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Heat transfer in concrete-filled carbon and stainless steel tubes exposed to fire

Zhong Tao *, Mohamed Ghannam

Institute for Infrastructure Engineering, University of Western Sydney, Penrith, NSW 2751, Australia

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A B S T R A C T

Nowadays, performance-based design methods are increasingly used for fire resistance assessment of structures. To implement these methods, it is paramount to determine the temperature development within a structural member exposed to fire as accurately and efficiently as possible. Numerical models are developed in this paper to simulate the temperature development in concrete-filled carbon and stainless steel tubes. It was found that the influence of the moisture content in concrete and the thermal contact conductance at the steel–concrete interface is significant. New models for thermal conductivity of concrete and thermal contact conductance at the interface are proposed in this paper. Comparisons of temperature development are made between numerical simulations and extensive experimental results. Improved agreement with test results is achieved when the proposed models are used in the heat transfer analysis.

1. Introduction

In recent times, the use of concrete-filled steel tubes (CFST) as structural members is growing, due to several highly appreciated advantages of the composite members, such as high speed of construction, high load-bearing capacity, high seismic resistance, reduced cross-section and high fire resistance [1]. To further improve the performance of CFST columns, stainless steel may be used in CFST construction to replace structural carbon steel [2–5]. This is owing to the fact that concrete-filled stainless steel tubes (CFSST) can utilise the beneficial material properties of both stainless steel and concrete. Thus, the durability and aesthetic appearance of the composite construction can be greatly improved, whilst the increased initial cost of using stainless steel can be offset by the relatively low cost of concrete and the reduced maintenance cost in the life-cycle of the structure. For clarity, CFST and CFSST columns will be referred to in the following as the columns comprised of carbon steel and stainless steel, respectively, unless otherwise specified.

Nowadays, performance-based design methods are increasingly used for fire resistance assessment of structures. When modelling the response of a structure upon subjection to fire, it is paramount to accurately and efficiently determine the temperature development within structural members [6]. This is owing to the fact that temperatures have a significant influence on material properties (e.g. strength, modulus of elasticity and deformation capacity) of structural elements. In general, the higher the temperature, the more rapidly materials will deteriorate. An overestimation of temperatures within a structure will lead to an increase in the insulation material thickness or cause more material to be used to resist the load. On the other hand, an underestimation of the temperatures may lead to unsafe structural design. In the past, numerous tests have been conducted to investigate the fire resistance of CFST columns [7]. Meanwhile, numerical models were developed by various researchers to conduct nonlinear heat transfer analysis and stress analysis of CFST columns in fire [8–14]. In those models, thermal conductivity and specific heat of steel and concrete materials were generally specified using empirical models presented in ASCE Manual No. 78 [15] or Eurocode 4 [16]. As far as the moisture content of concrete (θ_m) and the thermal contact conductance (h_j) at the steel tube–concrete interface are concerned, their influence on the heat transfer is generally not negligible, but various values were used by different researchers. Although currently available numerical models give generally reasonable predictions of temperature development in CFST columns, considerable deviations can be expected between various model predictions, which indicates that further research addressing this topic is needed. Meanwhile, very limited research has been conducted to investigate the heat transfer in the comparatively new CFSST columns.

This paper concerns the temperature development in concrete-filled steel tubes comprised of carbon steel or stainless steel. Numerical models are developed using the non-linear finite element package ABAQUS [17]. New models for thermal conductivity of

* Corresponding author. Tel.: +61 2 4736 0064; fax: +61 2 4736 0054.
E-mail address: z.tao@uws.edu.au (Z. Tao).

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Nomenclature

B	Overall width of square or rectangular section
C_c	Specific heat of concrete
CFSST	Concrete-filled stainless steel tube
CFST	Concrete-filled steel tube
D	Overall diameter of circular section or overall depth of rectangular section
$f_c{}'$	Cylinder compressive strength of concrete
h_j	Thermal contact conductance at the steel–concrete interface
L	Column length
t	Wall thickness of the steel tube
t_c	Age of concrete
T	Temperature
T_{cal}	Predicted temperature
T_{test}	Measured temperature
T_s	Surface temperature of the steel tube
W_e	Equilibrium water content of concrete
α_c	Convective heat transfer coefficient
ε_m	Emissivity coefficient
λ_c	Thermal conductivity of concrete
μ	Average value
θ_m	Moisture content by weight of concrete
ρ_c	Concrete density
ρ_s	Steel density
σ	Standard deviation

concrete (λ_c) and thermal contact conductance at the interface are proposed. Comparisons of temperature development in composite columns are made between numerical simulations and a wide range of experimental data, which demonstrates that improved prediction accuracy is obtained.

