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Fatigue behavior and design of welded tubular T-joints with CHS brace and concrete-filled chord

L.W. Tong[a,b,*], G.W. Xu[a,b], D.L. Yang[c], F.R. Mashiri[d], X.L. Zhao[e]

[a] State Key laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China
[b] College of Civil Engineering, Tongji University, Shanghai, China
[c] College of Civil Engineering and Architecture, Huanghuai University, Henan Province, China
[d] School of Computing, Engineering and Mathematics, University of Western Sydney, Penrith, NSW, Australia
[e] Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia

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ABSTRACT

Concrete-filled welded tubular structures have been increasingly used in large-span constructions such as truss bridges where fatigue failure is always a critical issue that should be focused on. This paper deals with fatigue behavior of CHS-CFSHS T-joints, which are made up of circular hollow section (CHS) braces and concrete-filled square hollow section (CFSHS) chords. Experimental results on stress concentration factor (SCF) were briefly summarized. Fatigue tests were conducted under cyclic tensile force in the brace, so that cracking patterns, failure modes and fatigue data of such joints were recorded. The tested CHS-CFSHS T-joints suffered from one of the following three failure modes: (i) brace-90°-side failure, (ii) chord-90°-side failure, (iii) chord-0°-side failure. Based on the fatigue data in terms of hot spot stress range ($S_{r,hs}$) versus number of cycles (N), fatigue design $S_{r,hs}$-N curves were determined using the deterministic and least-squares methods, respectively. It was found that most of the existing $S_{r,hs}$-N curves are unsafe for fatigue design of CHS-CFSHS T-joints, except for the X′ $S_{r,hs}$-N curve recommended by American Petroleum Institute [32] and American Welding Society [36]. In addition, the fatigue data of the CHS-CFSHS T-joints were found comparable with CHS-CFCHS T-joints (T-joints with CHS brace and concrete-filled CHS chord), hence a new fatigue design $S_{r,hs}$-N curve was proposed for the both types of concrete-filled joints. A comparison between CHS-CFSHS T-joints and empty CHS-SHS T-joints showed that CHS-CFSHS T-joints generally have better fatigue behavior compared to their empty counterparts except for the case of extremely large ratio of brace diameter to chord width (β).

1. Introduction

In the past decades, there has been a rapid development in the research and application of concrete-filled tubular structures [1–4], which is mainly because of its good performance attributed to good complementary behaviors between the two different materials: the in-filled concrete supports the tube wall and the steel tube confines the concrete core in turn. The presence of concrete can offer tubular structures better bearing capacity, ductility and fire resistance [4,5].

Because of high stress concentration near the weld toes, fatigue failure of the welded tubular joints is always a critical issue in constructions subjected to cyclic loading, such as truss bridges. So far, numerous studies have demonstrated that the welded tubular joints with concrete-filled chord have better fatigue behavior than corresponding empty joints [6–15]. Previous studies mainly focused on joints with circular hollow section (CHS) brace/braces and concrete-filled CHS (CFCHS) chord, involving T-, Y-, K-, KT-, X- and N-types. Through experimental and numerical studies, it has been indicated that the in-filled concrete can effectively reduce stress concentration factors (SCFs) of different types of concrete-filled CHS joints [6–14]. SCF formulae were established for CHS-CFCHS T-joints [10] and N-joints [11], respectively. Moreover, fatigue tests were performed on CHS-CFCHS T-joints [12] and X-joints [13], but no specialized fatigue design *S-N* curve was proposed. In addition, stress intensity factors for concrete-filled or grouted CHS T-joints were successfully calculated using finite element analysis by Gu et al. [16] and Shen and Choo [14], respectively. Shen and Choo [14] argued that the in-filled grout in the chord could reduce the degree of bending and hence lead to a shorter fatigue

Abbreviations: API, American Petroleum Institute; AWS, American Welding Society; CFSHS, concrete-filled square hollow section; CHS, circular hollow section; CIDECT, Comité International pour le Développement et l´Etude de la Construction Tubulaire; COV, coefficient of variation; DNV, DET NORSKE VERITAS; IIW, the International Institute of Welding; SCF, stress concentration factor; SD, standard deviation; SHS, square hollow section

* Corresponding author at: State Key laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China.
E-mail address: tonglw@tongji.edu.cn (L.W. Tong).

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Nomenclature

B0–B270	hot spot stress (or strain) measuring lines in brace
C0–C270	hot spot stress (or strain) measuring lines in chord
N3	through-thickness fatigue life
N4	end-of-test fatigue life
$S_{equ,rnom}$	equivalent constant nominal stress range
$S_{r,hs}$	hot spot stress range
$S_{r,nom}$	nominal stress range
b_0	external width of SHS chord (Fig. 1)
d_1	external diameter of CHS brace (Fig. 1)
t_0	wall thickness of chord (Fig. 1)
t_1	wall thickness of brace (Fig. 1)
t_{ref}	reference wall thickness
β	ratio of brace diameter to chord width (Fig. 1)
2γ	ratio of chord width to thickness (Fig. 1)
τ	ratio of brace wall thickness to chord wall thickness (Fig. 1)
σ_{logN}	standard deviation for log *N*

life compared to empty joints with the same hot spot stress range. Very few studies have been reported on fatigue behavior of concrete-filled square hollow section (SHS) joints. Mashiri and Zhao [15] reported an experimental investigation on SCF and fatigue life of SHS-CFSHS T-joints with thin-walled (t ≤ 4 mm) tubes. It was found that the SHS-CFSHS T-joints have much lower SCF than empty SHS T-joints, and that the $S_{r,hs}$-*N* curve ($S_{r,hs}$ represents the hot spot stress range) derived from empty SHS T-joints can be adopted for fatigue design of SHS-CFSHS T-joints [15]. K-joints with CFCHS chord and SHS braces have been proved to have lower SCFs than their empty counterparts through an experimental investigation under balanced axial loading, and corresponding SCF formulae were proposed by Chen et al. [17].

