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Analysis of axially loaded concrete filled circular hollow double steel tubular columns exposed to fire

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ABSTRACT

A series of new unified design formulas for calculating the temperature field and fire resistance under axial compressive loading of a circular solid or hollow concrete filled double steel tubular (CFDST) short and slender columns exposed to fire are presented in this paper. The results of the experiments are firstly derived from exploring the fundamental behavior of the CFSDT slender columns under the ISO 834 standard fire and temperature distributions. Failure modes and axial deformation versus time curves are also obtained and discussed. It was realized that a solid or slender CFDST column has different temperature fields, stronger limiting temperature and better fire resistance, as compared to columns filled with plain concrete. Also, the load ratio and steel ratio have no evident difference between the results of the solid and hollow CFDST columns. A three-dimensional finite element analysis (FEA) model is developed to calculate the temperature field of CFDST columns. After calibration of the FE model, the influences of important parameters on the temperature field of the composite columns are investigated and a unified formula for calculating average temperatures of the columns' cross-section is obtained. Combining the average temperature with the "Unified theory" under axial compression, a simplified design method is put forward, which provides a unified formulation for both the plain CFST and CFDST columns relating to the axial bearing capacity at room and elevated temperature. The proposed formulas are calibrated through comparisons with fire tests on the columns, and it was found that the method produces safe results on average.

1. Introduction

Concrete filled steel tubular structures have become an essential choice in practical applications with the tendency to be used for buildings or bridges, etc, that are large-span, tower and heavy-load [1–6]. Fire resistance of members with various cross sectional profiles is an important factor that must be taken into account in the safe and economical design process of steel-concrete composite structures. In order to have a comprehensive knowledge of the structural behavior of steel-concrete composite structures under elevated temperatures, the requirement for a safe, economical, easily applicable design models and calculation methods are needed especially in the case of large buckling and complicated stress states.

Researchers have carried out extensive theoretical and experimental investigations on fire resistance of solid and hollow CFST columns [7–14] exposed to fire under axial or eccentric compression with circular and rectangular cross-sections, normal and high strength concrete, self-consolidating concrete and short and slender columns. For instance, Huo et al. [9] carried out axial compressive dynamic loading experiments on normal strength concrete filled steel tubes at elevated temperatures of up to 800 °C. This was to study the effects of high temperatures on the behavior of CFST at those elevated temperatures. A formula was developed for stub columns by introducing the reasonable dynamic increase factor. Espinos et al. [13] presented large eccentric compressive tests on slender CFST columns with circular and square section shapes exposed to fire. The influence of the cross-section shape, load eccentricity combined with high slenderness and the percentage of reinforcement on the response of these columns at elevated temperatures is considered. Finally, both of the current design methods in Eurocode 4 and a proposed calculation method are evaluated based on the experimental results.

Other existing studies have proposed to insert steel sections into the concrete-filled hollow steel tubes with the advantages of an attractive slender appearance and high axial compressive capacity for heavily loaded columns of large-scale buildings. Neuenschwander et al. [15,16] analysed the load-carrying behavior of concrete-filled steel tubular columns with a massive steel core subjected to fire by developing a numerical model. The results showed that the finite element model

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Nomenclature

A_c	Cross-sectional area of concrete
A_s , A_{ss}	Cross-sectional area of outer and inner steel tube, respectively
A_{sc}	Cross-sectional area of CFDST column
D_o	Outer diameter of outer circular steel tube
D_i	Outer diameter of inner circular steel tube
I_s , I_{ss} , I_c	Moments of inertia of the outer, inner steel tube and concrete, respectively
f_s ,f_s^T	Yield strength of outer steel tube at room and elevated temperature, respectively
f_{ss} ,f_{ss}^T	Yield strength of inner steel tube at room and elevated temperature, respectively
f_{cu}	Concrete cube strength
f_y ,f_y^T	Yield strength of steel at room and elevated temperature, respectively
f_{ck} ,$\overline{\mathrm{f}}_{ck}^T$	Concrete compressive strength at room and elevated temperature, respectively
t	Fire resistance of each column
L	Column height
E_y ,E_y^T	Elastic modulus of steel at room and elevated temperature, respectively
E_c ,$\overline{\mathrm{E}}_c^T$	Elastic modulus of concrete at room and elevated temperature, respectively
E_s^T ,E_{ss}^T	Elastic modulus of outer and inner steel tube at elevated temperature, respectively
N_0 , N_0^T	Axial compressive strength and stability bearing capacity at room and elevated temperature, respectively
N_u^T	Axial compressive stability bearing capacity at elevated temperature
N_e	Axial load applied on each CFDST column
N_{uc}	Formulas predicted ultimate strength of CFDST column
N_c	Formulas predicted strength of CFDST column
t_o , t_i	Wall thickness of outer and inner steel tube, respectively
n	load ratio (defined as N_e/N_{uc})
ρ	Steel ratio of inner tube (designed as A_{ss}/A_c)
$\overline{T}_{s,c}$,$\overline{T}_{ss,c}$,$\overline{T}_{c,c}$	Calculated temperature field results of outer and inner steel tube, concrete, respectively
$T_{s,m}$, $T_{ss,m}$	Measured temperature field results of outer and inner steel tube, respectively
$\overline{T}_{c,n}$	Numerical results of average temperature field of concrete

