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Curved concrete filled steel tubular (CCFST) built-up members under axial compression: Experiments

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ABSTRACT

A series of tests on curved concrete filled steel tubular (CCFST) built-up members subjected to axial compression is described in this paper. Twenty specimens, including 18 CCFST built-up members and 2 curved hollow tubular built-up columns, were tested to investigate the influence of variations in the tube shape (circular and square), initial curvature ratio (β_r, from 0 to 7.4%), nominal slenderness ratio (λ_n, from 9.9 to 18.9), section pattern (two main components, three main components and four main components), as well as brace pattern (battened and laced) on the performance of such composite built-up members. The experimental results showed that the ultimate strength and stiffness of CCFST built-up specimens decreased with increasing β_r or λ_n. Different load-bearing capacities and failure modes were obtained for the battened and laced built-up members. A simplified method using an equivalent slenderness ratio was suggested to calculate the strength of CCFST built-up members under axial compression.

1. Introduction

Compared with curved single members, both the in-plane and out-of-plane stability of curved built-up steel tubular members can be improved noticeably. Thus the latter have been increasingly used in large-span spatial structures and long-span bridge structures, such as roof structures, sports stadiums and arch bridges, not only for economical reasons but also for aesthetic appeals. It is believed that there is great potential to apply curved concrete filled steel tubular (CCFST) built-up members formed by two or more CCFST components with tubular braces or section steels in long span and space structures. Many such kinds of structures, such as arch bridges with CCFST built-up members, have been built in China [1]. In most cases, concrete can be pumped into the curved steel tubes and non-destructive technology, such as ultrasonic technology can be used to ensure the compaction of the concrete infilled.

In the past, a large number of studies on traditional straight concrete filled steel tubular (CFST) columns [1] and built-up members [2–5] have been carried out for many years. However, seldom research has been conducted on CCFST members, especially on built-up CCFST members. Ghasemian and Schmidt [6] and Han et al. [7] conducted tests on circular or square CCFST members. A relatively simple method was proposed to calculate the strength of the CCFST members by Han et al. [7]. These tests were conducted only on curved single members, and the main parameters were the initial curvature ratio and the nominal slenderness ratio.

The current study is a further investigation to report a series of tests on CCFST built-up members. The main parameters varied in the tests are: tube shape (circular and square); initial curvature ratio (from 0 to 7.4%); nominal slenderness ratio (from 9.9 to 18.9); section pattern (two, three and four main components); and brace pattern (battened and laced members). An equivalent slenderness ratio was proposed, and a simplified method was suggested to calculate the ultimate strength of CCFST built-up members under axial compression.

2. Experimental program

2.1. Specimen preparation

A total of 20 composite built-up members, including 10 with circular tubes and 10 with square tubes, were tested. For clarity, these members are referred to as circular built-up members and square built-up members in the following. The initial curve shape was circular arc for all of the specimens. All the members were concentrically loaded. The initial curvature values for the specimens and the range of parameters for the experimental investigations were determined based on engineering practice in China. A summary of the specimens

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Nomenclature

A_s	Steel cross-sectional area
A_c	Concrete cross-sectional area
A_{sc}	Area of the composite built-up cross section
B	Overall dimension of the square steel tubular section
CCFST	Curved concrete filled steel tube
CFST	Concrete filled steel tube
D	Overall diameter of the circular steel tubular section
E_c	Elastic modulus of concrete
E_s	Elastic modulus of steel
f_{sy}	Yield strength of steel
f_{cu}	Cube compressive strength of concrete
I_{sc}	Moment of inertia of the composite built-up cross section
L	Distance between the ends of a curved member, in mm
M	Bending moment
N	Axial load
N_u	Axially compressive capacity
N_{uc}	Predicted ultimate strength
N_{ue}	Experimental ultimate strength
t	Wall thickness of the steel tube
u_o	Initial deflection at mid-height of the curved member
u_m	Mid-height deflection of the member
V	Shear force
α	Steel ratio ($\alpha = A_s/A_c$)
β_r	Initial curvature ratio ($\beta_r = u_o/L$)
ε	Strain
λ_n	Nominal slenderness ratio ($\lambda_n = L/\sqrt{I_{sc}/A_{sc}}$)
λ_{ox}	Equivalent slenderness ratio
γ	Shear angle
μ_s	Poisson's ratio of steel
ξ	Confinement factor ($\xi = \frac{A_s \cdot f_{sy}}{A_c \cdot f_{ck}}$)

is presented in Table 1. The main experimental parameters are listed below, along with the labels used to characterise each specimen:

