force of the plateau increased by 37% as the presence of the grout. Three major failure patterns were identified from both experimental and numerical results, as shown in Fig.6. The global flexural deformation was increased with the increase of the impact energy, while the impact momentum had minor effect. The results also showed the impact force decreased and the global deformation increased with the increase of the axial load level of chord.

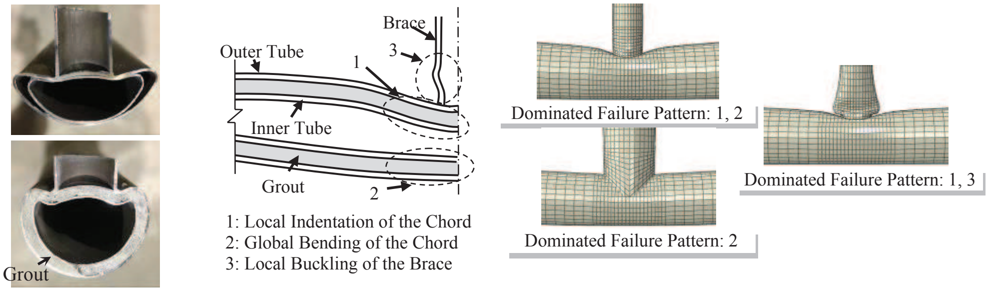


Figure 6. Joint under impact loading (Li et al., 2019b).

5 Confinement-based design

CFDST structures have gained increasing applications recently. The CFDST member could serve as the main load-resisting component in various kinds of structures, as shown in Fig.7.

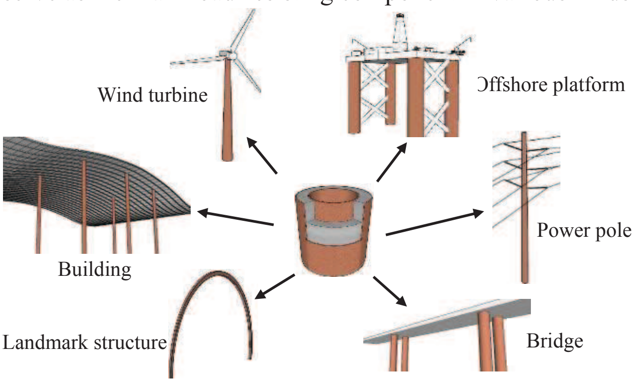


Figure 7. Application of CFDST structure.

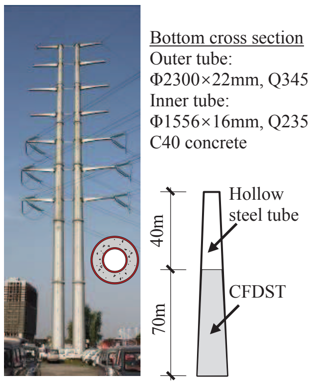


Figure 8. CFDST pole.

In the design of CFDST structures, the confinement effect has been recognized and the design confinement factor ξ_0 (=$\alpha_n \cdot f_o/f_c$, f_o is the design value for tensile, flexural and compressive strength for the steel of outer tube and f_c is the design value of concrete strength) was introduced in the calculation. For instance, the cross-sectional compressive strength of CFDST can be evaluated as follows (Han et al., 2018):

$$N_u = f_{osc} \cdot (A_{so} + A_c) + f_i \cdot A_{si} \tag{3}$$

$$f_{osc} = C_1 \cdot \psi^2 \cdot f_o + C_2 \cdot (1.14 + 1.02\xi_0) f_c \tag{4}$$

where $C_1=\alpha/(1+\alpha)$; $C_2=(1+\alpha_n)/(1+\alpha)$; $\alpha=A_{so}/A_c$; f_i is the design value of tensile, flexural and compressive strength for the steel of inner tube; ψ is the hollow ratio with the range of 0~0.75, defined as $(D_o\text{-}2t_o)/D_i$; D_o, D_i is the diameter of the outer and inner tube, respectively; t_o is the thickness of outer tube. The equation can also be used to predict the strength of CFDST member using high-strength steel.

Fig.8 shows the application of CFDST columns in power poles, where the total height and the maximum diameter of the pole is 110 metres and 2.3 metres, respectively. It is difficult to design with the single hollow steel tube unless tube with very large wall-thickness is applied. The CFDST pole uses less steel than the bare steel one, and the tube with thinner wall thickness can be applied. Moreover, the total overall weight is lighter than CFST one, therefore the cost of the foundation can be reduced. The compressive strength of CFDST column increases by approximately 20% than the hollow tubular one, which meets the requirement of the design.

6 Concluding remarks

The scope of concrete-filled double-skin steel tube has been widely extended by researchers and engineers in recent years. In general, the CFDST structure possesses favourable performance under various loading circumstances owing to the "confinement effect" between tube and concrete. Using advanced materials and improving design methods could prompt the development of this steel-concrete composite structure. The application of high-strength steel, stainless steel and some other high-performance materials could not only enhance the mechanical performance, but also bring social or environmental benefits. The CFDST structure can serve as a superior alternative system to the steel or concrete-filled steel tubular ones in some specific engineering applications. Further study should focus on the connection behaviour, the hybrid structural system using high-performance materials, the structural behaviour under extreme loading as well as the life-cycle structural performance.

Acknowledgments

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