Journal of Constructional Steel Research 147 (2018) 154–170

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Fire resistance of circular concrete-filled steel tubular (CFST) column protected by intumescent coating

Qian-Yi Song [a,b], Lin-Hai Han [a,*], Kan Zhou [a], Yuan Feng [b]

[a] Department of Civil Engineering, Tsinghua University, 100084, China
[b] China Southwest Architectural Design and Research Institute Corp., Ltd, 610093, China

ARTICLE INFO

Article history:
Received 21 December 2017
Received in revised form 16 March 2018
Accepted 28 March 2018
Available online xxxx

Keywords:
Concrete-filled steel tubular column
Fire resistance
Intumescent fire coating
Experimental investigation
Finite element modelling
Design process

ABSTRACT

For structural components with specific requirement of fire resistance rating for safety reasons, additional fire protection is usually necessary. Intumescent fire coating (IFC) is one of the well-used materials to protect steel structures, and it has advantages such as light weight, simple construction, aesthetic appearance, easy maintenance, etc. In this study, a group of eccentrically loaded concrete-filled steel tubular (CFST) columns with and without IFC protection was tested in standard fire circumstance up to 180 min. Three types of intumescent materials were adopted and different dry film thicknesses of the fire coating were designed. Temperature field of each CFST column and the load bearing behaviour were measured and analysed. Finite element modelling of the columns was also established for heat transfer analysis and fire resisting capacity analysis. The modelling was validated by the test data. This study expands the related experimental database with large scale column specimens. The investigation results provide further evidence that CFST column protected by intumescent fire coating could achieve excellent fire resistance. A technical process to determine intumescent fire coating for CFST columns coupling with experimental verification and FE modelling analysis is presented.

1. Introduction

Fire safety of building structures is becoming increasingly important in recent years throughout the world. Structural members should be designed to achieve the specific fire resistance rating according to codes or standards, such as GB50016-2014 [1], NFPA 5000 [2] and others in different countries. In these codes, multi-storey buildings are often required to satisfy fire resistance rating of 120 min or more. Particularly, in Chinese code GB50016–2014 [1], the structural columns classified as fire resistance class I are required to achieve fire resistance rating of 180 min. To satisfy such requirement, the use of additional fire protection is usually essential, particularly for steel structures which have limited fire resistance without protection [3,4].

Fire proof coating, including non-reactive type (e.g., sprays, cement mortar and concrete encasement) and reactive type (e.g. thin film intumescent fire coating), are normally used to protect steel and steel-concrete composite structures and they can form an effective fire insulation layer. The non-reactive fire proof coating materials have relatively constant physical and thermal properties and no chemical reaction occurs when heated. However, the non-reactive fire proof coatings have several defects such as high thickness, heavy weight, poor durability and difficult maintenance. Moreover, in order to achieve aesthetic appearance, additional decoration is also inevitable. The reactive fire proof coating, such as the intumescent fire coating (IFC), is composed of constituents including resin, dehydrating catalyser, carbonizing agent, vesicant, fillers and additives. Intumescent coating has advantages such as light weight, high performance, simple construction, aesthetic appearance, easy to maintenance, etc. Chemical reaction occurs when IFC is heated, and large amount of heat is absorbed by the smoke and fume produced in the chemical reaction. Meanwhile, the intumescent material would be charred, significantly swell and gradually change to a thick fluffy foamed layer which has relatively low heat conductivity.

In practices, non-reactive fire proof coatings can be used to protect steel and composite structural members satisfying fire resistance rating up to 180 min. Their properties are relatively stable for design and calculation, because they are usually made of simple ingredients with few additives. No chemical reaction would occur when they are heated, and the their thickness would keep constant during fire exposure. Moreover, the weight density and the thermal properties such as specific heat capacity and thermal conductivity can be determined according to temperature uniquely. In contrast, as the actual behaviour of intumescent material subjected to fire exposure is complex in physical and chemical characterizations, the data supporting the application of intumescent coating for steel structures are from testing of steel members. According to related manufactures or the ASFP publication [5], the determination of IFC for steel structures is normally dependent on three parameters in practice: 1) a required

* Corresponding author at: Department of Civil Engineering, Tsinghua University, Beijing 100084, China.
E-mail address: lhhan@tsinghua.edu.cn. (L.-H. Han).

https://doi.org/10.1016/j.jcsr.2018.03.038
0143-974X/

fire resistance rating; 2) section factor of a specific structural member; and 3) a limiting steel temperature. Intumescent fire coatings are usually used to protect steel structures with fire resistance rating of <90 min [6], and some products can provide fire protection up to 120–150 min according to the valid datasheet for application. The insulating performance of intumescent coating is complex and significantly affected by the composition, fire condition, and heating rate, etc. [7]. Besides experimental tests, so far, most of the modelling researches about IFC protected steel structures are carried out based on equivalent thermal properties [8,9]. As the equivalent thermal properties of IFC are usually affected by several factors such as the fire condition, heating rate of the protected steel, the coating thickness and the steel section factor, the calibrated equivalent properties of a particular intumescent coating can only be limitedly used in modelling of steel members similar to the tested samples. Besides, both Gillet et al. [10] and Zhang et al. [11] presented 1-D mathematical models for IFC materials taking into account accurate heat transfer and mass loss of the coating in fire. Recently, Cirpici et al. [12] presented an analytical method which can calculate the expansion of intumescent coating of different thickness under different heating and fire conditions, and validation of the model was reported to predict steel temperatures protected by intumescent coating under various conditions [13]. When intumescent coating is used for concrete-filled steel tubular (CFST) columns, temperature gradient of the coating could be significantly different. Moreover, the expansion of intumescent coating on circular steel tubular surface could be different with that on steel plates. Although above investigations provide critical insight to performance of intumescent coating under fire, performance of intumescent coating for CFST columns cannot be directly predicted by using the above research results. In addition, the formulae of IFC materials produced by different manufacturers are various and performance of the material is considerably affected by the formula details [14], and parameters of each product need to be calibrate respectively.

