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Flexural behaviour of concrete-filled stainless steel CHS subjected to static loading

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ABSTRACT

This paper presents a test program on flexural behaviour of concrete-filled stainless steel circular hollow section (CHS) tubes under in-plane bending. A total of 27 specimens including 18 concrete-filled stainless steel CHS flexural members and 9 empty stainless steel CHS 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 CHS 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 CHS tube. Furthermore, the concrete strength has little influence on the ultimate strength, initial stiffness and ductility of concrete-filled stainless steel CHS flexural members. The test flexural stiffness including both initial flexural stiffness and flexural stiffness at the serviceability limit state of concrete-filled stainless steel CHS tubes under in-plane bending were 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 CHS tubes under in-plane bending with high scatter of predictions.

1. Introduction

Stainless steel is nowadays increasingly used in many structural applications owing to its aesthetic appearance, high corrosion resistance, superior ductility and durability properties and excellent fatigue and fire resistances [1]. Because of the initial high costs of stainless steel, its application is limited so far in structural engineering. This limitation can be removed by using life-cyclic cost analysis.

Typical applications of stainless steel include tubular structures and long-span spatial structures in corrosive environments. Circular hollow section (CHS) is one of the widely used tubular forms in railway station, airport terminal, great theatre, sports stadium, exhibition hall and many other long-span and spatial structures due to their streamline appearance, uniform flexural rigidity and good static and dynamic behaviour. Concrete filling is one of the commonly used strengthening methods for tubular structures with inadequate resistance and its primary hollow section members cannot be changed, which is particularly appealing for architecturally exposed steelwork.

With the development of concrete-filled stainless steel tubes (CFSST) in the structural applications [2], extensive researches [3–16] were so conducted on CFSST under axial compression.

The behaviour and design of axially loaded concrete-filled stainless steel tube columns were experimentally and numerically investigated. Experiments and numerical simulation were conducted to investigate the effects of geometrical parameters and concrete strength on the mechanical behaviour of the CFSST columns under compression. A serial of design equations of strength was proposed. Transverse impact resistance of hollow and concrete filled stainless steel columns with or without pre-compressive load was experimentally investigated by Yousuf et al. [17–18].

The aforementioned literatures were all conducted on the compressive behaviour of CFSST columns under static loading and impact loading. There is little research being carried out on the flexural behaviour of CFSST. The pure in-plane bending tests were ever conducted by Chen et al. [19] on concrete-filled stainless steel beams. This paper focuses on the flexural behaviour of concrete-filled stainless steel CHS tubes under in-plane bending. The corresponding empty stainless steel CHS flexural members were also tested under in-plane bending for comparison. The ultimate strengths, failure modes, flexural stiffness and midspan deflections of all specimens are reported in this study. The test results are used to calibrate the current design specifications for

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the concrete-filled stainless steel CHS flexural members. Furthermore, the effect of concrete filled in the empty stainless steel CHS tubes on the ultimate strength and flexural stiffness of all specimens was also evaluated.

2. Experimental investigations

2.1. Test specimens

A total of 27 specimens including 18 concrete-filled stainless steel CHS tubes and 9 empty stainless steel CHS tubes were tested under in-plane bending. All specimens were manufactured from the same batch of stainless steel CHS tubes SUS 201 in accordance with Chinese code for design of stainless steel structures [20]. The CHS tubes consist of a large range of section sizes, which have nominal overall diameters (d) ranged from 89 to 133 mm, and nominal thickness (t) ranged from 1.1 to 2.0 mm. The overall length (L) of all specimens was taken to be a constant value of 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. 1a and b for empty and concrete-filled stainless steel CHS tubes, respectively. The authors did not measure the initial geometric imperfection of CHS stainless steel tubes before testing.

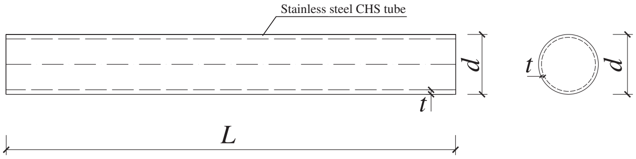
2.2. Specimen labelling

The specimens are labelled according to their cross-section shape, cross-section dimensions and concrete infill. For example, the label '133 × 1.1C0' defines the following specimen:

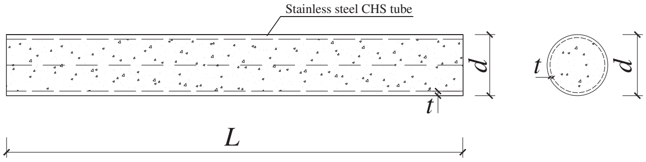
- The first letter 'C' indicates that the cross-section shape of the specimen is circular hollow section.
- The following expression '133 × 1.1' indicates the cross-section dimensions of the specimen, which have the nominal overall diameter (d) of 133 mm, and the wall thicknesses (t) of 1.1 mm.
- The 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.

