Journal of Constructional Steel Research 83 (2013) 127–136

Contents lists available at SciVerse ScienceDirect

Journal of Constructional Steel Research

Behavior and calculation of tapered CFDST columns under eccentric compression

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ARTICLE INFO

Article history:
Received 4 November 2012
Accepted 22 January 2013
Available online 21 February 2013

Keywords:
Concrete-filled double skin tube (CFDST)
Concrete
Tapered column
Eccentric compression
Stability
Equivalent column

ABSTRACT

The tapered concrete-filled double skin steel tubular (CFDST) columns have been used in transmission towers with potential for other types of composite frame structures. However, the behavior of the tapered CFDST column under eccentric compression has not yet been studied, which will hinder the employment of such members. This paper reports an investigation on eccentrically loaded tapered CFDST columns with different load eccentricities. The numerical investigation was also carried out by using the finite element model to predict the behavior of the tapered member. Comparisons were made between the tapered and straight members on the strength and stress distribution. The stability of the tapered column was studied through numerical calculation. Finally, the load carrying capacity of the tapered CFDST column under eccentric compression was predicted using the concept of "equivalent column".

1. Introduction

Concrete-filled double skin steel tubular (CFDST) columns have been used in transmission towers in China, as shown in Fig. 1. They can be also used as members in other structures such as frames and trusses. These members inherit advantages from conventional concrete-filled steel tubes (CFST) and are characterized by a smaller self-weight. It might also be a better solution than the solid members when dealing with members of large cross-sectional profile. The behavior of this kind of steel and concrete composite member has been studied by many researchers, such as Wei et al. [1], Zhao and Han [2], Zhao et al. [3], Han et al. [4,5] and Tao et al. [6]. Reasonable static, dynamic and fire resisting capacities have been shown for the CFDST members. Therefore, the CFDST members could be used in engineering projects such as bridges, high-rise buildings, and tower structures etc.

In the previous study, the researchers have revealed that for the CFDST member with uniform cross-sectional profile along the member (referred as "straight member" in this paper), the outer tube provides an effective confinement to the concrete, and the inner tube also provides a support when the concrete expands. The tapered members have their specific characteristics although some similarities exist when compared to the members with uniformed cross section. Han et al. [7] have conducted a study on the behavior of tapered CFST columns under axial compression, as well as tapered stainless steel composite columns [8]. For the tapered CFDST stub column, Li et al. [9] have conducted experimental and numerical investigations. The results showed that the concrete and the outer and inner tubes could work together well despite the tapered angle. Within the tapered angle investigated (0–9°), the outer tube could provide effective confinement and the inner tube could provide support to the concrete. When the wall thickness of the tube was uniformed along the longitudinal direction of the member, the strength of tapered stub column was controlled by the "critical cross section", which was the cross section with the minimum sectional area.

In recent years, although the tapered CFDST column has been used in the engineering projects, there's a lack of understanding on the behavior of the tapered CFDST long column under eccentric compression. Therefore it is important to study the differences in the compression and bending behavior of the CFDST long columns as compared to the non-tapered ones, and the concept of "equivalent straight column" for the tapered column should be necessarily rethinked.

The tapered member dealt with in this study is such where the cross-section profile is variable along the axial direction but the wall thickness of the inner and outer tubes remains constant. In comparison, the "straight member" referred to is the one with a uniform cross-section along the height of the member. The objectives of this research are threefold: (i) to provide a new series of experimental results on tapered CFDST long columns under eccentric compression, including the failure mode and the load versus deformation curves of the specimens; (ii) to study the column behavior using the verified numerical model, including the stress distribution and the confinement effects of the tubes; and (iii) to

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http://dx.doi.org/10.1016/j.jcsr.2013.01.010

Notations

D	Diameter of outer circular steel tube
D_b	Diameter of outer circular steel tube for the bottom cross section (mm)
D_t	Diameter of outer circular steel tube for the top cross section (mm)
d	Diameter of inner circular steel tube
d_b	Diameter of inner circular steel tube for the bottom cross section (mm)
d_t	Diameter of inner circular steel tube for the top cross section (mm)
E_c	Young's modulus of concrete
E_s	Young's modulus of steel
EI_{sc}	Flexure stiffness for CFDST cross section ($=E_sI_{so}+E_cI_c+E_sI_{si}$)
e	Load eccentricity
f_{ck}	Characteristic concrete strength ($f_{ck}=0.67\ f_{cu}$ for normal strength concrete)
f_{cu}	Characteristic 28-day concrete cube strength
f'_c	Concrete cylinder strength
H	Column height
H_{eq}	Height of non-tapered column equivalent to the tapered one
I_c	Second moment of area of concrete
I_{si}	Second moment of area of inner steel tube
I_{so}	Second moment of area of outer steel tube
l	Column effective length
M_{ue}	Average bending moment of CFDST column
N	Axial compressive load
N_E	Elastic critical strength for straight CFDST column
N_{Et}	Elastic critical strength for tapered CFDST column
N_{ue}	Average ultimate strength of CFDST column
$N_{u,FEA}$	Predicted ultimate strength of CFDST column by finite element model
N_{um}	Observed ultimate strength of CFDST column
t_{so}	Wall thickness of outer steel tube
t_{si}	Wall thickness of inner steel tube
Δ	Axial deformation of the column
ε	Strain
θ	Tapered angle
γ	Tapered ratio, $\gamma=(D_b–D_t)/D_t$
χ	Hollow ratio, given by $d/(D\text{-}2t_{so})$

study the elastic stability of the tapered column, and to discuss the column capacity by using the concept of “equivalent columns”.

