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# Fire design method for concrete filled tubular columns based on equivalent concrete core cross-section

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ABSTRACT

In this work, a method for a realistic cross-sectional temperature prediction and a simplified fire design method for circular concrete filled tubular columns under axial load are presented. The generalized lack of simple proposals for computing the cross-sectional temperature field of CFT columns when their fire resistance is evaluated is evident. Even Eurocode 4 Part 1-2, which provides one of the most used fire design methods for composite columns, does not give any indications to the designers for computing the cross-sectional temperatures. Given the clear necessity of having an available method for that purpose, in this paper a set of equations for computing the temperature distribution of circular CFT columns filled with normal strength concrete is provided. First, a finite differences thermal model is presented and satisfactorily validated against experimental results for any type of concrete infill. This model consideres the gap at steel–concrete interface, the moisture content in concrete and the temperature dependent properties of both materials. Using this model, a thermal parametric analysis is executed and from the corresponding statistical analysis of the data generated, the practical expressions are derived. The second part of the paper deals with the development of a fire design method for axially loaded CFT columns based on the general rules stablished in Eurocode 4 Part 1-1 and employing the concept of room temperature equivalent concrete core cross-section. In order to propose simple equations, a multiple non-linear regression analysis is made with the numerical results generated through a thermo-mechanical parametric analysis. Once more, predicted results are compared to experimental values giving a reasonable accuracy and slightly safe results.



## 1. Introduction

In recent years, the use of concrete filled tubular (CFT) columns has increased and concurrently, the interest of engineers and architects in the fire design of theses composite columns has also augmented. In fire situation, CFT columns show a high resistance even when no external protection is used. The steel tube protects the concrete core from the direct exposure to fire and, in turn, the concrete infill delays the heating of the steel profile. Mechanical properties of both materials degrade as temperature increases, but steel loses its resistance faster than concrete. Determining with accuracy the cross-sectional temperature distribution when modeling a CFT column in fire is crucial, and moreover if a realistic fire resistance prediction is expected.

European code EN 1994-1-2 [1] in its Clause 4.3.5.1 establishes a general method to study the fire resistance of composite columns. This procedure takes into account the temperature dependent thermal and mechanical properties of the material but no recommendations are given regarding the calculation of the cross–sectional temperature field along time.

A simple calculation model explicitly for CFT sections in fire proposed in Annex H of the same code [1] indicates that the temperature distribution shall be calculated neglecting the thermal resistance at steel-concrete interface for simplicity and in accordance with Clause 4.4.2. This section provides a series of guidelines regarding thermal actions, variation of thermal properties with temperature and concrete moisture content for thermal response in advanced calculation models, which are only applied in specific situations when the actual behavior is required.

In summary, EN 1994-1-2 [1] does not provide any direct method to obtain the time dependent cross-sectional temperature distribution in a CFT column for the standard fire classes (R30, R60, R90 and R120). Designers are obliged to turn to numerical models or to implement complex methods available in published research works [5].

Thermal analysis is the first step to carry out when the whole

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**Nomenclature**

| | |
|---|---|
| $A/V$ | section factor |
| CFT | concrete filled tube |
| CXXX-T-L-FF-EE | (i.e. C159-6-3-30-0), where C stands for circular, XXX is the diameter in mm, "T" the thickness in mm, L the nominal length in meters, FF the nominal concrete strength in MPa, and EE is the applied eccentricity. |
| $D$ | diameter of the column |
| FC | fiber reinforced concrete |
| $FRR$ | fire resistance rating |
| $f_c$ | compressive cylinder strength of concrete at room temperature (test date) |
| $f_y$ | yield strength of structural steel at room temperature |
| $L$ | length of the column |
| $l_\theta$ | buckling length in the fire situation |
| RC | reinforced concrete |
| $T$ | temperature |
| $t$ | thickness of the steel tube |
| $\mu = N/N_{Rd}$ | axial load level |
| $\xi$ | relative error |

response of a CFT column is analyzed. In the reviewed literature, some of the studies considered realistic features regarding the heat transfer process, such as the three-dimensional model presented by Espinos et al. [2] which took into account the gap at the steel-concrete interface and the water content of the concrete core; or the numerical model developed by Lu et al. [3] which assumed a heat contact conductance parameter to represent the gap between the two materials. But these works focused on models to study the global fire behavior of CFT columns. Computing the temperature distribution of the column was just an implicit step within the entire calculation. Therefore, they do not present any simple and specific procedure for computing the cross–sectional temperature.

