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Behaviour of CFST stub columns with initial concrete imperfection: Analysis and calculations

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ABSTRACT

Gap between the steel tube and concrete core can be considered as a kind of initial concrete imperfection in concrete-filled steel tubular (CFST) structures.This paper performs a nonlinear analysis of CFST stub columns with a circumferential gap or spherical-cap gap under axial compression. A nonlinear finite element model is developed, where the nonlinear material behaviour and the effect of gap on the interface behaviour of the concrete and steel tube are included. Close agreement is achieved between the test and calculated results in terms of load–deformation response and ultimate strength. In light of the numerical results, the behaviour of CFST columns with a circumferential gap or spherical-cap gap is analysed. Parametric studies are then carried out to investigate the influence of different parameters on the ultimate strength of CFST stub columns with gaps. Finally, the maximum limit of the gap ratio is proposed for CFST stub columns with circumferential gaps, and a simplified formula is proposed to estimate the effect of spherical-cap gap on the ultimate strength of CFST stub columns as well.
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1. Introduction

In real concrete filled steel tubular (CFST) structures, two types of gaps [1], i.e. circumferential gap and spherical-cap gap, may be found to be existing, as shown in Fig. 1(a) and (b), respectively. Normally, the circumferential gap is caused by the concrete shrinkage in the circumferential direction, and the spherical-cap gap mainly originates from the constructional process. In the practical engineering, the circumferential gap may appear at vertical CFST members such as CFST columns and CFST piers, and the spherical-cap gap is found to occur at horizontal CFST members such as CFST arch bridges and CFST truss structures. In the companion paper [1], a series of tests for CFST columns with a circumferential gap and CFST columns with a spherical-cap gap under axial compression were presented, where the main testing parameter was the gap ratio (χ):

$$\text{For CFST with a circumferential gap (as shown in Fig. 1(a))}: \chi = \frac{2d_c}{D} \quad (1a)$$

$$\text{For CFST with a spherical-cap gap (as shown in Fig. 1(b))}: \chi = \frac{d_s}{D} \quad (1b)$$

where d_c and d_s are the dimensions of the circumferential gap and spherical-cap gap respectively, and d_c and d_s are designated as the maximum distance from the concrete edge to the inner surface of the steel tube, as shown in Fig. 1; D is the outer diameter of the tube section. The test results showed that the gaps can affect the failure modes and ultimate strength of CFST columns under axial compression. However, how the gaps imposed these effects, especially their effects on the confinement of the steel tube to concrete, cannot be clarified by the physical tests.

In the past, many numerical studies had been carried out on CFST stub columns under axial compression by using finite element analysis. Schneider [2], Hu et al. [3] and Ellobody and Young [4] developed nonlinear finite element models for concrete filled steel stub columns with a circular section or a square section. Tao et al. [5] performed a finite element analysis on the concrete-filled stiffened thin-walled steel tubular columns under axial compression. Tao et al. [6], Hassanein [7] and Ellobody and Young [8] carried out nonlinear finite element analysis on the concrete filled stainless steel stub columns. Dai and Lam [9] established a nonlinear finite element model for the analysis of concrete filled steel stub columns with elliptical section. Huang et al. [10] and Hu and Su [11] used ABAQUS software to conduct a nonlinear analysis on the behaviour of concrete filled double skin steel stub columns. So far, no nonlinear finite element analysis on CFST stub columns with a circumferential gap or spherical-cap gap has been conducted.

This paper aims to carry out a nonlinear analysis of CFST stub columns with a circumferential gap or spherical-cap gap under axial compression. The main objectives of this research are threefold. First, to develop a three-dimensional nonlinear finite

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Nomenclature

A_c	cross-section area of concrete
A_s	cross-section area of the steel tube
CFST	concrete filled steel tube
d_c	dimension of the circumferential gap
d_s	dimension of the spherical-cap gap
D	diameter of the circular tube section
E_c	elastic modulus of concrete
E_s	elastic modulus of steel
f_y	yield strength of steel
f_{ck}	characteristic concrete strength ($=0.67f_{cu}$ for normal strength concrete)
f_{cu}	cube strength of concrete
f'_c	cylinder strength of concrete
N	axial load
N_u	ultimate strength
N_{uc}	predicted ultimate strength
N_{ue}	measured ultimate strength
p	interaction stress
p_{ave}	average interaction stress
SI	strength index
t	wall thickness of the steel tube
α	steel ratio ($=A_s/A_c$)
ε	strain
ε_{cu}	ultimate axial stain
χ	gap ratio ($\chi=2d_c/D$ for circumferential gaps; or $\chi=2d_s/D$ for spherical-cap gaps)
ξ	confinement factor ($=\alpha(f_y/f_{ck})$)

