SIMPLE APPROACH FOR PERFORMANCE-BASED FIRE SAFETY DESIGN OF CIRCULAR CFT COLUMNS IN LARGE ENCLOSURE

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Received: 5 August 2014; Revised: 1 January 2015; Accepted: 19 March 2015

ABSTRACT: The usage of concrete filled steel tubular (CFT) columns in large space buildings is increasing. Flashover is unlikely to happen in a large enclosure and the localized fire model is preferable to model the fire environment in a large enclosure fire. This paper proposed a simple approach to evaluate the fire resistance of circular CFT columns in localized fires. Simple model was provided to calculate the column temperatures in a localized fire. The concept of equivalent fire severity or time equivalent was used to correlate the localized fires with the standard fire. The simple model used in the Chinese code was used to calculate the load capacity of the circular CFT columns subjected to the equivalent standard fire exposure. The proposed approach, by correlating real fires with the standard fire, only includes heat transfer analysis and avoids the complex structural analysis, which provides an easy and efficient way for performance-based fire safety design. A case study is also provided to demonstrate the application of the approach.

Keywords: Concrete filled steel tubular (CFT) columns, Fire resistance, Large enclosure, Localized fires, Simple method, Time equivalent, Performance-based design

DOI: 10.18057/IJASC.2016.12.1.3

1. INTRODUCTION

Concrete-filled steel tubular (CFT) columns have many advantages, including high load carrying capacity, fast construction, small cross-section, and high fire resistance. These attractions have enabled CFT columns to be used in many large space, and high-rise buildings [1].

Traditionally, the fire resistance of CFT columns is determined by a standard fire resistance test conducted on an isolated member subjected to a specified heating such as ASTM E119, ISO834. The standard fire resistance test is time consuming and expensive, and the dimension of the test specimen is limited by the size of the furnace. As an alternative to the test method, calculation approaches are also developed to assess the fire resistance of CFT columns [1-5]. Lie and Chabot [2] developed a mathematical model to calculate the temperatures and fire resistance of circular CFT columns. In the model, the cross-section area of the column was subdivided into a number of concentric layers to calculate the column temperatures, and a finite difference method was applied to solve the heat transfer equations. The strength and stiffness was calculated by subdividing the cross-section area into a number of annular elements. The representative temperature of an element was taken as the average temperature of the layer in which the element was located. In the Eurocode EC4-1-2 [3], a simple model is provided in the Annex H to calculate the fire resistance of CFT columns by subdividing the cross-section area into several elements and respectively calculate the strength and stiffness accordingly. Kodur [4] proposed a simplified equation based on the results of parameter studies supported by an experimental program on circular and square CFT columns under fire. The equation is widely used in North America, and it directly provides the fire resistance time of the column in minutes as a function of different parameters such as the concrete strength, the column diameter and effective length, the type of concrete filling, cross-sectional shape and percentage of steel reinforcement [5]. Han and co-workers [1] proposed a formulation to determine the strength index of CFT columns based on regression analysis of the results of parametric and experimental studies. The formulation is incorporated in the Chinese technical code CECS200 [6] for fire safety design [7].

The behavior of a real fire is complex, which depends on many parameters such as active fire detection and suppression systems (smoke detector and sprinkler), fire loads (amount and distribution), combustion, ventilation, compartment size and geometry, and thermal properties of compartment boundaries [8]. In large enclosures, flashover (which is the rapid transition between a local fire and a general conflagration within a compartment when all fuel surfaces are burning [9]) is unlikely to happen, and the potential fires are characterized as pre-flashover or localized fires [10]. The current methods to calculate the fire resistance of CFT columns are developed for post-flashover fires, and there is no available simple method for calculation in localized fires.

This paper proposes a simple method to evaluate the fire resistance of circular CFT columns in localized fires. Simple model to calculate the temperatures of circular CFT columns in localized fires was provided. The concept of equivalent fire severity or time equivalent was used to relate real fires with a standard fire. The simple method given in CECS200 [6] was applied to calculate the fire resistance of circular CFT columns in the standard fire. A case study for the performance-based fire safety design of the circular CFT columns in a railway station building was presented to demonstrate the application of the proposed method.

