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Interaction diagram based method for fire resistance design of eccentrically loaded concrete-filled steel tubular columns

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ABSTRACT

Previous investigations have highlighted that the current design method in Annex H of EN 1994-1-2 for the calculation of fire resistance of slender concrete-filled steel tubular (CFST) columns was unsafe, which led to the appointment of a Project Team (SC4.T4) by the European Committee for Standardization (CEN) to develop a new Annex H in EN1994-1-2 to replace the existing one. This paper presents the outcome of the Project Team, a new simplified fire design method for CFST columns, focusing in particular on eccentrically loaded columns for which there had been no systematic research. An extensive parametric study consisting of 5046 analysis cases has been carried out, covering all the practical ranges of application of CFST columns. The method accounts for minor and major axis eccentricities with large eccentricities up to $e/D = 1$. Different bending moment diagrams, ranging from single curvature to double curve bending, were considered. The proposed new design method is in line with the cold design method in EN1994-1-1 and achieves the criteria of acceptance for safe and accurate design of structures in fire which were set by the CEN/TC250 Horizontal Group Fire.

1. Introduction

Concrete-filled steel tubular columns are an attractive structural solution but their applications are hampered by the lack of a safe, accurate and widely applicable simplified calculation method for fire design. At present, there are two methods in Europe. In the main part of Eurocode 4 Part 1-2 (EN1994-1-2 [1]), a general calculation method is provided to estimate the buckling resistance of composite columns in braced frames at elevated temperatures. However, this method is only applicable to axially loaded CFST columns without any bending moment. If there are bending moments in the CFST column, which is usually the case in practice, the existing Eurocode method is presented in Annex H of EN 1994-1-2 [1]. However, despite complexity in implementation, this method lacks a robust technical base, and has been demonstrated to be unsafe for slender columns [2,3], leading to an addenda approved by CEN/TC250/SC4 [4] which limits the maximum relative slenderness to 0.5. Also, this method is only valid for CHS and SHS columns, being out of scope for other geometries used in practice, such as rectangular or elliptical sections. This method is not allowed in many countries such as France [5,6], Finland [7], the United Kingdom [8] and Spain [9,10], where it has been replaced by alternative design rules.

Other methods exist worldwide for the evaluation of fire resistance of CFST columns, such as those used in North America [11], China [12] or Japan [13], but they all have severe limitations in their scopes of application.

This unsatisfactory situation has led the European Committee for Standardization (CEN) to appoint a Project Team to develop a new simplified fire resistance design method for CFST columns. Prior to this Project Team's activities, the authors of this paper completed the European RFCS funded research project entitled "Fire Resistance of Innovative and Slender Concrete Filled Tubular Composite Columns" (FRISCC) [14]. As a result of this project, a simplified method was developed. A key contribution of the simplified method is to assume that the effects of non-uniform temperature in the CFST cross-section can be represented by an equivalent uniform temperature for each of the different components (steel tube, concrete infill, reinforcement) of the CFST cross-section. Although the FRISCC project also proposed a calculation method for CFST columns under eccentric loading, the method was quite tedious to apply and was for single curvature only.

For CFST columns with bending moments, the UK design method, based on the work of Wang and Orton [15], recommends using the cold design method for composite columns in Eurocode EN 1994-1-1 [16].