With regard to studies dealing exclusively with the thermal analysis of CFT columns, just few publications can be located. A numerical method using the Green's function approach was developed by Wang et al. [4] for protected steel members and later it was extended by Wang and Tan [5] to solve the heat transfer problem in CFT columns. However, the concrete and steel properties were considered temperature independent, perfect contact between materials was assumed and also the presence of moisture in the concrete was neglected. These conservative assumptions made the method lose accuracy.

Another approach to solve the sectional heat transfer problem in CFT columns is employing finite differences. Hence, Lie [6] developed a formulation for circular CFT columns based on the methodology proposed by Dusinberre [7]. Again, perfect contact was assumed at steel–concrete interface.

Although some realistic features were not considered, these works presented effective procedures to obtain temperature distribution at the cross-section of CFT columns. In spite of this, since no straightforward equations were provided, designers might find tedious and time-consuming implementing them in the daily practice.

Relating to fire design methods for CFT columns following the general rules of EN 1994-1-2 [1], some works can be found where the authors have treated the cross-sectional thermal analysis step separately. Thus, researchers like Espinos et al. [8] proposed an effective design procedure as a result of an extensive parametric study carried out by means of their validated three-dimensional model [2]. However, this method assumed an equivalent temperature for the concrete core so the cross-sectional temperature distribution was no explicitly calculated. In the same line, Yu et al. [9] developed a simple calculation method for the fire resistance of CFT columns but again on the assumption of average temperatures for both steel tube and concrete core cross-sections.

This work can be divided into two parts: on the one hand, practical expressions for computing the cross-sectional temperatures of circular CFT columns are developed; on the other hand, a simple design method for obtaining the fire resistance of axially loaded CFT columns is proposed.

Therefore, the outline of this paper is as follows. First, a finite differences method for solving the heat transfer problem is developed improving the initial approach of Dusinberre [7] by considering the effect of the gap conductance at steel–concrete interface and, in general, all the detected nonlinearities involved in the heat transfer process to obtain a response as realistic as possible. The finite differences method is valid for a wide range of concrete infill: plain, bar reinforced and steel fiber reinforced concrete of both normal and high strength. The thermal model is validated against experimental results showing good agreement.

Next, an extensive thermal parametric analysis is carried out in order to obtain a regression equation for calculating the cross-sectional temperature field. Although the thermal model developed has proven to be valid for protected and unprotected CFT columns with any type of concrete infill, as a first step, the parametric analysis and the proposed adjustment equations are specifically focused on unprotected circular CFT columns filled with normal strength concrete. In order to extend the current equations or to obtain new temperature expressions for other types of concrete infill, it is necessary to perform the pertinent parametric analysis taking into account the corresponding thermal properties.

The concept of equivalent concrete core cross-section at room temperature is exposed right after, since it is the starting point to develop the fire design method proposed, which is verified against experimental results.

Finally, a case of CFT column fire design is included to exemplify the use of the calculation procedure presented.

## 2. Heat transfer model

The heat transfer model involves the calculation of the temperatures given by the fire curve to which the column is exposed and the determination of column cross-sectional temperatures.

The model formulation is based on the finite differences method with an explicit scheme and follows the line proposed by Dusinberre [7]. Previously, Lie [6] had already taken as a basis the same approach to solve the heat transfer problem for circular CFT columns but ignoring the gap conductance that appears between the steel tube and the concrete core which clearly reduces the thermal response accuracy.

In this paper, only the expressions to obtain cross-sectional temperatures are presented since the derivation of these equations is explained with detail in previous works [7].

### 2.1. Discretization of the section

The nomenclature used by Lie [6] will be maintained in order to make easier any comparison between both formulations. Due to axisymmetric conditions, the heat transfer problem becomes unidirectional what simplifies the discretization of the section as well as the calculation process.