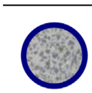
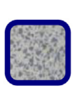
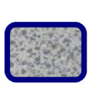
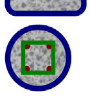
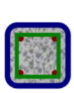
2. Review of fire tests conducted on CFST and CFSST columns

Over the last few decades, numerous fire tests have been conducted on CFST columns. More recently, with the increasing interest in using stainless steel, some fire tests have been conducted on CFSST columns as well. In the present study, a database containing the test results of 153 CFST columns and 14 CFSST columns was assembled from an extensive survey of the open literature. In the database, 27 tests were conducted on specimens with fire protection coating. It is expected that the thermal properties of most fire protection materials are somewhat temperature-dependent, but the thermal properties of the insulation material at elevated temperatures were normally not reported in the literature. For this reason, these fire-protected specimens have been excluded from comparison. Furthermore, steel fibre reinforced concrete under elevated temperatures exhibits thermal properties that are slightly different from those of plain concrete [18]. As this study is limited to plain concrete, 19 specimens using steel fibre reinforced concrete as filling material have also been excluded. In the end, test results of 107 CFST columns (including 57 circular, 46 square and four rectangular specimens) and 14 CFSST columns (including two circular and 12 square specimens) were used in this paper as shown in Tables 1 and 2, respectively. These 121 tests were reported by Lie and Chabot [19], Wainman and Toner [20], Kodur and Latour [21], Romero et al. [22], Sakumoto et al. [23], Han et al. [24], Lu et al. [12], Han et al. [25], Kordian and Klingsch [26], Chabot and Lie [27], Myllymäki et al. [28], Han et al. [29], Renaud [30], and Lee [31]. It should be noted that 45 specimens in Tables 1 and 2 had steel reinforcement embedded in concrete to improve the fire resistance. Since the presence of steel bars in concrete has insignificant effect on the temperature development in most cases, their existence can generally be ignored [32]. This can be argued by the fact that the ratio of the total area of the steel rebars to the overall cross-sectional area of the column is generally very small.

The details of the collected data are summarised in Tables 1 and 2 for CFST and CFSST columns, respectively, including the section type, the overall diameter of circular columns (D) or the overall width of square columns (B), the tube thickness (t), the specimen length (L) and the cylinder compressive strength of concrete ($f_c{}'$). For the four rectangular columns presented in Table 1, B and D are the overall cross-sectional width and depth, respectively. Austenitic stainless steel was used for all the specimens listed in Table 2.

All specimens presented in Tables 1 and 2 were exposed to fire on all sides, and in most cases the furnace temperature was

Table 1
Summary of test data of CFST columns exposed to fire.

Section shape	Number of specimens	D (mm)	B (mm)	t (mm)	L (mm)	$f_c{}'$ (MPa)	Source
	38	141–406	–	4.8–12.7	3810	23.8–82.2	Lie and Chabot [19]
	3	245–356	–	6.3–9.5	3400	52.4	Wainman and Toner [20]
	1	273	–	6.35	3810	107	Kodur and Latour [21]
	5	159	–	6	3180	28.6–71.1	Romero et al. [22]
	6	–	152–305	6.35	3810	46.5–58.8	Lie and Chabot [19]
	1	–	300	9	3500	37.5	Sakumoto et al. [23]
	2	–	299–600	5	800	24	Han et al. [24]
	6	–	150–200	5-6	760	99	Lu et al. [12]
	4	300	150–200	1.5–2	3810	40.2	Han et al. [25]
	1	273		5	4200	44	Kordian and Klingsch [26]
	2	273	–	6.35	3810	47	Chabot and Lie [27]
	2	219–406	–	6.35–12.7	3810	81.7–93.2	Kodur and Latour [21]
	5	159	–	6	3180	23.9–77	Romero et al. [22]
	21	–	200–300	6.3–12.5	3700–5200	28.5–65	Kordian and Klingsch [26]
	6	–	203–305	6.35	3810	47–48.1	Chabot and Lie [27]
	1	–	203	6.35	3810	81.7	Kodur and Latour [21]
	3	–	150–300	5–8	3810	31–36	Myllymäki et al. [28]