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DEVELOPMENT OF AN EXCEL-BASED CALCULATION TOOL FOR INTERACTION CURVES OF RECTANGULAR CONCRETE COLUMNS SUBJECTED TO FIRE

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ABSTRACT

A simplified cross-sectional calculation tool is developed to calculate interaction curves for rectangular concrete columns subjected to both bending and compression in case of fire. First, the proposed framework based on Eurocode 2 is explained and additionally some simplifications are made. As a first step in the verification process, the accuracy of the proposed calculation method is verified, considering traditional analytical calculation methods for interaction curves at ambient temperatures. Subsequently, the performance at elevated temperature is examined in more detail considering a scholar example. The influence on the interaction curves is investigated by taking into account fire exposure of 1, 2, 3 or 4 sides. Finally, interaction curves of columns are developed for different slenderness ratios. Comparing the interaction curves with available research results, the accuracy of this simplified numerical calculation approach is verified.

Keywords: Eurocodes, structural fire analysis, numerical calculations, interaction curves

INTRODUCTION

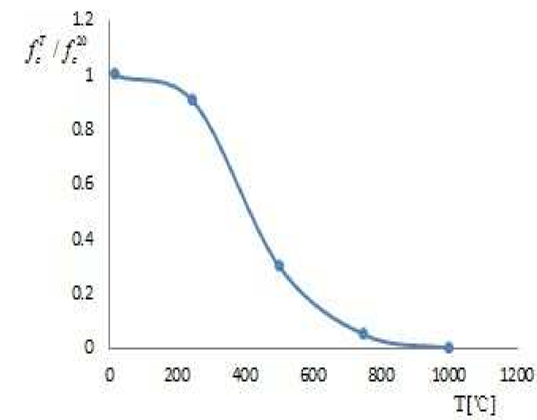
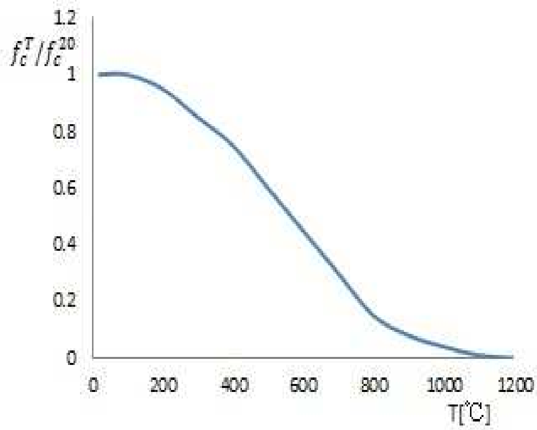
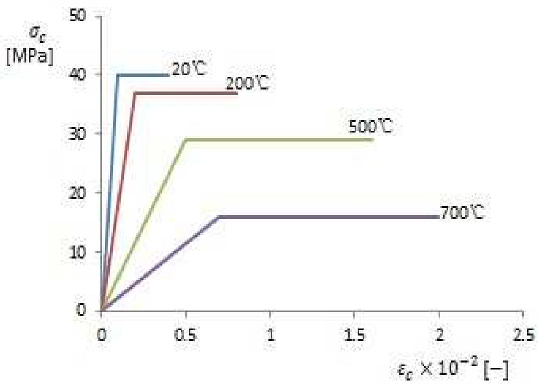
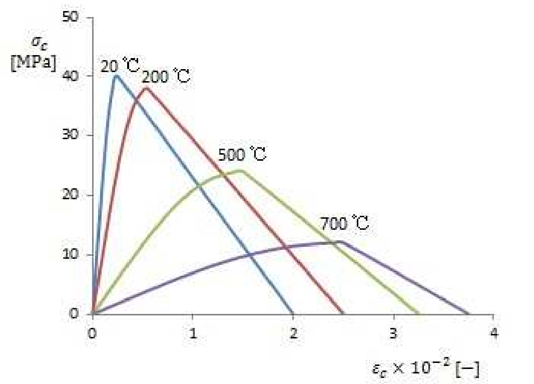
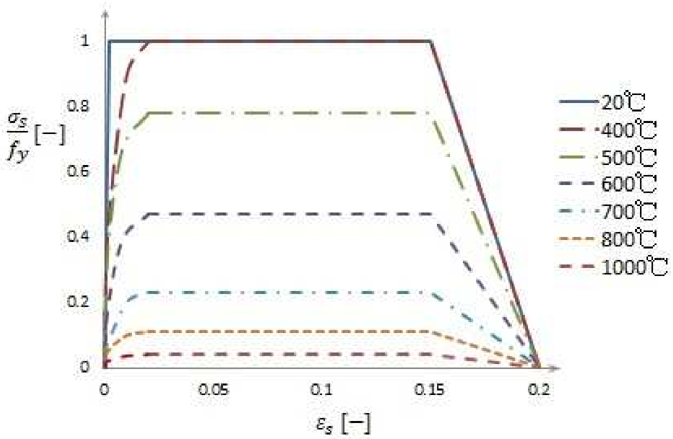
Columns are important structural load members, not only bearing the vertical reaction forces transferred from slabs and beams, but also bending moments. Hence, they are most often objected to combined bending. When exposed to fire, their performance seems to be more complicated. On the one hand, both strength and stiffness are reduced with fire duration. The buckling of columns, on the other hand, could occur even when the concrete strength has not reached its limit.