- Tube shape (C for circular, S for square);
- Overall nominal slenderness ratio λ_n (S for $\lambda_n = 9.9$ or 10.5, L for $\lambda_n = 18.9$ or 17.8. For clarity, $\lambda_n$is referred to as nominal slenderness ratio hereafter):

$$\lambda_n = \frac{L}{r} \tag{1}$$

  where L is the distance between the ends of the curved member, as shown in Fig. 1; r is the radius of gyration for the composite section of the built-up member, $r = \sqrt{I_{sc}/A_{sc}}$, I_{sc} and A_{sc} are the moment of inertia and total cross-sectional area of all the CFST components of the built-up member, respectively. If take a build-up member with four circular main components for example, $A_{sc} = 4 \times \pi D^2/4$, $I_{sc} = 4 \times \pi D^4/64 + 4 \times (\pi D^2/4) \cdot (h/2)^2$, in which D is the overall diameter of the main components, and h is the height of the composite section of the built-up member, as shown in Fig. 1;
- Section pattern (the number after the first two letters denotes the section pattern, where 2 for two main components, 3 for three main components, 4 for four main components. For clarity, as shown in Fig. 1c, these members are referred to as "Type I", "Type II" and "Type III" in the following, respectively);
- Brace pattern (B for battened members, D for laced members, as shown in Fig. 1a and b, respectively);
- Initial curvature ratio (β_r), which is defined as:

$$\beta_r = \frac{u_o}{L} \tag{2}$$

  where u_o is the initial deflection at the mid-height of the curved built-up members, as shown in Fig. 1 (a for $\beta_r = 0$, b for $\beta_r = 3.6$ or 3.7, c for $\beta_r = 7.2$ or 7.4).

According to the above designation, the specimen with a label of "CL3D-c" stands for the curved laced built-up member with three circular CFST main components, and its nominal slenderness ratio and initial curvature ratio are 18.9 and 7.4%, respectively. To distinguish the built-up members with hollow main components from other specimens, an additional letter "h" is included in their labels, such as "CL3Dh-b" and "SL3Dh-b".

It should be noted that the geometric and material properties of all individual CFST components in a built-up member were kept the same in the tests. Details of the manufacturing and fabricating methods are quite similar to those of curved single members, as can be found in Han et al. [7]. The battens or braces were fillet welded to the chords. The welds were designed to ensure that the ultimate strength of the specimen could be achieved. The specimen was then placed upright and self-consolidating concrete (SCC) was used to fill the chords without any vibration.

2.2. Material properties

Table 2 shows the average yield strength (f_{sy}), tensile strength (f_u), elastic modulus (E_s) and Poisson's ratio (μ_s) for all the steel tubes used in the tests. The 0.2% proof stress was adopted as the yield strength.

SCC mix with a compressive cube strength (f_{cu}) at 28 days of approximate 40 MPa was designed in the test. The mix proportions were as follows: cement: 300 kg/m^3; fly ash: 200 kg/m^3; water: 200 kg/m^3; sand: 814 kg/m^3; coarse aggregate: 900 kg/m^3; and additional high-range water reducer (HRWR): 5 kg/m^3. The fresh properties of the SCC mixture were: slump flow: 260 mm; flow speed: 62 mm/s; and flow distance: 610 mm. The average cube compressive strength (f_{cu}) and the elastic modulus (E_c) of the concrete at 28 days were 33.4 MPa and 27,800 N/mm^2, respectively. Owing to a longer curing period of concrete, the measured f_{cu} was 45 MPa at the time of tests.

2.3. Experimental procedures

A curved CCFST member is highly likely to be used in a continuous member configuration, only a segment of the structure was chosen and tested as pin-ended supported in this paper. The details of the stiff platens used to simulate the pin-ended condition can be found in Han et al. [7]. Fig. 2 gives a general view of a Type I CCFST built-up specimen before testing. The longitudinal and transverse strains of the main components (or chords) and braces, the additional lateral deflections along the specimen height (not including the initial deflection for curved specimens), the axial shortening, the angle changes between the chord and batten, the axial deformation of laced members, and the bending deformation of battened members were all measured during the testing.

3. Experimental results and discussion

3.1. Testing phenomenon and failure modes

In general, all the specimens were conducted in a smooth and controlled way in the tests without out-of-plane deformations. The chords and braces worked well with each other. And the lateral deflections above and below the mid-height were almost symmetrical. During loading, the in-plane deflection increased until the specimen failed due to the global instability.

In the initial stage of loading, as the specimen was still in the elastic state, the axial load versus additional deflection curve (N–u_m) at the