Table 1
Details of test specimens.

Specimen	d (mm)	t (mm)	L (mm)	L_e (mm)	d/t	M_u (kN·m)	M_{uw} (kN·m/kg)
C133 × 1.1C0	133	1.1	1000	900	120.91	1.25	0.383
C133 × 1.1C30		1.1			120.91	11.88	0.355
C133 × 1.1C50		1.1			120.91	11.37	0.340
C133 × 1.5C0		1.5			88.67	2.81	0.635
C133 × 1.5C30		1.5			88.67	18.13	0.529
C133 × 1.5C50		1.5			88.67	17.85	0.521
C133 × 2.0C0		2.0			66.50	4.61	0.784
C133 × 2.0C30		2.0			66.50	21.55	0.611
C133 × 2.0C50		2.0			66.50	22.19	0.629
C114 × 1.1C0	114	1.1			103.64	1.47	0.528
C114 × 1.1C30		1.1			103.64	8.85	0.355
C114 × 1.1C50		1.1			103.64	8.99	0.361
C114 × 1.5C0		1.5			76.00	3.23	0.853
C114 × 1.5C30		1.5			76.00	12.69	0.497
C114 × 1.5C50		1.5			76.00	12.73	0.498
C114 × 2.0C0		2.0			57.00	5.49	1.094
C114 × 2.0C30		2.0			57.00	16.17	0.613
C114 × 2.0C50		2.0			57.00	16.22	0.614
C89 × 1.1C0	89	1.1			80.91	1.53	0.706
C89 × 1.1C30		1.1			80.91	5.12	0.331
C89 × 1.1C50		1.1			80.91	5.03	0.325
C89 × 1.5C0		1.5			59.33	2.81	0.954
C89 × 1.5C30		1.5			59.33	6.86	0.428
C89 × 1.5C50		1.5			59.33	7.03	0.439
C89 × 2.0C0		2.0			44.50	5.17	1.323
C89 × 2.0C30		2.0			44.50	9.08	0.545
C89 × 2.0C50		2.0			44.50	9.64	0.578



(a) Empty stainless steel CHS tube



(b) Concrete-filled stainless steel CHS tube

Fig. 1. Definition of symbols for test specimens.

2.3. Material properties

All specimens were fabricated by using Chinese Standard stainless steel (AISI 201). Tensile coupon tests were conducted to determine the mechanical properties of the hot-rolled seamless stainless steel tubes. The coupons were taken from the center face of the CHS tubes in the longitudinal direction and tested according to the recommendations of Chinese Code of Metallic Materials (GB/T 228.1-2010) [21]. The material properties obtained from the tensile coupon tests are summarized in Table 2, which include the elastic modulus (E), the tensile yield stress (f_y), the ultimate tensile stress (f_u), the Poisson's ratio (v) and the Strain-hardening Coefficient (n). The material Strain-hardening Coefficient n of stainless steel used in the specimens referring to the definition given in Eurocode 3 is reported in revised Table 2. Typical full-range stress-strain curves for CHS stainless steel is presented in Fig. 2. An actual stress-strain curve has been provided in Fig. 2. The curve was derived from the tension test of a coupon cut from CHS 133 × 2.0 tube.

The concrete-filled stainless steel CHS tubes were fabricated by filling the concrete with nominal cube strengths of 30 MPa and 50 MPa in the specimens along their full length. The concrete mix includes 425# ordinary Portland cement, medium-coarse sand, and coarse aggregate with diameter ranged from 5 mm to 15 mm. The material properties of concrete were determined from the compressive concrete cube tests. The standard concrete cubes with the nominal side length of 150 mm were prepared and tested based on the recommendations of

Table 2
Material properties of stainless steel tubes.

Specimen	E_s (GPa)	f_y (MPa)	f_u (MPa)	v	Coefficient n	
					Longitudinal direction	Transverse direction
CHS 133 × 1.1	199	456	576	0.31	6.78	8.17
CHS 114 × 1.1	200	448	543	0.28	6.58	8.43
CHS 89 × 1.1	204	434	587	0.28	6.13	8.88
CHS 133 × 1.5	205	462	551	0.29	6.06	8.05
CHS 114 × 1.5	196	444	563	0.32	6.74	8.21
CHS 89 × 1.5	208	447	575	0.26	6.99	8.53
CHS 133 × 2.0	209	436	596	0.29	6.39	8.29
CHS 114 × 2.0	201	458	582	0.29	6.29	8.39
CHS 89 × 2.0	199	474	577	0.29	6.47	8.32