2. LARGE ENCLOSURE FIRE

2.1 Localized Fire Model

Localized fire model is used to model the fire environment in a large enclosure. As shown in Figure 1, a localized fire is loosely divided into the lower combustion (flame) and the upper non-combustion (plume) regions. The ceiling jet is also illustrated.

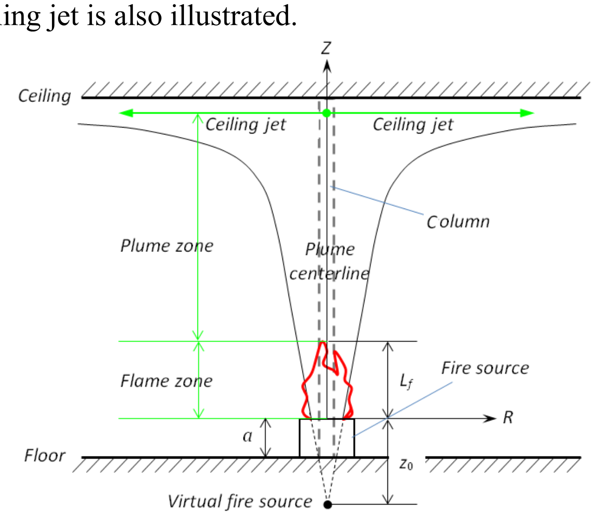


Figure 1. Illustration of a Localized Fire Model

The centerline gas temperature, T_g, in a localized fire is calculated by [10]

$$T_g = 20 + \min(\Delta T_{plume}, \Delta T_{flame}) \quad (1)$$

where ΔT_{plume} is the plume centerline temperature increment calculated by [11]

$$\Delta T_{plume} = 20 + 0.25(1000\dot{Q}_c)^{2/3}(z - z_0)^{-5/3} \quad (2)$$

and ΔT_{flame} is the flame centerline temperature increment, as calculated by Quintiere and Grove [12]. For simple calculation [13]

$$\Delta T_{flame} = 1500(1 - \chi_r) \quad (3)$$

where $\dot{Q}_c = (1 - \chi_r)\dot{Q}$ is the convective part of the heat release rate (*HRR*) of the fire source, in which $\dot{Q}$ is the *HRR* of the fire source and χ_r is the radiative fraction. For situations where χ_r is unknown, the flame centerline temperature may be simply taken as 900 ^{o}C as in EC1-1-2 [11]. z_0 is the height of the virtual fire source, calculated by

$$z_0 = -1.02D + 0.083\dot{Q}^{2/5} \quad (4)$$

where $D = \sqrt{4A/\pi}$ is the equivalent diameter of the fire, in which A is the area of the fire source.

Eq. 3 assumes that all of the air entrainment into the flame zone is completely consumed. However, in practice, with increasing height the amount of air entrainment will become more than that of the air required for reaction and the exceeded air will cool the flame zone temperature.

2.2 Heat Release Rate and Fire Duration

Heat release rate (*HRR*) is the most import variable in measuring fire severity. The *HRR* of a real fire can be measured by cone calorimeter. In design work, the Natural Fire Safety Concept (*NFSC*) is widely used to represent the fire conditions [11,14-17]. As shown in Figure 2, the *NFSC* fire is assumed to be t-square in the growth stage and decay stage begins at the time when 70% of design fire load is consumed.

