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# Compressive behavior of CFRP-confined post heated square CFST stub columns

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ABSTRACT

The axial compressive behavior of carbon fiber reinforced polymer (CFRP)-confined post heated square concrete-filled steel tube (CFST) stub columns is experimentally investigated in this paper. Twenty CFRP-confined post heated square CFST stub columns and one CFST stub column left untreated at ambient temperature were axially tested. Subsequently, the failure mode, ultimate strength, load versus displacement curves, load versus strain distribution curves, initial stiffness, and ductility of the specimens were obtained and analyzed. The maximum temperature (600 °C , 800 °C,1000 °C, 1100 °C) CFST stub columns exposed to and the number of the layer of CFRP sheets (zero, one, two, three and four) were considered as main parameters. The test results showed that, in general, the CFST stub columns wrapped with CFRP sheets shown a better mechanical behavior than those without CFRP sheets wrapping. Furthermore, the more the layers of CFRP sheets are, the higher the ultimate strength and initial stiffness of the CFST stub columns are. Based on the regression of the test data, the simplified formulae for ultimate strength of CFRP-confined post heated square CFST stub columns was proposed. Accuracy of the formulae was evaluated by comparison between the calculated and experimental results.

## 1. Introduction

While an extensive variety of composite columns are available today, concrete filled steel tubular (CFST) sections are the ones most commonly used. These members are widely recognized for their excellent structural performance, and furthermore have been applied in the construction industry for more than 40 years. In recent years, many steel and CFST structures have been found to be suffering from a variety of deteriorations, including cracking, yielding and large deformation. These deteriorations are caused by a variety of factors, including fire, ageing, environmental degradation and large deformation and corrosion. Nowadays, numerous research studies have been conducted on the performance of CFST members under different conditions, and some attention has been paid to the fire resistance of CFST members or their residual properties after exposure to high temperatures [1,2]. Though fire-protection coatings provide protection for structural steel, some may release toxic fume and thereby threaten building occupants and firefighters. Besides, demerits of spraying fireproofing coatings are more or less high cost and fussy construction. Therefore, fore-protection coatings were not used in the tests. The behavior of a CFST stub columns in fire conditions is governed by the properties of concrete and steel at a high temperature. Both concrete and steel undergo considerable reduction in their strength, physical properties and stiffness by the effects of heating and some of the changes are not recoverable after subsequent cooling. Chemical changes may also occur in siliceous aggregate concrete and steel due to heating. An understanding of these changes is essential in predicting or assessing the performance of the frame structure during fire and subsequent cooling. When a CFST stub columns is exposed to devastating fires accidentally for long periods resulting in high rise of temperature and reduction in strength, rehabilitation of fire-damaged CFST stub columns is very important. Recently, Elchalakani et al.[3–6] conducted a series of tests to study the rehabilitation ability of steel structures using CFRP sheets, and found that CFRP wrapping can improve the mechanical behavior of steel structures to some extent. Wang et al. [7] tested twenty-four specimens to study the static performance of axially compressed square concrete filled CFRP-steel tubular (S-CF-CFRP-ST) columns. The tested results indicate that the transverse CFRP in tension provides effective confinement on the specimens and the longitudinal CFRP in tension provides effective enhancement on the flexural stiffness. Ahmed et al. [8] experimentally and numerically studied the behavior of various sections of rectangular CFST beams repaired with unidirectional CFRP sheets. The results demonstrated that the moment capacity of strengthened CFST beams increased significantly with increasing CFRP layers. Wrapping carbon fiber reinforced polymer (CFRP) sheets method is an effective solution for the repair of CFST stub column exposed to high temperature to restore or enhance their strength and stiffness. It was found that the additional confinement provided by CFRP sheets increased the bearing capacity of the column and delayed its local buckling [9].

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**Nomenclature**

| | |
|---|---|
| CFST | Concrete-filled steel tube |
| CFRP | Carbon fiber reinforced polymer |
| $B$ | Wide of square steel tube |
| $t$ | Wall thickness of circular steel tube |
| $L$ | Height of columns |
| $f_u$ | Ultimate tensile stress of circular steel tube |
| $f_y$ | Tensile yield stress of circular steel tube |
| $f_{frp}$ | Tensile strength of CFRP sheets |
| $E$ | Elastic modulus of square steel tube |
| $\varepsilon_f$ | Elongation after fracture |
| $\nu$ | Poisson's ratio |
| $f_{cu}$ | Concrete cube strength |
| $T$ | Temperatures the square CFST stub columns exposed to |
| $F$ | layer of CFRP sheets specimens wrapped |
| $P$ | Axial load |
| $\Delta$ | Vertical displacement |
| $\Delta_y$ | Vertical displacement corresponding to the yield load |
| $\Delta_u$ | Vertical displacement corresponding to the ultimate load |
| $\Delta_u/\Delta_y$ | Ductility ratio |
| $N$T U | Experimental ultimate strength |
| $N$20 U | Experimental ultimate strength of CFST stub columns under the reference temperature of 20 °C without wrapping CFRP sheets |
| $N_{u0}$ | Ultimate strength of square CFST stub columns at ambient temperature without wrapping CFRP sheets |
| $N_u$ | Calculated ultimate strength using the formulae proposed |
| $\varepsilon$ | Strain |
| $K_s$ | $N$T U/ $N$20 U |
| $K_r$ | Comprehensive corrected coefficient |
| $A_c$ | Cross-section area of concrete filled in the square steel tube |
| $A_s$ | Cross-section area of square steel tube |
| $A_{sc}$ | Cross-section area of concrete-filled steel tube |
| $A_{frp}$ | Cross-sectional area of CFRP sheets |
| $\beta$ | Dimensionless temperature coefficient |
| $\gamma$ | Dimensionless CFRP sheets coefficient |
| G($\beta$) | Function of $\beta$ |
| G($\gamma$) | Function of $\gamma$ |

