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Effects of sustained axial load and cooling phase on post-fire behaviour of concrete-filled steel tubular stub columns

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ABSTRACT

This paper experimentally investigated the effects of pre-load and cooling phase on the residual strength and stiffness of concrete-filled steel tubular (CFT) stub columns which were heated and cooled down to room temperature under sustained axial load. CFT stub columns were axially loaded and heated to specified high temperatures in a specially built electrical furnace. After the specimens cooled down to room temperature while the axial load was kept constant, the stub columns were loaded to failure. The test results showed that the mechanical behaviour of the fire-damaged CFT stub columns with pre-load was obviously different from those without pre-load. The axial load level and the high temperature exposure had more significant effects on the stiffness of CFT stub columns than the residual strength. The sustained pre-load led to significant residual deformations of CFT stub columns during the cooling phase. Based on the test results, it is recommended that the effects of sustained axial loads and fire cooling phase should be taken into consideration in assessing the fire-damaged CFT columns.

1. Introduction

Concrete-filled steel tubular (CFT) columns have several structural and constructional benefits, such as high strength and fire resistance, large stiffness and ductility, restraint to local buckling of the steel tube provided by the infill of concrete core, omission of formwork and thus a reduction in the construction cost and time. These advantages have been recognized and have led to the increased use of CFT columns in several recent tall buildings in China. More and more composite columns used in tall buildings make it imperative to obtain a wide knowledge and comprehensive understanding of the fire performance and post-fire behaviour in order to make a reasonable strategy to restore a fire-damaged structure with minimum post-fire repair. Investigations into the fire resistance of CFT columns were conducted since the early 1980s [1–5], and the practical design method to determine the fire resistance of CFT columns had been incorporated into some design codes [6–8].

Although there are a large number of research studies on realistic performance of CFT columns under fire conditions, some researchers began to experimentally and theoretically study the post-fire behaviour of this type of composite columns in the past five years. Han et al. [9] reported results of monotonically loaded CFT stub columns subjected to high constant temperatures. Han and Huo [10], Han and Lin [11] studied monotonically and cyclically loaded beam–columns with different section types after exposure to the ISO-834 standard fire [12]. Han et al. [13] studied the compressive and flexural behaviour of concrete filled steel tubes after exposure to standard fire. Han et al. [14] reported a series of new tests on the behaviour of steel beam to concrete-filled steel tubular column connections after exposure to fire. But all the specimens in these pieces of literatures were not loaded during fire exposure because of the facility constraint. Yang et al. [15] developed a finite element analysis program to analyze the behaviour of concrete-filled steel tubular columns during the entire stage of fire exposure, including loading at ambient temperature, heating, cooling to the ambient temperature and post-fire loading to failure. The analytical results showed that the ambient temperature loading and heating and cooling history had obvious effects on the cooling and post-fire behaviour of CFT columns, while the influence needs to be verified by experimental results.

This paper provides new test data pertaining to the axial compressive behaviour of concrete-filled steel tubular stub columns with sustained axial load during the exposure to high temperatures.

2. Experimental program

2.1. Specimen preparation

Fifteen stub columns were tested to investigate the effects of sustained pre-load and cooling phase on the residual strength and stiffness of CFT stub columns after exposure to high temperatures.

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Notations

A_c	Cross-section area of concrete
A_s	Cross-section area of steel tube
D	Sectional dimension
E_c	Concrete modulus of elasticity
E_s	Steel modulus of elasticity
EA_c	Predicted axial stiffness of composite section
EA_e	Tested axial stiffness of composite section
f_{cu}	Concrete cube strength
f_y	Yield strength of steel
f_u	Ultimate tension strength of steel
L	Length of column
n	Axial load level
N	Axial load
N_o	Constant axial load applied in the column
N_{uc}	Predicted ultimate compression resistance of composite section
N_{ue}	Tested ultimate compression resistance of composite section
t	Fire duration time
t_R	Fire resistance
T	Maximum temperature of fire exposure
t_s	Wall thickness of steel tube
ε	Strain
ε_{cr}	Creep strain
ε_{th}	Thermal strain
ε_y	Yield strain of steel
ε_σ	Stress-induced strain

The investigation was conducted by changing the following parameters:

- the column cross-sectional dimensions;
- the level of axial load in the column n, which is defined as $n = N_o/N_u$, where N_o is the axial load applied in the column and N_u the axial compressive capacity of the column at ambient temperature;
- the maximum temperature, T of fire exposure and different temperature versus time relations.

