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Analytical behaviour of concrete-filled double skin steel tubular (CFDST) stub columns

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ABSTRACT

This paper reports a finite element analysis of the compressive behaviour of CFDST stub columns with SHS (square hollow section) or CHS (circular hollow section) outer tube and CHS inner tube. A set of test data reported by different researchers were used to verify the FE modelling. Typical curves of average stress versus longitudinal strain, stress distributions of concrete, interaction of concrete and steel tubes, as well as effects of hollow ratio on the behaviour of CFDST stub columns, were presented. The influences of important parameters that determine sectional capacities of the composite columns were investigated.

1. Introduction

Concrete-filled double skin steel tubular (CFDST) members are composite members which consist of an inner and outer steel skin with the annulus between the skins filled with concrete. This type of sandwich cross-section was shown to have high bending stiffness that avoids instability under external pressure. Some background information can be found in [1].

In recent years, many studies have been performed on CFDST stub columns, such as [2–13]. A state-of-the-art review was given by Zhao and Han [1]. A summary of research conducted on CFDST stub columns is presented in Table 1. It can be seen from Table 1 that the past studies concentrate mainly on experimental investigations or predicting the load-bearing capacities of stub columns.

According to Han et al. [3] and Tao et al. [6], hollow ratio χ is an important parameter that affects column behaviour. This ratio is defined as $d/(D-2t_{so})$, where d and D are the major dimensions of the inner and outer tubes, respectively, and t_{so} is the thickness of the outer tube. If hollow ratio χ is equal to 0 for a column, the column is actually a conventional concrete-filled steel tube (CFST). Generally, the CFDST columns have almost all the same advantages as conventional CFST members.

In this paper, a finite element (FE) modelling was developed based on the commercial FE package, ABAQUS [14], to study the compressive behaviour of CFDST stub columns. Several key issues in the FE modelling are introduced briefly, i.e. the material models for concrete and steel, interface model to simulate the concrete and steel interface, element type, mesh, and boundary conditions.

For CFDST columns, there are four possible combinations of square hollow section (SHS) and circular hollow section (CHS) as outer or inner tubes. Since a CHS is less susceptible to local buckling than a SHS, it is good to use CHSs as both inner and outer tubes for a CFDST in practice. However the beam–column joint for a square column is easier to be fabricated and installed compared with that of a circular column. For this reason, two types of CFDST columns, i.e., section with CHS inner and CHS outer, and section with CHS inner and SHS outer are investigated.

The main objectives of this paper are threefold: first, a set of test results reported by different researches are used to verify the FE modelling. Second, typical curves of average stress versus longitudinal strain, stress distributions of concrete, interaction of concrete and steel tubes and hollow ratio effect are investigated. Third, the influence of important parameters that determine the sectional capacities of the composite columns is identified.

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Nomenclature

A_c	Cross-sectional area of concrete
A_{ce}	Nominal cross-sectional area of concrete
A_{sco}	Cross-sectional area of the outer steel tube and the sandwich concrete ($=A_{so} + A_c$)
A_{sc}	Cross-sectional area of CFDST ($=A_{so} + A_c + A_{si}$)
A_{si}	Cross-sectional area of inner steel tube
A_{so}	Cross-sectional area of outer steel tube
CFDST	Concrete-filled double skin tube
CFST	Concrete-filled steel tube
d	Outer diameter of inner steel tube
D	Outer dimension of outer steel tube
f_{ck}	Characteristic concrete strength ($f_{ck} = 0.67 f_{cu}$ for normal strength concrete)
f_{cu}	Characteristic 28-day concrete cube strength
f_c'	Concrete cylinder strength
f_{syi}	Yield strength of inner steel tube
f_{syo}	Yield strength of outer steel tube
N	Axial compressive load
N_u	Ultimate strength of CFDST stub column
N_{uc}	Predicted ultimate strength of CFDST stub column by using FE modelling
N_{ue}	Experimental ultimate strength of CFDST stub column
p_1	Interaction stress between the concrete and outer tube
p_2	Interaction stress between the concrete and inner tube
t_{so}	Wall thickness of outer steel tube
t_{si}	Wall thickness of inner steel tube
α_n	Nominal steel ratio, given by $\alpha_n = A_{so}/A_{ce}$
χ	Hollow ratio, given by $d/(D - 2t_{so})$
ε	Strain
μ	Coefficient of friction between the steel tube and core concrete
τ_{bond}	Bond strength between the steel tube and core concrete
ξ	Confinement factor ($=\alpha_n f_{syo}/f_{ck}$)