developed, considering temperature-dependent material properties as well as the bonding behavior between steel and concrete, may be utilized for further studying the fundamental structural behavior of composite columns and determining their fire resistances. Recently, Schaumann and Kleiböemer [17,18] presented a large-scale fire resistant experimental and numerical investigation on a circular concrete filled tubular slender column with an embedded massive steel core, and the measured temperatures were compared to the numerical calculation. The eccentricity of the column was e=7 mm, and the load level was 0.37 during the fire loading. Considering the cross section form, the steel core was thermally protected by the filling of the concrete, thus, the fire-resistance time of 108 min was obtained in the test.

To gain further benefit from the CFST columns, the concrete-filled double skin steel tubular (CFDSST) member has been proposed in recent years, which is a composite member consisting of an inner and outer steel skin with the annulus between the skins filled with concrete, as indicated in Fig. 1. The CFDST columns have high bending stiffness that avoids instability under external pressure and are lighter. Numerous research work has been done on these type of members in the past (Lu et al. [19], Yang and Han [20], Liu et al. [21] and Cong et al. [22]), and it was found that the members inherited a similar behavior from the CFST member. However CFDSST column may have a reasonable heat resistance period as its inner tube is protected by the sandwich concrete. Subjected to fire the outer steel tube is directly exposed to the fire and therefore heats up quickly. The concrete inside the tube decelerates the heating of the inner steel tube, in which Yang and Han [20] calculated the strength index of the circular and square hollow CFDST columns under fire based on the results of parametric studies and previous outcome of the theoretical model, and proposed also formulas for calculating the fire resistance and the thickness of the fireproof. Cong et al. [22] established a finite element model to study the section temperature field of the hollow CFDST columns through considering the moisture of the concrete and thermal contact resistance based on the Eurocode 2. The effects of the diameter of steel tube and type of aggregate on section temperature field were studied. The section temperature field distribution of columns was given for further analysis of the capability of the fire resistance.

As illustrated in Fig. 1, this paper also reports a new type of composite member, namely concrete filled double steel tubular (CFDST) column. This composite column consists of two concentrically placed steel tubes within which there's a concrete filling in both the whole sections. Concrete-filled steel tube sections with inner steel tubes are used for highly loaded members and also for minimizing the size of the members. Compared with CFST members, the amount of concrete can be reduced by the inner steel filling in it. At elevated temperatures the strength and stiffness of steel and concrete decreases. The reduced strength and stiffness at elevated temperatures must be considered for calculating both the cross-sectional resistance and slender column strength capacity.

The above literature review indicates that there have been very limited experimental studies [19,23,24] on the behavior of hollow circular concrete filled double steel tubular (CFDST) short or slender columns and the research on solid CFDST slender columns has been reported only in the literature published by Romero et al. [23] about the hollow steel tubular columns, in filled with ultra-high strength concrete. This paper studies the fire resistance of circular solid or hollow concrete filled double steel tubular (CFDST) columns exposed to fire under axial loading. A series of fire-resistant experiments are carried out on CFDST slender columns to explore the fundamental

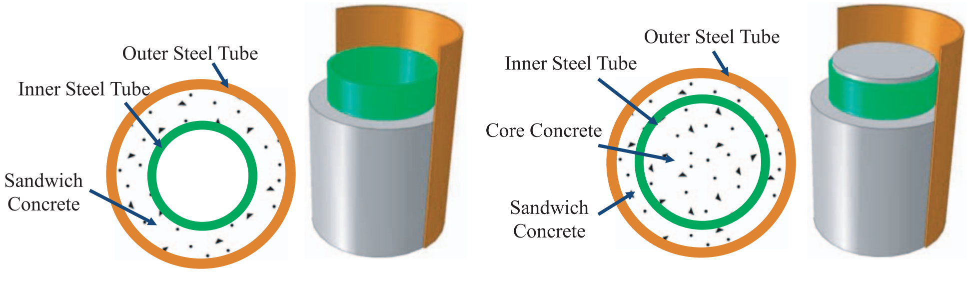

Fig. 1. Typical section form of CFDST columns.