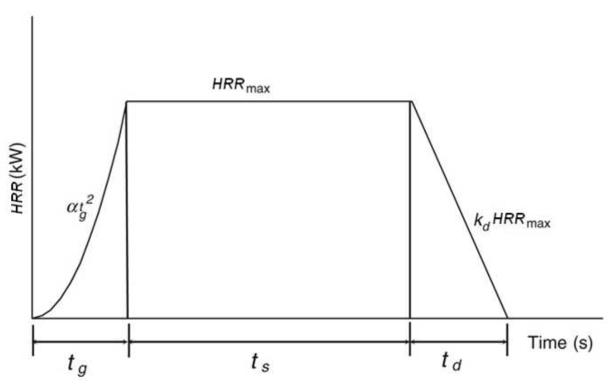


Figure 2. Illustration of the *HRR* History in a NFSC Fire

In a *NFSC* fire, at the growth stage, the *HRR* is given by

$$HRR = \alpha t^2 \tag{5}$$

the fire growth time, t_g, is given by

$$t_g = \sqrt{\frac{HRR_{\max}}{\alpha}} \tag{6}$$

and the fuel energy consumed at the fire growth stage, Q_g, is

$$Q_g = \int_0^{t_g} \alpha t^2 dt = \frac{\alpha t_g^3}{3} \tag{7}$$

where α is the fire intensity coefficient, taken as 0.00293 kW/s^2, 0.0117 kW/s^2 and 0.0466 kW/s^2 for slow, medium and fast growth fires, respectively.

The duration time of steady burning in a *NSFC* fire is given by

$$t_s = \frac{0.7 q_f A_f - Q_g}{HRR_{\max}} \tag{8}$$

and the duration of decaying stage is given by

$$t_d = \frac{0.6 q_f A_f}{HRR_{\max}} \tag{9}$$

where q_f, A_f are design fire load density and floor area, respectively; and $HRR_{\max}$ is the maximum heat release rate. In EC1-1-2 [11], values for fire load density and maximum heat release rate per unit area for various occupancies are provided.

The total duration time of an NFSC fire is given by

$$t_f = t_g + t_s + t_d \tag{10}$$

3. TEMPERATURE OF CIRCULAR CFT COLUMNS

In current structural fire design codes, there is no calculation approach to predict the temperature of circular CFT columns in a localized fire. Here, the simplifications and assumptions for calculation in post-flashover fires [8,18-19] were applied to calculate the temperature of a circular CFT column fully engulfed in a localized fire,

- The temperature of the gas surrounding a column is calculated by Eq. 1;
- For calculating radiative heat transfer from a fire to the column surface, the surrounding gas and the exposed surface are represented as infinitely parallel grey planes, and the view factor is, therefore, taken as 1;
- The convective heat transfer from a fire to the column surface is calculated by Newton's law of cooling.

Correspondingly, the heat flux to an exposed column surface is

$$\dot{q}''_{net} = \dot{q}''_c + \dot{q}''_r \tag{11}$$

where $\dot{q}''_c$ and $\dot{q}''_r$ are convective and radiative heat fluxes, calculated by

$$\dot{q}''_c = h_c(T_g - T_{surf}) \tag{12}$$

and

$$\dot{q}''_r = \varepsilon_{res}\sigma[(T_g + 273)^4 - (T_{surf} + 273)^4] \tag{13}$$

where h_c is the convective heat transfer coefficient, taken as 9 W/(m^{2}K) for localized fires [11]; T_{surf} is the column surface temperature; ε_{res} is the resultant emissivity at the exposed surface; and σ is the Stefan-Boltzmann constant. For calculating in a standard fire, the gas temperature T_g is taken as the fire temperature.

Ignoring the thermal conduction along column length, the temperatures in a cross section of the circular CFT column are calculated by solving the two-dimensional heat conduction equation under the heat flux boundary condition below,

$$-k_s \frac{\partial T}{\partial s}(0,t) = \dot{q}''_{net} \tag{14}$$

where s denotes the inward radial direction; and k_s is the thermal conductivity of the steel. At the steel-concrete interface, temperature continuity is assumed. The cross sections engulfed by flame have the maximum temperatures.

Although the correlations in Eq.1 are derived for a localized fire that is burning without obstruction (like a column), the above approach is recommended for simple calculation because of the following reasons:

- The approach is conservative. The gas temperatures in a horizontal plane of a fire plume decrease with plume radius. The approach uses the maximum gas temperature at the plume center for calculation. Also, ignoring the thermal conduction along column length yields higher maximum cross section temperatures [20].
- The present of the circular CFT column does not affect the flame temperature, ΔT_{flame} in Eq.1, although it affects the plume temperature.

