Journal of Constructional Steel Research 150 (2018) 209–220

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Design of concrete-filled high strength steel tubular joints subjected to compression

Hai-Ting Li, Ben Young *

Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China

ARTICLE INFO

Article history:
Received 14 April 2018
Received in revised form 21 July 2018
Accepted 27 July 2018
Available online xxxx

Keywords:
Cold-formed steel
Concrete-filled
Connections
Finite element analysis
High strength steel
Joints
Rectangular hollow sections
Square hollow sections
Tubular structures

ABSTRACT

Design of concrete-filled high strength steel tubular joints subjected to compression is examined. A numerical investigation on concrete-filled high strength steel rectangular hollow section (RHS) joints is presented in this paper. The high strength steel RHS tubes had nominal yield stresses of 700 and 900 MPa. The concrete infills had nominal concrete cylinder strengths of 35 and 100 MPa. Finite element (FE) models were developed and verified against test results, showing the capability of replicating the experimental ultimate strengths, failure modes and load-deformation histories. Upon verification, a parametric study comprised 312 FE analyses was carried out. The ultimate strengths of the concrete-filled high strength steel RHS joints obtained from the parametric study together with available test results in the literature were compared with the nominal strengths calculated from existing design provisions. It is shown that the CIDECT predictions exhibited significant scatter and generally conservative for the concrete-filled high strength steel RHS joints. However, the CIDECT predictions overestimated the strengths of concrete-filled high strength steel RHS joints with chord sidewall slenderness ratio exceeded 50. Therefore, new design rules are proposed in this study for concrete-filled high strength steel RHS joints subjected to compression. Furthermore, reliability analysis was performed to assess the design rules.

1. Introduction

Tubular steel sections, such as rectangular and circular hollow sections (RHS and CHS), have been widely used in buildings, bridges, roof systems, offshore platforms and other structural applications due to their structural efficiency and aesthetic appearance [1]. In some lattice structures, rectangular (which also includes square in the context of this paper) hollow sections could be more favourable to their CHS counterparts, as RHS allow easy connections to their flat faces while CHS require specialised profiles for their connections. Vibrant research in various areas on tubular section joints have been conducted over the past five decades [2–10] and design provisions for RHS joints are currently available in the International Institute of Welding (IIW) [11] recommendations and Comité International pour Ie Développement et l'Étude de la Construction Tubulaire (CIDECT) Design Guide [12]. The IIW [11] and CIDECT [12] are consistent with each other and are the basis for the RHS joint provisions in the AISC Standard [13], European Code [14] and ISO Standard [15].

The design of hollow section joints requires considerable expertise and many occasions exist where the tubular joints in a truss or similar lattice structures need to be reinforced [16]. A commonly used method for hollow section joints strengthening is to weld stiffening plates to the exterior of the chords. However, due to the visible stiffening plates, this approach might ruin the aesthetic appearance of the elegant tubular structures. Alternatively, a less visible method could be achieved by means of filling the hollow section chords with concrete. Along with increasing the joint strengths, this concrete infill strengthening method may reduce stress concentrations and lead to increased fatigue lives of the joints [17]. Furthermore, the fire resistance of the connections can also be enhanced. Currently, design provisions for concrete-filled RHS joints are available in the CIDECT [12], which is the only existing guideline that provides specific provisions for designing concrete-filled RHS joints. It is noteworthy that for concrete-filled RHS X-joints and T-joints subjected to compression, the CIDECT [12] provisions were developed based on 11 concrete-filled RHS X-joint tests. These tests, reported in Packer [16], had the measured yield stress on steel tubes of 330 MPa. High strength steels are becoming increasingly attractive in a range of structural applications. Although several experimental investigations [18–21] were conducted on concrete-filled tubular chords under concentrated bearing loads, as reviewed previously by the authors in [22], research into concrete-filled high strength steel RHS joints remains scarce.

An experimental investigation on concrete-filled high strength steel RHS joints subjected to compression was initiated by the authors [22]. The data obtained from the test program [22] are limited and covered

* Corresponding author.
E-mail address: young@hku.hk (B. Young).

https://doi.org/10.1016/j.jcsr.2018.07.030

nominal chord sidewall slenderness ratio up to 40. In this study, finite element (FE) models were first developed to replicate the concrete-filled RHS joint tests as reported in [22]. Upon verification of the FE models, an extensive parametric study comprised of 312 FE analyses was carried out to generate further numerical data over a wider range of key joint parameters such as the chord sidewall slenderness ratio, chord aspect ratio, chord width to thickness ratio and brace to chord width ratio. The nominal chord sidewall slenderness ratio was up to 90 in this study. The appropriateness of the design provisions in the CIDECT [12] and Feng and Young [23] to concrete-filled high strength steel with yield stresses of 700 and 900 MPa RHS joints was assessed based on the numerical and experimental results. New design rules are proposed and recommended for concrete-filled high strength steel RHS joints subjected to compression.

2. Summary of experimental investigation

A total of 31 tests was conducted by the authors [22] on concrete-filled high strength steel RHS joints subjected to compression. In order to avoid brace failure and to reveal the real capacity of the compression-loaded concrete-filled RHS joints, steel bearing plates were employed to simulate the brace members. This test method had also been used by Packer [16], based on which the CIDECT [12] provisions for concrete-filled RHS X- and T-joints subjected to compression were developed. Two types of joints were investigated in the test program. The specimen of the first type consisted of a concrete-filled chord with bearing plates (braces) on both top and bottom chord faces, as illustrated in Fig. 1. These specimens had the appearance of typical X-joints with the braces replaced by the bearing plates, and were designated as X-specimens in the test program. On the other hand, the specimens of the second type had only one bearing plate (brace) on the top chord face and the concrete-filled chord was seated on a solid base plate, as illustrated in Fig. 2. Based on the joint type classifications in Section 4.1 of the CIDECT [12], these specimens with full bottom chord support, designated as XF-specimens in the test program, would be classified as X-joints. However, it should be noted that these specimens had the appearance of T-joints supported on solid base plates, and the test results showed that the indentations of the XF-specimens were localized at the chord top face only, which exhibited similar behaviour as T-joints.

