Available online at www.sciencedirect.com

ScienceDirect

Journal of Constructional Steel Research 63 (2007) 1116–1126

JOURNAL OF CONSTRUCTIONAL STEEL RESEARCH

www.elsevier.com/locate/jcsr

# Compressive and flexural behaviour of CFRP-repaired concrete-filled steel tubes after exposure to fire

Zhong Tao[a,*], Lin-Hai Han[b,c], Ling-Ling Wang[a]

[a] *College of Civil Engineering, Fuzhou University, Gongye Road 523, Fuzhou, Fujian Province, 350002, People's Republic of China*
[b] *Department of Civil Engineering, Tsinghua University, Beijing, 100084, People's Republic of China*
[c] *Key Laboratory of Structural Engineering and Vibration of China Education Ministry, Tsinghua University, Beijing, 100084, People's Republic of China*

Received 5 May 2006; accepted 20 September 2006

## Abstract

This paper presents the results of axial compression and bending tests of fire-damaged concrete-filled steel tubes (CFST) repaired using unidirectional carbon fibre reinforced polymer (CFRP) composites. Both circular and square specimens were tested to investigate the repair effects of CFRP composites on them. The test results showed that the CFRP jackets enhanced the load-bearing capacity of the stub columns effectively. Enhancement of the columns' stiffness due to the CFRP jackets was also observed. However, for beams, the test results demonstrated that the repair effect was not as good when compared with that for stub columns. From the test results, it is recommended that other appropriate repair measures should be taken in repairing severely fire-damaged CFST beams, or those members subjected to comparatively large bending moments.

*Keywords:* Composite columns; Composite beams; FRP; Post-fire; Residual strength; Concrete-filled steel tubes; Repairing

## 1. Introduction

In recent years, concrete-filled steel tubes (CFST) have become more widely accepted, and are used in tall buildings and in arch bridges, for example [19,3]. They have proven to be economical as well, providing for rapid construction and saving of additional costs from elimination of formwork while also being labour saving.

Fire safety has always been an important issue for high-rise buildings. With the increasing use of CFST in engineering practice, there is a growing need to study the fire resistance and postfire repairability of CFST members for fire safety purposes [17]. In the past, many studies have been performed on the fire resistance of CFST columns, such as [12] and [3]. Another issue which has attracted growing research interest lately is the residual strength of such composite columns [6,4,5]. This may be used to assess the potential damage caused by fire, and help to establish an approach in calculating the structural fire protection needs for minimum postfire repair. With an aim of reinstating their original functionality, adequate repair measures should be applied to enhance the strength and/or ductility of composite columns due to fire damage. Furthermore, such 'repairs' may also be carried out if changes in the use of the structures impose higher functional requirements than those anticipated in the original design.

In practice, several different methods for the repair/strengthening of CFST members exist for restoring their strength or modulus. These repair methods may include section enlargement, steel wrapping and wrapping with fibre reinforced polymer (FRP) composites, etc. [17]. Generally, section enlargement can be achieved by reinforced concrete jacketing, or by steel tube and sandwiched concrete jacketing.

Fibre reinforced polymer is composed of fibres embedded in a resin matrix, and is characterized by its high strength-to-weight ratio, high corrosion resistance, and ease of installation. However, it is well known that FRPs have limited fire resistance because of the low glass transition temperature of their epoxy resins. Until the high temperature mechanical properties of the FRP materials are improved significantly, it is believed that FRP materials will perform poorly in fires, and thus result in

---

[*] Corresponding author. Tel.: +86 591 87892459; fax: +86 591 83737442.
*E-mail address:* taozhong@fzu.edu.cn (Z. Tao).

