Extension of tabulated design parameters for rectangular columns exposed to fire taking into account second order effects and various fire models

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Abstract

Fire, as one of the most severe load conditions, has an important impact on concrete structures. It does not only affect the material strength, but also the structural stiffness and stability. A concrete column, compared to other structural members, has most often to cope both with vertical forces and bending moments transmitted by slabs and beams. Consequently, it is essential to find a reliable and practical way to establish interaction curves for the overall structural behaviour of concrete columns subjected to fire. In this paper, a cross-section calculation method based on the material models of Eurocode 2 is explained and adopted to calculate interaction curves for a typical rectangular column exposed to the ISO834 standard fire. Subsequently, an iterative approach is introduced to develop interaction curves taking into account second order effects in case of four-side heated fire exposure. The maximum permitted slenderness ratios of columns under different fire durations are obtained and compared with Eurocode 2 provisions. Finally, this method is applied to calculate the maximum permitted slenderness ratios for columns exposed to hydrocarbon fires and natural fires.

Key words: concrete column, interaction curve, slenderness, second order effects, hydrocarbon fire, natural fire, Eurocode

1. INTRODUCTION

There are basically three methods used to evaluate the fire resistance of structural members: experimental tests, numerical simulations and simplified analytical methods [1]. With respect to concrete columns exposed to fire, Lie [2] carried out tests to study the influences of concentric loads, cross-section, moisture and aggregate type on the structural fire resistance. At the same time, experiments were done at the Technical University of Braunschweig, Ghent University and University of Liège on the fire resistance of columns with different slenderness ratios [5]. Meanwhile, based on other experimental data, a mathematical approach to predict the fire resistance of circular reinforced concrete columns was developed in [3]. This method was further developed in order to include rectangular cross-section columns [4]. Dotreppe et al. [5] developed a computer code to simulate the structural behaviour under fire conditions. Meda et al. [6] made comparisons between the M-N interaction curves for normal-strength concrete and high-performance concrete. Most recently, Kodur [7] proposed a simplified approach to predict the fire resistance of reinforced concrete columns under biaxial bending. Van Coile et al. [8] developed a cross-sectional calculation model in order to calculate the bending moment capacity for a concrete beam exposed to fire in the framework of reliability calculations. This model was further used as a basis for the lifetime cost optimization of the structural fire resistance of concrete slabs [9]. In the current contribution, the calculated tool developed by Van Coile et al. is applied and expanded to allow for the calculation of interaction diagrams for concrete columns subjected to fire.

Structural fire analysis consists of an integrated approach of both transient thermal analysis and structural analysis. Transient thermal analysis, on the one hand, is a procedure to evaluate the temperature distribution by considering fire effects, the material density, the thermal conductivity, the specific heat capacity and the convection coefficient. On the other hand, the structural deformation as well as the stress and strain increase in the case of fire are quantified using a structural analysis. Jeffers [10] [11] introduced a heat transfer element model to account for both transverse and longitudinal temperature variations in a structural member and then implemented this element formulation into a finite element code.

In the last two decades, several simplified methods have been introduced to calculate interaction curves of structural members exposed to fire [14]. Nevertheless, these approaches focus on a cross-sectional calculation without considering second order effects. Even in EN 1992-1-2 [13], no detailed calculation guidelines are provided for quantifying second order effects during fire exposure. However, second order effects cannot be neglected if the slenderness ratio is higher than a certain value λ_{lim} [12]. In order to solve this problem, a numerical cross-sectional calculation method is proposed in this paper to calculate interaction curves for slender columns incorporating second order effects. Furthermore, the proposed calculation model can be widely used and properties of columns, boundary conditions as well as fire scenarios can easily be altered in a flexible way. During heating, moisture movements occur, but these are commonly not considered in structural analysis methods, and hence also not in this paper.

2. CALCULATION MODEL

A numerical calculation tool is proposed to calculate the combined effect of an axial force (N) and bending moment (M) on columns, taking into account material strength reduction and thermal strains in case of fire. This calculation model takes the material model of EN 1992-1-2 [13] as a basis for both the thermal analysis and structural analysis.

2.1 Material model

The material models are the same as provided in EN 1992-1-2 [13]. It should be noted that the tensile strength of concrete is not considered. In table 1, the basic assumptions of the implemented properties of concrete and steel for interaction curves calculation are compared with those used by Meda in [6].

Table. 1

2.2 Transient thermal model

The heat transfer and temperature calculation is based on Fourier's law for conduction, Newton's law for convection and Stefan-Boltzmann's law for radiation. Consequently, the heat flow between nodes of a cross-section can be calculated by defining a matrix. the formulas for the transient heat calculation differ for two cases: elements which are directly exposed to the surroundings and elements located in the interior of the column. The heat flow of the external surface area directly exposed to the fire is determined by [13]:

$$\Delta H = \phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot [(\Theta_r + 273)^4 - (\Theta_m + 273)^4] \quad [\mathrm{W/m^2}] \qquad (1)$$

where

ϕ is the configuration factor

ε_m is the surface emissivity of the member, ε_m = 0.8

ε_f is the emissivity of the fire, general as 1.0

σ is the Stephan Boltzmann constant (= 5.67×10^{-8} W/m^2K^4)

Θ_r is the effective radiation temperature of the fire environment [°C]

Θ_m is the surface temperature of the member [°C]

The heat flow between internal surfaces is calculated as:

$$\Delta H = \sum_{flow\ in} \lambda \cdot \frac{\Theta_{higher} - \Theta_{lower}}{s} - \sum_{flow\ out} \lambda' \cdot \frac{\Theta_{higher'} - \Theta_{lower'}}{s} \quad [\mathrm{W/m^2}] \qquad (2)$$

where

λ, λ' are thermal conductivities

$\Theta_{higher}, \Theta_{lower}, \Theta'_{higher}, \Theta_{lower}{}'$ are the temperatures of the member nodes [°C]

s is the distance for the heat transfer [m]

As the first step for the node temperature calculation, the cross-section under consideration is discretized into small rectangles. A 1 mm×1 mm square is set as a basic calculation element. Considering different boundary conditions (fire duration, exposed surface, heat transfer direction, etc.), a program implemented in [15] has been developed to calculate the temperature distribution for different fire exposed surfaces.

Fig. 1

The temperature distribution of the cross-section is first calculated with the proposed methodology and validated with the finite element program [16] and Eurocode 2 provision (Fig .2). For the temperature simulation, the lower limit of the thermal conductivity, the concrete moisture 1.5 % and the concrete density 2300 kg/m^3 are considered.

Fig. 2

From Fig. 2, it's clear that the temperature distribution prediction from the newly developed routine [15] has a good agreement with that from Eurocode [13] and finite element software analysis [16]. As a result, node temperatures from this methodology are implemented into the cross-sectional model (also implemented in a routine [15]) to calculate interaction curves of columns exposed to fire. The thermal strain of concrete for different types of aggregates can be considered. Taking siliceous aggregates for instance, a formula of the thermal strain presented in EN 1992-1-2 [13] is adopted in the current calculation:

$$\varepsilon_{c(\theta)} = \min\{-1.8 \times 10^{-4} + 9 \times 10^{-6}\theta + 2.3 \times 10^{-11}\theta^3, 14 \times 10^{-3}\} \qquad (3)$$

with θ the node temperature

2.3 Structural model

The same cross-sectional discretization is used for the structural analysis. The mechanical strain is expressed as follows [17]:

$$\varepsilon_{mech(\xi,\eta)} = \varepsilon_{tot} - \varepsilon_{th} = \varepsilon_0 + k_0\eta - \varepsilon_{th} \quad (4)$$

where ε_{tot} is the total strain, ε_{th} is the thermal strain, ε_0 is the strain at the centroid point and k_0 is the curvature around the neutral axis.

In EN 1992-1-2 [13], the transient strain is implicitly considered in the mechanical strain term. The stress-strain curves of concrete and reinforcement bars given in Eurocode [13] are adopted in this paper.

In Fig. 3, the relationship between the total strain, the thermal strain and the mechanical strain is illustrated.

Fig. 3

For the cross-sectional structural resistance, the basic calculation model is described in Fig. 4. The compression strains are considered to be positive.

Fig. 4

For slender columns, second order effects still need to be reasonably considered. In order to solve this problem, the cross-sectional calculation tool is further developed to take into account second order effects and different slenderness ratios.

The deflection is calculated as:

$$d = \int m.\frac{M}{EI}dx = \int m.\chi dx \quad (5)$$

With M the bending moment at the local cross-section

EI the stiffness of the cross-section

χ the curvature of the local cross-section

Due to the eccentric loads effects, additional bending moments occur along the column. As a result, M and consequently χ are not constants along the column as is the case when considering only first order effects. M- χ curves are obtained based on the cross-sectional calculation.

As the first step of calculations, the curvature χ in case of the first order bending moment can be obtained based on the cross-sectional calculation. According to equation (5), deflections at any position of the column are calculated. Then, additional bending moments caused by deflections under eccentric loads are obtained. Next, a new χ corresponding to the new bending moment can be found from cross-sectional calculation. This procedure is repeated until the bending moment converges and further iterations do not alter the bending moment significantly. Take the simply supported column for instance, the cases of columns for slenderness ratios 35, 70, 105, 140 are calculated, most of which can be finished within 7 iterations.