As for concrete-filled joints made up of an empty CHS brace and a concrete-filled SHS chord (CHS-CFSHS joints, see Fig. 1), however, neither experimental nor numerical research on fatigue behavior is available in literature, even though significant research on fatigue behavior of empty CHS-SHS T-joints has been reported since 1990s [18–24]. Gandhi and Berge [18] and Bian and Lim [19] successively conducted experimental investigation on SCF and fatigue strength of CHS-CHS T-joints subjected to axial and in-plane bending loads, respectively. The SCF values of CHS-SHS T-joints were generally found between CHS-CHS T-joints and SHS-SHS T-joints. Mashiri et al. [20,21] and Tong et al. [22] focused on fatigue behavior of thin-walled CHS-SHS T-joints through experimental and numerical investigations. It was found that the thin-walled CHS-SHS T-joints had slightly lower SCF and therefore longer fatigue life than thin-walled SHS-SHS T-joints under in-plane bending. Packer et al. [23] demonstrated that the branch conversion method could be used for static and fatigue design of CHS-SHS T-joints, based on the existing design rules. Tong et al. [24] conducted hot spot stress tests on eight CHS-SHS T-joints with common wall thickness, based on which FE analysis was carried out thereby resulting in a series of specialized SCF formulae for CHS-SHS T-joints.

This paper presents an experimental investigation on fatigue behavior of the identical CHS-SHS T-joints reported by Tong et al. [24] but with CFSHS chord. A brief summary of the specimens and the experimental SCF results are firstly given. Then the fatigue tests and corresponding results, including cracking patterns, failure modes, through thickness fatigue life (*N3*) and end-of-test fatigue life (*N4*), are presented and discussed. On the basis of the experimental fatigue data, fatigue design *S-N* curve in hot spot stress concept is determined for concrete-filled joints involving both CHS-CFSHS and CHS-CFCHS T-joints, thus a new *S-N* curve is proposed. Finally, fatigue strength is compared between CHS-CFSHS T-joints and empty CHS-SHS T-joints in terms of nominal stress and hot spot stress, respectively.

2. Test specimens

In the present investigation, eight CHS-CFSHS T-joints were manufactured from the empty CHS-SHS T-joints discussed in Ref. [24], by filling expansive concrete into the SHS chord member (see Fig. 1). Table 1 presents the geometric parameters and material information of each specimen. Particularly, specimen CT8 was designed to explore the influence of an extremely large non-geometric parameter (that is, β = 0.9). In order to avoid the influence of end constraints, the chord member was designed with a length of $6b_0$ for each specimen, where b_0 refers to its external width. The length of the brace member (L_1) was kept constant at 665 mm.

The steel tubes in the specimens were made from high strength low alloy structural steel Q345B, with a minimum nominal yield stress (f_y) of 345 MPa and a minimum ultimate tensile strength (f_u) of 470 MPa, which complies with the Chinese standard GB/T1591-2008 [25]. Each specimen was filled with expansive concrete of grade C50 which has a cube (150 mm × 150 mm × 150 mm) compressive strength of 50 MPa with 95% guaranteed rate according to Chinese standard GB50010-2010 [26]. In addition, the brace and the chord members were connected through full penetration weld by the gas-metal arc welding method.

3. Experimental data on stress concentration factor (SCF)

Before fatigue tests, the specimens were tested under axial tension in the brace for stress concentration factors (SCFs). The test setup and the arrangement of strip strain gauges along the weld are shown in Fig. 2. Axial tensile force was applied to the end of the brace member with both ends of the chord member simply supported. As with the test for empty CHS-SHS T-joints reported by Tong et al. [24], strip strain gauges were placed on the chord and brace, respectively, at potential critical locations along the weld (see Fig. 2(b) and (c)). The measured SCFs of each specimen are listed in Table 2, in which the values for 0° and 90° locations (i.e. C0, B0, C90 and B90) are actually the averages of the symmetrical locations.

4. Fatigue test setup and failure criteria

Fatigue tests were carried out on the specimens following hot spot stress measurements. Each specimen was pin-supported at the two ends

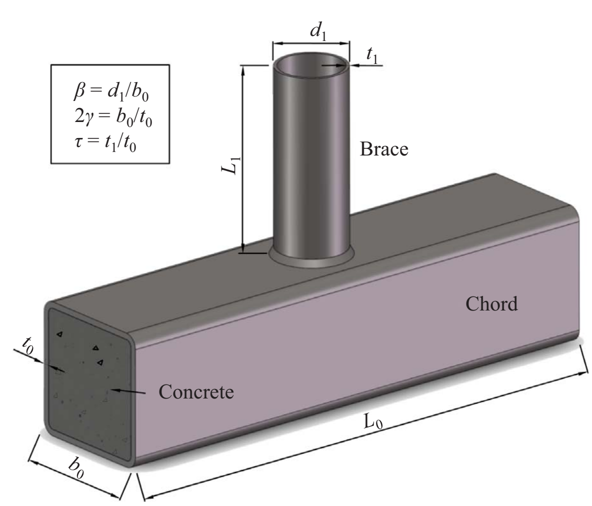

Fig. 1. Schematic diagram of CHS-CFSHS T-joint.