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Behaviour and design of concrete-filled mild-steel spiral welded tube short columns under eccentric axial compression loading

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ABSTRACT

Spiral-welded steel tubes (SWTs) are fabricated by helically bending a steel plate and welding the resulting abutting edges. These tubes enable larger diameters, longer joint-less lengths, smaller dimensional tolerances, and more cost-effective construction compared to other types of steel tubes. Notwithstanding this, the use of SWTs for concrete-filled steel tubes (CFSTs) has been rather limited. Many international design standards contain guidelines on strength assessment of CFST columns. Even so, unlike for other tube types, there is a lack of experimental verification of the applicability of those guidelines for concrete-filled spiral welded steel tube (CF-SWST) columns. This has inhibited their widespread use, especially since the residual stresses in SWTs are generally larger than for other tubes. Given this context, twelve self-compactingCF-SWST short columns with nominal diameters (D)equal to 102, 152, 203 and 229 mm were tested under axial compression, considering load eccentricities of 0, 0.15D and 0.4D. The tube walls were nominally 2 mm thick while the effective length to diameter ratios were in the range 4.5–6.0. A ductile failure mode was observed for all the tests consisting of flexural local buckling in the maximum compression region, which was observed during post-peak deformation. The spiral weld seam was observed to neither provide a preferential location for failure nor be detrimental to the strength capacity. On average, the predicted capacities as per six commonly used international standards agreed well with the experimentally obtained values. The predicted capacities were observed to be more conservative for eccentric loading compared to concentric loading. For eccentric loading, fibre-element analyses using material models proposed for confined concrete provided better predictions of the actual capacity. This suggested that greater confinement benefit than considered in the codes is effective for eccentrically loaded CF-SWST short columns. The study provided evidence of equivalent behaviour of CF-SWST columns to other tested CFSTs and the applicability of existing guidelines for assessing their strength.

1. Introduction

Circular concrete-filled steel tubes (CFSTs) have widely been used in the construction industry over the years as structural columns. Such CFST columns have found applications in electrical transmission towers, buildings, bridge piers, and piled foundations [1]. CFSTs used as columns are advantageous as they provide enhanced strength capacity, ductility and speed of construction [2]. The strength enhancement occurs due to the confinement of the concrete core by the steel tube and also since the local buckling mode of the tube wall is constrained to be an outward one [3]. The published literature contains a large number of investigations which looked into the structural behaviour of CFST columns under different loading types [2,3]. These include monotonic and cyclic loading of columns under pure axial compression or combined axial compression and bending moment.

The steel tubes that were used for the CFSTs in the afore-mentioned investigations were overwhelmingly either longitudinally seam-welded tubes (LWTs) or seamless tubes. An alternative form of steel tube is the spiral welded tube (SWT). First patented in the late 1870s [4], SWTs are fabricated using steel plates which are bent into the shape of a helix and welded along the resulting abutting edges. On an industrial scale, the fabrication of these tubes is typically carried out using a process similar to that shown in Fig. 1 [5]. The helical seam is typically welded both from the outside as well as the inside of the joint using tandem submerged arc welding (SAW) [6]. The afore-mentioned process of double-sidedSAW is typical for SWTs with larger diameters, ranging from 600 mm to 3000 mm where the tube wall thickness varies from 6 to 25 mm [5,7]. SWTs of smaller diameters (76–1524 mm) and thinner walls (1.2–5 mm) are also available [8]. Due to space limitations, for these smaller diameters, welding of the spiral weld seam is typically only carried out from the outside of the joint and commonly using