3. VALIDATION OF INTERACTION CURVES

3.1 Validation of interaction curves based on cross-sectional calculations

In order to verify the calculation method, the results obtained for the specific case of a square column with cross-section 600 mm× 600 mm; 24 bars with diameter 20 mm and concrete cover 50 mm; 20°C concrete compressive strength f_{ck} = 40 MPa, reinforcement yield strength f_y = 430 MPa and Young's modulus of steel $E_s = 2\times10^5$ N/mm^2 are compared to the results from Meda [6], where the same dimension of columns, the reinforcement, the strength and Young's modulus of concrete and the reinforcement at ambient temperature were used for the analysis. There are two differences between the calculation model from Meda [6] and the current calculation: first, the compressive strength of concrete at elevated temperatures in [6] is based on tests from Meda, while the current method is based on Eurocode 2 [13]. Secondly, stress-strain laws of concrete in compression at elevated temperatures are different (Table 1) in order to compare to Eurocode 2 prescriptions.

The results of the interaction curves in the case of fire exposure at all sides are visualized in Fig. 5 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 design values of normal forces and bending moments respectively for concrete and steel reinforcement, b is the width of the column and h is the height of the cross-section.

Fig. 5

Fig. 5 indicates that interactive curves at 0 min and 30 min obtained in [6] are less conservative than results from the proposed analytical method. This is because different material models are chosen. For stress-strain laws of concrete in compression, elastic and perfectly-plastic stress-strain curves are adopted in [6], whereas decreasing branches are considered in the proposed method. As a result, the corresponding maximum permitted bending moments are a little smaller than those in [6]. The differences are apparent when the temperatures of the column are low.

Subsequently, the cases of columns with 1 to 4 exposed surfaces are compared to the data from Caldas [14] who used the same input parameters as Meda [6]. The cases of columns with different exposed surfaces subjected to the ISO standard fire at 90 minutes and 300 minutes have been illustrated in [18]. The results prove to be very close to results found in [6] and [14].

3.2 Validations of interaction curves based on theoretical and experimental data considering second order effects

In EN 1992-1-1 [19], it figures out that second order effects may be ignored if the slenderness λ is below a certain value λ_{lim}.

$$\lambda = \frac{l_{eff}}{\sqrt{I/A}} \tag{6}$$

$$\lambda_{lim} = 20 \cdot A \cdot B \cdot C \tag{7}$$

where

l_{eff} is the effective length

I is the area moment of inertia

A is the cross-sectional area

$A = 1 / (1 + 0.2\varphi_{ef})$

$B = \sqrt{(1 + 2\omega) / n}$

$C = 1.7 - r_m$

φ_{ef} effective creep ratio; if φ_{ef} is not known, A = 0.7

$\omega = Asfyd / (Acfcd)$ mechanical reinforcement ratio; if ω is not known, B = 1.2

A_s total area of longitudinal reinforcement

$n = N_{Ed} / (A_c f_{cd})$ relative normal force

$r_m = M_{01} / M_{02}$; moment ratio

M_{01}, M_{02} first order end moments, $|M02| \geq |M01|$

In the current study, interaction curves are respectively compared with Eurocode 2 [13] and experimental data [2]. First, based on the interaction curve for λ = 0 at normal temperature and deflection calculation formula shown in (5), interaction curves for different slenderness ratios are obtained and compared to background documents associated to Eurocode 2 [13] (Fig. 6).where e_0 is an initial eccentricity and e_2 is an additional deflection caused by eccentric loads.

Fig. 6

Subsequently, this method is adopted to study the second order effects of columns exposed to fire. A basic column with two clamped end sections was chosen in accordance with an experiment carried out by Lie [2] in order to validate the performance of the developed cross-section calculation tool. The same experimental fire temperatures as well as geometric and material properties are taken into account. Considering the clamped end conditions, a factor K = 0.6 was used to calculate the effective length of columns as Lie [2] proposed. A comparison of the results is given in Table 2.

Table 2

Further, two more comparisons have been performed with respect to tests from Braunschweig University of Technology [20] (Table 3) and University of Liège [21] (Table 4), respectively. Table 3

Table 4

From Table 2, Table 3 and Table 4, it's observed that experimental results are closely corresponding to the predictions of the calculation method presented here.

3.3 Comparison of calculated ISO834 standard fire resistance time of rectangular concrete columns with EN 1992-1-2 tabulated guidelines for different slenderness ratios and eccentricities

With respect to fire resistance of columns in braced structures, EN 1992-1-2 [13] provides tables with the minimum required cross-section for different slenderness ratios and ISO 834 standard fire durations. In order to compare with EN 1992-1-2 [13], the same input data has been used for the analytical method described above. In EN 1992-1-2 [13], the moisture content of concrete for all the tabulated tables is 1.5% and this value is further adopted for all the fire calculations in this paper. It is worth mentioning that explosive spalling is unlikely to occur when the moisture content of concrete is less than 3% [13] [22], so explosive spalling is not taken into account for all the cases in this paper. The effect of imperfections is considered as an eccentricity $e_i = l_0/400$ presented in EN 1992-1-1 [19], where l_0 is the effective length of the column. Other parameters, like the reinforcement ratio ($\omega = \frac{A_s f_{yd}}{A_c f_{cd}}$) and load eccentricity (e) are varied over the different tables, i.e. ω = 0.1, 0.5, 1.0; e = 0.025b, 0.25b, 0.5b. The cases with the ISO 834 standard fire at 30 min, 60 min, 90 min and 120 min are illustrated in Tables 5-13, with $n = N_{0Ed,fi} / (0.7(A_c f_{cd} + A_s f_{yd}))$ as proposed in EN 1992-1-2 [13], where A_c is the cross sectional area of concrete, A_s is the cross sectional area of reinforcement bars, f_{cd} is the design value of concrete compressive strength, f_{yd} is the design yield stress of reinforcement, $N_{0Ed,fi}$ is the design value of the applied axial force.

Table 5~ Table 13

From the tables above and comparing these with the tabulated data provided in Eurocode 2 [13], it is seen that the tables from Eurocode 2 [13] are not safe for the case of a reinforcement ratio of 0.1, as well for a reinforcement ratio of 0.5 when the axial load is large. On the other hand, some minimum dimensions are overly conservative in case the reinforcement ratio is 1.0. Further, the present study is very helpful to provide guidelines for a minimum cross-section design for columns subjected to fire.

4. Extension of the tabulated data for concrete columns exposed to hydrocarbon fire and natural fires

Eurocode [13] only provides minimum dimensions with respect to the ISO 834 standard fire, but this standard fire does not provide a true indication of how structural members and assemblies will behave in an actual fire or when exposed to a hydrocarbon fire. As resistance to hydrocarbon fires may be required in specific situations and little data is available on the design of concrete columns exposed to hydrocarbon fires, extending the tables of the Eurocode with respect to this more severe design fire is important. Hence, the same analytical method is used to determine the required cross-section characteristics for columns exposed to these other fire curves. Hydrocarbon fires represent the burning of for example gasoline pool fires and are widely used when designing technical facilities and tunnels. Natural fires, known as compartment fires, account for the fire load present in the compartment and decrease in intensity once the fuel has been burned. Both of these two types of fires are typical fires, so they are adopted for fire resistance of columns.

The hydrocarbon temperature-time curve is given by [13]:

$$Q_g = 1080\,(\,1 - 0.325\,e^{-0{,}167\,t} - 0.675\,e^{-2{,}5\,t}\,) + 20 \qquad [°C] \qquad (4)$$

where Q_g is the gas temperature in the fire compartment [°C]

t is the time [min]

4.1 Fire resistance of columns subjected to hydrocarbon fire

The same material properties and boundary conditions as EN 1992-1-2 [13] are considered in case of this hydrocarbon fire. The minimum required cross-sections of columns at 30 min, 60 min, 90 min and 120 min are shown in the same tables as in case of the ISO 834 standard fire (Table 5~ Table 13).

Table 5~ Table 13

4.2 Fire resistance of columns subjected to natural fires

Besides considering standard ISO 834 fires or hydrocarbon fires, this calculation analysis can also be used when columns are subjected to natural fires. Interaction curves of columns are obtained here in case of dwellings and offices. The fire load densities are listed in Table 14 [23].

Table 14

In EN 1992-1-2 [12], the mean value of the fire load density is provided for the typical occupancy and the characteristic value is proposed to be the 80-percentile of a Gumbel distribution. In this case, the same fire compartment as [24] is adopted for both the case of the dwelling and the office with the an A_f = 16m^2, height H = 3m, area of openings A_w = 8m^2 and average height of openings h_w = 2.50 m.

It is worthwhile to note that these natural fires start to decrease after about 50 min in the dwelling and 30 min in the office.

Next, a square column subjected to these fire conditions is analyzed: the cross-section is 300 mm × 300 mm, with one diameter 32 mm reinforcement bar in each corner and concrete cover 25 mm; concrete compressive strength f_{ck} = 55 MPa, reinforcement yield strength f_y = 500 MPa and Young's modulus of steel $E_s = 2\times10^5$ N/mm^2. The reinforcement temperature as a function of the fire exposure time is shown in Fig. 7 & 8, for the two fire simulations respectively.

Fig. 7

Fig. 8

It can be observed that the reinforcement temperature begins to decrease at 75 min in the dwelling and 60 min in the office. Considering plastic damages and strength losses of concrete material, the stress-strain relationship for cooling down is not the same as for increasing fire temperature. However, no specific guidelines are given in Eurocode to calculate the cooling down branch. In order to solve this problem, an analytical method is proposed. This analytical approach, on the one hand, supposes that there is no strength recovery of concrete material and adopts the same stress-strain model to calculate the upper limit curve during cooling down period (considering perfect recovery). On the other hand, it considers the stress-strain model associated with the maximum local concrete temperature obtained during the fire is maintained. By this way, a lower limit curve can be obtained (considering no recovery). As a result, the bending moment capacity of columns should be located between these two curves. The current analytical tool, however, has not been explored for the full cooling phase yet. The maximum local concrete temperature is a simplified and conservative way to predict the tendency of fire resistance when the fire temperature begins to decrease. Take the dwelling for instance, upper and lower limit curves (Fig. 9 and 10) in the case of different normal forces are calculated, where $n = N_{0Ed,fi} / (0.7(A_c f_{cd} + A_s f_{yd}))$ as proposed in EN 1992-1-2 [13]..

