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Concrete-filled circular steel tubes subjected to local bearing force: Experiments

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ABSTRACT

Concrete filled steel tubular (CFST) members are subjected to local bearing forces in a large number of truss and lattice structures. Previous research has focused on rectangular CFST members under such loading condition. There is a lack of understanding on circular CFST members subjected to local bearing force. This paper intends to fill the knowledge gap in this area. A series of tests were conducted on circular CFST, unfilled circular hollow section (CHS) steel tube and plain concrete specimens loaded with local bearing force. The load was applied either perpendicularly to the member or at an angle of 45°. A deformation limit was adopted to define the ultimate strength of the specimen since the load verse deformation curve exhibits a ductile behavior. The effects of important parameters were investigated based on the test results. Finally, design formulae were developed to predict the ultimate strength of circular CFST members under local bearing forces.

1. Introduction

It is well known that concrete filled steel tubular (CFST) members have many advantages in structural performance (Han and Li, 2011 [1]; Zhao et al., 2010a [2]; Wardenier et al., 2010 [3]; Nethercot, 2003 [4]; Wang, 2002 [5]), they thus have an increasing application in a large amount of trusses, buildings, bridges and tower structures.

In practice, CFST is often loaded on local cross-sectional area in many occasions, such as in bridge piers, load-introduction members in high-rise buildings, or bottom bearing members of rigid frames. Thus, some studies had been conducted for CFST columns under local compression, such as Bergmann (1994) [6], Porsch and Hanswille (2004) [7], Han et al. (2008a, b) [8,9], Yang and Han (2009, 2011) [10,11], etc. In these literatures, the behavior and design methods of locally loaded CFST columns with circular, square and rectangular sections were investigated both experimentally and theoretically. It is found that generally, CFST columns under local compression behave in a ductile manner.

When being used as a chord member in trusses and bridges, CFST may be subjected to concentrated forces. It is well known that filling the hollow section chord member with concrete is an effective method to improve the strength and stiffness of truss connections. Fig. 1 shows some typical CFST structures in China, including a CFST truss bridge (Han, 2007) [12], a CFST tower and a CFST built-up structure. It can be seen that in the tubular joints of such structures, concentrated forces are transferred to CFST chords from the braces.

Packer and Fear (1991) [13] conducted tests on 14 rectangular concrete-filled hollow section specimens under transverse compression forces and proved that concrete could significantly benefit the strength and deformation of a branch-compressed joint. Zhao (1999) [14] carried out tests on rectangular hollow section members partially filled with concrete subjected to local bearing forces and established models to predict the load carrying capacity. Feng and Young (2008, 2009) [15,16] studied square and rectangular concrete-filled stainless steel tubular chords under local bearing forces. However, no research has yet been conducted on circular CFST members subjected to local bearing forces transferred through bearing plates, although tests were conducted in the past on welded CHS tubular T and K-joints (HSE, 1989 [17]; Van der Vegte et al., 2008 [18]). This paper attempts to fill the knowledge gap in this area

The objectives of this paper are thus threefold: (i) to report a series of tests on circular CFST specimens under local bearing forces. Unfilled circular hollow section (CHS) steel tube and plain concrete are also tested as reference values for comparison. (ii) to investigate the effects and mechanism of the local bearing force on the deformation and stress distribution around the connection area of CFST member. (iii) to develop a design formula for the ultimate strength of circular CFST under such loading.

2. Experimental program

2.1. Specimen preparation

A total of 21 specimens were tested in this program, including 4 reference hollow section specimens and 4 reference plain concrete specimens. Schematic views of the specimen are shown in Fig. 2. The

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Nomenclature

A_1	Bearing area over which local bearing force is applied
A_2	Dispersed bearing area
d_i	Outer diameter of the brace tube
d_0	Outer diameter of the chord tube
E_c	Elastic modulus of concrete
E_s	Elastic modulus of steel
f_{ck}	Characteristic strength of concrete ($=0.67f_{cu}$ for normal strength concrete)
f_{cu}	Cube strength of concrete
f_c'	Crushing strength of concrete by cylinder tests ($=0.8f_{cu}$)
f_u	Ultimate strength of steel
f_y	Yield strength of steel
K_i	Initial compression stiffness of the chord
K_s	Serviceability-level compression stiffness of the chord
L	Length of specimen
N	Local bearing force
n	Chord stress ratio
$N_{3\%d0}$	Local bearing force at the flange indentation of $3\%d_0$
N_{max}	Maximum test load of the specimen
N_{uc}	Predicted ultimate strength
N_{ue}	Tested ultimate strength
t_i	Steel wall thickness of the brace tube
t_0	Steel wall thickness of the chord tube
ε	Strain
ε_{ue}	Strain corresponding to the ultimate strength
ε_y	Yield strain of the steel
Δ	Flange indentation of the chord
α	Steel ratio ($=A_s/A_c$)
β	Brace to chord diameter ratio ($=d_i/d_0$)
γ	Half diameter to thickness ratio of the chord ($=d_0/2t_0$)
υ	Side deformation of the chord
η	Extrusion of the concrete core
ξ	Confinement factor ($=A_s f_y/A_c f_{ck}$)
θ	Angle between the brace and the chord

tested specimens are generally two types, i.e., vertical-brace members (the angle between the brace and chord $\theta=90°$) and inclined-brace members ($\theta=45°$), as to investigate the effects of the angle of local bearing force. Detailed information of the specimens are listed in Table 1, where d_0 and t_0 are the diameter and wall thickness of the chord tube, respectively; d_i and t_i are the diameter and wall thickness of the brace tube, respectively; L is the length of the chord.