An additional two CFT columns (CFT1 and CFT2 shown in Table 1) were heated and the temperature distributions in the CFT columns were recorded during the whole heating and cooling phase to verify the predicted results obtained by using a FE analysis model. Another specimen CFT3 was heated to failure under a constant axial load, not only to obtain a reference fire resistance, but also to verify the FE model of fire resistance of CFT stub columns.

The dimensions of these tubes are given in Table 1, where D, t_s and L refer to the cross-sectional dimension, steel thickness and specimen length in mm. The diameter to thickness ratios of the circular tubes is 37.5 and 36 for the two tested series of columns respectively, thus local buckling was not expected.

The circular specimens were made of seamless steel tube. The ends of the steel tube sections were cut and machined to the required length. The insides of the tubes were wire brushed to remove any rust and loose debris. Any deposit of grease and oil was cleaned away. Each tube was welded to a circular steel cover plate 10 mm thick at each end of the specimens except for Specimens C2, CF28 and CF282. The concrete was filled in layers and was vibrated by a poker vibrator. The specimen was placed upright to air-dry until heating. Two semi-circular holes of 20 mm in diameter, antisymmetrically located at the junctions between the tube and the top and bottom cover plates were drilled in the steel tube wall of all the specimens with two steel cover plates. They were provided as vent holes for the water vapor pressure produced during fire exposure. The specimens were made with two steel cover plates at both two ends to simulate the real thermal responses of CFT columns under fire condition, because the vent holes are compulsory to release the water vapor pressure in engineering practice. The thicker steel cover plates are also expected to reinforce the local strength of the end of CFT column so that they can compensate the negative effect of high stress concentration at the vent holes on the behaviour of CFT columns. Three specimens without steel cover plate and vent hole at one end were made to compare the influence of the vent holes on the post-fire behaviour of CFT.

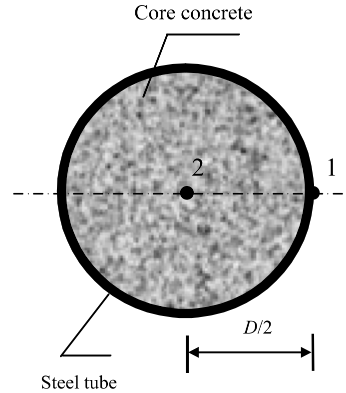

Fig. 1. Thermocouples' locations in column section.

Two thermocouples were mounted at mid-height of the Specimens CFT1 and CFT2. One was mounted onto the exterior steel wall and one within the core concrete of the column, for the purpose of measuring temperatures of the section. Fig. 1 shows the locations (1 and 2) of the thermocouples.

2.2. Material properties

Strips of the steel tubes were made into tensile coupons and tested in tension. Three coupons were taken from the two series of steel tubes respectively. From these tests, the average yield strengths, f_y were found to be 374.5 MPa and 273.45 MPa for the steel tubes with thickness of 4 mm and 3 mm respectively, the average ultimate tension strengths, f_u were 461 MPa and 435.7 MPa respectively and the modulus of elasticity, E_s about 200 000 MPa.

The concrete mix proportions and mechanical properties are shown in Table 2. Two types of concrete were used to make the CFT columns for the CF1 and CF2 series respectively. In the concrete mix, the fine aggregate was silica-based sand, the coarse aggregate was carbonate stone from Changsha City, Middle South of China. The average cube strengths, f_{cu} at the time of the fire tests was 55.6 MPa and 43.7 MPa respectively.

2.3. Test apparatus

A specially built electrical furnace was fixed to a 2000 kN capacity testing machine, as shown in Fig. 2. Two fire-resistant reaction blocks, which were fixed to the upper and lower loading plates of the testing machine respectively, were used to transfer compressive force to the specimen when a specimen is being heated in the furnace. The fire-resistant block is made of silicate high-alumina brick with a compressive strength of approximately 40 MPa and a low thermal expansion coefficient of 4×10^{-7} m/(m °C). The furnace is composed of two semi-cylinders with an inner diameter of 240 mm and a height of 330 mm. Each semi-cylinder has two units of heating modules made of metallic spiral heating elements embedded in foamed ceramic fiber insulation. The furnace rating was 12 kW/220 V/2