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Fire resistance of concrete filled steel tube columns subjected to non-uniform heating

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ABSTRACT

Concrete filled steel tube columns have been widely applied in modern construction. However, limited work has been done on the resistance of concrete filled steel tube columns subjected to non-uniform fire conditions, and a calculation method with clear physical meanings is useful to structural engineers. Columns are usually exposed to 1-, 2-, 3-face heating under real fire scenarios. In the current work, a 3D finite element model was developed to simulate the concrete filled steel tube columns exposed to non-uniform fire conditions. After validating the proposed FE model, the failure mechanism of concrete filled steel tube columns under non-uniform fire was discussed. Parametric studies were conducted to investigate the influence of critical structural parameters. A theoretical approach was proposed to calculate the fire resistance of concrete filled steel tube columns exposed to non-uniform heating. By comparing the experimental data and numerical simulations, the developed approach was validated to be sufficiently accurate to predict the ultimate load capacity of concrete filled steel tube columns under 1-, 2-, 3-face heating scenarios.

1. Introduction

Concrete filled steel tubular (CFST) columns have been widely used in construction industry owing to their satisfactory structural performance and construction convenience. Fire safety of buildings is a key issue of structural design, therefore it is essential to achieve a better understanding about the fire performance of CFST columns. In the existing literature, fire performance of CFST columns has been studied experimentally and theoretically.

In the past few decades, a few experiments have been performed to investigate the performance of CFST columns in fire. Lie et al. [1–4] conducted a series of experiments to study the fire resistance of concrete filled circle and square hollow section columns filled with plain concrete and bar-reinforced concrete. Kodur et al. [5] and Romero et al. [6] studied the fire resistance of steel tubular columns filled with high strength concrete. However, all the research works mentioned above were focused on the heating phase, and carried out following the ISO-834 standard fire curves. In order to simulate the real fire scenarios, Han et al. [7,8] studied the behaviour of CFST columns under fire conditions considering a uniform cooling phase. Yao and Hu [9] studied the cooling behavior and residual strength of pose-fire CFST columns based on the natural fire curve from Cardington fire tests. Although research works have been performed on the fire resistance of CFST columns, limited information is available on CFST columns subjected to non-uniform fire conditions, and an effective approach to predict the ultimate load of CFST column under fire conditions with clear physical meaning is still absent.

Regarding analytical approaches, the conventional Rankine method has been extended by Tan and Tang [10] to plain and reinforced CFST columns under 4-side fire conditions. This method provides structural engineers a physical tool to predict the squashing capacity and elastic buckling capacity of columns. Yao and Li [11,12] extended the Rankine method to the slender concrete filled steel tubular columns subjected to eccentrically load and the concrete filled double skin steel tubular columns. It should be noted that for simplicity of analysis, previous researchers generally assumed that all sides of CFST columns are subjected to uniform fire conditions. As shown in Fig. 1, besides the uniform fire condition, only some sides of the columns subjected to fire attack are more frequently encountered and realistically meaningful in practice. Yang et al. [13,14] studied the performance of concrete-filled rectangular and square hollow section columns exposed to fire on 1- and 3-sides experimentally. Based on their experimental results, an empirical method using a reduction factor was developed for the design of CFST columns exposed to non-uniform fire. However, some of the parameters are lack of clear physical meaning in the reduction factor prediction method.

In the present work, a thermal-stress sequential coupling 3D finite element (FE) model was developed to simulate the thermal and mechanical responses of CFST columns exposed to non-uniform fire conditions. The FE model was developed by a commercial finite element package ABAQUS [15] and validated against the results from experimental studies in literature considering the cases of columns exposed

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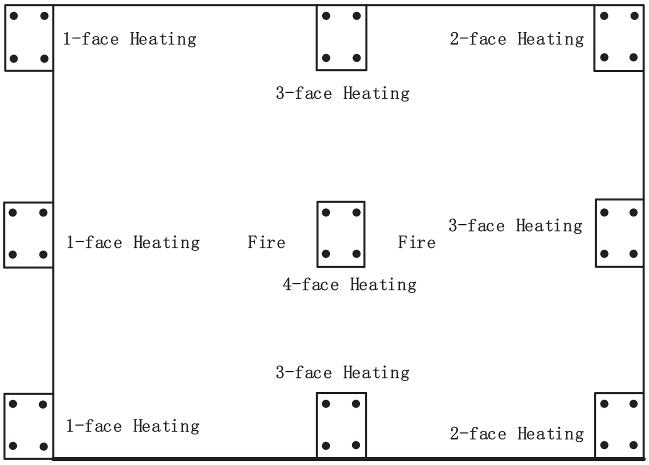

Fig. 1. Columns under different thermal boundary conditions in a compartment.

to 1- and 3-face ISO-834 standard fire heating. Based on the validated FE model, the mechanical behavior of CFST columns was numerically simulated to understand the fire resistance and failure mode under non-uniform fire conditions. A parametric study was performed to investigate important engineering design parameters that may affect the fire resistance of CFST columns under 1-, 2-, 3-side non-uniform heating and 4-face heating. Finally, an extended Rankine approach was developed to predict the fire resistance of CFST columns exposed to non-uniform fire, and a worked example is provided in Appendix A for the convenience of engineering practice.

