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Proposal of a new method in EN1994-1-2 for the fire design of concrete-filled steel tubular columns

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ABSTRACT

Previous investigations proved the unsafety of the current design guidelines in Annex H of EN 1994-1-2 for the calculation of the fire resistance of slender concrete-filled steel tubular (CFST) columns. In this paper, a new simplified design method based on the general rules in Clause 4.3.5.1 of EN 1994-1-2 is presented for correcting this inaccuracy. For the development of the method, an extensive parametric study consisting of about 20.500 analysis cases was carried out by using numerical models, which in turn were validated against a wide range of experimental results. The proposed method provides a significant extension over the current EN 1994-1-2 applicability limits, reaching high member slenderness, large eccentricities and being valid for all the commercially available geometries, including elliptical hollow sections. The design proposal is divided into two parts: thermal, where a simplified cross-sectional temperature field can be obtained based on equivalent temperatures for the composite section constituents, and mechanical, where a full method for evaluating the ultimate buckling load in the fire situation is given. The proposed method is valid for axially and eccentrically loaded columns, accounting for eccentricities on both minor and major axis and reaching large eccentricities of e/D = 1. Finally, it is proved that the proposed method provides safe predictions as compared to experimental results and meets the CEN/TC250/SC4 accuracy criteria.

1. Introduction

Concrete-filled steel tubular (CFST) columns are among the most commonly used composite members in modern buildings due to their high stiffness, ductility and in particular excellent fire performance. However, the current design guidelines for the fire resistance of CFST columns in Annex H of EN 1994-1-2 [1] have been found unsafe for relative member slenderness over 0.5, which is a frequent situation for columns in car-parks, high-rise, commercial, or industrial buildings. Previous works from Romero et al. [2] for circular CFST columns pointed out that only a reduced fire resistance (FR) can be obtained in slender columns, where the FR was generally lower than 30 min, while the current design rules in EC4 predict a higher FR, thus resulting unsafe. This work agreed with previous results from Renaud et al. [3] and Leskela [4] and led to the approval of an amendment by the committee CEN/TC 250/SC4 which limits the relative slenderness at ambient temperature to 0.5 in the application of Annex H of EC4, which is specific for CFST columns exposed to fire. In consequence, this committee created an Ad-hoc group to redefine the current Annex H.

The interest in the use of simple design rules for concrete-filled steel tubular columns has grown in the last decades, due to the increased usage of this structural typology [5]. Nevertheless, only a limited number of methods are available to designers for evaluating the fire resistance of this type of composite columns, which are a result of the numerical and experimental investigations carried out by the main research groups working in this field (Han et al. [6,7], Kodur et al. [8–10], Park et al. [11,12]).

Therefore, apart from EC4, other methods can be found in the literature for calculating the fire resistance of CFST columns. Kodur [8,10] proposed a simplified equation developed through the results of a parametric studies supported by an experimental programme. This approach is used in the United States and Canada after having been incorporated into several building codes. The applicability of the equation proposed by Kodur is limited to l_0 = 2000–4000 mm, therefore the method cannot be applied to columns with high slenderness. Additionally, Han, Zhao and co-workers proposed a formulation which was incorporated to the Chinese code DBJ13-51-2003 [13] limited for circular CFST columns infilled with plain concrete. The formulation of this method

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Nomenclature

$A_{i,\theta}$	cross-sectional area of the part i of the composite section at the temperature θ
A_m/V	section factor
B	width of the square section or smaller outer dimension of an elliptical or rectangular section
CFST	Concrete-Filled Steel Tube
CHS	Circular Hollow Section
D	outer diameter of the circular section
e	load eccentricity
$E_{i,\theta}$	modulus of elasticity of the i material at the temperature θ
$(EI)_{fi,eff}$	effective flexural stiffness in the fire situation
EHS	Elliptical Hollow Section
EC4	Eurocode 4
f_c	compressive cylinder strength of concrete at room temperature
f_y	yield strength of structural steel at room temperature
f_s	yield strength of reinforcing steel at room temperature
H	larger outer dimension of an elliptical or rectangular section
$I_{i,\theta}$	second moment of area of the part i of the cross-section at the temperature θ
$k_{i,\theta}$	reduction factor for a material property at elevated temperature
l_θ	buckling length in the fire situation
$N_{fi,cr}$	elastic critical load in the fire situation
$N_{fi,pl,Rd}$	plastic fire design resistance of the cross-section to axial compression
$N_{fi,Rd}$	design axial buckling load in the fire situation
$N_{fi,Rd,\delta}$	design buckling load in the fire situation in case of eccentric load
N_{Rd}	design axial buckling load at room temperature
$N_{Rd,\delta}$	design buckling load at room temperature in case of eccentric load
R	standard fire resistance time (min)
RHS	Rectangular Hollow Section
SHS	Square Hollow Section
t	steel tube wall thickness
θ	temperature
$\bar{\lambda}$	relative slenderness at room temperature
$\bar{\lambda}_\theta$	relative slenderness in the fire situation
ξ	relative error
$\varphi_{i,\theta}$	reduction coefficient to make allowance for the effect of thermal stresses
χ	resistance reduction factor according to the European buckling curves