Fig. 9

Fig. 10

Fig. 9 indicates that the maximum permitted bending moment does not decrease much when the normal force is low (n is less than 0.3). It is because second order effects are insignificant under loads with small eccentricities. As soon as n reaches 0.3, the maximum permitted bending moment decreases significantly when the eccentric load is increasing. It is worth mentioning that the lower limit curve increases again when the reinforcement bars are cooling down. It is possible to obtain the minimal curves (the most critical case during the fire). Comparing curves in Fig. 10, it is observed that the lower limit curve does not decrease much further below the most critical point of the upper limit curve. The same analysis has been performed for the office in case of a natural fire and the maximum permitted bending moments in function of fire duration are shown in Table 15.

Table 15

Take the case of n = 0.3 for instance, the possible maximum permitted bending moment curve during cooling down is indicated as the shaded area in Fig. 11.

Fig. 11

Finally, the lower limit curve can be adopted to calculate interaction curves of columns for different slenderness ratios. As an example, interaction curves based on the lower limit curve at the most critical time for the dwelling and the office are provided in Fig. 12 & Fig. 13, with $n = \frac{N_c+N_s}{0{,}7(A_c f_{cd} + A_s f_{yd})}$ and $m = \frac{M_c+M_s}{0{,}7(A_c f_{cd} + A_s f_{yd})*h}$,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.

5. CONCLUSION

An analytical method is developed, which proves to be an easy-to-use way to predict interaction curves of columns exposed to fire. The minimum dimensions of columns in case of ISO 834 standard fire are recalculated and some comparisons with experimental results are provided in order to validate the obtained calculation tool. It is found that Eurocode provisions on the one hand are not safe for the case of the reinforcement ratio is 0.1 as well as the reinforcement ratio is 0.5 when the axial load is large. On the other hand, tabulated data is found to be too conservative for high reinforcement ratios ω = 1.0, which results in inefficient and uneconomical solutions for the practice. Considering an economical aspect as well as the safety issue, the tabulated tables obtained in the current work provide more precise references for the design of concrete columns exposed to fire. Furthermore, the application area is extended to other fire scenarios. The minimum column dimensions are presented for hydrocarbon fires. Comparing the results for the hydrocarbon fire with the tables obtained for the ISO 834 standard fire, it is noted that fire resistance to the hydrocarbon fire may result in very stringent requirements. Moreover, some specific examples are given in case of columns subjected to natural fires. Both the upper limit and lower limit curves are introduced to investigate the fire resistance of columns when the fire temperature begins to decrease. The results prove that second order effects are insignificant when normal force is low. When the eccentric loads are large enough, the maximum permitted bending moment of the column firstly decreases continuously during the fire, and then have a slight increase at a certain point during the cooling phase. As a result, this value based on the lower limit curve could be recognized as the design value during this specific fire. In conclusion, this analytical method and calculation tool is significant and can be possible in effectively quantifying interaction curves of columns exposed to any types of fires considering second order effects.

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LIST OF FIGURES

Table 1. Material model comparison

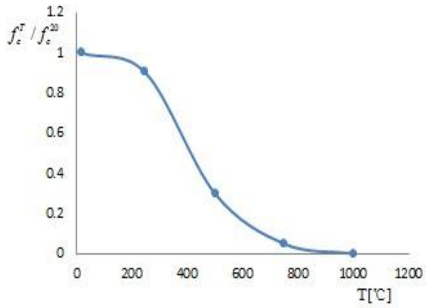
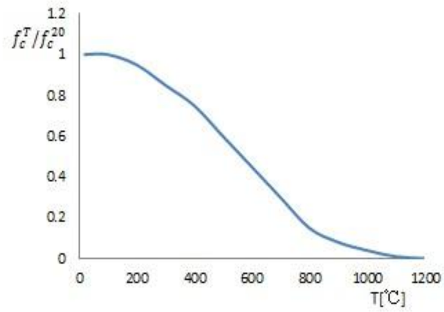
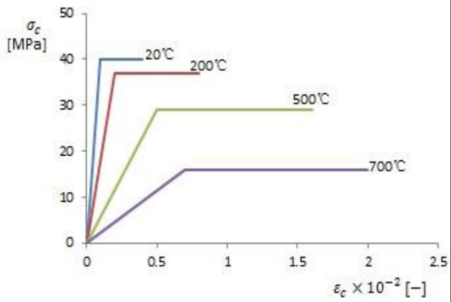
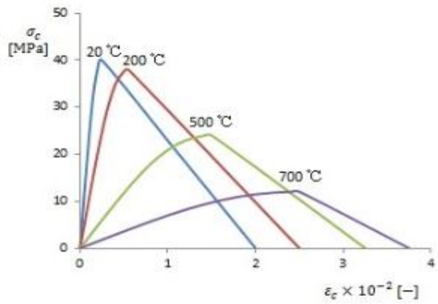
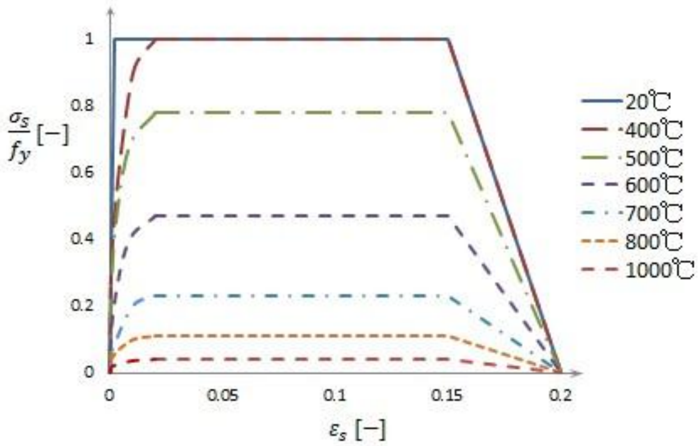
	Meda's model [6]	Material model（as implemented in the current contribution）
Concrete compressive strength at elevated temperatures		
Stress-strain laws of concrete in compression at elevated temperatures		
Stress-strain relationships of reinforcing steel in tension at elevated temperatures		

Table 2. Comparison of fire resistance of columns subjected to second order effects with experimental test observation [2]

Test case	A		B	
Fire duration (hr : min)	2:50		2:26	
Current calculation model	eccentricity (mm)	Load (kN)	eccentricity (mm)	Load (kN)
	0	1603	0	1887
	1.1	1335	1.8	1790
	1.9	1237	2.3	1778
	2.7	1172	3.1	1758
Experimental results [2]	0 ~ 2.5 mm (assumed)	1333	0 ~ 2.5 mm (assumed)	1778

Table 3. Comparison of fire resistance of columns subjected to second order effects with experimental test from Braunschweig University of Technology [20]

NO.	Cross-section （mm × mm）	Cover thickness (mm)	Reinforcement bar (mm)	f_c (N/mm^2)	f_y (N/mm^2)	Height (m)	Eccentricity (mm)	Fire duration (min)	N_0 (kN)		Cal / Exp
									Experiment	Calculation	
1	200 ×200	20	4Φ20	29.0	487	3.76	0	58	420	371	0.88
2	200 ×200	20	4Φ20	29.0	487	4.76	0	48	340	325	0.96
3	200 ×200	20	4Φ20	37.0	487	4.76	10	49	280	281	1.00
4	200 ×200	20	4Φ20	37.0	462	4.76	20	36	240	311	1.30
5	200 ×200	20	4Φ20	37.0	462	4.76	60	49	170	178	1.05
6	200 ×200	20	4Φ20	37.0	418	4.76	100	53	130	126	0.97
7	200 ×200	20	4Φ20	39.0	443	5.76	10	40	208	250	1.20

Table 4. Comparison of fire resistance of columns subjected to second order effects with experimental test from University of Liège [21]

NO.	Cross-section (mm × mm)	Cover thickness (mm)	Reinforcement bar (mm)	f_c (N/mm^2)	f_y (N/mm^2)	Height (m)	Eccentricity (mm)	Fire duration (min)	N_0 (kN)		Cal / Exp
									Experiment	Calculation	
1	300 ×300	25	4Φ16	31.6	576	3.9	20	0	2000	2161	1.08
2	300 ×300	25	4Φ16	32.3	576	3.9	0	61	950	1221	1.29
3	300 ×300	25	4Φ16	32.8	576	3.9	0	120	622	561	0.90
4	300 ×300	25	4Φ16	32.7	576	3.9	20	125	220	221	1.00
5	300 ×300	40	4Φ16	31.8	576	3.9	20	123	349	372	1.07
6	300 ×300	25	4Φ25	27.9	591	3.9	20	120	475	364	0.77

Table.5 Minimum dimensions and concrete covers for reinforced concrete columns with rectangular section (ISO 834). Mechanical reinforcement ratio ω = 0.1. Low first order moment: e = 0.025b with e ≥ 10 mm

