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Fire design method for bar-reinforced circular and elliptical concrete filled tubular columns

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ABSTRACT

A method for calculating the design axial buckling load in the fire situation of unreinforced axially loaded concrete filled circular hollow section columns was presented by the authors in a previous paper [1]. In the present paper, the method is extended to bar-reinforced columns of circular and elliptical cross-section, as a necessary continuation to complete the proposal. The method presented here is based on the guidelines of Clause 4.3.5.1 in Eurocode 4 Part 1.2 for the fire design of composite columns and is developed on the basis of the results of new parametric studies, with varying values of the outer diameter of the column, steel tube wall thickness, relative slenderness, percentage of reinforcement and fire exposure time. From the results of these parametric studies, appropriate expressions and tables for the different parts which integrate the design method are derived. The proposed method is valid for centrally loaded bar-reinforced circular and elliptical concrete filled tubular columns, with a maximum percentage of reinforcement of a 5% and makes allowance for columns with a high slenderness, extending the current limits of Eurocode 4 Part 1.2.

1. Introduction

The interest in the use and development of simple methods for calculating the fire resistance of concrete filled tubular (CFT) columns is growing, due to the increased usage of this structural typology [2]. Nevertheless, only a limited number of methods are accessible 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 [3–9].

In Europe, a method is available in EN 1994-1-2 [10] for calculating the fire resistance of CFT columns. Clause 4.3.5.1 describes a simple calculation model for evaluating the design axial buckling load of composite columns in the fire situation based on the elastic buckling theory. A specific method for columns composed of unprotected concrete filled hollow sections can also be found in Annex H of the same code. Given the complexity of the specific method in Annex H and after being revealed that it produces unsafe results for slender columns [11–13], authors are more inclined to follow the general principles in Clause 4.3.5.1. The work by the CTICM group in France [12,14] must be pointed out, which has led to the rules published in the French National Annex to EN 1994-1-2 [15].

The authors of this paper presented a proposal for evaluating the design axial buckling load in the fire situation of unprotected CFT columns of circular shape [1], based on the general rules in Clause 4.3.5.1 of EN 1994-1-2. This new proposal was supported by the results of an extensive parametric study carried out with the help of a validated numerical model [16,17]. The method developed by the authors improved the accuracy of the current methods in EN 1994-1-2 and extended its current field of application. Nevertheless, the calculation of columns with reinforcement was not covered by the previous method, reason why the parametric study is extended here to complete the design proposal.

Another aspect that is of the interest of the authors is to extend the new proposal to concrete filled elliptical hollow section (CFEHS) columns, as no method is available yet for the fire design of this type of composite sections.

Despite the room temperature behaviour of elliptical hollow section (EHS) columns being widely studied in the last few years [18], with some incursions on the effect of filling these sections with concrete [19–22], the performance of CFEHS columns in the fire situation has not yet been investigated. Some recent work on unfilled EHS columns subjected to fire can be found in the literature [23,24], but no experimental studies have been carried out so far on concrete filled EHS columns exposed to fire. The only work which can be found in the literature on CFEHS columns exposed to fire is that presented by the authors of this paper [25] and the recent work from Dai and Lam [26], who studied numerically the effect of the sectional shape on the fire behaviour of

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Nomenclature

a	half larger outer dimension of an elliptical section	L	length of the column
b	half smaller outer dimension of an elliptical section	ℓ_θ	buckling length of the column in the fire situation
A_i	cross-sectional area of the part i of the composite section	N	applied axial load
A_m/V	section factor	NF	French National Annex to Eurocode 4 Part 1-2
CFCHS	concrete filled circular hollow section	$N_{fi,cr}$	elastic critical load in the fire situation
CFEHS	concrete filled elliptical hollow section	$N_{fi,pl,Rd}$	design cross-sectional plastic resistance to axial compression in fire
CFT	concrete filled tube	$N_{fi,Rd}$	design axial buckling load of the column in the fire situation
D	outer diameter of the circular section	P	perimeter of the section
$E_{a,\theta}$	modulus of elasticity of structural steel at the temperature θ	R	standard fire exposure time
$E_{c,\theta}$	tangent modulus of concrete at the temperature θ	t	wall thickness of the steel tube
$E_{s,\theta}$	modulus of elasticity of reinforcing steel at the temperature θ	u_s	concrete cover
$(EI)_{\mathrm{fi,eff}}$	effective flexural stiffness in the fire situation	α	imperfection factor for the buckling curves
EC4	Eurocode 4	$\bar{\lambda}$	relative slenderness of the column at room temperature
EHS	elliptical hollow section	$\bar{\lambda}_\theta$	relative slenderness of the column in the fire situation
f_c	compressive cylinder strength of concrete	ξ	relative error
f_s	yield strength of reinforcing steel	$\varphi_{\mathrm{i},\theta}$	reduction coefficient to make allowance for the effect of thermal stresses
f_y	yield strength of structural steel	$\theta_{\mathrm{i,eq}}$	equivalent temperature of the part i of the cross-section
$I_{i,\theta}$	second moment of area of the part i of the cross-section at the temperature θ	χ	member slenderness reduction factor ($\chi = N_{fi,Rd}/N_{fi,pl,Rd}$)
		ρ	percentage of reinforcement

