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Concrete-filled circular steel tubes subjected to local bearing force: Finite element analysis

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ABSTRACT

This paper presents a finite element analysis (FEA) of circular concrete filled steel tubular (CFST) members under local bearing forces applied either perpendicularly to the member or at an angle of 45°. The established FEA modeling was verified by the experimental results that have been published in an international journal. The FEA modeling was then used to perform analysis on the typical failure modes and full-range load-deformation relations of CFST subjected to local bearing forces. Finally, simplified formulae for calculating the strength of CFST under local bearing forces was presented. Practical guidance was also given to avoid premature local buckling of brace member and premature fracture of chord member.

1. Introduction

Concrete filled steel tubular (CFST) structures have an increasing utilization in trusses, tall buildings, bridges and tower structures due to their advantages in structural performance [9,14,4,19,17,11,15]. In many occasions, CFST components in these structures may be subjected to local bearing forces, particularly for some chord members in CFST trusses and built-up structures, as illustrated in Hou et al. [7]. In such case, the behaviour under the lateral concentrated forces transferred from the braces is a critical issue to the capacity of the tubular connections as well as the safety of the structures.

From the literature reviews presented in Hou et al. [7], it appeared that although studies on rectangular CFST under transverse compression forces could be found in the literature (e.g. [12,18], and [1,2,3]), very limited experimental or theoretical investigation was carried out on circular CFST members under local bearing forces transferred though bearing plates. Hence there is a need to study such cases to ensure reliable and ductile connections for circular CFST construction [8].

The authors of the current paper [7] recently presented experimental results for circular CFST members under local bearing forces. In the tests, the local bearing force was applied either perpendicularly or at an angle of 45° to the CFST, unfilled circular hollow section (CHS) steel tube, as well as plain concrete specimens. Fig. 1 gives schematic views of the two types of specimens during the testing, i.e., vertical-brace member (the angle between the brace and chord $\theta=90^{\circ}$) and inclined-brace member ($\theta=45^{\circ}$). The testing results in Hou et al. [7] demonstrated that circular CFST members under local bearing forces generally have more ductility and higher capacity, compared with the reference CHS alone and plain concrete. However, there is a lack of understanding of the load transfer mechanism and full-range behaviour of circular CFST subjected to local bearing forces.

This paper thus presents an analytical study on the behaviour of CFST under local bearing forces. The objectives of this paper are thus threefold: (1) to present a finite element analysis (FEA) modeling on circular CFST members under local bearing forces, which is then verified using the test data reported in Hou et al. [7]; (2) to carry out investigations on the typical failure modes, load versus deformation relations and stress distributions of circular CFST members under local bearing forces; (3) to conduct validation on the simplified prediction method and to give recommendations for practical designing of circular CFST members subjected to local bearing forces.

2. Finite element analysis (FEA) modeling

2.1. General description of the FEA modeling

A numerical model to account for circular CFST members subjected to local bearing forces transferred from either steel bearing plate or CHS brace is developed using the finite element package ABAQUS. The FEA modeling is a further development of the analysis used for modeling CFST members presented by Han et al. [5].

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Nomenclature

A_1	bearing area over which local bearing force is applied
A_2	dispersed bearing area
d_i	diameter of the brace tube
d_0	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
f_u	ultimate strength of steel
f_y	yield strength of steel
L	length of specimen
N	local bearing force
$N_{3\%d0}$	local bearing force at the flange indentation of 3%d_0
N_{max}	maximum test load of the specimen
N_{ua}	analyzed ultimate strength
N_{uc}	predicted ultimate strength
N_{ue}	tested ultimate strength
t_0	steel wall thickness of the chord tube
t_{0eq}	equivalent steel wall thickness of the chord tube
t_i	steel wall thickness of the brace tube
ε	strain
ε_y	yield strain of the steel
Δ	flange indentation of the chord
α	steel ratio ($=A_s/A_c$)
υ	side deformation of the chord
ξ	confinement factor ($=A_s f_y/A_c f_{ck}$)
θ	angle between the brace and the chord
μ_s	Poisson's ratio of steel

Models for vertical-brace members and inclined-brace members are both developed, in which the local bearing force is applied to CFST perpendicularly or at an angle of 45°, respectively.