can be found in [6]. Finally, amongst the simplified methods for the calculation of the fire resistance of CFST columns existing worldwide, the Japanese approach published in the design manual of the Association of New Urban Housing Technology (ANUHT) [14] should be mentioned.

Turning to EC4, its simplified method for calculating the fire resistance of CFST columns has been proved to be unsafe and besides presents some limitations. The application of the general principles in Clause 4.3.5.1, instead of Annex H, may be an alternative to the referred Annex, although in practice this is not possible for this type of columns, as the reduction coefficients to account for the effect of the thermal stresses are not given for concrete-filled hollow sections. In this situation, the common procedure in practice is to assume them equal to unity [15] or obtain them from Annex G, which is specific for partially encased sections. Certainly, this problem can be solved using the French National Annex to EN 1994-1-2 [1] where specific values for the flexural stiffness reduction coefficients have been included. Nevertheless, this option provides too conservative results [16]. Alternatively, the specific method in Annex H for CFST columns can be used, although as it has been highlighted, the method results unsafe for slender columns and its applicability has been limited to a maximum slenderness of 0.5. In Annex H, the buckling length is also limited to $l_\theta \leqslant 4.5$ m and standard fire resistance times under 120 min, which is insufficient for many practical applications.

Another limitation of the method is the shape of the sections. It is limited to circular and square hollow sections while in practice, new shapes such as elliptical hollow sections have become increasingly common because of their architectural aesthetics. An important drawback of the current methods in EC4 is the need for the designer of obtaining the cross-sectional temperature field as a preliminary step, for the subsequent calculation of the design axial buckling load, while the code does not provide any simplified method for that purpose. This makes designers feel unwilling to use these methods, and therefore a simplified way for obtaining the cross-sectional temperature field, like that proposed by Ibañez et al. [17] for CHS columns, would be of interest for practitioners and ultimately for promoting the use of this type of composite sections. Other way to deal with this drawback, different from the one exposed in this work, was developed by the authors through the concept of an equivalent concrete core cross-section at room temperature [17].

In order to solve the exposed shortcomings, the European Union decided to support a research project entitled "Fire Resistance of Innovative and Slender Concrete Filled Tubular Composite Columns" (FRISCC), through a financial grant of the Research Programme of the Research Fund for Coal and Steel.

This paper presents a simplified design method, developed under the aforementioned project, which extends the current EC4 method limitations and corrects its inaccuracy. The proposed method has been developed through the results of an extended parametric study carried out using numerical models which were in turn supported by validation against experimental results. It includes innovative cross-sections, such as elliptical hollow sections. The proposed simplified method is developed to deal with unprotected CFST columns under ISO standard fire condition. A new set of reduction coefficients are developed to account for the effect of thermal stresses in CFST columns, in order to propose a simple calculation model which follows the general principles in Clause 4.3.5.1 of EN 1994-1-2 [1]. Additionally, in order to make easier for designers the calculation of the cross-sectional temperature field, a simplistic proposal is presented, based on the equivalent temperature concept. Finally, a method with coefficients to cover the design of CFST columns with large eccentricities is proposed.

2. Review of existing design guidance from Eurocode 4

In the current version of EN 1994-1-2 [1] (EC4), simplified design rules are available for calculating the fire resistance of CFST columns, specifically Clause 4.3.5.1 describes a general method for evaluating the ultimate load of composite columns in the fire situation based on the elastic buckling theory. Besides, Annex H