2. Finite element modelling

2.1. Material models

(1) Steel

A steel constitutive model for structural steel presented in [15] is utilised to represent uniaxial stress–strain relation of steel. For carbon steel tubes, an elastic–plastic stress–strain relation model, consisting of five stages (i.e. elastic, elastic–plastic, plastic, hardening and fracture) is used. More details of the stress–strain relationship can be found in [15]. Mises yield function with associated plastic flow is used in the multiaxial stress states.

The steel is assumed to have isotropic hardening behaviour, i.e., the yield surface changes uniformly in all directions so that yield stresses increase or decrease in all stress directions when plastic straining occurs [14]. Elastic modulus (E_s) and Poisson's ratio for steel are taken as 2×10^5 (N/mm^2) and 0.3, respectively.

(2) Concrete

Concrete is a brittle material with different failure mechanism in compression and tension, i.e., crushing in compression and cracking in tension. The damage plasticity model defined in ABAQUS is used in the analysis [14]. The concrete damage plasticity model adopts a unique yield function with non-associated flow and a Drucker–Prager hyperbolic flow potential function to describe the plasticity of concrete. Therefore, independent uniaxial stress–strain relations for concrete both in compression and tension are the basic input data due to the difference in strength and failure mechanism in compression and tension.

It is expected that the inner tube can restrict the inner indent of the concrete core if the hollow ratio is not too large, so the sandwich concrete in the gap has the same behaviour with that in a fully in-filled steel tube without the inner void. It was found that in this case the failure features of the CFDST specimens were very similar to those of CFST columns [3,6]. Therefore, uniaxial stress–strain relation for concrete in CFSTs is used for the analysis of CFDST members in this paper. The increasing of the plasticity of core concrete as a result of the passive confinement of the steel tube depends on the confinement factor ξ [15–17]. The confinement factor for a CFDST can be defined as:

$$\xi = \alpha_n \frac{f_{syo}}{f_{ck}} \tag{1}$$

in which, α_n is the nominal steel ratio of CFDST columns, which is given by $\alpha_n = A_{so}/A_{ce}$. A_{ce} is the nominal cross-sectional area of concrete, which is given by $A_{ce} = \frac{\pi}{4}(D - 2t_{so})^2$ for section with CHS inner and CHS outer, and $A_{ce} = (D - 2t_{so})^2$ for section with CHS inner and SHS outer. A_{so} is the cross-sectional area of outer steel tube, f_{syo} is the yield stress of outer steel tube, and f_{ck} is the characteristic compression strength of concrete. The value of f_{ck} is approximately equal to 67% of the compressive strength of cube blocks (f_{cu}) for normal strength concrete.

An equivalent stress–strain model presented by Han et al. [17], which is suitable for the FE analysis using ABAQUS software for CFSTs, is used in this paper for the analysis of CFDSTs. Fracture energy versus displacement cross crack relation is used to describe

Table 1
Summary of research conducted on CFDST stub columns.

Researchers	Combinations	Research results
Wei et al. [8,9]	CHS outer and CHS inner	Test results; An analytical model is presented, and an empirical formula is presented for the peak strength.
Lin and Tsai [4]		Test results.
Zhao et al. [10]		Test results; Mechanics models and simplified models are developed.
Tao et al. [6]		
Zhao and Grzebieta [13]	SHS outer and SHS inner	Test results; Theoretical models are developed to predict the ultimate strength.
Zhao et al. [11]		Test results; Plastic mechanism methods are used to predict the unloading behaviour.
Elchalakani et al. [2]	CHS outer and SHS inner	Test results; A simplified formula is derived to determine the compressive capacity.
Han et al. [3]	SHS outer and CHS inner	Test results; Mechanics models and simplified models are developed.
Zhao et al. [12]		Test results; Theoretical models are developed to predict the ultimate strength.
Tao et al. [7]	RHS outer and RHS inner	Test results; Mechanics models are developed.
Tao and Han [5]		