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Nomenclature

A_s	Cross sectional area of steel tube
A_c	Cross sectional area of concrete core
C_3	Factor used in AISC-360 to calculate bending stiffness of CFSTs
CFST	(Circular) Concrete Filled Steel Tube
D	Outside diameter of steel tubes
DI	Ductility index
e	Eccentricity of applied axial load
$e_{initial}$	Initial eccentricity of applied axial load
e_{eff}	Effective eccentricity of applied peak load at mid-height
$e_{eff\_predict}$	Predicted effective eccentricity at peak load at mid-height
E_c	Concrete modulus of elasticity
E_s	Steel modulus of elasticity (=200 GPa)
EI	Bending stiffness of column
f'c	Characteristic concrete cylinder compressive strength
fc'	Specified compressive strength of concrete
f_{ck}	Characteristic concrete cylinder compressive strength
$f_{ck,cu}$	Characteristic concrete cube strength (=0.67 f_{cu})
f_{cm}	Mean concrete cylinder compressive strength
f_{cu}	Mean concrete cube strength
f_{sy}	Yield strength of steel
f_u	Ultimate tensile strength
f_{yL}	Lower yield strength
f_{yH}	Upper yield strength
I_s	Second moment of area of steel tube
I_c	Second moment of area of concrete core
$K_{initial}$	Initial axial stiffness of CF-SWST
L	Length of steel tube/SWT
L_e	Effective column length
LWT	Longitudinally welded tube
M	Bending moment
M_{mh}	Moment at mid-height section
M_{mh_pmax}	Moment at mid-height at P_{max}
M_{sx}	Pure flexural capacity calculated as per AS5100.6
m	Empirical coefficient (=4.0)
N_{us}	Nominal section capacity under pure axial compression as per AS5100.6
N_{uc}	Nominal un-enhanced member capacity under pure axial compression as per AS5100.6 (=$\alpha_c N_{us}$)
P	Applied axial load
P_{max}	Peak axial load during tests
$P_{predicted}$	Predicted axial capacity
t	Wall thickness of tube
SAW	Submerged Arc Welding
SWT	Spiral Welded Tube
CF-SWST	Concrete filled spiral welded steel tube
s	Distance across section height measured from extreme compressive fibre
ULS	Ultimate limit state
y	Distance across section height measured from extreme compressive fibre
α_c	Member slenderness reduction factor as per AS5100.6
β	Empirical factor
δ_b	Moment magnification factor
δ_{h_pmax}	Measured mid-height lateral displacement at peak axial load
δ_h	Measured mid-height lateral displacement
δ_s	Steel contribution ratio
δ_v	Measured axial displacement
δ_{v1}	Measured axial displacement at 0.9P_{max} at deformations below the peak load
δ_{v2}	Measured axial displacement at 0.9P_{max} at deformations above the peak load
ε_y	Strain at first yield
ε_u	Strain at fracture
ε_{trans}	Measured circumferential strain
ε_{long}	Measured longitudinal strain
γ_c	Strength reduction factor for concrete
γ_s	Strength reduction factor for steel tube
κ	Curvature
λ_e, λ_{ey}, λ_{emax}	Section, yield and maximum allowable slenderness as defined in AS5100.6
σ_c	Concrete stress level in plastic stress distribution
σ_{cc}	Maximum confined concrete strength
σ_{sc}	Steel compressive stress level in plastic stress distribution
σ_{st}	Steel tensile stress level in plastic stress distribution
σ_{lat}	Lateral confining pressure acting on concrete core
σ_{trans}	Transverse (circumferential) stress in steel tube
ξ	Factor to take into account constraining effect of steel tube on concrete core

metal inert gas welding. Nevertheless, a full penetration through thickness weld is still achieved through this process.

SWTs offer many advantages compared to their alternatives. Unlike LWTs, SWTs of a range of different diameters can be formed using a plate of the same width by simply changing the forming angle. This results in tubes with much larger diameters being possible. SWTs have also been reported to be more cost effective, faster to produce, and able to achieve smaller dimensional tolerances [9,10]. They can also be fabricated to any length that is practicable. Hollow carbon-steel SWTs have been widely used for structural engineering applications such as pile foundations [11–13], soil and water retaining structures [7], and wind turbine towers [10]. However, despite their numerous advantages, reported instances in the industry for which SWTs have been used for CFSTs are rather limited [11,14].

In addition, compared to CFSTs containing either LWTs or seamless tubes, only a limited number of investigations have been reported in the published literature which looked into the behaviour of concrete-filled spiral welded steel tube (CF-SWST) columns [15–19]. This is also true for hollow SWT columns [15,20]. In contrast, the flexural behaviour of hollow SWTs has previously been investigated [21–24]. All previous investigations of CF-SWST columns, details of which are given in Table 1, were carried out under concentric axial loading. No study has been reported in the literature which considered eccentric axial loading behaviour of either hollow or concrete-filled SWTs. This is a significant shortfall since any practical column is in general an eccentrically loaded one, due to unavoidable construction tolerances. There are many international codes of practice which contain guidelines for the design of mild steel and higher-strength steel CFST columns [25–30]. Even though this is the case, there is a lack of experimental verification of the suitability of these standards to assess the behaviour of CF-SWST columns. This has inhibited the wide scale adoption and application of SWTs in CFSTs, in spite of their many benefits. Obtaining experimental verification of the behaviour CF-SWST columns is especially important since the magnitude of residual stresses in SWTs can be larger compared to other tube types. High levels of residual stresses relative to the yield strengths have been reported for SWTs, though the stresses were found to be localised in the weld zone [31–35]. The effects of these residual stresses, which are often detrimental [19], are not apparent until the respective SWT (or CF-SWST) is under load [31].

However, investigations into hollow SWT columns found that the observed failure mode was similar to that reported for other types of hollow steel tubes. The failure behaviour reported in the literature for CF-SWST