4. FIRE RESISTANCE OF CFT COLUMNS IN THE STANDARD FIRE

The calculation method proposed by Han et al. [1] is incorporated in the Chinese code CECS200 [6] to evaluate the fire resistance of CFT columns.

In [6], a strength index, k_t, is defined to quantify the strength of the CFT columns subjected to standard fire, which is expressed as

$$k_t = \frac{N_u(t)}{N_u} \quad (15)$$

where $N_u(t)$ is the ultimate strength corresponding to the fire resistance time t of the CFT columns; and N_u is the ultimate strength of the CFT columns at normal temperatures, which can be calculated using the equations given by design codes.

For the CFT columns without fire protection, the strength index can be calculated by the following expressions as [1]

$$k_t = \frac{1}{1 + a t_0^{2.5}}, \quad \text{for } t_0 \le t_1 \quad (16a)$$

$$k_t = \frac{1}{b t_0 + c}, \quad \text{for } t_1 < t_0 \le t_2 \quad (16b)$$

$$k_t = k t_0 + d, \quad \text{for } t_0 > t_2 \quad (16c)$$

with

$$a = (-0.13\lambda_0^3 + 0.92\lambda_0^2 - 0.39\lambda_0 + 0.74)(-2.85D_0 + 19.45)$$
$$b = D_0^{-0.46}(-1.59\lambda_0^2 + 13.0\lambda_0 - 3.0); \quad c = 1 + a t_1^{2.5} - b t_1; \quad d = 1/(b t_2 + c) - k t_2$$
$$k = (0.02\lambda_0^3 - 0.31\lambda_0^2 + 1.46\lambda_0 + 0.03)(0.01D_0^3 - 0.12D_0^2 + 0.48D_0 - 0.59)$$
$$t_1 = (0.0072D_0^2 - 0.02D_0 + 0.27)(-0.0131\lambda_0^3 + 0.17\lambda_0^2 - 0.72\lambda_0 + 1.49)$$
$$t_2 = (0.01D_0^2 - 0.03D_0 + 0.39)(-0.03\lambda_0^3 + 0.31\lambda_0^2 - 1.12\lambda_0 + 1.89)$$
$$t_0 = t/100; \quad D_0 = D_c/400; \quad \lambda_0 = \lambda/40$$

where D_c is the diameter of the circular section; and λ is the slenderness ratio.

Taking Eq. 10 into Eq. 9, we obtain the ultimate strength $N_u(t)$ of the unprotected CFT columns corresponding to fire resistance time t.

5. TIME EQUIVALENT METHOD

The concept of equivalent fire severity, commonly referred as time equivalent, is used to relate the severity of an expected real fire to the standard fire. So that results or methods based on the standard fire can be extended to realistic fires. To date, a number of methods and empirical formulae have been developed for evaluating the equivalent fire severity. These methods include equal area method, maximum temperature method, minimum load capacity concept and energy based method [14,21]. Take the maximum temperature method for example, as illustrated in Figure 3, the equivalent time of a real fire is the time when a structural element is subjected to the standard fire exposure that would give the same critical temperature as the maximum temperature the structural element will get when subjected to the real fire exposure.

In CECS200 [6] and in EC1-1-2 [11], equations based on the maximum temperature method are recommended to calculate the time equivalent. Those equations, however, are developed for calculation in fully-developed compartment fires in which the gas temperatures are approximately uniform because of flashover. In this study, the maximum temperature method was applied to calculate the time equivalent in localized fires.

