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

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ABSTRACT

The post-fire behaviour of slender reinforced concrete columns confined by circular steel tubes is investigated experimentally and numerically in this paper. Experiments were performed firstly to explore the fundamental behaviour of steel tube confined reinforced concrete (STCRC) slender columns after exposure to the ISO 834 standard fire, including the cooling phase. Temperature distributions, load versus lateral displacement curves, strains in the steel tube and failure modes were obtained and discussed. Next, a 3D finite element model was developed with the program ABAQUS using a sequentially coupled thermal-stress analysis. After validation of the FE model, parametric studies were carried out to identify the influence of key parameters on the load-bearing capacity and buckling reduction factor of slender STCRC columns. The considered parameters were the heating time, cross-sectional dimension, slenderness ratio, material strength, steel tube to concrete area ratio and reinforcement ratio. Finally, a simplified design method was proposed for predicting load-bearing capacity of STCRC slender columns after exposure to standard fires.

1. Introduction

Steel tube confined reinforced concrete (STCRC) columns differ from conventional concrete-filled steel tubular (CFST) columns in that steel tubes in STCRC columns are terminated at the beam to column connections (Fig. 1). Thus, the steel tube does not directly bear longitudinal force and acts primarily as hoop reinforcement to the concrete, maximising the confinement and minimising the possibility of local buckling of the steel tube. Furthermore, the connections between reinforced concrete beams and STCRC columns can be designed and constructed following established methods for conventional reinforced concrete structures, avoiding the complexities associated with connecting reinforced concrete beams to CFST columns.

Plain concrete columns confined by steel tubes were initially used by Gardner and Jacobson [1], Orito et al. [2] Prion and Boehme [3] O'Shea and Bridge [4,5], and Fam et al. [6] as a means of loading CFST columns. The concept of steel tube confined reinforced concrete columns as a structural member was first proposed by Tommi and his research group [7–9], with the aim of preventing shear failure and improving the ductility of reinforced concrete stub columns or boundary reinforced concrete columns in shear walls. This kind of member has subsequently attracted increasing research interest, most of which has focused on axial compressive behaviour [10,11] and seismic performance [12–14].

To date, no research has been reported on the response of STCRC columns subjected to elevated temperatures. Hence, the focus of the present investigation is the post-fire behaviour of STCRC columns. Building upon the recently reported work by the authors on the post-fire behaviour of STCRC stub columns [15], this second paper examines the post-fire behaviour of STCRC slender columns.

Experimental and numerical studies were performed to investigate the behaviour of STCRC slender columns following exposure to the ISO 834 standard fire [16]. The temperatures of the furnace, the steel tube, the reinforcing bars and the concrete core were monitored and recorded during the heating and cooling phases. The load versus displacement curves, the strains in the steel tube and failure modes were obtained in the subsequent compression tests. A 3D finite element (FE) model was developed using the program ABAQUS with a sequentially coupled thermal-stress analysis, and validated against the test results. Parametric studies were then performed based on the validated FE model to identify the influence of key parameters on the residual capacity of the columns, post-fire. Finally, a simplified design method was proposed for predicting the load-bearing capacity of STCRC slender 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_s	diameter of bars
D	outer diameter of the steel tube
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 structural steel at ambient temperature
E_{sT}	Young's modulus of structural steel after fire exposure
f_b	yield strength of reinforcement at ambient temperature
f_{bu}	ultimate tensile strength of reinforcement
f_{bT}	yield strength of reinforcement after fire exposure
f_{ck}	characteristic concrete strength, $f_{ck}=0.67\ f_{cu}$
f_{cu}	concrete cube strength
$f_{cu,28}$	concrete cube strength at 28 days
$f_{cu,test}$	concrete cube strength at the test day of the specimens
f_c'	concrete cylinder strength
f_{cT}'	concrete cylinder strength after fire exposure
f_{tT}'	concrete tensile strength after fire exposure
f_{su}	ultimate tensile strength of structural steel
f_y	yield strength of structural steel at ambient temperature
f_{yT}	yield strength of structural steel after fire exposure
k	factor accounting for the delay of temperature rise of concrete
L	length of column
L_e	effective length of column
N_e	load-bearing capacity of slender composite column
N_u	cross-sectional capacity of composite column
t_h	heating time to the maximum fire temperature
t_s	wall thickness of the steel tube
T	temperature
T_{max}	the 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, $\alpha_s=A_s/A_c$
λ	slenderness ratio, $\lambda=L_e/i$, where i is the radius of gyration
ν_s	Poisson's ratio of structural steel
ξ	confinement factor, $\xi=f_y\ A_s/f_{ck}\ A_c$
χ	buckling reduction factor

