Thin-Walled Structures 98 (2016) 547–557

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Theoretical and numerical analysis to concrete filled double skin steel tubular columns under fire conditions

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ARTICLE INFO

Article history:
Received 19 May 2015
Received in revised form
18 August 2015
Accepted 27 October 2015
Available online 6 November 2015

Keywords:
CFDST column
Fire resistance
Finite element
Rankine approach

ABSTRACT

As one of the recently developed steel–concrete composite structural members, concrete filled double skin tubular (CFDST) columns have been used in current construction industry due to its good structural performance. However, CFDST columns could be vulnerable under fire attack. In the current work, the fire resistance of CFDST columns has been studied. Finite element analysis (FEA) models were developed to investigate the fire resistance of unprotected CFDST columns. The FEA models were verified with experimental data from literature. Based on the developed numerical model, the failure mechanism of CFDST columns under fire conditions were studied and a parameter study was performed on the fire resistance design for CFDST columns. Based on the computational analysis, the conventional Rankine approach was extended to predict fire resistance of CFDST columns. Experimental data were used to validate the accuracy of the proposed method; it shows that the proposed method can predict the fire resistance of CFDST columns with reasonable accuracy compared with experimental data.

1. Introduction

Concrete filled steel tubular (CFST) columns have been widely used in recent construction industry because of the good structural behavior. Fire performance of CFST columns have been studied experimentally and theoretically by many researchers Lie et al. [1–4], Sakumoto et al. [5], Kodur [6], Han et al. [7], Tan and Tang [8] and Hong et al. [9].

Recently, concrete filled double skin steel tubular (CFDST) columns have become popular in structural design as load bearing members. As a new type of CFST columns, CFDST columns perform well in engineering structures because of the interaction between concrete and steel tube. However, the reliability of CFDST columns could be decreased under elevated temperatures. It is essential to investigate the mechanical behavior of CFDST columns under different conditions. The mechanical behavior of CFDST columns at ambient temperature were studied by a few of researches [10–12]. However, for the fire performance of CFDST columns, the study is far from enough. In the current study, the main objective is to investigate the fire resistance of CFDST columns under ISO-834 standard fire conditions.

Up till now, to the authors' best knowledge, only two groups of standard fire tests were performed on CFDST columns at Monash University and Tsinghua University [13,14]. Due to rare experimental data, a 3D finite element analysis model was developed to study the fire resistance of CFDST columns using finite element software ABAQUS [15].

In the past decade, there are some numerical models being developed to study the fire behavior of traditional concrete filled steel tubular (CFST) columns [9,16,17]. Essentially, the process of establishing CFST columns model under fire conditions tends to be uniform and their models have been validated to be reasonable and accurate. In the current work, a thermal-stress sequential coupling finite element analysis (FEA) model was developed for CFDST columns. The numerical model was validated by test results from literature [14]. Based on the FEA model, the mechanical behavior of CFDST columns was investigated to understand the failure mode under fire conditions. Then a parametric study was performed to investigate some important engineering design parameters which may affect the fire resistance of CFDST columns, suggestions were proposed on the fire resistance design of CFDST columns from the analysis. Based on the computational analysis, the conventional Rankine approach was extended to predict the fire resistance of CFDST columns. Reasonable accuracy and reliability was achieved compared with experimental data.

2. Finite element model

2.1. General

A three-dimensional sequentially-coupled thermal-stress analysis model was established. The model consisted of two sub-

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http://dx.doi.org/10.1016/j.tws.2015.10.024
0263-8231/

Notations

c	the thickness of concrete
$D_o(B_o)$	diameter or width of outer steel tube
$D_i(B_i)$	diameter of width of inner steel tube
e	load eccentricity
E_c	elastic modules
$E_{s,i}$	elastic modules of inner steel tube
f_c	compressive strength of concrete
f_c'	cylindrical compressive strength of concrete
f_y	yield stress of steel
$f_{y,o}$	yield stress of steel for outer steel tube
$f_{y,i}$	yield stress of steel for inner steel tube
I_c	second moment of area of concrete
$I_{s,i}$	second moment of area of inner steel tube
$k_{y,o}^{tube}(t)$	strength reduction factor of outer steel tube
L	length of the columns
L_e	effective column length
P	applied axial load
P_p	plastic collapse load
P_e	elastic critical load
Q_c	concrete contribution to plastic squashing load
$Q_{y,i}$	inner steel tube contribution to plastic squashing load
t	fire exposure time
t_o	the thickness of outer steel tube
t_i	the thickness of inner steel tube
β_c	reduction factor to concrete at elevated temperatures
$\beta_{y,i}$	reduction factor to inner steel tube at elevated temperatures
δ	axial load level
Λ_r	modified normalized slenderness ratio
λ	relative slenderness ratio
φ_e	reduction factor of elastic critical load
φ_p	reduction factor to plastic collapse load
CFST	concrete filled steel tubular
CFDST	concrete filled double skin steel tubular columns
SD	standard deviation
FEA	finite element analysis
FRT	fire resistant time