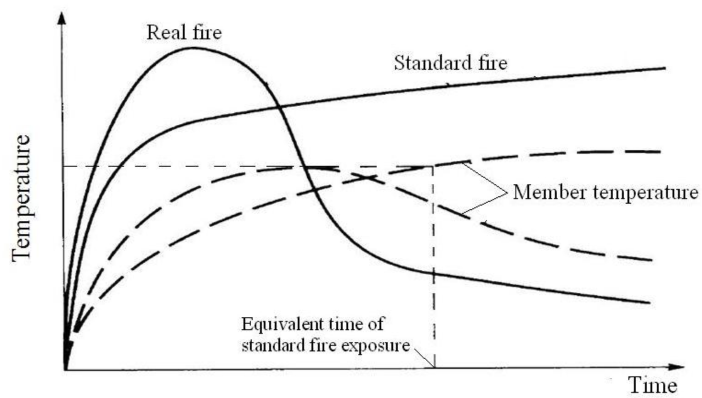


Figure 3. Illustration of the Maximum Temperature Method to Calculate Time Equivalent

Therefore, the fire resistance of a circular CFT column in a large enclosure can be evaluated by following the steps given below:

- Step 1: Determine the design fire scenarios (e.g. fire load density, fire type, *HRR*, location and area of the fire load) by fire risk analysis;
- Step 2: Calculate the fire durations (by Eq. 10) and gas temperatures (by Eq. 1) in the design fires;
- Step 2: Calculate the temperatures of the column in the design fires and obtain the maximum temperature time curve in design fires;
- Step 3: Calculate the temperature of the column in the standard fire and obtain the equivalent standard fire exposure time by maximum temperature method;
- Step 4: Calculate the strength index of the circular CFT column k_t by Eq. 16;
- Step 5: Calculate the ultimate strength of the column in the design fire $N_u(t)$ from Eq. 9 (The ultimate strength of the column at normal temperature N_u is calculated separately);
- Step 6: Check the load bearing capacity of the circular CFT column in the design fires by comparing $N_u(t)$ with the action force in the design fire P_T. If $N_u(t)$ is greater than P_T, the circular CFT column has sufficient load capacity in the design fire scenario and can be left unprotected; and if $N_u(t)$ is less than P_T, the circular CFT column has insufficient load capacity and should be protected.

6. A CASE STUDY

Problem: Figure 4 shows the bird view of a railway station building in China. The building has a construction area of about 182340 m^2 and a height of about 56.6 m. Circular CFT columns were used to support the roof structure of the building. The dimensions of the circular CFT columns are 16 m (height) × 1600 mm (diameter) × 60 mm (tube thickness). The filled concrete is plain weight normal concrete (NWC). Performance-based approach was approved and used in the fire safety design of the building. By fire risk analysis, the most hazard fire to the circular CFT columns is a shopping center fire. Determine the strength index of the column in the design fire.

Solution:

1) Calculate the fire duration time t_f. For shopping center, the floor fire load density is taken as q_f = 1300 MJ/m^2 according to CECS200 [6], and the fire intensity coefficient and the maximum heat release rate are α = 0.0466 kW/s^2, $HRR_{\max}$ = 250 kW/m^2 according to EC1-1-2 [11]. Therefore,

$$t_g = \sqrt{\frac{HRR_{\max}}{\alpha}} = \sqrt{\frac{250}{0.0466}} = 73 \quad \text{s}$$

$$t_s = \frac{0.7 q_f A_f - Q_g}{HRR_{\max}} = \frac{0.7 \times 1300 \times 1000 - 1/3 \times 250 \times 73}{250} = 3616 \quad \text{s}$$

$$t_d = \frac{0.6 q_f A_f}{HRR_{\max}} = \frac{0.6 \times 1300 \times 1000}{250} = 3120 \quad \text{s}$$

$$t_f = t_g + t_s + t_d = 73 + 3616 + 3120 = 6809 \quad \text{s}$$

2) Calculate the temperature of the circular CFT column in the design fire. The finite element method (FEM) program ANSYS is used to solve the heat transfer problem. 2D thermal solid element PLANE55 and thermal surface effect element SURF151 as used in a previous work [18] were applied in the numerical simulations. Figure 5 shows the FE model for the circular CFT column. Using symmetry, a partial section instead of the whole section was considered. A constant flame temperature of 900 ^{o}C was used for the duration of the design fire. Figure 6 shows results for temperature distributions in the circular CFT column when exposed to the design fire.