0143-974X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jcsr.2006.09.007

**Nomenclature**

| | |
|---|---|
| $B$ | width of square steel tube |
| CFRP | carbon fibre reinforced polymer |
| CFST | concrete-filled steel tube |
| $D$ | diameter of circular steel tube |
| DI | ductility index |
| $E_{\mathrm{sce}}$ | longitudinal stiffness of stub column |
| $f_{cu}$ | characteristic cube strength of concrete |
| $f_y$ | yield strength of steel |
| FRP | fibre reinforced polymer |
| $K_{ie}$ | initial flexural stiffness of composite section |
| $K_{se}$ | serviceability-level flexural stiffness of composite section |
| $L$ | length of specimen |
| $M$ | bending moment |
| $M_{ue}$ | ultimate strength of composite beam |
| $N$ | axial load |
| $N_{ue}$ | experimental ultimate strength of composite column |
| SEI | strength enhancement index |
| $t$ | fire duration time |
| $t_s$ | wall thickness of steel tube |
| $u_m$ | deflection at mid-height of beam |
| $\varepsilon$ | strain |
| $\phi$ | curvature |

unsatisfactory fire endurance for FRP-strengthened structural members.

From fire experiments reported in the literature however, it appears that FRP-strengthened columns and beam-slab assemblies have demonstrated satisfactory fire endurance under load when supplemental insulation to the FRP composites has been applied [10]. The provision of fire protection systems is acceptable in practice in such cases where only a few columns, which have undergone a localized fire, need to be strengthened. Supplemental insulation applied to the FRP materials is capable of dramatically improving the fire endurance of the strengthened specimens [2]. Moreover, uninsulated FRP composites may even be considered ineffective during a fire if fire endurance is defined in terms of the load-carrying capacity of the un-strengthened specimens. Therefore, FRP composites are apt to be used as strengthening materials only provided they are properly designed.

Over the past few decades, FRP material has gained its popularity as a jacketing material in retrofitting/repairing existing concrete structures or steel structures [7,15,18,11,9]. More recently, some research results have been reported on the strengthening of CFST columns, which have preliminarily demonstrated the effectiveness of carbon fibre reinforced polymer (CFRP) wraps in increasing the axial loading capacity of CFST stub columns [21,22,16]. However, no research has been conducted so far concerning the effectiveness of repairing fire-damaged CFST members by wrapping them in FRP composites.

This paper provides new test data concerning concrete-filled steel tubular stub columns and beams that have been exposed to and damaged by the standard ISO-834 fire and subsequently repaired. Sixteen specimens, including eight stub columns under axial compression, and eight beams under bending, were tested.

The fire-damaged CFST specimens were repaired by wrapping CFRP around them, as shown in Fig. 1. The repair effects of CFRP on their strength, stiffness and ductility are investigated in this paper.

## 2. Experimental investigation

### 2.1. General

Sixteen specimens, including eight stub columns under compression, and eight beams under bending, were tested. In each test series, four specimens with circular cross-sections and another four specimens with square cross-sections were included. The specimens can be classified into three categories: specimens without fire exposure and no repairing, specimens with fire exposure but without repairing, and specimens with fire exposure and repairing. Repair of specimens was achieved by the external wrapping of unidirectional carbon fibre sheets, with their fibres oriented in the lateral direction. Specimen details for both stub columns and beams are provided in Tables 1 and 2. In Tables 1 and 2, specimen designations starting with a C or S refer to specimens with circular or square cross-sections. Following the C or S, the letters SC represent stub columns, and the letter B represents beams. In order to indicate the specimens with fire exposure, an additional letter F is used to label them, followed by a suffix number of 0, 1 or 2 indicating the number of layers of CFRP used for wrapping. The length of the CFST stub columns ($L$) was chosen to be three times the diameter of the circular section ($D$) or three times the width of the square section ($B$). All beam specimens were 1500 mm in length, with a clear span of 1180 mm.

### 2.2. Material properties

Cold-forged steel tubes were used in the construction of the specimens. The average external radius of the rounded corners for the square tubes is 5.0 mm. Tensile tests on steel coupons cut from the original steel tubes were conducted. The measured properties of the steel tubes obtained from these tests are given in Table 3.

The tensile properties of the cured CFRP, determined from tensile tests of flat coupons according to ASTM D3039 [1], are given in Table 4, where the values presented are the averages from five test coupons, calculated on the basis of the nominal thickness of 0.17 mm for the fibre sheet. The tensile properties of the epoxy, as provided by the supplier, are also given in Table 4.

All the specimens were cast with one batch of self-consolidating concrete. The maximum size of the coarse aggregate was 20 mm. In order to increase the slump and