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Post-fire behaviour of eccentrically loaded reinforced concrete columns confined by circular steel tubes

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ABSTRACT

The post-fire behaviour of eccentrically loaded reinforced concrete columns confined by circular steel tubes, also known as circular steel tube confined reinforced concrete (STCRC) columns, is investigated in this paper. A total of 12 experiments were conducted on eccentrically loaded circular STCRC stub columns after exposure to the ISO 834 standard fire, including both the heating and cooling phases. The temperatures across the tested sections, the axial load versus lateral displacement responses and the strains in the steel tubes were all measured and discussed. A finite element (FE) model was developed using the program ABAQUS, and validated against the test results from the present study, as well as related studies. Parametric studies were then performed to identify the influences of key parameters on the residual capacity of the eccentrically loaded STCRC columns, including eccentricity ratio, heating time, cross-sectional diameter, slenderness ratio, material strengths, steel tube to concrete area ratio and reinforcement ratio. Finally, a simplified method was proposed for predicting the residual load-bearing capacity of the eccentrically loaded STCRC columns after fire exposure.

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Nomenclature

A_b	cross-sectional area of reinforcing bars
A_c	cross-sectional area of concrete core
A_s	cross-sectional area of steel tube
A	cross-sectional area of composite section, $A = A_s + A_c + A_b$
D	outer diameter of cross-section
e	load eccentricity
E_b	Young's modulus of reinforcement at ambient temperature
E_{bT}	Young's modulus of reinforcement after fire exposure
E_c	Young's modulus of concrete at ambient temperature
E_{cT}	Young's modulus of concrete after fire exposure
E_s	Young's modulus of steel at ambient temperature
E_{sT}	Young's modulus of steel after fire exposure
f_b	yield strength of reinforcement at ambient temperature
f_{bT}	yield strength of reinforcement after fire exposure
f_c'	concrete cylinder strength
f_{cT}'	concrete cylinder strength after fire exposure
f_y	yield strength of steel
f_{yT}	yield strength of steel after fire exposure
k	factor accounting for delay of temperature rise of concrete
L	length of column
$N_{ecc,T}$	load-bearing capacity of eccentrically loaded column after fire exposure
$N_{axi,T}$	load-bearing capacity of axially loaded column after fire exposure
N_u	cross-sectional capacity of composite column
r	radius of steel tube, $r = D / 2$
t_h	heating time to the maximum fire temperature
t_s	wall thickness of the steel tube
T	temperature
T_{max}	maximum temperature achieved during the heating and cooling phases
α_b	ratio of reinforcement, $\alpha_b = A_b / (A_c + A_b)$
α_s	steel tube to concrete area ratio, $\alpha_s = A_s / A_c$
ε	strain
λ	slenderness ratio, $\lambda = L / i$, where i is the radius of gyration
χ_e	reduction factor accounting for effect of load eccentricity
χ_T	buckling reduction factor

1. Introduction

Reinforced concrete columns confined by steel tubes, also referred as steel tube confined reinforced concrete (STCRC) columns, are composite members with outer steel tubes terminated at the beam-to-column connections. The steel tube in STCRC columns acts principally as hoop reinforcement, maximising its confinement to the concrete and reducing the possibility of local buckling, compared with concrete-filled steel tubular (CFST) columns. The confinement effect greatly enhances the strength and ductility of the in-filled concrete. Therefore STCRC

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columns possess high load-bearing capacity and excellent seismic performance. The desired break in continuity of the steel tube enables the reinforced concrete beam to STCRC column connections to be designed and constructed following the same approach as for conventional reinforced concrete structures, which avoids the complexities associated with reinforced concrete beam to CFST column connections [1,2].

Previous studies, conducted by Tommi et al. [3–5], Sun et al. [6], Aboutaha et al. [7,8], Han et al. [9,10], Liu et al. [11–13] and Yu et al. [14], have all focused on the compression behaviour or seismic performance of steel tube confined reinforced (or plain) concrete columns at ambient temperature. Following on from recent research by the authors on the post-fire behaviour of axially loaded STCRC stub columns [1] and STCRC slender columns [2], the post-fire behaviour of eccentrically loaded STCRC columns is investigated herein.

A total of 12 specimens were firstly exposed to the ISO 834 standard fire conditions [15] and were then loaded eccentrically, to investigate the residual behaviour of these STCRC columns and provide benchmark data for the verification of the finite element (FE) model. The temperatures of the steel tube, reinforcing bars and concrete, as well as the load versus lateral displacement curves, strains in the outer steel tube and failure modes were all measured and analysed. A FE model was developed in the program ABAQUS, using a sequentially coupled thermal-stress analysis, by first performing a pure heat transfer analysis and then a stress analysis. Parametric studies were conducted to investigate the influences of key parameters on the residual capacity of the eccentrically loaded STCRC columns after fire exposure. Finally, a simplified method was proposed for predicting the load-bearing capacity of eccentrically loaded STCRC columns after fire exposure.