element model, in which the nonlinear material behaviour and the effect of gap on the interface behaviour of concrete and the steel tube are included. Previous test results will be used to verify the feasibility of the finite element model. Second, to study the mechanical behaviour of the CFST stub columns with gaps, especially to reveal the influence of gaps on the interaction behaviour between concrete and the steel tube. Third, to perform a parametric study, and then propose the maximum allowed gap ratio for CFST stub columns with a circumferential gap, as well as a simplified formula to estimate the effect of spherical-cap gap on the ultimate strength of CFST stub columns.

2. Finite element model and verification

2.1. General description

ABAQUS software is employed throughout the finite element analysis. The steel tube is simulated by using 4-node shell elements with reduced integration. The concrete core is modelled using 8-node brick elements, with three translation degrees of freedom at each node. A mesh convergence study is performed to identify an appropriate mesh density to achieve reliable results. Fig. 2 shows the sectional mesh of columns.

Loading was applied in a displacement control mode at the top of a column to simulate the axial loading condition. For an axially loaded column with a relatively large slenderness, a lateral deflection of $L/1000$ at the mid-height was adopted to consider the global initial imperfection, where L is the effective length of the column [12]. To simulate the triangular hinge in the previous physical tests [1], two rigid plates were added as shown in Fig. 2. The rigid plate was assumed to be an elastic rigid block, and its modulus of elasticity and Poisson's ratio were taken as 10^{12} N/mm^2 and 0.00001, respectively. All degrees of freedom except the rotation around the y-axis were constrained at the loading line of the bottom rigid plate, whilst at the top rigid plate an appointed displacement was applied on the loading line along the z-axis, and the translations along x- and y-axes and the rotations about the x- and z-axes were restrained. The boundary conditions are shown in Fig. 2(c). For a stub column, the ends of the column were fixed against all degrees of freedom except for the vertical displacement at the top end.

2.2. Material properties

The steel was simulated by an elastic–plastic model using a stress−strain relation that consists of five stages [13]. The elastic modulus (E_s) and Poisson's ratio (ν_s) of steel were taken as 206,000 N/mm^2 and 0.3, respectively.

The damage plasticity model was used for modelling concrete material in the current finite element model [14,15]. The modulus of elasticity (E_c) of concrete was taken as $4730\sqrt{f'_c}$ according to [16], where f'_c is the cylinder compression strength of concrete. Poisson's ratio (ν_c) was taken as 0.2. For CFST without any gap, an equivalent stress−strain model proposed by Han et al. [13] was used to simulate the plastic behaviour of the core concrete in CFSTs under compression:

$$y=\begin{cases} 2x-x^2 & (x\le 1) \\ \dfrac{x}{\beta_0\cdot(x-1)^{\eta}+x} & (x>1) \end{cases} \quad (2)$$

where $x=\varepsilon/\varepsilon_0$, $y=\sigma/f_c'$; ε_0, β_0, η are model parameters where expressions can be found in Han et al. [13]. The factor ξ [$=A_s f_y/(A_c f_{ck})=\alpha(f_y/f_{ck})$, in which $\alpha=A_s/A_c$ is the steel ratio, A_s and A_c are

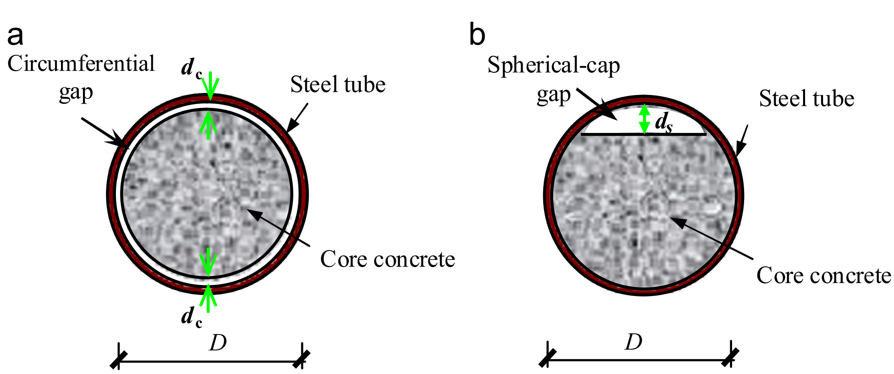

Fig. 1. A schematic view of gaps in CFST cross-sections. (a) Circumferential gap and (b) spherical-cap gap.

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