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Design of intumescent fire protection for concrete filled structural hollow sections

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ABSTRACT

Design of intumescent protection systems for concrete filled structural steel hollow (CFS) sections in the UK typically requires three input parameters in practice: (1) a required fire resistance rating; (2) and 'effective' section factor; and (3) a limiting steel temperature for the hollow structural section. While the first of these inputs is generally prescribed in building codes, the latter two require greater engineering knowledge and judgement. This paper examines results from standard furnace tests on 26 CFS sections, 14 of which were protected with intumescent coatings by application of current UK design guidance. The protected sections demonstrate highly conservative fire protection under standard fire exposure, a conservatism not typically observed for protected unfilled steel hollow sections. The possible causes of the observed conservatism are discussed, and it is demonstrated that the method currently used to calculate the effective section factor for protected CFS columns is based on a false presumption that both unprotected and protected CFS columns can be treated in the same manner. A conservative method for determination of the steel limiting temperature for CFS columns is proposed; this can be applied by designers to more efficiently specify intumescent fire protection for CFS members.

1. Introduction

Architects and engineers increasingly specify concrete filled steel hollow structural sections (CFS) in the design and construction of multi-storey buildings. A CFS sections consist of hollow steel sections that are in-filled with concrete to provide, through composite action, superior load carrying capacity and structural fire resistance as compared with unfilled steel tubes. CFS sections are an attractive, efficient, and sustainable means by which to design and construct compressive members in highly optimized structural frames. The concrete infill and the steel tube work together, at both ambient temperatures and during fire, yielding several benefits: the steel tube acts as stay-in-place formwork during casting of the concrete, thus reducing forming and stripping costs, and provides a smooth, rugged, architectural surface finish; the concrete infill enhances the steel tube's resistance to local buckling; and the steel tube sheds axial load to the concrete core (whether reinforced or unreinforced) when heated during a fire, thus enhancing the fire resistance of the column [1].

Multi-storey buildings often require structural fire resistance ratings of 2 h or more [2], which CFS sections can provide without the need for applied fire protection in some cases. However where the structural fire design guidance [1,3–6] shows that adequate fire resistance is unachievable, external fire protection must be applied to the steel tube; in the UK the preferred method of fire protection is often intumescent coating.

In practice, the design of intumescent fire protection systems for CFS sections requires an assumed (typically prescribed) limiting steel temperature at some predefined (also prescribed) period of standard fire exposure. This is a difficult task for three reasons. First, there is a paucity of test data on the performance of intumescent coatings when applied on CFS sections due to the sensitive and unique composition of each specific intumescent coating product. Second, quantifiably observing the comparatively complex thermal response of intumescent coatings during fire resistance tests in furnaces is difficult. Intumescent fire protection coatings expand up to 100 times their original thickness [7] when exposed to heat by creating a fragile multi-cellular protective insulating layer, which is unique to the heating rate, chemical composition and the initially applied dry film thickness (DFT) of the coating. Lastly, fundamental differences exist between the evolution of

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Nomenclature

A_i	area (mm^2)
b_i	internal breadth (mm)
c_i	specific heat capacity (J/kg °C)
d_p	dry film thickness (DFT) (mm)
$\dot{h}_{net}$	net heat flux (W/m^2)
H_p	heated perimeter (mm)
H_p/A_{eff} (Th)	current effective section factor (m^{-1})
H_p/A_{eff} (exp)	new effective H_p/A (m^{-1})
$(H_p/A_{eff})'$	instantaneous effective H_p/A (m^{-1})
$(H_p/A_{eff})'_{(Eq.\ area)}$	equivalent area effective H_p/A (m^{-1})
$(H_p/A_{eff})'_{t,ave}$	time averaged effective H_p/A (m^{-1})
t_{ce}	equiv. thickness from concrete (mm)
t_{FR}	required fire resistance (min)
t_s	steel tube thickness (mm)
t_{se}	effective steel thickness (mm)

Greek

Δt	time step (s)
η	concrete core efficiency factor
θ_i	temperature (°C)
$\lambda_{p,t}$	thermal conductivity of coating (W/m °C)
ρ_i	density (kg/m^3)

Subscripts

s	steel tube
c	concrete
eff	effective

thermal gradients within protected, as opposed to unprotected, CFS sections.