axially loaded CFT stub columns. It is worth noting that no design method for the calculation of the fire resistance of CFEHS columns has been developed yet.

In this paper, an extensive parametric study is carried out by means of a previously validated numerical model [16,17], where different values of the percentage of reinforcement are considered (2.5% and 5%). By means of the results of these parametric studies, the simple calculation model proposed in the previous paper [1] is extended here to bar-reinforced columns. Appropriate values of the flexural stiffness reduction coefficients and buckling curves as a function of the percentage of reinforcement are developed in this paper, as well as expressions for the equivalent temperatures of the components of the composite section at different standard fire periods. Using the results of previous numerical investigations on CFEHS columns exposed to fire [25] the method is extended to be valid also for the increasingly used elliptical shapes. With this addition, the proposed simple calculation model is applicable to CFT columns of circular and elliptical shape, filled with normal strength concrete and using a maximum percentage of reinforcement of a 5%. A wide range of column slenderness are covered in this method, with buckling lengths at elevated temperature up to 10 m, diameters from 139.7 mm to 508 mm (major axis dimension from 150 mm to 500 mm in the case of elliptical columns) and standard fire classes from R30 to R120.

2. Proposed simple calculation model for unreinforced circular CFT columns

A method was proposed in the previous paper [1] which permits to evaluate the design axial buckling load in the fire situation ($N_{fi,Rd}$) of unreinforced CFT columns of circular cross-section, based on the general rules in Clause 4.3.5.1 of Eurocode 4 Part 1.2 [10]. A brief description of this method is given next.

2.1. Simplified cross-sectional temperature field

The first part of the proposed approach consists of a simple method for evaluating the cross-sectional temperature field of a concrete filled circular hollow section (CFCHS) column. A single equivalent temperature for the whole concrete core and another one for the steel tube are proposed, so as to obtain the same fire resistance of the column as by using the real non-uniform temperature distribution. In this way, the designer can evaluate the design axial buckling load of the column by using a single strength and stiffness value for each component of the composite cross-section corresponding to its temperature. A detailed explanation of the procedure for obtaining the equivalent temperatures of the different components of the cross-section can be found in [1].

A selection chart was proposed (Table 1) to facilitate designers obtain the equivalent temperature of the concrete core ($\theta_{c,eq}$) and the steel tube ($\theta_{a,eq}$) for a particular fire period directly from the value of the section factor of the column. For intermediate values of the section factor, linear interpolation can be used. Note that the section factor of a circular CFT column is calculated as $4/D$ (m^{-1}).

A regression equation for the equivalent temperature of the concrete core valid for any fire resistance period was also developed, which includes the effect of A_m/V and R:

$$\theta_{c,eq} = -186.44 + 5.764R - 0.026R^2 + 22.577A_m/V - 0.32(A_m/V)^2 + 0.14R \cdot A_m/V \quad (1)$$

For the steel tube, the following equation can be used for evaluating the equivalent temperature, in function of A_m/V and R:

$$\theta_{a,eq} = 342.1 + 10.77R - 0.044R^2 + 3.922A_m/V - 0.025R \cdot A_m/V \quad (2)$$

These equations can be used as an alternative to the selection chart for obtaining the equivalent temperatures at the standard fire periods (i.e. R30, R60, R90 and R120).

2.2. Flexural stiffness reduction coefficients

The application of the general principles in Clause 4.3.5.1 of EN 1994-1-2 [10] to CFT columns requires the definition of a set of reduction coefficients ($\varphi_{i,\theta}$) for the evaluation of the effective