Engineering Structures 134 (2017) 159–171

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Flexural behaviour of concrete-filled stainless steel SHS and RHS tubes

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ARTICLE INFO

Article history:
Received 7 April 2016
Revised 17 December 2016
Accepted 19 December 2016

Keywords:
Concrete-filled
Ductility
Flexural behaviour
Midspan deflection
Square and rectangular hollow section
Stainless steel

ABSTRACT

This paper presents an experimental investigation on flexural behaviour of concrete-filled stainless steel square and rectangular hollow section (SHS and RHS) tubes under uniaxial bending. A total of 24 specimens including 16 concrete-filled stainless steel SHS and RHS flexural members and 8 empty stainless steel SHS and RHS flexural members were tested. The ultimate strengths, failure modes, flexural stiffness, ductility, bending moment-midspan deflection curves, overall deflection curves and strain distribution curves of test specimens are reported. It is demonstrated that the ultimate strength, initial stiffness and ductility of empty stainless steel SHS and RHS flexural members are significantly enhanced by filling the concrete in the specimen along its full length. The enhancement is increased with the increase of the thickness of the SHS and RHS tube. Furthermore, the concrete strength has little influence on the ultimate strength, initial stiffness and ductility of concrete-filled stainless steel SHS and RHS flexural members. The test flexural stiffness including both initial flexural stiffness and flexural stiffness at the serviceability limit state of concrete-filled stainless steel SHS and RHS tubes under uniaxial bending are compared with the design flexural stiffness calculated using the current AIJ standard, BS 5400, Eurocode 4 and AISC specification for concrete-filled steel tubes. It is shown from the comparison that the current design rules are all unconservative for initial flexural stiffness and flexural stiffness at the serviceability limit state of concrete-filled stainless steel SHS and RHS tubes under uniaxial bending with high scatter of predictions.

1. Introduction

Stainless steel has unique characteristics of aesthetic appearance, high corrosion resistance, superior ductility, excellent fatigue and fire resistances compared to mild steel. However, the use of stainless steel in the structural applications is rather limited owing to its high material costs [1]. Concrete filling is one of the commonly used strengthening methods which could be used for stainless steel structures to greatly improve the structural behaviour on the one hand, and effectively reduce the amount of stainless steel used in the structure. Therefore, concrete-filled stainless steel tube is the optimum choice to facilitate the use of stainless steel and offset the higher material costs of stainless steel, in which concrete-filled stainless steel square and rectangular hollow sections (SHS and RHS) have been employed in the field of civil engineering [2].

Extensive researches were conducted on concrete-filled stainless steel tubes. Extensive researches have been conducted in recent years on the static behaviour of short [3–13] and slender [14–17] concrete-filled stainless steel tubular columns under axial compression. The aforementioned studies were all conducted on the compressive behaviour of concrete-filled stainless steel tubes. There is little research being carried out on the flexural behaviour of concrete-filled stainless steel tubes. The pure uniaxial bending tests were conducted by Asgar [6] on concrete-filled stainless steel beams. A total of 8 specimens including 4 concrete-filled stainless steel SHS flexural members and 4 empty stainless steel SHS flexural members were tested. This paper focuses on the flexural behaviour of concrete-filled stainless steel SHS and RHS tubes under uniaxial bending. The corresponding empty stainless steel SHS and RHS flexural members were also tested under uniaxial bending for comparison. The ultimate strengths, failure modes, flexural stiffness, ductility, midspan deflections and strain distributions of all specimens are reported in this study. The ultimate strength and initial stiffness of empty stainless steel SHS flexural members are significantly enhanced by filling the concrete in the specimen because of reinforcement of stainless steel on concrete. The test results are used to compare with calculated results by using the current design specifications for the concrete-filled stainless steel SHS and RHS flexural members.

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http://dx.doi.org/10.1016/j.engstruct.2016.12.035