The concrete-filled high strength steel RHS chords had measured overall depths (h_0) ranged from 50.0 to 200.5 mm, overall widths (b_0) ranged from 80.2 to 120.8 mm, steel wall thicknesses (t_0) ranged from 3.91 to 4.94 mm, and external corner radii (R_0) ranged from 8.4 to 13.4 mm. The chord lengths (L_0) were designed to be $5h_0 + h_1$. The bearing plates which simulate the braces had measured overall depths (h_1) and widths (b_1) ranged from 39.7 to 119.9 mm and 39.7 to 100.0 mm, respectively. The corner radii (R_1) and heights (L_1) of the bearing plates were designed consistently as 8 and 40 mm, respectively. The concrete-filled high strength steel RHS joints had measured h_0/b_0 (chord aspect ratio) values varied between 0.5 and 1.7, b_1/b_0 (brace-to-chord width ratio) values varied between 0.33 and 0.83, h_0/t_0 (chord sidewall slenderness ratio) values ranged from 12.6 to 40.6, and b_0/t_0 (chord width-to-thickness ratio) values varied between 20.3 and 30.9. The high strength steel RHS had 2 nominal steel grades: 700 and 900 MPa. The steel grades can be identified from the cross-section labels of the RHS, where "H" and "V" represent nominal steel grades of 700 and 900 MPa, respectively. The measured 0.2% proof stresses from tensile flat coupon tests ranged from 679 to 997 MPa, while the values from tensile corner coupon tests varied between 860 and 1151 MPa. The high strength steel RHS chords were infilled with normal strength concrete (NSC) and high strength concrete (HSC) along their full lengths. The NSC (grade C35) and HSC (grade C100) had measured concrete cylinder strengths of about 37 and 96 MPa, respectively. A servo-controlled hydraulic testing machine was used to test the compression-loaded concrete-filled high strength steel RHS joints. A lockable ball bearing that initially free to rotate in any direction was used in the test setups. The measured load-chord face indentation curves (chord face indentation always refers to the indentation of one chord face only) as well as load-chord sidewall deformation curves were reported. The test program is detailed in Li and Young [22].

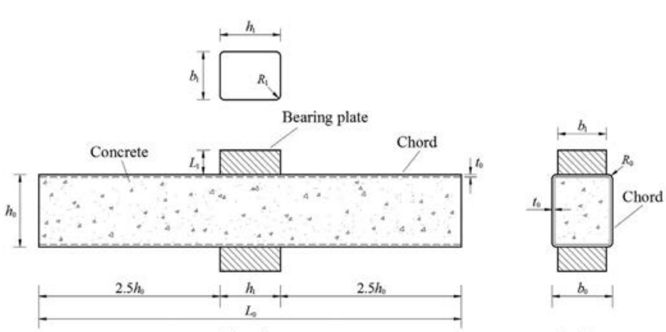

Fig. 1. Definition of symbols for concrete-filled RHS X-specimens.

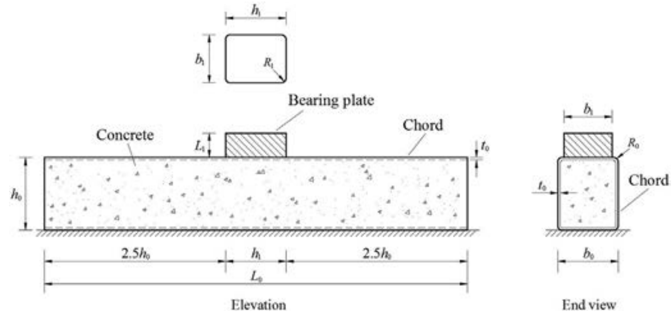

Fig. 2. Definition of symbols for concrete-filled RHS XF-specimens.

3. Numerical modelling

3.1. Finite element models

3.1.1. Element types and discretization

Finite element (FE) models were developed using FE package ABAQUS [24] to simulate the concrete-filled high strength steel RHS joint tests reported by Li and Young [22]. The FE models were built on the measured geometries. A 4-node quadrilateral shell element S4R, which has been shown performed well in similar numerical studies [25–27], was selected to simulate the high strength steel RHS tubes. For the infilled concrete, an 8-node solid element C3D8R was employed herein. The braces, which were simulated by solid steel bearing plates, were modelled using discrete rigid 3D elements. The mesh sizes were investigated to achieve suitably accurate numerical results within reasonable computational time. The selected mesh sizes ranged from approximately 6 to 12 mm depending on the size of the RHS. Finer mesh sizes were assigned at the round corners to ensure the corner regions were accurately modelled. The structured mesh technique was employed in order to achieve proper hexahedral elements.

3.1.2. Material properties

The measured stress-strain curves obtained from tensile coupon tests [22] were used for the cold-formed high strength steel RHS tubes. The experimentally obtained stress-strain curves were converted to true stress and true plastic strain curves before incorporating into the FE models. It is noteworthy that cold-formed steel RHS typically demonstrate different mechanical properties in the sections. Due to the manufacturing processes, corner regions of the cold-formed high strength steel RHS were work-hardened, and therefore, the material properties obtained from the flat and corner coupons were assigned to