Fire resistance	λ	Minimum dimensions (mm) / Column width b_{min} [mm]/axis distance a [mm]											
		Columns exposed on more than one side											
		n=0.15			n=0.3			n=0.5			n=0.7		
		standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire
		Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation
R30	30	150/25		150/25	150/25		150/25	150/25		200/25	150/25		200/25
	40	150/25		150/25	150/25		150/25	150/25		200/25	150/30:200/25	150/25	250/25
	50	150/25		150/25	150/25		200/25	150/30:200/25	150/25	250/25	200/25		300/35:350/25
	60	150/25		150/25	150/25		250/35:300/25	200/35:250/25	200/25	300/50:350/25	300/30:350/25	250/25	350/50:400/25
	70	150/25		200/25	200/25	150/25	300/35:350/25	300/50:350/25	250/25	350/50:550/25	350/50:450/25	300/25	500/50:550/25
	80	150/25		200/25	250/25	200/25	350/50:600/35	350/50:500/25	250/30:300/25	500/50:600/45	450/50:600/25	350/25	550/60:600/45
R60	30	150/25		200/25	150/25		200/25	200/25		200/40:250/25	200/25	200/30:250/25	250/50:300/25
	40	150/25		200/25	150/30:200/25	150/25	200/40:250/25	200/30:250/25	200/25	250/50:300/25	250/40:300/25	250/25	350/25
	50	150/25		200/40:250/25	200/30:250/25	200/25	250/50:350/25	250/50:300/25	250/25	350/50:400/25	350/35:400/25	300/25	450/25
	60	150/30:200/25	150/25	200/40:300/25	250/40:350/25	200/40:250/25	350/50:500/25	350/50:400/25	250/40:300/25	500/50:550/25	500/40:550/25	350/30:400/25	550/60:600/25
	70	200/25		250/50:350/25	350/50:400/25	250/30:300/25	500/50:600/45	500/60:600/25	300/40:350/25	600/60	550/40:600/60	450/35:550/25	600/80
	80	200/25	200/30:250/25	350/50:550/25	500/60:600/45	250/40:300/25	550/60	550/60:600/60	400/30:450/25	①	①	550/60:600/35	①
R90	30	150/25		200/25	200/25		250/25	250/25	200/50:250/25	250/50:300/25	250/40:300/25	250/30:300/25	350/25
	40	200/25	150/35:200/25	250/25	200/35:250/25	200/30:250/25	250/50:300/25	250/50:300/25	250/25	350/25	300/50:350/25	300/25	400/25
	50	200/35:250/25	200/25	250/50:350/25	250/40:350/25	250/25	300/50:400/25	300/50:450/25	300/25	450/25	450/50:500/25	350/50:400/25	550/25
	60	200/35:300/25	200/35:250/25	250/50:500/25	350/50:550/25	250/40:300/25	500/50:600/25	500/60:550/25	350/35:400/25	600/80	600/60	450/50:550/25	①
	70	250/50:400/25	250/25	350/50:550/25	500/60:600/45	300/35:350/25	600/80	550/60:600/80	400/45:550/25	①	①	600/40	①
	80	350/50:500/25	250/30:300/25	550/60	550/60:600/60	350/35:400/25	600/80	①	550/40:600/25	①	①		①
R120	30	200/25		250/25	250/25		250/25	250/50:300/25	250/25	300/25	300/50:350/25	300/45:350/25	400/35:450/25
	40	250/25		300/25	250/40:300/25	250/25	300/50:350/25	350/25	300/25	350/25	400/50:450/25	400/25	500/35:550/25
	50	250/40:350/25	250/25	300/50:350/25	350/50:400/25	300/25	400/50:500/25	500/25	350/50:400/25	550/40:600/25	550/40:600/25	450/50:500/25	600/25
	60	250/50:400/25	250/25	350/50:600/25	500/60:600/25	350/25	550/60	600/25	450/40:500/25	①	600/80	550/50	①
	70	350/50:500/25	250/50:300/25	500/50:600/35	600/60	400/25	600/80	600/80	500/60:550/25	①	①		①
	80	500/25	300/25	600/80	600/80	450/40:500/25	①	①	600/45	①	①		①

*① Requires a width larger than 600 mm.

Table.6 Minimum dimensions and concrete covers for reinforced concrete columns with rectangular section (ISO 834). Mechanical reinforcement ratio ω = 0.1. Moderate first order moment: e = 0.25b with e ≤ 100 mm

Fire resistance	λ	Minimum dimensions (mm) / Column width b_{min} [mm]/axis distance a [mm]											
		Columns exposed on more than one side											
		n=0.15			n=0.3			n=0.5			n=0.7		
		standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire
		Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation
R30	30	150/25		150/25	150/25		200/25	200/25	200/30:250/25	300/35:400/25	400/25	300/30:350/25	500/25
	40	150/25		200/25	200/25	150/30:200/25	300/25	350/35:400/25	300/25	400/50:500/25	500/25	500/40:550/25	550/40:600/45
	50	150/25		200/40:250/25	300/25	200/40:250/25	400/35:500/25	450/50:500/25	350/40:500/25	550/40:600/45	550/60:600/25	550/25	①
	60	150/25		250/35:350/25	400/50:450/25	300/25	500/50:600/35	550/40:600/25	550/25	①	①	600/30	①
	70	200/25		300/50:500/25	500/40:600/25	350/40:500/25	550/60:600/45	①	550/30:600/25	①	①		①
	80	300/30:400/25	250/25	500/35:600/35	600/45	550/25	①	①		①	①		①
R60	30	150/25	150/30:200/25	200/40:300/25	250/25	200/40:300/25	300/35:400/25	350/50:400/25	300/40:500/25	400/50:550/25	500/25		550/60:600/80
	40	200/25	200/30:250/25	250/50:350/25	300/50:400/25	300/35:350/25	400/50:600/35	500/25	450/50:550/25	550/60:600/80	550/60:600/25	550/40:600/25	①
	50	200/35:300/25	200/40:300/25	300/50:600/35	450/50:500/25	350/45:550/25	550/60:600/45	550/60:600/25	550/30:600/30	①	①	600/55	①
	60	300/50:500/25	250/35:400/25	400/50:600/35	550/60:600/25	450/50:550/25	600/80	①	600/35	①	①		①
	70	400/50:500/25	300/40:500/25	550/60:600/45	600/80	550/30:600/25	①	①	600/80	①	①		①
	80	500/40:600/45	400/40:550/25	550/60:600/80	①	600/30	①	①		①	①		①
R90	30	200/35:300/25	200/40:250/25	250/50:400/25	300/50:400/25	300/40:400/25	350/50:550/25	450/50:500/25	500/50:550/25	500/50:600/45	550/60:600/45	550/40:600/25	①
	40	250/40:400/25	250/40:350/25	300/50:600/35	400/50:600/25	350/50:550/25	500/50:600/45	550/60:600/45	550/35:600/25	①	①	600/50	①
	50	350/50:500/25	300/40:500/25	400/50:600/45	550/60:600/45	500/60:550/25	600/80	①	600/40	①	①		①
	60	400/50:600/45	300/50:550/25	550/60:600/80	600/80	550/45:600/25	①	①		①	①		①
	70	550/60:600/45	400/50:550/25	600/80	①	600/45	①	①		①	①		①
	80	550/60:600/60	500/60:600/25	①	①		①	①		①	①		①
R120	30	250/50:450/25	250/50:350/25	300/50:350/25	400/50:500/25	400/50:550/25	500/50:600/35	500/60:600/25	550/25	550/60:600/80	600/60	550/60:600/45	①
	40	300/50:500/25		400/50:600/45	500/60:600/25	500/50:550/25	550/60:600/80	600/80	550/55:600/25	①	①		①
	50	450/50:550/25	400/50:550/25	550/60:600/80	600/60	550/50:600/25	①	①	600/60	①	①		①
	60	500/60:600/45	500/50:550/25	600/80	600/80	550/55:600/50	①	①		①	①		①
	70	550/60:600/80	500/60:600/25	①	①	600/60	①	①		①	①		①
	80	600/80	550/50:600/25	①	①		①	①		①	①		①

*① Requires a width larger than 600 mm.

Table.7 Minimum dimensions and concrete covers for reinforced concrete columns with rectangular section (ISO 834). Mechanical reinforcement ratio ω = 0.1. High first order moment: e = 0.5b with e ≤ 200 mm

Fire resistance	λ	Minimum dimensions (mm) / Column width b_{min} [mm]/axis distance a [mm]											
		Columns exposed on more than one side											
		n=0.15			n=0.3			n=0.5			n=0.7		
		standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire
		Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation
R30	30	150/25		250/35:300/25	450/25	400/40:550/25	500/25	550/40:600/25	550/25	①	①		①
	40	200/25		300/35:400/25	500/40:550/25	550/25	550/60	①	550/35:600/30	①	①		①
	50	300/30:400/25	250/30:300/25	400/35:500/25	600/25	550/30:600/25	①	①		①	①		①
	60	400/50:450/25	300/40:550/25	500/50:600/35	①	600/50	①	①		①	①		①
	70	500/40:550/25	400/40:550/25	550/60:600/45	①		①	①		①	①		①
	80	550/40:600/25	550/25	①	①		①	①		①	①		①
R60	30	300/30:400/25	300/35:500/25	350/50:550/25	550/25	500/50:550/25	550/40	①	550/50:600/40	①	①		①
	40	400/50:550/25	350/40:550/25	500/35:600/35	600/25	550/40:600/30	①	①		①	①		①
	50	550/25	450/50:550/25	550/60:600/45	①	550/50:600/40	①	①		①	①		①
	60	550/40:600/25	550/30	①	①	600/80	①	①		①	①		①
	70	600/60	550/35	①	①		①	①		①	①		①
	80	①	550/40	①	①		①	①		①	①		①
R90	30	350/50:550/25		400/50:600/45	550/60:600/45	550/45:600/40	①	①	600/80	①	①		①
	40	450/50:600/45	500/60:600/30	550/60:600/80	①	550/60:600/50	①	①		①	①		①
	50	550/60:600/45	550/40	600/80	①	600/80	①	①		①	①		①
	60	550/60:600/60	550/50:600/45	①	①		①	①		①	①		①
	70	①	550/60:600/50	①	①		①	①		①	①		①
	80	①	600/70	①	①		①	①		①	①		①
R120	30	450/50:600/25	550/40:600/30	500/50:600/80	600/60	550/50	①	①		①	①		①
	40	500/60:600/45	550/50:600/45	550/60:600/80	①	600/70	①	①		①	①		①
	50	550/60:600/60	550/55:600/50	①	①		①	①		①	①		①
	60	600/80	550/60:600/50	①	①		①	①		①	①		①
	70	①	600/70	①	①		①	①		①	①		①
	80	①		①	①		①	①		①	①		①

*① Requires a width larger than 600 mm.