This paper assesses current fire resistant design guidance for intumescent fire protection systems applied on CFS sections in the UK, examining the prescription methods for DFTs on CFS sections and identifying the causes of conservative outcomes observed in a series of furnace tests on both protected and unprotected CFS columns; also presented herein. A conservative method to prescribe the design limiting steel temperature for protected CFS columns is suggested, and data and discussions supporting the ongoing development of rational, performance-based approaches to the structural fire design of CFS columns is given.

2. Specification of intumescent coatings for CFS sections

Design of intumescent fire protection (i.e. design DFTs) applied to structural steel is typically based on three input parameters: (1) the required *fire resistance*, F.R., which is typically a prescribed value based on local building code requirements (e.g. [2]) and is generally dependent on the type, height, and design of the building; (2) a *section factor*, defined as the ratio of the section's heated perimeter, H_p, to its cross sectional area, A; and (3) the assumed *limiting temperature* of the steel, which is the temperature at which the steel is presumed to fail under load during a standard furnace test (in most cases this is close to 520 °C). Engineers use these three input parameters in conjunction with empirically determined, product specific, design tables to determine the required DFT of the specific intumescent coating needed to maintain the critical temperature of the steel below its critical temperature for the required duration of standard fire exposure. The product specific design tables are based on numerous large scale furnace tests on plain structural steel sections with various H_p/A values and at a variety of DFTs.

To apply existing DFT tables for protection of CFS sections without the need to perform a very large number of furnace tests, an 'effective' section factor, H_p/A_{eff}, must be determined; this must incorporate the effect(s) of the concrete infill on the heating rates of the steel and on the load bearing capacity of the composite column. Eqs. (1) and (2) represent the current approach to determining the effective section factor for CFS sections [8] in the UK; this is based primarily on the required fire resistance time, t_{FR}. Eqs. (1) and (2) treat the problem by using DFT design guidance developed for unfilled steel sections but add an 'equivalent' steel wall thickness, t_{ce}, which is dependent on the internal breadth of the section, b_i, and t_{FR}, to the existing steel wall thickness, t_s, to account for the thermal sink effects of the concrete core, thus decreasing the effective H_p/A:

$$\frac{H_p}{A_{eff}} = \frac{1000}{t_{se}} = \frac{1000}{t_s + t_{ce}} \tag{1}$$

$$t_{ce} = \begin{cases} 0.15b_i, & b_i < 12\sqrt{t_{FR}} \\ 1.8\sqrt{t_{FR}}, & b_i \geq 12\sqrt{t_{FR}} \end{cases} \tag{2}$$

This approach seems physically unrealistic and thus limited (and potentially flawed) on a number of grounds, as discussed below. Neither the physical rationale nor the theoretical or empirical basis for Eq. (2) are clear (or reported in the literature), and therefore a further objective of the research presented herein was to validate (or otherwise) this approach. Regardless, this is the current approach that is applied on real projects in the UK.

3. Furnace tests on unprotected and protected CFS sections

To evaluate and improve the performance of the above approach for prescribing dry film thicknesses for the fire protection of CFS sections, 26 CFS columns, 14 protected and 12 unprotected, were exposed to the ISO-834 [9] standard fire in a fire testing furnace for 120 min, as outlined in Table 1 (one exception was a single specimen that was heated for a total duration of 180 min, as described below). The waterborne intumescent coating dry film thicknesses (DFT) for the 14 protected CFS sections in Table 1 was prescribed using effective H_p/A values given by Eq. (1) with a presumed limiting steel temperature of 520 °C and a required F.R. of 90 min. Exceptions were that one specimen was designed to a F.R. of 75 min (and tested for 120 min) and one was protected for 120 min F.R. (tested for 180 min). A schematic of typical test specimen layouts is given in Fig. 1.

Cross-sectional temperatures were recorded at two heights during testing, as shown in Fig. 1. Four K-type thermocouples measured steel tube temperatures and one K-type thermocouple measured concrete core temperatures at the centre of the cross-section at both sections. The majority of tests were conducted in a $4 \times 3 \times 2\ m^3$ ceramic tile lined full scale floor furnace in which gas temperatures were monitored using six thermocouples. The two protected specimens with DFTs designed for 75 and 120 min fire resistance (tests 23 and 24 in Table 1) were tested in a smaller $1.8 \times 1.8 \times 1.8\ m^3$ ceramic tile lined cube furnace in which temperatures were monitored with three thermocouples. All specimens were constructed from Grade S355 structural steel sections and filled with a hybrid steel and polypropylene (PP) fibre