With respect to design of concrete columns, a cross-sectional analysis is usually chosen as a simplified structural analysis method. A first mathematical approach to predict the fire resistance of circular reinforced concrete columns was given in (Lie and Celikkol, 1991). This method was further developed in order to include columns with rectangular cross sections (Lie and Irwin, 1993). Further, Meda et al. (2002) made comparisons between the M-N interaction curves for normal-strength concrete and high-performance concrete. Van Coile et al. (2011) developed an Excel-based cross-sectional calculation model in order to calculate the bending moment capacity for a concrete beam exposed to fire. In this contribution, the model proposed by Van Coile et al. (2011) is applied and expanded to allow for the calculation of interaction diagrams for concrete columns subjected to fire.

BASIC MODEL AND CALCULATION TOOL

Aiming at calculating the combined effect of axial force (N) and bending moment (M) on columns subjected to fire, a simplified method is introduced, based on a cross-sectional calculation and the material models as provided in EN 1992-1-2. In Table 1, the basic assumptions of the material models are compared with those in (Meda et al., 2002).

Table 1. Material model comparison

	Meda's model (2002)	The present model (based on EN 1992-1-2)
Concrete compressive strength at elevated temperatures		
Stress-strain laws of concrete in compression at elevated temperatures		
Stress-strain relationships of reinforcing steel in tension at elevated temperatures		
Tensile stresses in concrete	not taken into account	

In EN 1992-1-2 (2004), a general method and two simplified methods are introduced to calculate second order effects for columns. In this paper, interaction curves are obtained by a simplified cross-section calculation tool and those interaction curves are verified by comparing with results from (Meda et al., 2002) and background documents associated to Eurocode 2.

Some assumptions are proposed to simplify the calculation. First, plane sections are considered to remain plane. Secondly, creep strain and transient strain are not considered in this method. The total strain includes thermal strain and mechanical strain, expressed as:

$$\varepsilon_{tot} = \varepsilon_{mech} + \varepsilon_{th} \qquad (1)$$

In addition, the tensile strength and spalling of concrete are not considered. Based on these assumptions, interaction curves are calculated and investigated in the cross-sections.

THE EFFECTS OF ISOLATED SURFACES ON FIRE

In order to verify the calculation method, the results obtained for the specific case of a square column with cross-section 600 mm$\times$600 mm; 24 bars with diameter 20 mm and concrete cover 50 mm; concrete compressive strength f_c = 40 MPa, reinforcement yield strength f_y = 430 MPa and young modulus of steel E_s considered as 2×10^5 N/mm^2 are compared to the results obtained in (Meda et al., 2002), where the same geometrical and material properties were used for the analysis.

Five cases (see Fig. 1) were considered in the transient heat transfer calculation. Further, in order to calculate the mechanical effects of column subjected to the fire, the same parameters as in (Meda et al., 2002) were adopted: The density is considered as constant between 20 ºC and 600 ºC, while the volumetric specific heat increases from 2160 to 3120 kJ/m^{3}ºK when the temperature rises from 20 ºC to 1000 ºC.

