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Cooling behavior and residual strength of post-fire concrete filled steel tubular columns

Yao Yao [a,*], Xin Xin Hu [a]

[a] School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Shaanxi 710072, China

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ABSTRACT

An interaction approach to evaluate the residual strength of concrete filled steel tubular (CFST) columns after fire conditions is developed. The approach is based on strength reduction of steel tube and concrete as a function of the maximum temperature, which is obtained from the whole fire exposure process. Sixty-one CFST column tests to the residual strength of specimens subjected to uniform heating or ISO-834 standard fire were employed to benchmark the proposed approach. The predictions showed good agreement compared with experimental data. In order to obtain the post-fire load versus deformation relationships, a 3D finite element model was developed to investigate the behavior of CFST columns under different heating conditions. Based on the natural fire curve from Cardington fire tests and Fire Dynamics Simulator (FDS) software, parametric studies were performed to investigate the effects of parameters to the heating and post-fire behavior of CFST columns under natural fire conditions. From the theoretical and computational analysis, it can be concluded that the residual strength of CFST columns after natural fire exposure is generally affected by fire duration time, cross-sectional diameter and slenderness ratio.

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1. Introduction

Concrete filled steel tubular (CFST) columns have been widely applied in the modern high-rise buildings because of good structural performances [1]. However, fire resistance is a key issue in the design of CFST columns. In the past decades, the fire resistance of CFST columns under fire conditions has been investigated by different researchers. Lie and Chabot [2], Lie [3] and Sakumoto et al. [4] carried out fire resistance tests of CFST columns under fire conditions. Hass [5], Kodur [6], Lie and Stringer [7], Wang [8,9], Tan and Tang [10] and Hong and Varma [11] developed theoretical models to predict fire resistance of CFST columns. However, most of the studies only considered the fire performance of CFST columns during the heating phase. In realistic cases, there is always a cooling phase after reaching peak temperature. Armer and Moore [12], El-Rimawi et al. [13], Bailey et al. [14], Wang et al. [15] and Lien et al. [16] demonstrated that cooling phase has a significant influence on steel frame structure. Yao and Tan [17,18] investigated the fire performance of steel and reinforced concrete columns under different natural fire conditions. However, few studies have been performed on post-fire performance of CFST columns after fire exposure. Han [19], Han et al. [20,21] and Lin [22] conducted experiments to investigate the fire resistance of CFST columns under and post heating. Yang [23] and Song [24] proposed a finite element analysis (FEA) model to predict the residual strength of CFST columns after fire exposure. Research shows that combination of theoretical model and computational analysis is able to predict the post-fire behavior of CFST columns. In addition, the determination of residual strength after fire exposure is crucial in post-fire damage assessment and repair.

In the current study, a 3D finite element model is developed to investigate the behavior of CFST columns after uniform heating and ISO-834 standard fire conditions. Load versus deformation relationships of CFST columns obtained from the post-fire tests are employed to verify the accuracy of the numerical model. In order to study the behavior of CFST columns after realistic fire conditions, the natural fire curve from Cardington fire tests [25] and Fire Dynamics Simulator (FDS) software was used in the subsequent parametric study. From the parametric study, it can be concluded that the residual strength of CFST columns after natural fire is generally affected by fire duration time, cross-sectional diameter and slenderness ratio. Based on strength reduction of steel tube and concrete as a function of the maximum temperature, which is obtained from the whole fire exposure process, a theoretical approach is developed to evaluate the residual strength of post-fire CFST columns. The predictions of the proposed approach show good agreement compared with 61 CFST column tests after uniform heating or ISO-834 fire conditions.

2. Fire exposure

The air temperature can rise in different modes, namely, uniform heating, ISO-834 standard fire curve and natural fire curve, as shown

* Corresponding author at: School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Shaanxi 710072, China.
E-mail address: yaoy@nwpu.edu.cn (Y. Yao).

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in Fig. 1. All the fire curves have three phases: heating phase, cooling phase and post-fire phase. The temperature versus time relationship of the ISO-834 standard fire curve in the heating phase is given in Eq. (1):

$$T = T_0 + 345\log_{10}(8t+1) \quad (1)$$

where T_0 is the ambient temperature, t is the fire exposure time and T is the maximum temperature.

The uniform heating phase is tested under different temperatures, and the maximum temperature T is 20, 100, 200, 300, 400, 500, 600, 700, 800 and 900 °C, respectively.

The cooling phase of the uniform heating is given in Eq. (2):

$$T = \begin{cases} T_{\max} - (t - t_h) \times 15 & (t_h < t < t_h + (T_{\max} - T_0)/15) \\ 20 & (t \geq t_h + (T_{\max} - T_0)/15) \end{cases} \quad (2)$$

where T is the fire temperature in °C; t is the fire exposure time in min; t_h is the fire duration time in min; $T_{\max}$ is the maximum fire temperature in °C; and $T_0 = 20$ °C is the ambient temperature.

The natural fire curve is obtained from Cardington fire tests and Fire Dynamics Simulator (FDS) software, which will be described in detail in Section 2.1.