3) Calculate the equivalent standard fire duration time t_{eq}. As shown in Figure 7, by maximum temperature method $t_{eq} =$ 86 min. Figure 8 compares the temperature distributions in the circular CFT column exposed to the design fire and the standard ISO 834 fire. The steel temperatures are approximately equal in the two fires, while the concrete temperatures in the design fire are slightly higher than those in the standard ISO 834 fire. Considering the concrete temperatures were comparatively low, and many conservative assumptions were used in the calculation, an equivalent standard fire duration time of 90 min was used to calculate the strength index of the column in fire condition.

4) Calculate the strength index. Taking $t = 90$ min, $D_c = 1600$ mm and $\lambda = 4L/D = 40$ into Eq. 16, we get $t_0 = 0.9$, $D_0 = 4$, $\lambda_0 = 1$, $t_1 = 0.283$, $t_2 = 0.452$, $k = 0.06$, $a = 9.18$, $b = 4.44$, $c = 0.133$, $d = 0.44$, and $k_t = 0.494$.

Figure 4. A Railway Station Building in China

The above calculation shows that by using performance-based approach, the fire resistance requirement for the circular CFT columns was reduced from 3.0 h as specified in the prescriptive code to 1.5 h. By comparing the design load with the load bearing capacity of the circular CFT columns in the design fire, the CFT columns without fire protection were found to have sufficient fire resistance.

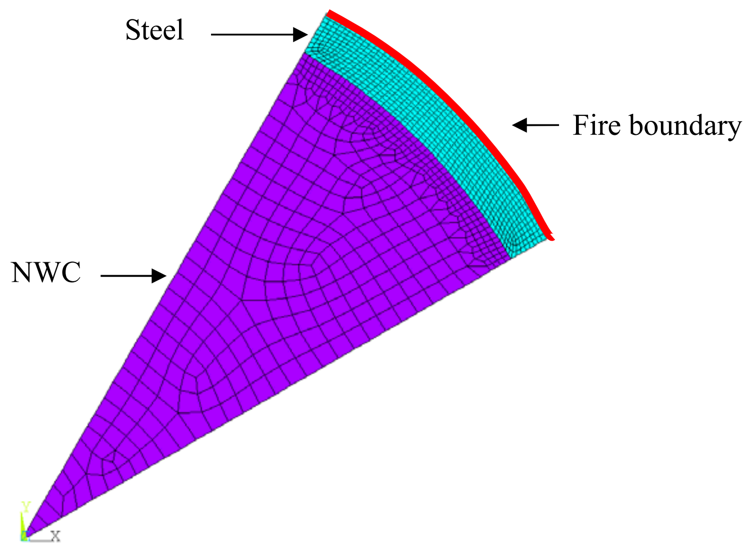
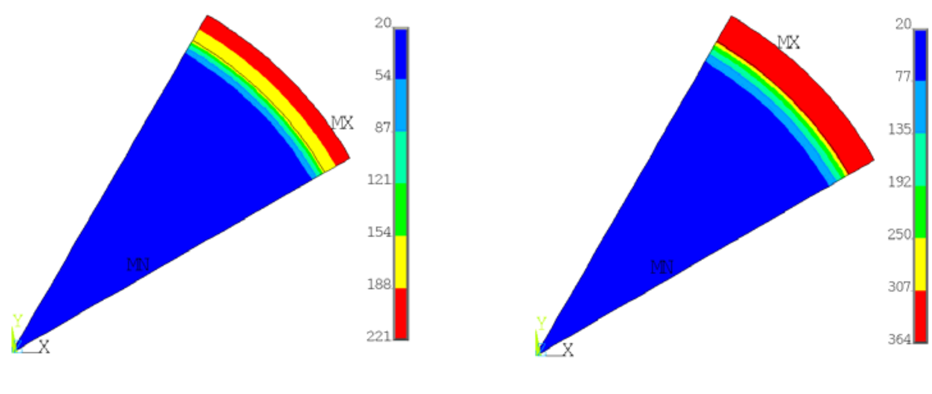