Extensive researches have been conducted in recent years on the static and dynamic behavior of undamaged CFST stub columns strengthened by CFRP sheets. The structural improvements of CFST sections with normal strength concrete externally bonded with CFRP composites were experimentally investigated by Sundarraja and Ganesh [10]. The external bonding of CFRP strips provides external confinement pressure effectively and intended to delay the local buckling of steel tube and also to improve the load carrying capacity further. Suitability of CFRP strips composites in strengthening of CFST columns under compression were experimentally and analytically investigated by Ganesh and Sundarraja [11]. Axial deformation control and load bearing capacity of the confined columns increases as the number of layers increases in addition to that increases in the load bearing capacity mainly depends upon the proper spacing between the CFRP strips. Dong et al. [12] present experimental research on structural behavior of normal and recycled aggregate concrete filled steel tube columns externally strengthened with CFRP sheets and subjected to axial loading. Stiffness of the strengthened columns is increased significantly due to the restraint offered by the external CFRP wrapping on hoop deformations. Some composite CFST columns were designed according to the principle of same amount, ultimate compressive strength and composite elastic modulus by Zhang and Zhang [13]. Carbon fiber reinforced polymer cylinder had the most benefit for repair and retrofit of concrete-filled steel tube structure. Ganesh et al. [14] presented the feasibility analysis on the application of CFRP composite strips to strengthen the CFST column member under axial loading. CFRP strips at a spacing of 20 mm or 30 mm is suitable for strengthening of a CFST circular column member. The dynamic response of normal or recycled aggregate concrete filled steel tube columns subjected to lateral projectile impact and the effect of the CFRP jacketing on the structural behavior of those columns were experimentally investigated by Shakir et al. [15]. The additional confinement of the CFRP reduces the global displacements for CFST specimens. Numerical simulations were carried out to evaluate the effect of CFRP strengthening of full scale CFST columns under vehicular impact by Alam et al. [16]. Adhesively bonded CFRP sheets provide enhanced impact resistance capacity of strengthened columns by reducing lateral displacement about 40% compared to ordinary CFST columns. Unified Theory of CFST into counting strength of composite CFST columns subjected to axial compression was used by Zhang and Zhang [17]. The method is more convenient and simpler approach for design work of composite CFST structures.

Some of the studies have been focused on the mechanical behavior of fire-exposed CFST long columns repaired with CRFP wraps. Fire-exposed circular and square CFST columns repaired by unidirectional carbon CFRP composites were experimentally investigated by Tao and Han [18]. The strength enhancement from CFRP confinement decreased with the increasing of eccentricity or slenderness ratio. Dynamic behavior of fire-damaged circular and square CFST long columns repaired by unidirectional CFRP composites were experimentally investigated by Tao et al. [19]. The ultimate lateral strength, flexural stiffness and ductility can be enhanced to some extent due to the CFRP confinement effect.

In addition, static behavior of fire-exposed concrete column and joints repaired with CFRP sheets were discussed. Behavior of the circular columns of concrete under axial compression confined by an envelope of CFRP and protected by a layer of mortar cement or plaster coating were experimentally investigated by Mostefa et al. [20]. Ultimate load and axial strain of heated columns can be restored up to the original level or greater than those of unheated columns. Structural resistance of two post-earthquake fire reinforced concrete beam-column joints were experimentally and numerically studied by Behnam et al. [21].

Various approaches to strengthening CFST columns through the use of CFRP sheets have been investigated; however, most of the studies have been focused on the undamaged CFST columns. The aforementioned literatures were conducted on the compressive behavior of fire-exposed CFST long columns repaired with CRFP wraps. There is little research being carried out on the compressive behavior of CFRP-confined post heated square CFST stub columns.

This paper focuses on the mechanical behavior of CFRP-confined post heated square CFST stub columns under axial compression. The corresponding square CFST stub columns specimens without fire exposure and no CFRP sheets repairing, and square CFST stub columns specimens with fire exposure but without repairing were also tested under axial compression for comparison.

The ultimate strengths, failure modes, displacement, strain distribution and axial stiffness of all specimens are reported in this study. Furthermore, the effects of temperature CFST stub columns exposed to and the layer of CFRP sheets on the ultimate strength, ductility and axial stiffness of all specimens was also evaluated. The design equations of strength are proposed for CFRP-confined post heated square CFST stub columns under axial compression.

## 2. Material properties

There are three materials used in this study: concrete, low carbon steel and CFRP sheets. The average compressive strength of the concrete cubes after 28-days curing (C-1, C-2, C-3) tested, according to the Code for