models. First, a thermal analysis model was developed to obtain temperature field in the CFDST columns under fire conditions. Then a 3-D stress analysis model was established to perform coupled thermal–mechanical analysis. A constant load was applied to the load bearing plate. Then the temperature field obtained from the thermal analysis was input as temperature load. To guarantee the temperature field transferred into the stress analysis exactly, the time period in the analysis steps and the element families stay the same.

The thermal analysis model consists of three parts, namely, outer steel tube, concrete, and inner steel tube. In the stress analysis, two end plates were added to the ends of the columns. To make sure the applied load transmitted to the columns properly, the end plates were assumed as perfectly elastic to avoid deformation. The dominant factors governing the models were the geometry dimension of the columns, the property of materials at elevated temperatures and the thermal and mechanical interaction models between steel tubes and concrete. Considering the effects of boundary conditions, full scale models were set up for all the models.

Three dimensional eight-node brick elements were adopted for all parts of the model in thermal and stress analysis. The element types were "heat transfer" and "3D stress" in thermal and stress analysis, respectively. In order to achieve an accurate and effectiveness analysis for the thermal and mechanical behavior of the CFDST columns, a maximum element size of 20 mm was taken. The finite element mesh for representative CFDST column is shown in Fig. 1.

2.2. Material properties

In the developed finite element model, the influence of temperatures to the material properties was taken into account. Temperature dependent thermal and mechanical properties were adopted. For both concrete and steel, the thermal dynamic properties models proposed by Lie et al. [3] were employed. The specific heat and conductivity varied with temperature. In the stress analysis, a uni-axial stress–strain relationship, a yield function and plastic flow rule to describe material behavior under multi-axial stress state were required to simulate the inelastic material properties. Concrete damage plasticity model and an elastic–plastic model were employed for concrete and steel, respectively. The mechanical properties of concrete and steel were defined as function of temperature.

The constitutive model of concrete at elevated temperature proposed by Han et al. was adopted [18]. The advantage of this model is that the bonding effect of the steel tube to the concrete could be taken into consideration. The stress–strain relationships of steel at elevated temperature proposed by Lie et al. were used [3], which shows good accuracy and has been verified by Song et al. [19]. The initial secant elastic modulus of the stress–strain relationship accounting for temperature was taken as the Young's modulus of steel. In this model, constant expansion coefficient for both concrete and steel were adopted. The values were $6\times10^{-6}{}^\circ C^{-1}$and $12\times10^{-6}{}^\circ C^{-1}$as recommended by Hong and Varma [9], which could meet the accuracy of the model [17].

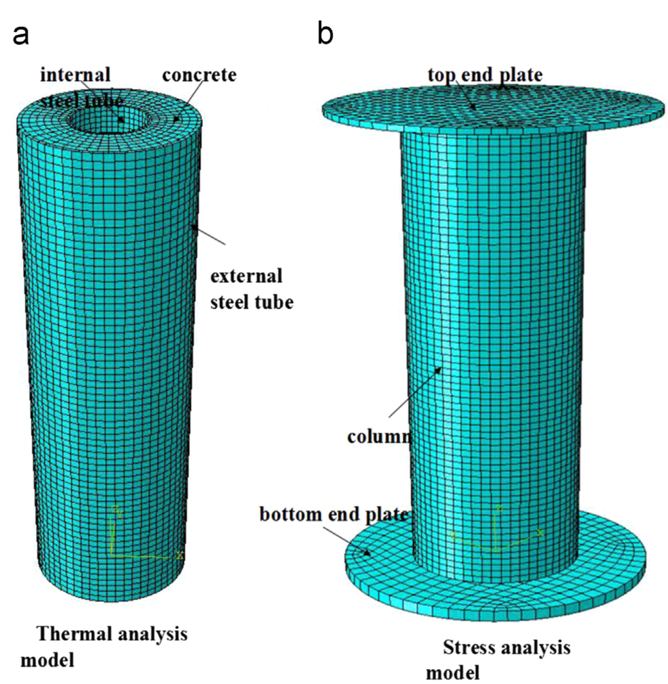

Fig. 1. Representative FEA model for CFDST columns.