In summary, the parameters varied in the tests include:

- Chord type, i.e. CFST chord, hollow section chord and plain concrete chord, respectively.
- CFST chord wall thickness t_0, 2.38 mm and 3.32 mm, respectively.
- Brace to chord diameter ratio of CFST: β ($=d_i/d_0$), 0.351 to 0.702.

In order to avoid the local buckling failure of brace so as to focus on the failure of CFST chord, very rigid brace is designed. Circular steel bearing plate brace is used in this test, meanwhile, hollow section brace with a thickness $t_i=6$ mm is also used for comparison. The diameter of the brace (d_i) varies from 40 to 80 mm, the corresponding brace to chord diameter ratio β varies from 0.351 to 0.702.

The following labels are used to define each specimen: 1) The initial character "v" or "i" stands for the vertical-brace or inclined-brace specimens, respectively; 2) The following character "h" or "c" (if any) stands for the hollow section or plain concrete chord sections, respectively; 3) The character "d" and the following Arabic numeral stands for diameter of the chord section; 4) The additional label "h" (if any) stands for the hollow section brace sections; 5) The additional label "T" (if any) stands for the a larger tube thickness; and 6) The last Arabic numeral stands for the different specimen in the same group. For example, the specimen with the label "icd60h-1" denotes the first specimen with a hollow section brace and a plain concrete chord, and $d_i=60$ mm.

Two types of steel plate are used to manufacture the chord tubes. For $t_0=2.38$ mm steel tube, the measured yield strength (f_y) and ultimate strength (f_u) are 351.0 N/mm^2 and 473.0 N/mm^2, respectively; the modulus of elasticity (E_s) for steel is 208,000 N/mm^2 and the Poisson's ratio (μ_s) is 0.27. Whereas for the steel tube with $t_0=3.32$ mm, $f_y=344.6$ N/mm^2, $f_u=468.0$ N/mm^2, $E_s=205{,}000$ N/mm^2, and $\mu_s=0.26$. For brace tube, $f_y=471.7$ N/mm^2, $f_u=560.6$ N/mm^2, $E_s=210{,}000$ N/mm^2, and $\mu_s=0.27$. Self-consolidating concrete (SCC) mixture was designed and used, the measured compressive cube strength (f_{cu}) at 28 days is 51.2 N/mm^2, while the measured cube strength is 55.4 N/mm^2 at the time of test, and the corresponding modulus of elasticity (E_c) is 32,000 N/mm^2.

2.2. Test setup

The tests were carried out using a servo-controlled hydraulic testing machine. Compression force was applied from the testing machine to the brace of the specimen. Schematic views and photos of the testing setup of CFST specimens are shown in Figs. 3 and 4, respectively.

In order to simulate the pure local bearing force condition without any bending moment applied, the chord member is constrained by a concrete base, as can be seen in Figs. 3 and 4, respectively. The concrete base is reinforced to provide enough rigidity under compression. In the upper surface of the concrete base, a circular arc is manifested with a central angle of 60° and the same radius as the chord to fit the specimen. Actually, it could be conceived that the central angle of this arc surface should neither be too small, as it would not be able to provide sufficient support for the specimen during loading; nor be too big, as to avoid the excessive constraint upon the specimen. It was observed that the interface of both the specimen and the concrete base remained solid and smooth during the loading process.

For inclined-brace specimens, a steel rigid base is used to provide a 45° surface for the specimen so that the compression load can be applied from the testing machine directly to the brace, as shown in Figs. 3(b) and 4(b), respectively. In order to keep the load transmission specific, rigid sliding wheel is used to prevent the friction along the contact surface, and load transducer is arranged to measure the component force along the axial direction of the chord.

Both the steel bearing plate brace and the hollow section brace are fabricated through a numerical controlled process to gain a void-free contact surface with the chord. For inclined-brace specimen, as the chord is obliquely arranged, the brace is thus welded to the chord to insure the position of the connection area and the direction of the local bearing force, with an average fillet weld leg length of 5.2 mm. As the flexure deformation of the chord is constrained by the concrete base, the effects of welding condition on the strength of the specimens are negligible.

During the test, strains of the chord face around the connection area were measured by 16 strain gages. Another 22 strain gages were used to measure the strains along the outer steel tube of the chord. Meanwhile, displacement transducers were arranged to monitor the deformation of the specimen, as shown in Fig. 5. Two displacement transducers were positioned diagonally on the bottom end plate to measure the axial shortening of the specimen, from which the chord flange indentation (Δ) was obtained. Two other transducers were arranged at the center of the chord side to record the side deformation (ν), which was determined as the average value of the left reading (ν_l) and the right reading (ν_r). The possible concrete extrusion at the front (η_f) and bottom (η_b) end of the specimen is also observed by another two transducers.