CFST columns have good load bearing performance and fire resistance because the core concrete can help to bear load and absorb heat [15–22]. Fire resistance of CFST columns can be further improved by the steel reinforcement in the concrete core [23–25] and use of fire-resistant steel or stainless steel [26–28]. Besides fire tests and validated FE modelling, the simplified methods suggested by Eurocode 4 [29] and Albero et al. [30] are available to predict the fire resistance of unprotected CFST columns. However, fire protection is still necessary to ensure structural fire safety of CFST columns particularly when the columns have great slenderness ratio or high load level. It is found that the required thickness of sprays or cement mortar of CFST columns is much smaller than that of bare steel columns when parameters such as the geometric sizes, material and fire resistance rating are identical [16]. Similarly, intumescent fire coating can also economically provide fire protection for CFST columns. In the experimental investigations by Sakumoto et al. [31] and Edwards [32,33], the fire resistance of intumescent coating protected circular and square CFST columns was found significantly higher than the expected value according to datasheets for hollow steel columns. Two CFST columns reinforced by inner H-steel and protected by IFC were tested in fire by Binh [34]. In these experimental studies, the fire resistance of two CFST columns protected by intumescent coatings exceeded 180 min. The above studies together with the heat transfer tests of IFC protected CFST columns by Edwards [32] and Rush et al. [35] also demonstrated much slower increase of the specimen temperature than the bare CFST columns.

Although IFC protected CFST columns exhibit enhanced fire resistance based on previous researches, the data which help to understand their performance in fire are still insufficient. The determination of IFC for various CFST columns satisfying a given fire resistance rating is difficult in practice due to the lack of well-accepted simple calculation method for IFC materials. A similar method as the determination of IFC for steel structures was proposed to determine IFC for CFST columns by using an alternative limiting temperature and an equivalent section factor which considers the contribution of core concrete [5]. However, recent research results indicated that this method could be overly conservative and unreliable [35]. Because most of the available design datasheets of intumescent fire coatings only cover the fire protection of steel structures for <120 min, the application of IFC for CFST columns is now limited particularly for those with higher fire resistance requirement.

Variables that may affect fire resistance of IFC protected CFST columns are complex and the IFC products investigated in existing studies are far less than those in the market. The mechanical behaviour of the CFST columns in fire, such as the temperature field, the limiting temperature at failure and the load redistribution process between steel tube and concrete, would change significantly when intumescent coatings are used. A research gap still exists between theoretical understanding and engineering practices. Since accurate modelling of independently predicting fire performance of IFC protected CFST columns is still unavailable, experimental investigation on loaded or unloaded columns is essential to comprehensively understand the fire performance of CFST columns protected by IFC according to Eurocode 3 [36].

After weighting pros and cons of various fire proof materials, intumescent coating was chosen as fire protection for the CFST columns classified as fire resistance class I [1] in an airport terminal in China (Fig. 1). Because of the complex physical and chemical performance of intumescent fire coating in fire and the lack of reliable design method, accurate modelling and calculation of intumescent coating is always a challenge for various structures. To investigate the fire performance of IFC protected CFST columns subjected to fire exposure up to 180 min and to support the application in constructional practice (Fig. 1), experimental investigation and finite element modelling of a group of circular CFST columns with protection of IFC exposed to ISO-834 standard fire [37] are presented in this paper. The temperature distribution and the fire resistance of the circular CFST columns and performance of the intumescent coatings are investigated. The existing design method of IFC for CFST columns is assessed. A technical process combining experimental verification and FE modelling analysis is proposed to determine intumescent fire coating for CFST columns. Finally, an application example of IFC protected CFST columns in an airport terminal is introduced.

2. Experimental program

2.1. Specimen design and fabrication

Seven circular CFST specimens, including one unprotected and six IFC protected columns were fabricated. A typical CFST specimen is shown in Fig. 2. The specimens consisted of steel tube, concrete core, end plates and fire protection coating. The circular steel tubes were made by roll bending from hot rolled steel plate. Geometrical properties of the specimens are listed in Table 1. UPC denotes unprotected column, while IPC denotes intumescent coating protected columns. For example IPCA1 indicates a protected specimen painted with the coating of type-A and the number 1 is a serial number. The steel tubes were 600 mm in diameter with wall thickness of 14 mm. Self-compact concrete was used. The thickness of the square end plates was 30 mm. Stiffeners (20 mm in thickness) were welded on both ends of the specimens. The height of each column specimen was 3760 mm. Ten holes (20 mm in diameter) were drilled for each specimen to release moisture during fire test. In addition, an eccentricity of 70 mm (23.33%) of the end plates was set to meet the eccentric loading in tests.

The expected fire resistance of the protected columns was at least 180 min in this study. Three types of intumescent coating products were used and labelled as type-A, type-B and type-C, as listed in Table 1. The characteristics of the chosen types of intumescent coating products are presented in Section 2.4. Before determination of the dry film thickness (DFT) for CFST specimens, the design datasheet of the three types IFC products for steel hollow sections and related test details