Table.8 Minimum dimensions and concrete covers for reinforced concrete columns with rectangular section (ISO 834). Mechanical reinforcement ratio ω = 0.5. Low first order moment: e = 0.025b with e ≥ 10 mm

Fire resistance	λ	Minimum dimensions (mm) / Column width b_{min} [mm]/axis distance a [mm]											
		Columns exposed on more than one side											
		n=0.15			n=0.3			n=0.5			n=0.7		
		standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire
		Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation
R30	30	150/25		150/25	150/25		150/25	150/25		150/25	150/25		200/25
	40	150/25		150/25	150/25		150/25	150/25		200/25	150/25		200/25
	50	150/25		150/25	150/25		150/25	150/25		200/25	200/25		250/25
	60	150/25		150/25	150/25		150/25	150/25		250/25	200/30:250/25		300/35:400/25
	70	150/25		150/25	150/25		200/25	200/25	150/25	300/35:350/25	300/25	250/25	350/50:450/25
	80	150/25		150/25	150/25		200/35:250/25	250/30:300/25	200/30:250/25	300/50:450/25	350/35:400/25	300/25	400/50:600/40
R60	30	150/25		150/25	150/25		150/40:200/25	150/25	150/30:200/25	200/35:250/25	200/25	200/35:250/25	250/35:300/25
	40	150/25		200/25	150/25		200/35:250/25	200/25		250/35:300/25	250/25	250/30:300/25	300/35:400/25
	50	150/25		200/25	150/35:200/25		200/35:250/25	200/30:250/25	200/40:250/25	250/50:350/25	300/30:350/25	250/40:350/25	350/50:450/25
	60	150/25		200/35:250/25	200/25	200/30:250/25	250/35:300/25	250/40:350/25	250/30:300/25	350/50:450/25	350/40:450/25	300/40:450/25	450/50:600/40
	70	150/25		200/35:250/25	200/25	200/35:250/25	250/50:350/25	350/40:450/25	250/40:350/25	400/50:600/40	400/50:600/45	350/45:600/25	600/60
	80	150/25	150/35:200/25	200/35:250/25	250/25	250/30:300/25	300/35:400/25	350/40:550/35	300/40:500/25	450/50:600/60	400/50:600/45	450/50:600/35	600/60
R90	30	150/25		200/25	200/25	150/40:200/25	200/35:300/25	200/30:250/25	200/40:250/25	250/50:300/25	250/35:300/25	250/40:300/25	300/50:400/25
	40	150/25		200/35:250/25	200/25	200/35:250/25	250/35:300/25	250/30:300/25		300/35:400/25	300/40:400/25		350/50:500/25
	50	150/40:200/25		200/35:300/25	200/30:250/25	200/45:250/25	250/50:400/25	300/40:400/25	250/45:350/25	350/50:500/25	350/40:550/25	350/45:550/25	600/40
	60	200/25		250/35:300/25	250/30:300/25	250/35:300/25	300/35:450/25	350/40:500/25	300/45:400/25	600/40	550/50:600/45	400/50:550/25	600/60
	70	200/25	200/35:250/25	250/35:350/25	300/30:400/25	250/45:350/25	300/50:550/25	350/40:600/45	350/45:600/25	600/60	600/60	550/50:600/45	600/80
	80	200/30:250/25	200/45:250/25	250/50:400/25	300/35:400/25	250/50:400/25	350/50:600/40	600/60	400/50:600/35	600/80	①	600/60	①
R120	30	200/25	150/35:200/25	200/35:250/25	200/25	200/40:250/25	250/35:300/25	250/35:300/25	250/45:300/25	300/50:350/25	300/40:400/25	350/45:500/25	350/50:500/25
	40	200/25		250/35:300/25	250/30:300/25	250/25	250/50:350/25	300/40:400/25	300/45:350/25	350/50:450/25	350/40:500/25	400/50:550/25	450/50:550/25
	50	200/30:250/25	200/40:250/25	250/50:350/25	250/40:350/25	250/45:300/25	300/50:450/25	350/40:500/25	350/45:450/25	400/50:600/40	500/50:600/45	450/50:600/25	600/60
	60	200/30:300/25	200/50:250/25	250/50:450/25	300/40:400/25	300/45:350/25	300/50:600/40	500/50:550/50	400/50:550/25	600/60	600/80	500/60:600/35	①
	70	250/30:350/25	250/35:300/25	250/50:450/25	350/40:550/25	350/45:450/25	400/50:600/40	600/60	500/50:600/40	600/80	①	600/45	①
	80	250/40:400/25	250/45:300/25	250/50:600/40	350/40:600/45	400/50:550/25	450/50:600/60	600/80	500/60:600/45	①	①	600/60	①

*① Requires a width larger than 600 mm.

Table.9 Minimum dimensions and concrete covers for reinforced concrete columns with rectangular section (ISO 834). Mechanical reinforcement ratio ω = 0.5. Moderate first order moment: e = 0.25b with e ≤ 100 mm

Fire resistance	λ	Minimum dimensions (mm) / Column width b_{min} [mm]/axis distance a [mm]											
		Columns exposed on more than one side											
		n=0.15			n=0.3			n=0.5			n=0.7		
		standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire
		Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation
R30	30	150/25		150/25	150/25		150/25	150/25		200/25	200/25	200/30:250/25	300/25
	40	150/25		150/25	150/25		150/25	200/25	150/25	250/25	250/25	300/45:350/25	400/35:450/25
	50	150/25		150/25	150/25		200/25	200/25	200/30:250/25	300/25	350/40:450/25		450/35:500/25
	60	150/25		150/25	150/25		200/35:250/25	300/25	250/30:300/25	350/50:450/25	450/35:500/25	500/30:550/25	600/40
	70	150/25		150/25	150/35:200/25		250/35:300/25	350/40:450/25	350/30:400/25	450/35:550/25	550/35:600/25	550/35:600/30	①
	80	150/25		200/25	200/25	200/30:250/25	300/50:400/25	400/35:500/25	400/40:500/25	600/40	①	600/50	①
R60	30	150/25		150/40:200/25	150/25	150/35:200/25	200/35:250/25	250/25	250/35:350/25	300/35:350/25	350/30:400/25	350/40:550/25	450/35:500/25
	40	150/25		200/25	200/25	200/30:300/25	250/35:300/25	300/25	300/35:500/25	350/35:450/25	450/35:500/25	450/50:600/30	600/40
	50	150/25	150/30:200/25	200/35:250/25	200/25	200/40:350/25	250/50:300/25	350/40:500/25	300/45:550/25	550/25	500/50:600/25	500/30:550/25	600/60
	60	150/25	150/35:200/25	200/35:300/25	250/30:300/25	250/40:500/25	300/25	500/35:550/25	400/45:600/30	600/40	600/60	600/45	①
	70	200/25	200/30:300/25	250/35:300/25	300/40:400/25	300/40:500/25	400/50:550/25	550/50:600/45	500/40:600/35	600/60	①	600/80	①
	80	200/25	200/35:300/25	250/35:400/25	350/40:450/25	350/40:600/25	450/50:600/40	600/60	550/55:600/40	①	①		①
R90	30	150/35:200/25		200/35:300/25	200/30:250/25	200/45:300/25	250/50:400/25	300/40:400/25	300/45:550/25	350/50:450/25	450/35:500/25	500/50:600/40	600/40
	40	200/25	200/35:250/25	250/35:300/25	250/30:300/25	250/45:500/25	300/50:450/25	350/40:450/25	350/50:600/25	450/50:600/40	550/50:600/45	550/50:600/45	600/60
	50	200/30:250/25	200/40:300/25	250/50:400/25	300/30:400/25	300/45:550/25	350/50:500/25	500/35:600/25	500/50:600/35	600/40	600/80	600/55	①
	60	200/30:300/25	200/50:400/25	250/50:450/25	350/40:450/25	350/50:600/25	450/50:600/40	600/45	500/55:550/45	600/60	①		①
	70	250/35:350/25	300/35:500/25	300/50:450/25	350/40:550/35	400/50:600/35	600/40	600/80	600/50	①	①		①
	80	250/40:400/25	300/40:600/25	300/50:600/25	500/50:600/45	500/55:600/40	600/60	①	600/80	①	①		①
R120	30	200/30:250/25	200/45:300/25	250/35:300/25	250/40:350/25	300/45:550/25	300/50:450/25	350/40:450/25	450/50:600/25	400/50:600/40	500/50:600/45	500/60:600/50	600/60
	40	200/30:300/25	200/50:350/25	250/50:400/25	300/40:450/25	350/50:550/25	350/50:550/25	350/40:600/45	500/50:600/40	600/40	600/60	600/55	①
	50	250/35:350/25	250/45:450/25	250/50:450/25	350/40:550/25	450/50:600/25	400/50:600/40	550/50:600/45	500/55:550/45	600/60	①	600/80	①
	60	300/40:450/25	300/50:500/25	300/50:600/40	350/40:600/45	500/45:600/40	600/60	600/80	550/60:600/60	①	①		①
	70	300/40:450/25	350/50:550/25	350/50:600/40	550/50:600/45	500/50:550/45	600/60	①	600/75	①	①		①
	80	350/40:600/25	400/50:600/25	400/50:600/40	600/60	500/55:600/40	600/80	①		①	①		①

*① Requires a width larger than 600 mm.