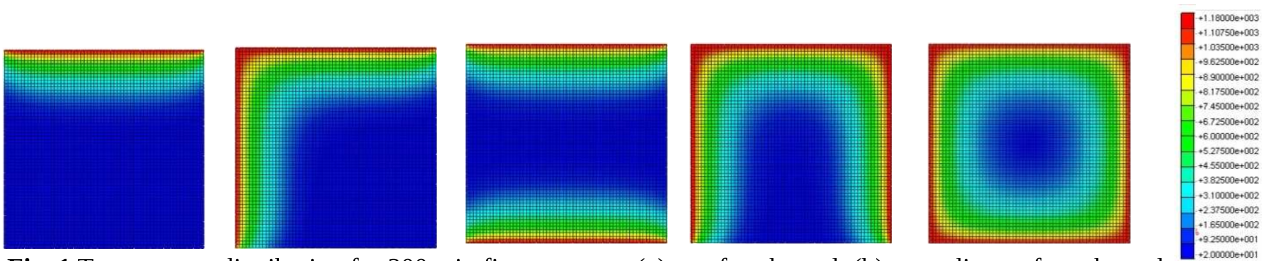


Fig. 1 Temperature distribution for 300 min fire exposure: (a) one face heated; (b) two adjacent faces heated; (c) two opposite faces heated; (d) three faces heated; (e) four faces heated

The results of the interaction curves in the case of four faces exposed to the fire are visualized in Fig. 2 considering $n = \frac{N_c+N_s}{f_c bh}$ and $m_x = \frac{M_c+M_s}{f_c bh^2}$, where N_c, M_c, N_s, M_s are maximum forces and bending moments respectively for concrete and reinforcement, b is the width of the column and h is the height of the cross-section. Compressive forces have a positive sign and the horizontal central axis in Fig. 1 is the bending axis.

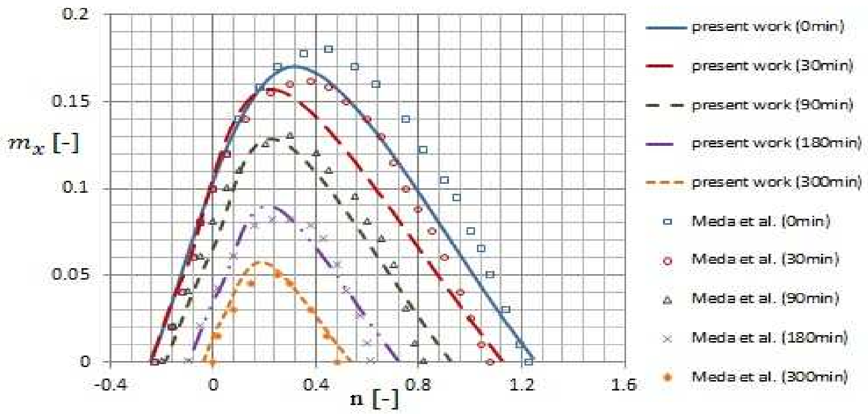


Fig. 2 Comparison of M-N interaction curves with results available in (Meda et al., 2002)

Subsequently, the cases of columns with different exposed surfaces are compared to the data from Caldas (Caldas et al., 2010) who used the same input parameters as Meda. The results prove to be very close to results in (Meda et al., 2002) and (Caldas et al., 2010), which means this analysis method could be used for interaction curves calculation. The effects of different exposed surfaces on M-N interaction curves at 90 min and 300 min are illustrated in Fig.3.

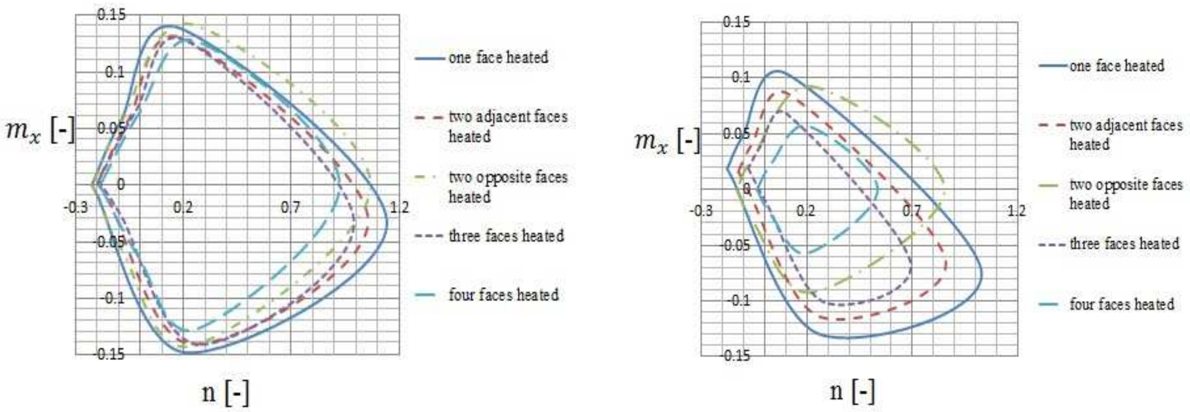


Fig. 3 The effects of different exposed surfaces on M-N interaction curves at 90 min (left) and 300 min (right)

From these two diagrams in Fig. 3, it can be seen that the effects of different exposed surfaces subjected to fire are not so apparent during the first 30 minutes. As the fire duration increases, the difference of the interaction curves between different considered cases becomes clear.