2. Experimental investigation

2.1. Test specimens

A total of 12 circular STCRC stub columns were tested after fire exposure. The key test parameters were concrete compressive strength (C30, C50) and load eccentricity e (25 mm, 50 mm), which were also used to label the specimens. The specimen labelling system can be explained by the means of an example - consider specimen C30-e25-a; C30 is the concrete grade, e denotes that the load was applied eccentrically, 25 is the load eccentricity in mm, and the final letter identifies different specimens in a specimen group with the same parameters. Details of the parameters of the specimens, including the cross-section diameter D, the thickness of steel tube t_s, the length of specimens L, the load eccentricity e, the steel tube to concrete area ratio α_s ($\alpha_s = A_s / A_c$), the reinforcement ratio α_b ($\alpha_b = A_b / (A_c + A_b)$) and the heating time t_h (the time corresponding to the maximum furnace temperature), are presented in Table 1.

The steel tubes in the circular STCRC columns were cold-formed from steel sheets and seam welded. Two 300 mm × 300 mm × 20 mm steel plates were welded to the top and bottom ends of the columns. Two gaps, with a width of 10 mm, were introduced into the steel tube, 50 mm away from each end plate, in order to prevent the load being applied to the steel tube directly. Six longitudinal reinforcing bars with a diameter of 20 mm were tied at 200 mm intervals with 8 mm stirrups. The longitudinal reinforcing bars were welded and anchored to the end plates, to prevent the possibility of bond failure due to insufficient anchorage. The concrete cover from the outer perimeter of the reinforcing bars to the concrete edge was 20 mm. Details of the test specimens are shown in Fig. 1.

An additional stub column, with a length of 500 mm (Fig. 2) and the same constituent components (steel tube, reinforcing bars and concrete) as the other test specimens, was specially fabricated to measure temperatures in the specimens during the heating and cooling phases. The gaps introduced in the steel tube could act as vent holes for moisture produced during the test, as shown in Fig. 2. Type K thermocouples, with a diameter of 1.0 mm, were employed to measure the temperatures of the steel tube, reinforcing bars and concrete in several locations at two cross-sections, which were 150 mm away from each end plate. The uniformity of temperature along the longitudinal direction could then be verified by comparing the corresponding temperatures at the two different heights. The layouts of the thermocouples are shown in Fig. 2.

The steel tube, reinforcing bars and concrete used for the test specimens examined herein came from the same batch of materials as used in previous tests by the authors on circular STCRC stub columns [1] and slender columns [2]. The properties of the steel tube and reinforcing bars were tested by performing tensile coupon tests and were presented in [1,2]. Herein, their properties are briefly described. The yield strength of the steel tube was 318.9 N/mm^2 and 295.2 N/mm^2, respectively, before fire exposure and after 30 min heating. The yield strength of the longitudinal reinforcement and stirrups were 357.4 N/mm^2 and 435.4 N/mm^2, respectively, before fire exposure. The concrete cube strengths were tested at 28 days and the test day of the specimens [1,2]. For the grade C30 and C50 concrete, the cube strength reached 53.8 N/mm^2 and 76.3 N/mm^2, respectively, at the test days of the specimens.

2.2. Test setup and procedure

Regarding the residual strength of the concrete after fire exposure, studies on concrete material [16–18] and concrete members [19,20] have confirmed that the determination of properties in the unstressed condition during the heating and cooling phases is more conservative than in the stressed condition. Hence, the STCRC columns were heated in an unstressed condition within a specially built furnace for testing structural members. Details of the furnace may be found in [1].

Fires in an enclosure usually undergo three stages: i) fire growth, ii) steady burning and iii) decay. Since it is not straightforward to obtain accurate fire temperature versus time relationships for real fires due to the inherent complexities and uncertainty of their nature, for the purposes of fire safety design, some approximate fire temperature versus

Table 1
Detailed parameters of the test specimens.

Column no.	D (mm)		t_s (mm)		L (mm)	e (mm)	α_s (%)	Reinforcing bars	α_b (%)	t_h (min)
	Nominal	Measured	Nominal	Measured						
C30-e25-a	250.0	249.5	2.20	2.18	750.0	25.0	3.62	6Φ20	3.98	30.0
C30-e25-b	250.0	249.3	2.20	2.17	750.0	25.0	3.62	6Φ20	3.98	30.0
C30-e25-c	250.0	249.7	2.20	2.18	750.0	25.0	3.62	6Φ20	3.98	30.0
C30-e50-a	250.0	249.2	2.20	2.18	750.0	50.0	3.62	6Φ20	3.98	30.0
C30-e50-b	250.0	249.5	2.20	2.19	750.0	50.0	3.62	6Φ20	3.98	30.0
C30-e50-c	250.0	249.5	2.20	2.17	750.0	50.0	3.62	6Φ20	3.98	30.0
C50-e25-a	250.0	249.7	2.20	2.20	750.0	25.0	3.62	6Φ20	3.98	30.0
C50-e25-b	250.0	249.2	2.20	2.18	750.0	25.0	3.62	6Φ20	3.98	30.0
C50-e25-c	250.0	249.2	2.20	2.17	750.0	25.0	3.62	6Φ20	3.98	30.0
C50-e50-a	250.0	249.3	2.20	2.16	750.0	50.0	3.62	6Φ20	3.98	30.0
C50-e50-b	250.0	249.0	2.20	2.18	750.0	50.0	3.62	6Φ20	3.98	30.0
C50-e50-c	250.0	249.8	2.20	2.17	750.0	50.0	3.62	6Φ20	3.98	30.0

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