2. Finite element model for CFST columns

A three-dimensional sequentially coupled thermal-stress FE model was developed in the present study. Firstly, a pure heat transfer analysis sub-model was conducted to obtain the temperature field of CFST columns under non-uniform fire conditions. A three-dimensional stress analysis model was then established, and the coupled temperature field was imported into the stress analysis model as a predefined temperature field.

In order to simulate the exact temperature field under non-uniform fire conditions, a layer of 100 mm thick fiber ceramic blanket was attached to the column surface, as shown in Fig. 2, which can endure the temperature up to 1200 °C and provide no bearing capacity. In the stress analysis, two end blocks were added to the ends of columns, and a constant load was applied to the top one. To ensure the load transmitted to the columns properly, the end blocks were assumed as rigid body without any deformation. Additionally, the type of elements should belong to the same element families. Namely, the 3D solid elements for thermal and structural analyses were DC3D8 and C3D8, respectively. The finite element discretization scheme for representative CFST column is shown in Fig. 3. Three dimensional 8-node brick elements were adopted for all parts of the FE model in both thermal and stress analysis. The mesh density was determined by computational mechanics analysis, and an element size of 30 mm is found to be sufficient to accurately predict the thermal and stress behavior of CFST columns under fire conditions.

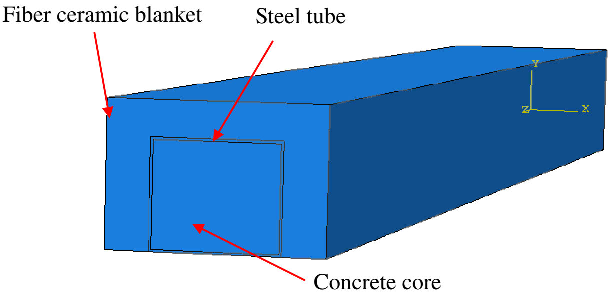

Fig. 2. Representative thermal assembly model for CFST columns.

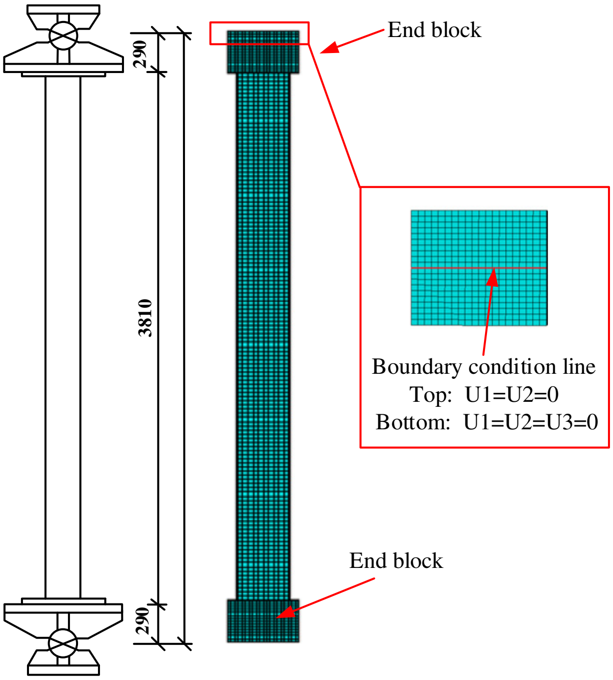

Fig. 3. Representative FE model to simulate the experiment reported by Yang et al. [14].

2.1. Material properties

The temperature dependent thermal and mechanical properties of the materials are taken into account in the numerical model. For both concrete and steel, the thermal properties models proposed by Lie et al. [2] were adopted in the thermal analysis. The concrete damaged plasticity model in ABAQUS [15] was adopted for concrete elements in the stress analysis. There are two failure mechanisms considered in the developed model, tensile cracking and compressive crushing. A modified Drucker–Prager yield surface with non-associated flow was applied to define the plastic flow. The stress–strain relationship of concrete at fire conditions proposed by Lu et al. [16] was employed, which considers the bonding effect of the steel tube to the concrete core. A classic metal material model with Von Mises yield surface and associated plastic flow rule was chosen for steel material. The stress–strain relationship of steel at elevated temperatures proposed by Lie et al. [3] was adopted, which shown good accuracy to predict the fire behavior of CFST columns [17]. Two constant expansion coefficients recommended by Hong and Varma [18] were adopted and the values were 6×10^{-6}/°C and 12×10^{-6}/°C for concrete and steel, respectively.

Table 1
Thermal properties of the fiber ceramic blanket [14].

Properties	T (°C)		
	<600	800	1000
Density (kg/m^3)	128		
Thermal conductivity (W/(m °C))	0.12	0.16	0.23
Specific heat (J/(kg °C))	878.85		
Allowable temperature (°C)	1260		