THE EFFECTS OF SLENDERNESS RATIOS

Based on the simplified method, an interaction curve of a cross-section 300mm×300mm at normal temperature was obtained and used to calculate cases with different slenderness ratios. A basic column model with two pinned ends and the same material parameters as in the background document of Eurocode 2 (i.e. concrete grade C80/95, $\omega = 0.2$, $\varphi_{ef} = 0$) was chosen in order to validate the accuracy of this simplified method from another angle.

The general method as mentioned in Eurocode 2 was adopted to calculate the cases of different slenderness ratios. Considering the initial imperfection of an eccentrically loaded column, a general homogeneous solution is given by Archer (Archer et al., 1978)

$$w = A\sin\sqrt{\frac{P}{EI}}x + B\cos\sqrt{\frac{P}{EI}}x + Cx + D \quad (2)$$

The boundary condition w = 0 at x = 0 and x = l, and

$$M = EI\frac{d^2w}{dx^2} = Pe \tag{3}$$

Hence,

$$w = -e\left(\frac{1-\cos\sqrt{\frac{P}{EI}}L}{\sin\sqrt{\frac{P}{EI}}L}\sin\sqrt{\frac{P}{EI}}x + \cos\sqrt{\frac{P}{EI}}x - 1\right) \tag{4}$$

In equation (4), e is an eccentricity of the external load. Based on EN 1992-1-1, the stiffness of the column can be evaluated as 0.4 $E_{cd}I_c$ in case of a cracked section while 0.8 $E_{cd}I_c$ can be considered in case of an uncracked section, where E_{cd} is the design value of the modulus of elasticity of concrete and I_c is second moment of area of the column.

Making use of the interaction curve for λ= 0 at normal temperature, curves for different slenderness ratios were obtained and compared to background documents associated to Eurocode 2 in Fig. 4.

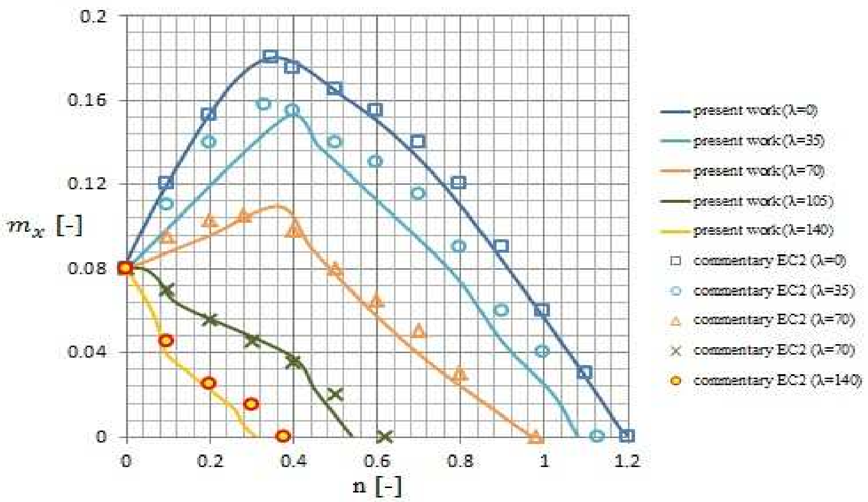


Fig. 4 Interaction curves for columns of different slenderness, calculated with the general method and comparison to background documents of Eurocode 2 (2008)

Clearly, it is seen that the interaction curves based on this simplified method are very close to results from background documents.