2.1.1. Material properties

Elastic-plastic model is used to describe the constitutive behaviour of steel. The elasto-plastic stress-strain relation model presented by Han et al. [6] was adopted in this analysis. The modulus of elasticity (E_s) and Poisson's ratio (μ_s) for carbon steel are set to 206,000 N/mm^2 and 0.3, respectively.

For concrete, the damage plasticity model is used to define the material behaviour. It is well known that when under hydrostatic pressure, the compressive strength and ductility of concrete could be enhanced. In this analysis, the equivalent stress–strain relation proposed by Han et al. [5] was adopted to simulate the plastic behaviour of the concrete core in CFST under compression. This material model (see Eq. (1)) had been used to simulate CFST columns under compression, shear, bending, and torsion [5].

$$y=\begin{cases} 2\times x-x^2 & (x\le 1)\\ \frac{x}{\beta_0\times(x-1)^{\eta}+x} & (x>1)\end{cases} \tag{1}$$

where, $x=\varepsilon/\varepsilon_0$, $y=\sigma/\sigma_0$, σ and ε are the stress and strain of concrete respectively, in N/mm^2; σ_0 is the maximum stress of concrete, and ε_0 is the strain corresponding to the maximum stress of concrete.

In this material model, the "composite action" between the steel tube and its concrete core is quantified by a confinement factor ξ, which is defined as follows,

$$\xi=\frac{A_s f_y}{A_c f_{ck}}=\alpha\frac{f_y}{f_{ck}} \tag{2}$$

where, A_s is the cross-sectional area of the steel tube; A_c is the cross-sectional area of the concrete core; f_y is the yield strength of the steel; and f_{ck} is the characteristic compression strength of concrete. The value of f_{ck} for normal strength concrete is determined using 67% of the cube strength of concrete (f_{cu}). In Eq. (2), $\alpha(=A_s/A_c)$ is called the steel ratio, which can reflect the effects of width-to-thickness ratio (d_0/t_0) of the steel tube. More details of this model could be found in Han et al. [5].

2.1.2. Element types and meshes

The concrete base, brace member and concrete core of the CFST chord were modeled using 8-node 3-D solid elements with reduced integration, which is also applied for modeling the loading plate and fillet weld leg. The steel chord wall was modeled using 4-node shell element with full integration.

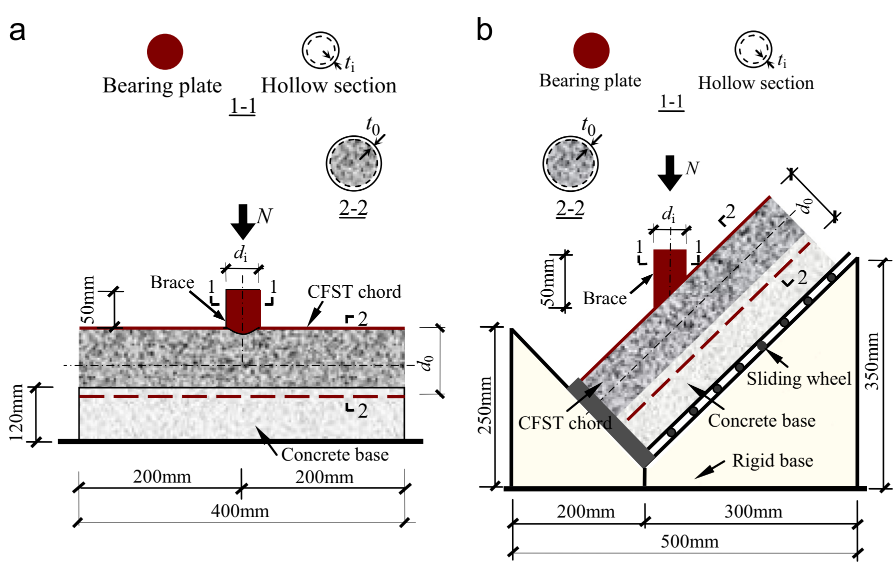

Fig. 1. Schematic views of the specimen tested in [7]. (a) Specimen with vertical brace ($\theta=90°$), (b) specimen with inclined brace ($\theta=45°$).