2.1. Natural fire curve

As part of the European collaborative research program, the European Coal and Steel Community (ECSC) has supported an extensive program of work to develop a new fire safety concept based on the behavior of structures under natural fires. The Building Research Establishment (BRE) in the United Kingdom carried out a series of full-scale fire tests in a purpose-built compartment at Cardington [25]. The tests have been performed in a compartment with overall dimensions of 12 m × 12 m, and the investigated parameters were location of ventilation opening, type of fire load and thermal properties of the compartment linings. All the parameters are summarized in Table 1 [25]. The quantity of fuel load, area of ventilation opening and size of compartment are identified for all the tests.

The opening factor ($A_v\sqrt{h}/A_t$) is an important parameter in the full-scale fire tests. The ventilation characteristics are divided into two types as shown in Table 2 [25]. In all the tests, the value of the fire load is 40 kg/m^2 of wood in the floor area. The quantity of fire load is well established from statistical data and a number of tests have been carried out [26]. Two types of fire load are used in the test scenario: (1) 100% timber and (2) 80% timber/20% plastic by calorific value. The calorific values for calculation are H_u of 17 MJ/kg for wood and 34 MJ/kg for polypropylene. The properties of the materials adopted in the test compartment are shown in Table 3 [25]. Thermal parameters such as density,

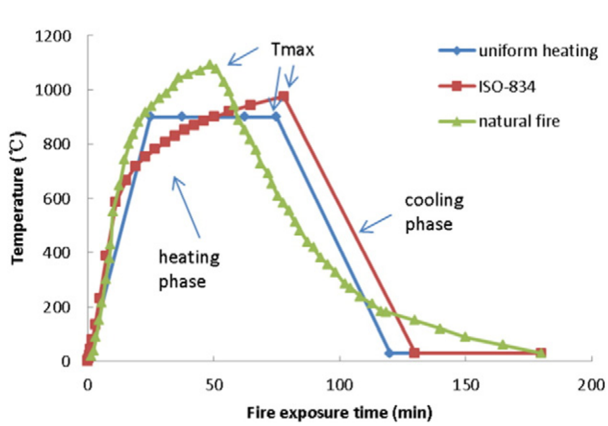

Fig. 1. Full process of temperature load–time paths.

Table 1
Details of ECSC test program in Cardington fire test [25].

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Fire load	40	40	40	40	40	40	40	40
Type	W	W	WP	W	WP	W	WP	WP
Ventilation	H	H	H	H	H	H	H	H
Lining	I	HI	HI	HI	HI	I	I	I
Size	L	L	L	L	L	L	L	L
Opening	F	F	F	FB	FB	FB	FB	F

Note: W: 100% wood and WP: 80% wood, 20% plastic; H: ventilation factor 0.08–0.1 m^2; I: compartment lining-insulating; HI: highly insulating; L: large compartment; F: front opening only; FB: front and back openings.

thermal conductivity and specific heat recommended in Eurocode are employed corresponding to the value at ambient temperature.

2.2. Verifications to the FDS model

A Fire Dynamics Simulator (FDS) model is developed to simulate the natural fire in a compartment compared with the scenario of Cardington full-scale fire tests. The overall dimension of the compartment is 12 m × 12 m × 3.6 m. In order to monitor the temperature variation of each area in the compartment, the compartment is divided into 60 × 60 × 18 units. Forty-nine cribs are used in the Cardington fire tests, spreading uniformly throughout the compartment. It should be noted that the method of ignition in the FDS model is a fully developed fire, and 18 thermocouples were set up to measure the temperature distribution in the compartment. The test scenario and thermal material parameters listed in Tables 2 and 3 are employed. The representative test compartment and numerical models are shown in Fig. 2. Fig. 3 shows the temperature distribution of inner compartment with a reduction of fuel.

Fig. 4 shows the average compartment temperatures of eight full-scale fire tests. Owing to the limit of paper length, only the comparisons of tests 2, 3, 4, and 6 are presented here. In general the simulation results show good agreement compared with experimental data. The simulation results are compared with Foster et al.'s [27] work who used FPRCBC-T software to simulate the fire tests and Eurocode [28], as shown in Fig. 5. According to the comparison, the FDS model can successfully simulate the natural fire in the compartment. In addition, the FDS software can monitor the simulation process at any time, which is beneficial to investigate the evolution of natural fire.

3. Finite element analysis model

A FEA model is developed to predict the load versus deformation relationships of CFST columns after fire exposure. This model can simulate the behavior of CFST columns subjected to a full process of temperature–time paths, as shown in Fig. 1. A sequentially coupled thermal-stress analysis module in ABAQUS software is developed. In the developed model, an uncoupled thermal analysis module is first developed to predict the transient temperature fields of CFST columns subjected to different fire curves including a cooling phase. Then the nodal temperatures are read from the thermal analysis, and input to the stress analysis solver as a temperature load, corresponding thermal analysis elements are changed to corresponding stress analysis elements. By

Table 2
Details of ventilation characteristic in Cardington fire test [25].

Parameter	Front opening (F)	Front and back opening (FB)
A_v (m^2)	24.48	24.48
h (m)	3.4	1.7
A_t (m^2)	451.2	451.2
H (m)	3.4	3.4
O (m$^{1/2}$)	0.1	0.07

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