Further, a simplified equivalent stiffness as mentioned in Eurocode 2 was used to calculate a reduced cross-section of the column.

$$(EI)_z = [k_c(\theta_M)]^2 \cdot E_c \cdot I_{Zc} + \mathrm{E}_{s(\theta)} \cdot I_{Zs} \tag{5}$$

where

$k_c(\theta_M)$ is a reduction coefficient for concrete at point M (see EN1992-1-2 B.2)

E_c is the elastic modulus of the concrete at normal temperature

I_{Zc} is the moment of inertia of the reduced concrete section

$\mathrm{E}_{s(\theta)}$ is the elastic modulus of the concrete at elevated temperatures

I_{Zs} is the moment of inertia of reinforcement bars

Based on interaction curves for λ = 0 at 30 min and 60 min obtained with the Excel calculation tool, curves for different slenderness-ratios are illustrated in Fig. 5 and Fig. 6.

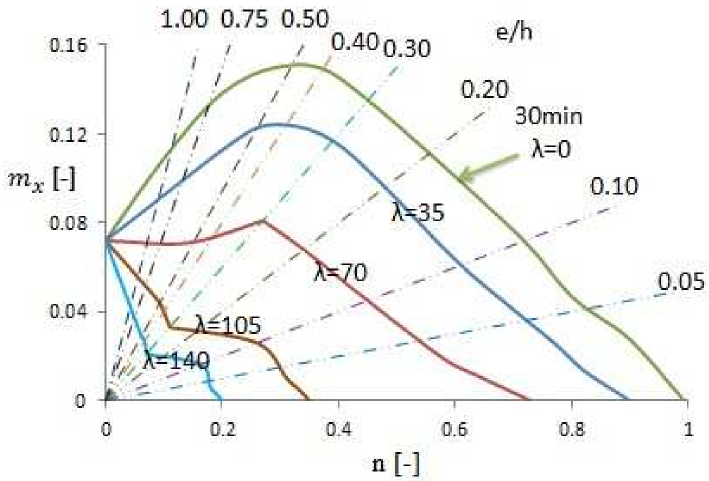


Fig. 5 Interaction curves for columns of different slenderness at 30 min on an ISO 834 fire

The dotted lines in Fig. 5 represent the first order relationship between normal force and bending moment for different eccentricities e/h for a slenderness ratio λ = 0. The intersections of the dotted lines with the interaction curve for λ = 0 indicate the maximum bearable normal force for the different eccentricities considering first order effects. In Fig. 6, both a first order relationship (dotted line) between n and m and a second order relationship (dashed line) are visualized. From Fig. 6, we can see second order effects should be considered. It shows first order effects on bending moments M_1 = Pe and second order effects on bending moments M_2 = P Δ .

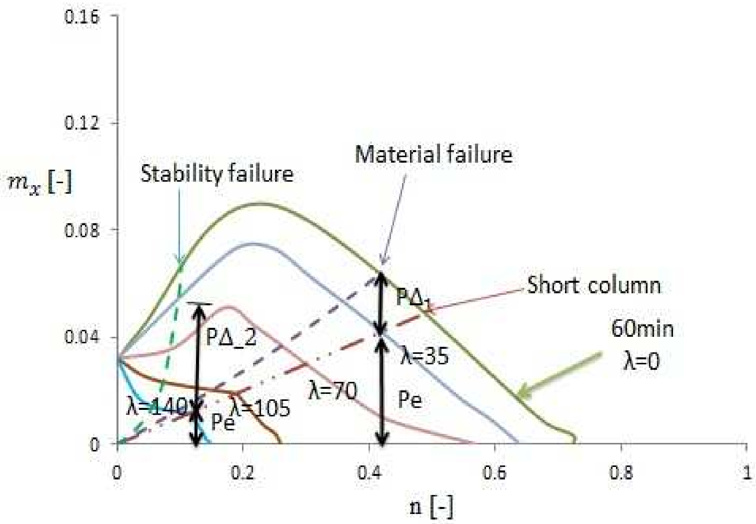


Fig. 6 Interaction curves for columns of different slenderness at 60 min on an ISO 834 fire

In Fig. 6, second order effects on the case of columns of λ = 140 are much larger than first order effects, while for the case of λ = 35 the second order effects are smaller. Therefore, second order effects need to be considered in case of slender columns.

Comparing the cases at 0 min, 30 min and 60 min fire duration, it is found that the load bearing capacity of columns decreases slightly during the fire from 0 min to 30 min, while there is a significant reduction from 30 min to 60 min.

CONCLUSION

In this study, a simplified method was developed for calculating interaction curves for columns in fire. By comparing with diagrams from (Meda et al., 2002) and background documents of Eurocode 2, it was proven to be a reliable and practical way to predict the maximum allowable combination of normal force and bending moment on columns. Further, the results from this simplified approach can be also applied for qualifying second order effects of columns subjected to fire.

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