Table.10 Minimum dimensions and concrete covers for reinforced concrete columns with rectangular section (ISO 834). Mechanical reinforcement ratio ω = 0.5. High first order moment: e = 0.5b with e ≤ 200 mm

Fire resistance	λ	Minimum dimensions (mm) / Column width b_{min} [mm]/axis distance a [mm]											
		Columns exposed on more than one side											
		n=0.15			n=0.3			n=0.5			n=0.7		
		standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire
		Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation
R30	30	150/25		150/25	150/25		200/25	250/25	250/35:300/25	400/25	500/25	500/40:550/25	550/25
	40	150/25		150/25	150/30:200/25		250/25	350/40:400/25	300/35:450/25	450/25	550/25	550/30	600/40
	50	150/25		150/25	200/25	200/30:250/25	300/25	450/25	400/40:500/25	550/25	600/45	550/50:600/40	①
	60	150/25		200/25	200/35:250/25		350/35:400/25	500/35:550/25	450/50:550/25	600/40	①		①
	70	150/25		200/25	300/30:350/25	250/40:400/25	450/35:500/25	550/35:600/25	500/40:600/30	①	①		①
	80	150/25		200/35:250/25	400/35:450/25	300/40:500/25	450/35:550/25	①	550/50:600/40	①	①		①
R60	30	150/25	150/30:200/25	200/35:250/25	200/30:250/25	200/40:450/25	300/35:400/25	450/35:500/25	450/50:550/30	450/50:500/25	550/50:600/40		600/60
	40	150/25	150/35:200/25	200/35:300/25	250/30:300/25	250/40:500/25	350/35:400/25	500/25	500/40:550/35	600/40	①	600/60	①
	50	200/25	200/35:300/25	250/35:300/25	350/25	300/45:550/25	400/50:500/25	550/50:600/45	500/55:550/40	600/60	①		①
	60	200/25	200/40:500/25	250/35:350/25	400/35:500/25	400/40:600/30	450/50:600/25	600/80	550/50:600/45	①	①		①
	70	200/30:250/25	200/40:550/25	300/35:400/25	500/35:550/25	500/40:550/35	600/40	①	600/60	①	①		①
	80	250/30:300/25	250/40:600/25	350/35:500/25	500/50:600/45	500/45:600/35	600/60	①		①	①		①
R90	30	200/30:250/25	200/40:450/25	250/35:400/25	300/30:400/25	300/50:500/25	350/50:450/25	500/35:550/25	500/55:600/40	600/40	①	600/80	①
	40	200/30:300/25	200/50:500/25	250/50:400/25	350/35:450/25	350/50:550/35	400/50:550/25	550/50:600/45	550/60:600/50	600/60	①		①
	50	300/25	250/45:550/25	250/50:450/25	450/35:500/25	500/45:550/40	600/40	600/80	600/60	①	①		①
	60	250/35:400/25	250/50:550/30	300/50:500/25	500/50:550/35	500/50:550/45	600/60	①	600/80	①	①		①
	70	300/40:450/25	300/50:550/35	350/50:600/40	550/50:600/45		600/80	①		①	①		①
	80	400/35:450/25	350/50:600/35	400/50:600/40	600/80	550/60:600/50	①	①		①	①		①
R120	30	250/35:350/25	250/50:550/25	250/50:450/25	350/40:450/25	500/50:550/40	400/50:600/40	550/50:600/45	550/50	600/60	①		①
	40	300/40:400/25	300/50:600/25	300/50:500/25	350/40:600/25	500/55:550/45	450/50:600/40	600/60	550/60:600/55	①	①		①
	50	300/40:450/25	400/50:550/35	300/50:600/40	500/50:600/45	500/60:600/45	600/60	①	600/80	①	①		①
	60	350/40:500/25	450/50:600/40	350/50:600/40	600/45	550/50	600/60	①		①	①		①
	70	350/40:600/45	500/50:550/45	450/50:600/40	600/80	550/60:600/55	①	①		①	①		①
	80	350/40:600/45	550/50:600/45	450/50:600/40	①	600/70	①	①		①	①		①

*① Requires a width larger than 600 mm.

Table.11 Minimum dimensions and concrete covers for reinforced concrete columns with rectangular section (ISO 834). Mechanical reinforcement ratio ω = 1.0. Low first order moment: e = 0.025b with e ≥ 10 mm

Fire resistance	λ	Minimum dimensions (mm) / Column width b_{min} [mm]/axis distance a [mm]											
		Columns exposed on more than one side											
		n=0.15			n=0.3			n=0.5			n=0.7		
		standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire
		Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation
R30	30	150/25		150/25	150/25		150/25	150/25		150/25	150/25		200/25
	40	150/25		150/25	150/25		150/25	150/25		150/25	150/25		200/25
	50	150/25		150/25	150/25		150/25	150/25		200/25	200/25	150/30:200/25	250/25
	60	150/25		150/25	150/25		150/25	150/25		200/40:250/25	200/25	200/30:250/25	300/35:350/25
	70	150/25		150/25	150/25		150/25	200/25	150/30:200/25	250/35:300/25	250/35:350/25	250/25	350/50:450/25
	80	150/25		150/25	150/25	200/25	200/25	200/25	200/30:250/25	300/35:350/25	300/35:400/25	250/30:300/25	350/50:550/25
R60	30	150/25		150/25	150/25		150/40:200/25	150/25		200/40:250/25	200/25	200/40:300/25	250/35:300/25
	40	150/25		150/25	150/25		200/25	200/25	200/30:250/25	200/40:300/25	250/25	250/35:350/25	300/35:400/25
	50	150/25		150/40:200/25	150/25	150/30:200/25	200/40:250/25	200/30:250/25	200/40:250/25	250/50:350/25	300/25	250/40:350/25	350/50:450/25
	60	150/25		150/40:200/25	150/30:200/25	150/40:250/25	200/40:300/25	250/35:300/25		300/35:450/25	350/40:450/25	300/40:600/25	400/50:600/45
	70	150/25		200/25	200/25	200/35:250/25	250/35:300/25	300/35:400/25	250/40:400/25	350/50:500/25	400/50:600/45	350/40:450/35	500/50:600/45
	80	150/25		200/40:250/25	200/30:250/25	200/40:300/25	250/35:400/25	300/50:450/25	300/40:550/25	400/50:600/45	450/50:600/45	350/45:450/40	600/60
R90	30	150/25		150/25	200/25		200/40:250/25	200/40:250/25		250/50:350/25	250/35:300/25	250/45:600/25	300/50:400/25
	40	150/25		200/25	200/25	200/35:250/25	250/35:300/25	250/35:300/25	250/35:350/25	250/50:400/25	300/50:450/25	300/45:600/30	350/50:600/25
	50	150/30:200/25	150/35:200/25	200/40:250/25	200/30:250/25	200/40:250/25	250/50:350/25	250/50:400/25	250/45:400/25	300/50:600/25	400/50:550/25	350/45:600/35	450/50:600/45
	60	200/25	150/40:250/25	200/40:300/25	200/40:250/25	250/55:300/25	250/50:450/25	300/50:450/25	300/45:550/25	400/50:600/45	450/50:600/35	400/50:600/40	600/60
	70	200/25	200/35:250/25	250/35:300/25	250/35:300/25	300/35:350/25	250/50:450/25	400/50:600/35	350/45:600/35	450/50:600/45	600/60	550/50:600/45	600/80
	80	200/30:250/25	200/40:250/25	250/35:400/25	250/50:400/25	300/40:500/25	300/50:600/45	450/50:600/45	350/50:600/40	600/60	600/80	550/65:600/55	①
R120	30	200/25	150/40:200/25	200/25	200/40:250/25	200/45:250/25	250/50:300/25	250/50:350/25	250/45:400/25	300/50:400/25	300/50:400/25	400/40:600/25	350/50:500/25
	40	200/25	200/30:250/25	200/40:250/25	250/35:300/25	250/25	250/50:350/25	250/50:400/25	300/45:400/25	300/50:500/25	400/50:600/25	400/50:600/30	450/50:600/25
	50	200/30:250/25	200/40:250/25	250/35:300/25	250/35:350/25	250/35:300/25	250/50:450/25	300/50:550/25	350/40:550/25	400/50:600/25	450/50:600/45	550/45:600/40	600/25
	60	200/40:300/25	200/45:250/25	250/50:400/25	250/50:400/25	250/45:400/25	300/50:600/25	400/50:600/35	400/50:600/25	450/50:600/25	600/60	550/60:600/50	600/80
	70	250/35:300/25	250/25	250/50:450/25	300/50:450/25	350/35:450/25	300/50:600/25	500/50:600/45	550/40:600/35	600/25	600/80	600/70	①
	80	250/35:400/25	250/35:300/25	250/50:450/25	300/50:600/35	350/40:550/25	350/50:600/25	600/60	550/50:600/45	600/80	①		①

*① Requires a width larger than 600 mm.