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Notation

$A_{i,\theta}$	cross-sectional area of the part i of the composite section at temperatureθ
A_m/V	section factor accounting for steel and concrete
A_{sn}	area of reinforcing bars within the region of depth h_n
B	width of the square section or smaller outer dimension of elliptical or rectangular section
CFST	Concrete-Filled Steel Tube
CHS	Circular Hollow Section
D	outer diameter of circular section
e	eccentricity of loading
e_{imp}	eccentricity from geometrical imperfection
$E_{i,\theta}$	modulus of elasticity of material i at temperature θ
$(EI)_{fi,eff}$	effective flexural stiffness for calculation of relative slenderness in the fire situation
$(EI)_{fi,eff,II}$	effective flexural stiffness for use in second order analysis in the fire situation
EHS	Elliptical Hollow Section
f_c	compressive cylinder strength of concrete at room temperature
f_s	yield strength of reinforcing steel at room temperature
f_y	yield strength of structural steel at room temperature
H	larger outer dimension of elliptical or rectangular section
$I_{i,\theta}$	second moment of area of part i of the cross-section at temperatureθ
$K_{e,II}$, K_0	correction factors for calculating the second order flexural stiffness at room temperature
K_θ	elevated temperature correction factor for calculating the second order flexural stiffness
$k_{i,\theta}$	reduction factor for a material property at elevated temperature θ
k_{fi}	amplification factor for second order effects at elevated temperatureθ
L	nominal length of column
l_θ	buckling length of column in the fire situation
$M_{fi,Ed}$	design bending moment applied to the composite section in the fire situation
$M_{fi,1,Ed}$	first order bending moment in the fire situation
$M_{fi,2,Ed}$	second order bending moment in the fire situation
$M_{fi,pl,N,Rd}$	design value of the plastic resistance moment of the composite section in the fire situation, taking into account the compressive normal force
$M_{fi,pl,Rd}$	design value of the plastic resistance moment of the composite section in the fire situation without compressive force
$N_{fi,cr}$	elastic critical normal force in the fire situation
$N_{fi,cr,eff}$	elastic critical normal force corresponding to the effective flexural stiffness in the fire situation
$N_{fi,Ed}$	design value of the compressive normal force in the fire situation
$N_{fi,pl,Rd}$	design value of the plastic resistance of the composite section to compressive normal force in the fire situation
r	end moment ratio
RHS	Rectangular Hollow Section
SHS	Square Hollow Section
t	steel tube wall thickness
t_{fi}	fire exposure time
W_{pa}	plastic section modulus of steel
W_{pan}	plastic section modulus of the steel region with depth $2h_n$
W_{pcn}	plastic section modulus of the concrete region with depth $2h_n$
W_{pc}	plastic section modulus of concrete
W_{ps}	plastic section modulus of reinforcing bars
W_{psn}	plastic section modulus of the reinforcing bars within depth $2h_n$
α_M	safety factor for reducing the M-N interaction curve
β	equivalent moment factor
β_i	coefficients for evaluating the equivalent temperature of reinforcing bars
θ	temperature
$\theta_{i,eq}$	equivalent temperature of part i of the cross-section
$\bar{\lambda}$	relative slenderness at room temperature
$\bar{\lambda}_\theta$	relative slenderness in the fire situation
$\varphi_{i,\theta}$	stiffness reduction coefficient to make allowance for the effect of thermal stresses
ρ_s	percentage of reinforcement
μ	axial load level
$\mu_{fi,d}$	ratio of available bending resistance under compression to bending resistance without compression in the fire situation

Thus, if the equivalent uniform temperatures of [16] are used in combination with the recommendation of Wang and Orton [15], the fire resistance calculation for CFST columns is simplified into a cold design problem, with modifications to use elevated temperature properties being the main change. The CEN Project Team SC4.T4 considered this attractive, because it has made the cold and fire resistance design of CFST columns consistent and has made it very easy to calculate the fire resistance of CFST columns.

However, for eccentrically loaded CFST columns with different bending moment distributions, the proposed new method did not have sufficient data for its validation. This is the subject of the present paper. This paper will first present the new simplified method and then use the results of an extensive numerical study to check its accuracy and acceptance.

2. Proposed simplified method

2.1. Equivalent temperatures and flexural stiffness at elevated temperatures

In this new method, instead of dealing with non-uniform temperatures in the different components of CFST columns, equations are provided to calculate the equivalent uniform temperatures for each of the CFST components (steel tube, concrete core, reinforcement), as schematized in Fig. 1. The equivalent uniform temperatures can be calculated as follows.

For the concrete core ($\theta_{c,eq}$):

$$\theta_{c,eq} = 81.8 - 5.05 \cdot t_{fi} + 0.003 \cdot t_{fi}{}^2 - 15.07 A_m/V + 0.3(A_m/V)^2 - 0.88 \cdot t_{fi} \cdot A_m/V + + 7.43 \cdot t_{fi}{}^{0.842} \cdot (A_m/V)^{0.714} \quad (1)$$

For the steel tube ($\theta_{a,eq}$):

$$\theta_{a,eq} = -824.67 - 5.58 \cdot t_{fi} + 0.007 \cdot t_{fi}{}^2 - 0.01 \cdot t_{fi} \cdot A_m/V + 645.08 \cdot t_{fi}{}^{0.269} \cdot (A_m/V)^{0.017} \quad (2)$$

For the reinforcing bars ($\theta_{s,eq}$):

$$\theta_{s,eq} = \beta_3 \cdot (t_{fi}/u_s^2)^3 + \beta_2 \cdot (t_{fi}/u_s^2)^2 + \beta_1 \cdot (t_{fi}/u_s^2) + \beta_0 \quad (3)$$

where the β_i coefficients depend on the CFST section shape and concrete cover, and are given in [16].

By using the equivalent uniform temperatures, a heated CFST column is converted into a cold CFST column with different material properties, except for the necessity to introduce modification factors to the flexural stiffness values of the different components of the CFST