Figure 5. FEM Model for Heat Transfer Analysis



(a) 900 s (b) 1800 s

(c) 3600 s (b) 6809 s

Figure 6. Temperature Distributions in the Circular CFT Column Exposure to the Design Fire

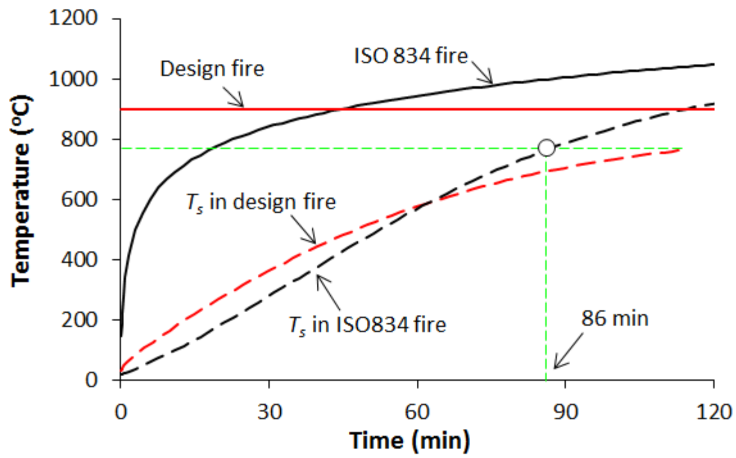


Figure 7. The Equivalent Standard Fire Exposure Time Determined by t-equivalence

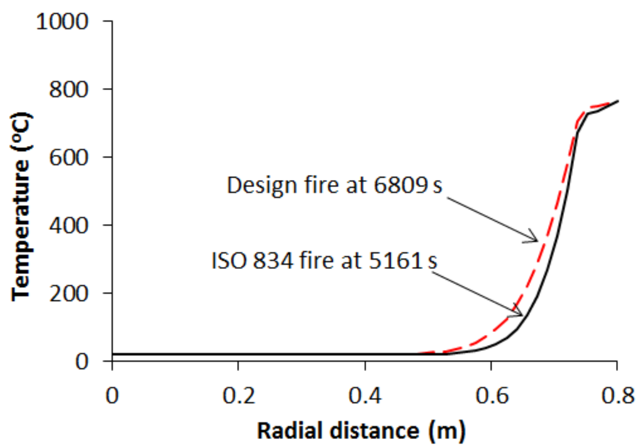


Figure 8. Temperature Distributions along the Radius

7. CONCLUSIONS AND SUGGESTIONS

The usage of concrete filled steel tubular (CFT) columns in large space buildings is rapidly increasing in recent years. There are many situations in which the performance-based methods (PBM) are applied to do the fire safety design of large space buildings. The interest in the use and development of simple methods for calculating the fire resistance of CFT columns is growing, due to the application of PBM. This paper proposed a simple approach to calculate the fire resistance of circular CFT columns in localized fires. The theory and assumptions of the approach are stated, and the usage of the approach is demonstrated by a case study example.

The approach uses the concept of equivalent fire severity to correlate localized fires with the standard fire. The time equivalent is calculated by the maximum temperature method which is used in both the Chinese and the European codes. Although the fire performance of a circular CFT column is affected by many parameters, the limiting or critical (steel) temperature method is used in practice to evaluate fire resistance of circular CFT columns, e,g. [22]. Therefore, the proposed approach which is also based on the limiting (steel) temperature method is recommended for simple calculations. Users, however, are advised to check the safety of results by, for example, comparing the temperature distributions in the cross section.

ACKNOWLEDGEMENTS

Financial support from the National Nature Science Foundation of China with Grant No. 51278387 is acknowledged.

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