Table.12 Minimum dimensions and concrete covers for reinforced concrete columns with rectangular section (ISO 834). Mechanical reinforcement ratio ω = 1.0. Moderate first order moment: e = 0.25b with e ≤ 100 mm

Fire resistance	λ	Minimum dimensions (mm) / Column width b_{min} [mm]/axis distance a [mm]											
		Columns exposed on more than one side											
		n=0.15			n=0.3			n=0.5			n=0.7		
		standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire
		Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation
R30	30	150/25		150/25	150/25		150/25	150/25		200/25	200/25	200/30:300/25	300/25
	40	150/25		150/25	150/25		150/25	150/25		250/25	250/35:300/25	250/30:450/25	350/50:400/25
	50	150/25		150/25	150/25		150/25	200/25		250/25	350/40:400/25	300/35:500/25	450/50:500/25
	60	150/25		150/25	150/25		200/25	250/25	200/30:250/25	300/50:400/25	450/25	400/40:550/25	500/50:600/25
	70	150/25		150/25	150/25		200/40:250/25	300/25	250/35:300/25	400/50:450/25	500/50:550/25	500/35:600/30	550/50:600/60
	80	150/25		150/25	200/25	150/30:250/25	250/25	350/40:400/25	300/35:500/25	450/50:550/25	600/35	500/60:600/35	①
R60	30	150/25		150/40:200/25	150/25	150/30:200/25	200/40:250/25	200/25	200/40:400/25	250/50:350/25	300/35:350/25	300/50:600/30	450/25
	40	150/25		150/40:200/25	150/30:200/25	150/40:250/25	200/40:300/25	250/35:300/25	250/40:500/25	300/35:400/25	450/25	400/50:600/35	500/50:600/25
	50	150/25		200/40:250/25	200/25	200/35:400/25	250/35:300/25	300/25	300/40:600/25	400/50:450/25	500/50:600/25	500/45:600/40	550/50:600/45
	60	150/25	150/30:200/25	200/40:250/25	200/30:250/25	200/40:450/25	250/50:400/25	400/50:450/25	400/40:600/30	450/50:600/25	600/45	550/40:600/40	600/80
	70	150/25	150/35:200/25	200/40:300/25	250/35:300/25	250/40:550/25	300/35:450/25	450/50:550/25	450/45:500/35	550/50:600/45	①	600/60	①
	80	150/25	200/30:250/25	200/40:300/25	300/35:350/25	300/40:550/25	350/50:450/25	500/50:600/35	500/50:600/40	600/60	①	600/80	①
R90	30	150/30:200/25	200/25	200/40:250/25	200/30:250/25	200/40:300/25	250/35:350/25	250/50:350/25	250/40:550/25	300/50:450/25	450/50:500/25	500/50:600/45	500/50:600/45
	40	200/25	200/30:250/25	200/40:300/25	200/40:300/25	200/50:400/25	250/50:400/25	300/50:450/25	300/50:600/35	350/50:600/45	500/50:600/35	500/60:600/50	600/45
	50	200/25	200/35:300/25	250/35:300/25	250/35:300/25	250/50:550/25	300/50:450/25	450/50:500/25	400/50:600/40	500/50:600/45	600/60	600/55	600/80
	60	200/30:250/25	200/40:400/25	250/35:400/25	300/35:400/25	300/45:600/25	300/50:600/25	500/50:600/35	500/50:600/45	600/45	①	600/70	①
	70	200/40:300/25	200/45:450/25	250/50:450/25	300/50:450/25	300/50:600/35	400/50:600/45	600/60	550/55:600/50	600/80	①		①
	80	200/40:300/25	200/50:500/25	250/50:450/25	400/50:550/25	400/50:600/35	450/50:600/45	600/80	600/55	①	①		①
R120	30	200/30:250/25	200/40:250/25	250/35:300/25	250/35:300/25	250/50:400/25	250/50:450/25	300/50:550/25	450/45:600/30	400/50:600/25	500/50:600/35	600/60	550/50:600/25
	40	200/40:300/25	200/45:300/25	250/50:400/25	250/50:400/25	300/40:500/25	300/50:500/25	400/50:600/35	500/50:600/35	450/50:600/25	600/45	①	600/25
	50	250/35:300/25	250/40:400/25	250/50:450/25	300/50:450/25	400/40:550/25	350/50:600/25	550/50:600/45		550/50:600/25	①		①
	60	250/35:400/25	250/50:450/25	250/50:450/25	400/50:600/25	400/50:500/35	400/50:600/25	600/45	600/55	600/25	①		①
	70	250/50:400/25	300/40:500/25	300/50:600/25	450/50:600/35	500/45:600/35	450/50:600/25	600/80	①	①	①		①
	80	250/50:450/25	300/50:550/25	300/50:600/25	500/50:600/35	500/60:600/40	550/50:600/25	①		①	①		①

*① Requires a width larger than 600 mm.

Table.13 Minimum dimensions and concrete covers for reinforced concrete columns with rectangular section (ISO 834). Mechanical reinforcement ratio ω = 1.0. High first order moment: e = 0.5b with e ≤ 200 mm

Fire resistance	λ	Minimum dimensions (mm) / Column width b_{min} [mm]/axis distance a [mm]											
		Columns exposed on more than one side											
		n=0.15			n=0.3			n=0.5			n=0.7		
		standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire	standard fire		hydrocarbon fire
		Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation	Numerical calculation	Eurocode 2	Numerical calculation
R30	30	150/25		150/25	150/25		150/25	200/25	200/30:300/25	300/25	500/25	500/30:550/25	500/50:550/25
	40	150/25		150/25	150/25		200/25	250/35:300/25	250/30:450/25	350/50:400/25	500/25	500/40:600/30	550/50:600/25
	50	150/25		150/25	150/25	150/30:200/25	250/25	350/40:400/25	300/35:500/25	450/25	550/50:600/25	550/35	600/45
	60	150/25		150/25	200/25	200/30:250/25	250/25	450/25	350/40:500/25	500/50:550/25	①	550/50	①
	70	150/25		150/25	200/30:250/25	200/30:300/25	300/25	500/25	450/50:550/25	550/50:600/25	①		①
	80	150/25		200/25	250/35:300/25	250/30:350/25	350/50:400/25	550/25	500/35:600/30	600/45	①		①
R60	30	150/25		200/25	200/25	200/35:450/25	250/35:300/25	350/25	350/40:600/30	450/25	550/25	550/45:600/40	600/45
	40	150/25	150/30:200/25	200/40:250/25	200/30:250/25	200/40:500/25	300/35:350/25	450/25	450/50:500/35	500/50:550/25	600/45	600/60	①
	50	150/25	150/35:250/25	200/40:300/25	250/35:300/25	250/40:550/25	300/35:400/25	500/50:550/25	500/40:600/35	550/50:600/45	①	600/80	①
	60	200/25	200/30:350/25	200/40:300/25	250/50:300/25	300/40:600/25	350/50:450/25	550/50:600/25	500/50:600/40	600/60	①		①
	70	200/25	250/30:450/25	250/35:300/25	350/40:450/25	350/40:600/30	450/50:550/25	600/45	550/50:600/45	①	①		①
	80	200/25	250/55:500/25	250/35:400/25	450/50:500/25	450/40:500/35	450/50:600/45	①	600/70	①	①		①
R90	30	200/25	200/35:300/25	250/35:300/25	250/35:300/25	250/50:550/25	300/50:450/25	450/25	500/50:600/40	400/50:600/45	600/80	600/70	①
	40	200/30:250/25	200/40:450/25	250/35:400/25	300/35:400/25	300/50:600/30	300/50:450/25	500/50:600/25	500/55:600/45	550/50:600/45	①		①
	50	200/40:300/25	200/45:500/25	250/50:400/25	300/50:450/25	350/50:600/35	400/50:600/25	550/50:600/35	550/50	600/60	①		①
	60	200/40:300/25	200/50:550/25	250/50:450/25	400/50:450/25	450/50:600/40	450/50:600/45	600/80	600/60	①	①		①
	70	250/35:300/25	250/45:600/30	300/50:450/25	450/50:600/25	500/50:600/45	500/50:600/45	①	600/80	①	①		①
	80	250/50:400/25	250/50:500/35	300/50:550/25	500/50:600/35	500/55:600/45	600/45	①		①	①		①
R120	30	250/35:300/25	200/50:450/25	250/50:450/25	300/50:450/25	450/45:600/25	350/50:550/25	450/50:600/45	550/55:600/50	500/50:600/25	①		①
	40	250/35:350/25	250/50:500/25	250/50:450/25	350/40:450/25	500/40:600/30	400/50:600/25	550/50:600/45	600/65	600/25	①		①
	50	250/50:400/25	300/40:550/25	300/50:500/25	400/50:600/25	500/50:600/35	450/50:600/25	600/60	①	①	①		①
	60	250/50:450/25	350/45:550/25	300/50:600/25	450/50:600/35	500/60:600/40	500/50:600/25	①		①	①		①
	70	300/50:450/25	450/40:600/30	350/50:600/25	550/50:600/45	550/60:600/50	600/25	①		①	①		①
	80	300/50:600/25	450/45:600/30	400/50:600/25	600/60	600/65	600/25	①		①	①		①

*① Requires a width larger than 600 mm.