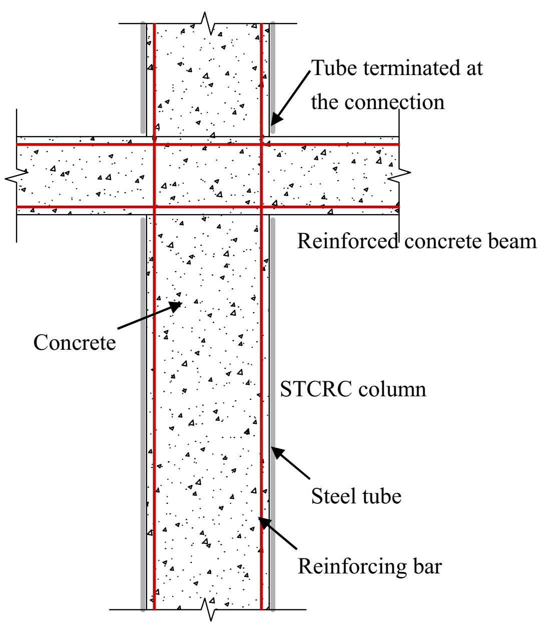

Fig. 1. Schematic view of the STCRC column and its beam to column connection.

2. Experimental study

2.1. Specimens

A total of 14 STCRC slender columns were prepared and tested in this study. The investigated parameters were heating time (the time corresponding to the maximum furnace temperature), cross-section diameter, slenderness ratio and compressive strength of concrete. For the circular steel tube confined reinforced concrete columns, the slenderness ratio (λ) may be defined as follows:

$$\lambda=\frac{L_e}{i}=\frac{4L_e}{D} \tag{1}$$

where L_e is the effective length of the column, i is the radius of gyration and D is the outer diameter of the steel tube.

Details of the test specimens are shown in Table 1, in which t_s is the thickness of the steel tube, α_s is the steel tube to concrete area ratio ($\alpha_s=A_s/A_c$), L is the length of the specimens, α_b is the reinforcement ratio ($\alpha_b=A_b/(A_b+A_c)$) and t_h is the heating time. Each specimen is labelled according to its cross-section diameter, length to diameter ratio, nominal concrete cube compressive strength and heating time. Consider specimen C250-6-30-60, for example; C represents the composite column, 250 is the cross-section diameter in mm, 6 is the length to diameter ratio, 30 is the nominal concrete cube compressive strength in N/mm^2 and 60 is the heating time in minutes. The steel tube to concrete area ratio and reinforcement ratio were maintained approximately constant for all test specimens, with nominal values of 3.6% and 4.0%, respectively.

Two end plates, with a thickness of 10 mm, were welded to the top and bottom ends of each test specimen. Two strips, each with a width of 10 mm, were cut from the steel tube, 100 mm away from the both end plates. This resulted in 10 mm gaps at both end of the steel members (i.e. breaks in longitudinal continuity of the steel tubes), which were introduced to prevent the steel tube from directly bearing longitudinal force. Six longitudinal reinforcing bars were tied at 200 mm intervals with 8 mm diameter stirrups. The concrete cover from the perimeter of the reinforcing bars to the edge of the concrete was 20 mm. A typical cross-section is shown in Fig. 2.

Three STCRC stub columns were fabricated to measure temperature distributions in the specimens during the heating and cooling phases. Two of these columns had an outer diameter of 250 mm while the third had an outer diameter of 200 mm. These specimens are referred to as C250-30 min, C250-60 min and C200-30 min, respectively. The steel tube, core concrete, reinforcing bars and stirrups of the three stub columns were the same as those in the corresponding test specimens. All three columns were 500 mm in length. Type K chromel–alumel thermocouples, with