2. Experimental program and test results

2.1. Experimental program

The aim of the current experimental program is to study the behavior of CFDST beam-column with hinged supports at both ends. Twelve specimens were tested, including 2 specimens of straight column and 2 tapered specimens without concrete filling. The schematic view of the test specimen is shown in Fig. 2(a), where D_t and d_t are the diameters of the outer and inner tubes for the circular hollow section (CHS) at the top, respectively; D_b and d_b are the diameters of outer and inner tubes for CHS at the bottom, respectively; H is the column height; θ is the tapered angle; e is the load eccentricity; and t_{so} and t_{si} are the wall thicknesses of outer and inner tubes, respectively.

The hollow ratio (χ) for the composite cross sections varies from 0.59 to 0.68, where χ is defined as $d/(D\text{-}2t_{so})$. D and d are the diameters of the outer and inner tubes, respectively. The tapered angle (θ) varies between 0 and 0.57°, and the height of the column varies from 1750 mm to 3500 mm. The main experimental parameter is the load eccentricity. The details of the specimens are listed in Table 1.

For the manufacture of tapered steel hollow section, the fan-shaped steel was cut off from plates and tack welded into a circular cross section with a single bevel butt weld. The inner and outer tubes were welded to thick steel base plate at the bottom before the concrete placement.

The wall thicknesses of the inner and outer steel tubes are 2.92 mm and 3.82 mm, respectively. The material properties, i.e., the average yield strength, the ultimate strength, the elastic modulus and the Poisson's ratio are listed on Table 2.

Self-consolidating concrete (SCC) was filled into the gap between the outer and inner tubes. The specimen was placed upright while the concrete was placed without any vibration. The mix proportions were as follows: cement: 385 kg/m^3, blast furnace slag: 165 kg/m^3, water: 190 kg/m^3, sand: 785 kg/m^3, coarse aggregate: 850 kg/m^3, and additional high-range water reducer (HRWR): 5.5 kg/m^3. The cubic compressive strength (f_{cu}) of the SCC at 28 days is 50 N/mm^2. The modulus of elasticity (E_c) of concrete was 33,000 N/mm^2. The concrete cubic strength at the test time is 64 N/mm^2.

A 5000 kN hydraulic ram was used to apply the eccentric load. The hinged supports were applied to simulate the boundary conditions of the beam-column specimen. The specimen was placed in the testing machine and the eccentric load was applied through knife-edge hinges at the ends. A schematic view of the test setup is shown in Fig. 2(a), and a photograph is shown in Fig. 2(b). Twenty-four strain gauges were placed on the outer tube to measure the strains on the cross sections at 1/4, 1/2 and 3/4 heights for each specimen. These cross sections are denoted as cross section 3–3, 2–2 and 1–1, respectively. There were 8 gauges on each cross section, including 4 longitudinal and 4 transverse gauges, as shown in Fig. 2(a). The top and bottom cross sections are denoted as cross section A–A and B–B, respectively. Two displacement transducers were placed vertically to observe the vertical deformation of the specimen in the loading direction, while three displacement transducers were placed to measure the horizontal deformation of the specimen. A load interval of less than one tenth of the estimated load carrying capacity was applied before the column was yielded. After the yielding, the loading was controlled by displacement control method. The unloading stage of each specimen was recorded. The loading was terminated for the safety reason when one of the instances was reached: 1) axial load fell to about 65% of the peak load; 2) weld failure occurred.

2.2. Test results

All specimens behaved in a ductile manner. The photographs of typical failure modes of the specimens are shown in Fig. 3(a). It can be seen from Fig. 3(a) that, the overall buckling is observed for the tapered column under eccentric loading. In Fig. 4, the bending curvatures of the tapered and straight specimens are shown when the load decreases to 85% of the ultimate value, where the transverse deflection at the middle height is denoted as u_{mid}. It can be seen from Fig. 4 that, for the straight member, the maximum horizontal deformation appeared at the middle of the specimen, and was very close to the half-sinusoid curve. For the tapered member, the maximum deformation occurred near cross section 1–1, depending on the tapered angle. No obvious local buckling was found in the inner tube. Both inner and outer tubes provided efficient supports to the concrete, no cracking or crushing was observed for the concrete except in the cross section where the maximum transverse deflection appeared. No cracking or slipping was observed in the interfaces between the tubes and concrete, even in the failure zones. The steel tubes and concrete worked together very well despite the tapered angle. For the hollow section tubes without filling concrete, both outward and inward buckling was observed on the tubes due to the lack of support by the concrete.