Nomenclature

A_s	cross-section area of steel tube
A_{sc}	cross-section area of concrete-filled steel tube
b	overall width of stainless steel SHS and RHS tube
h	overall depth of stainless steel SHS and RHS tube
r	radius of corners of SHS and RHS tubes
E_c	elastic modulus of concrete
E_s	elastic modulus of steel
f_c'	concrete cylinder strength
f_{cu}	concrete cube strength
f_u	ultimate tensile stress of stainless steel
f_y	tensile yield stress of stainless steel
I_c	moment of inertia of concrete infill
I_s	moment of inertia of steel tube
K	flexural stiffness
K_{AIJ}	flexural stiffness calculated using AIJ standard
K_{AS}	flexural stiffness calculated using AISC specification
K_{BS}	flexural stiffness calculated using BS 5400
K_{EC}	flexural stiffness calculated using Eurocode 4
K_i	initial flexural stiffness
K_s	flexural stiffness at serviceability limit state
L	overall length of specimen
L_e	effective span of specimen
M	bending moment
M_u	ultimate bending moment
M_{u0}	ultimate bending moment of empty stainless steel SHS and RHS flexural member
$M_{u1.1}$	ultimate bending moment of specimens with SHS and RHS tube thickness of 1.1 mm
$M_{u1.5}$	ultimate bending moment of specimens with SHS and RHS tube thickness of 1.5 mm
M_{u30}	ultimate bending moment of concrete-filled stainless steel SHS and RHS flexural member with nominal concrete cube strength of 30 MPa
M_{u50}	ultimate bending moment of concrete-filled stainless steel SHS and RHS flexural member with nominal concrete cube strength of 50 Mpa
M_y	bending moment at yield load
P	axial compression force
t	wall thickness of stainless steel tube
v	Poisson's ratio
Φ	midspan curvature
Φ_u	midspan curvature at ultimate load
Φ_y	midspan curvature at yield load
δ	vertical deflection
δ_m	midspan vertical deflection
δ_u	midspan vertical deflection at ultimate load
δ_y	midspan vertical deflection at yield load
ε	strain
ε_y	yield strain
μ	ductility (δ_u/δ_y)

2. Experimental investigations

2.1. Test specimens

A total of 24 specimens including 16 concrete-filled austenitic stainless steel SHS and RHS tubes and 8 empty austenitic stainless steel SHS and RHS tubes were tested under uniaxial bending. The SHS and RHS tubes consist of three different cross sections of 100×100, 80×80, 60×60 and one cross section of 100×50, respectively, with two different wall thicknesses (t) of 1.1 and 1.5 mm. The overall length (L) of all specimens is 1000 mm for comparison, with the effective span (L_e) between the end supports of 900 mm. The measured cross-section dimensions of all specimens are summarized in Table 1, using the nomenclature defined in Fig. 1 for concrete-filled stainless steel SHS and RHS tubes. EC3 (part 1–4) specification for stainless steel has provided accurate evaluation to the experimental values of bare stainless steel SHS and RHS tube, then the effect of the distortion is insignificant.

2.2. Specimen labelling

All specimens were fabricated by using Technical Specification for Stainless Steel Structures (CECS410-2015). The specimens are labelled according to their cross-section shape, cross-section dimensions and concrete infill. For example, the label 'S100 × 100 × 1.1C0' defines the following specimen:

- The first letter 'S' indicates that the cross-section shape of the specimen is square hollow section. If the letter is 'R', it indicates that the cross-section shape of the specimen is rectangular hollow section.
- The following expression '100 × 100 × 1.1' indicates the cross-section dimensions of the specimen, which have the nominal overall width (b) of 100 mm, the nominal overall depth (h) of 100 mm, and the wall thicknesses (t) of 1.1 mm.
- The last notation 'C0' indicates that there is no concrete in the specimen. If the notation is 'C30', it indicates the nominal concrete strength of 30 MPa filled in the specimen; If the notation is 'C50', it indicates the nominal concrete strength of 50 MPa filled in the specimen. The prefix letter 'C' refers to concrete.

2.3. Material properties

Tensile coupon tests were conducted to determine the mechanical properties of the hot-rolled seamless austenitic stainless steel tubes. The coupons were taken from the SHS and RHS tubes in the longitudinal direction and tested according to the recommendations of Chinese Code of Metallic Materials (GB/T 228.1-2010) [18]. The material properties obtained from the tensile coupon tests are summarized in Table 2, which include the elastic modulus (E_s), the tensile yield stress (f_y), the ultimate tensile stress (f_u), and the Poisson's ratio (v). Stress-strain curve of typical stainless steel coupon test is shown in Fig. 2.

The concrete-filled stainless steel SHS and RHS tubes were fabricated by filling the concrete with nominal cube compressive strengths of 30 MPa and 50 MPa in the hollow tubes along their full length. The concrete mix includes 425# ordinary Portland cement (compressive strength no less than 42.5 MPa), medium-coarse sand, and coarse aggregate with diameter ranged from 5 to 15 mm. The material properties of concrete were determined from compressive concrete cube tests. Standard concrete cubes with the nominal side length of 150 mm were prepared and tested based on the recommendations of Chinese Standard on Ordinary Concrete (GB/T 50081-2002) [19]. The material properties of the standard concrete cubes are summarized in Table 3, in which the mean values of the measured concrete cube strengths (f_{cu}) are 40 MPa and 51 MPa for the nominal cube strengths of 30 MPa and 50 MPa, respectively.