Table 14: Occupancy-specific fire load densities [MJ/m^2]

Occupancy	Mean	Standard Deviation	80-Percentile
Dwelling	780	234	948
Office	420	126	511

Table 15: Maximum permitted bending moment of columns during the fire in the case of an office

n t (min)	0		0.1		0.2		0.3		0.4		0.5		0.6		0.7		0.8		0.9		1	
	Perfect recovery	No recovery	Perfect recovery	No recovery	Perfect recovery	No recovery	Perfect recovery	No recovery	Perfect recovery	No recovery	Perfect recovery	No recovery	Perfect recovery	No recovery	Perfect recovery	No recovery	Perfect recovery	No recovery	Perfect recovery	No recovery	Perfect recovery	No recovery
0	188	188	241	241	290	290	326	326	345	345	332	332	301	301	271	271	238	238	199	199	154	154
15	188	188	241	241	290	290	325	325	342	342	331	331	298	298	265	265	229	229	187	187	143	143
30	183	183	237	237	278	278	297	297	297	297	270	270	236	236	197	197	158	158	116	116	73	73
45	182	182	235	234	272	270	283	278	275	266	244	237	200	193	166	156	126	117	86	80	48	41
60				233		269		274		259		227		188		144		112		75		36
75								273		259		227		188		143		111		73		33
90																				72		32

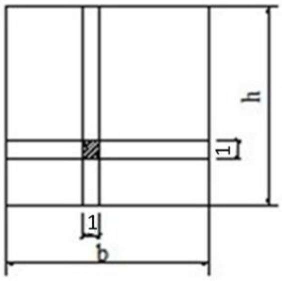


Fig. 1 Temperature calculation model

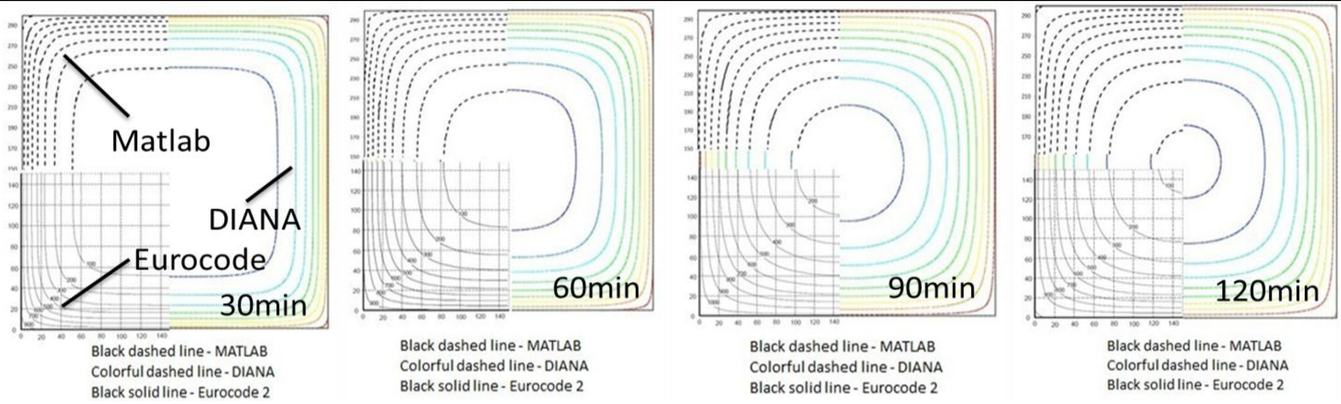


Fig. 2 Comparison of the temperature distribution calculated using the proposed methodology implemented in a Matlab routine, with graphs given in EN 1992-1-2 and results obtained with the finite element program DIANA at 30 min, 60 min, 90 min, 120 min

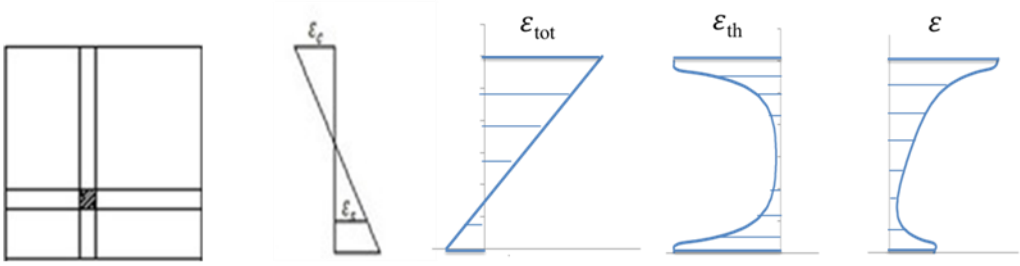
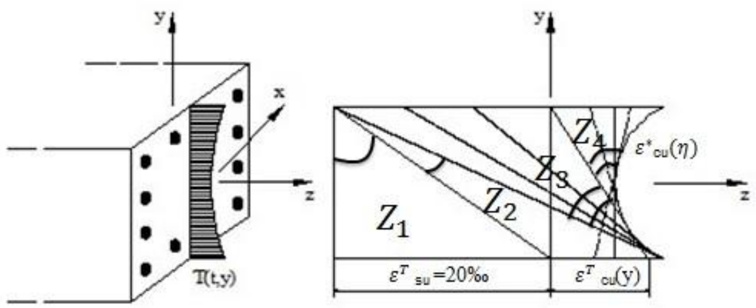


Fig. 3 Total, thermal and mechanical strain



(a) (b)

Fig. 4 (a) Temperature distribution along the height direction; (b) strain profiles and strain limits [17]

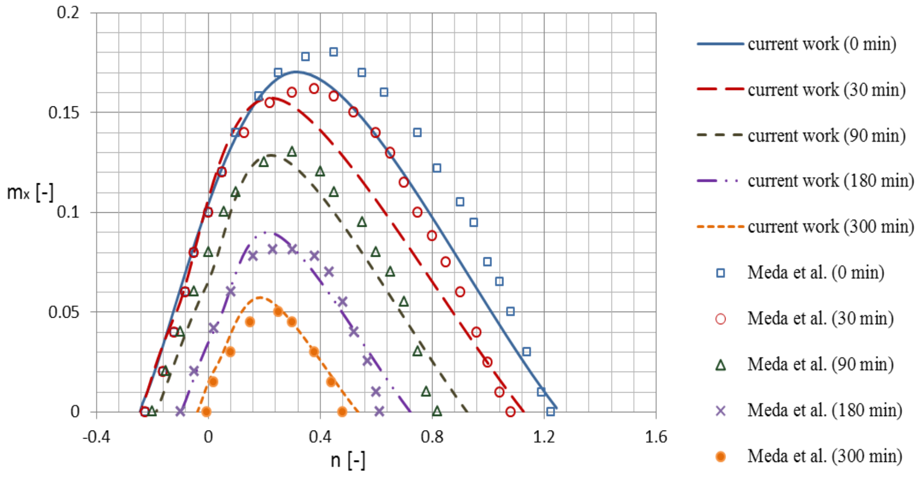


Fig. 5 Comparison of interaction curves with results available in [6]

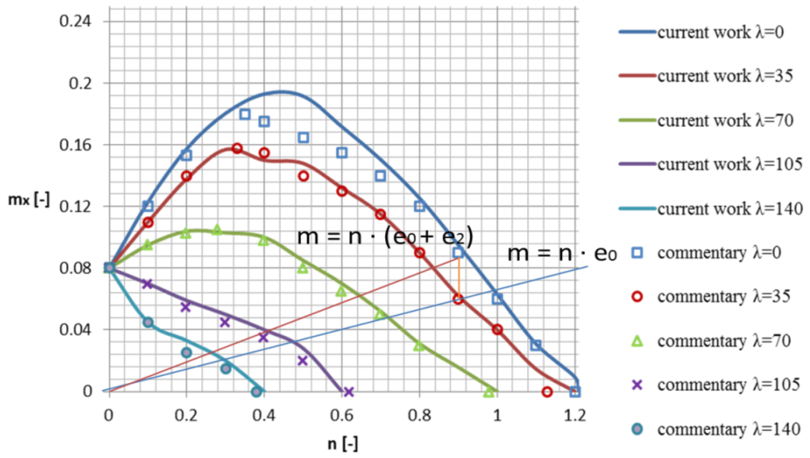


Fig. 6 Interaction curves for columns of different slenderness; comparison to background documents of Eurocode 2 [13]

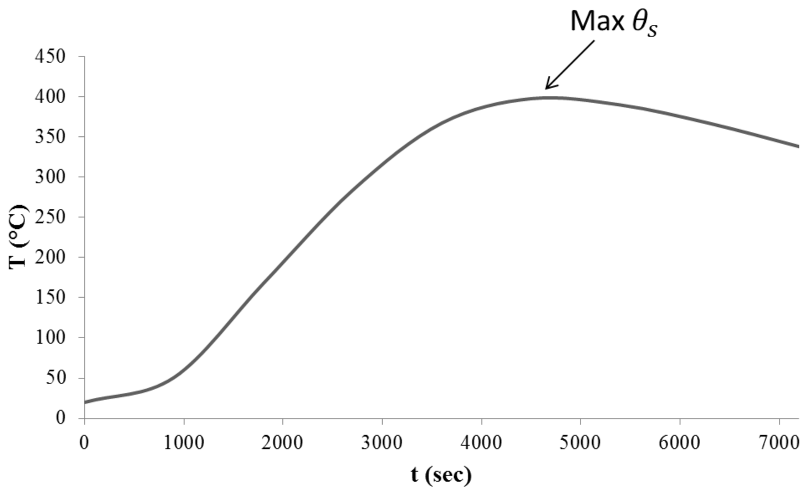


Fig. 7 Temperature-time diagram of the reinforcement bar (dwelling)

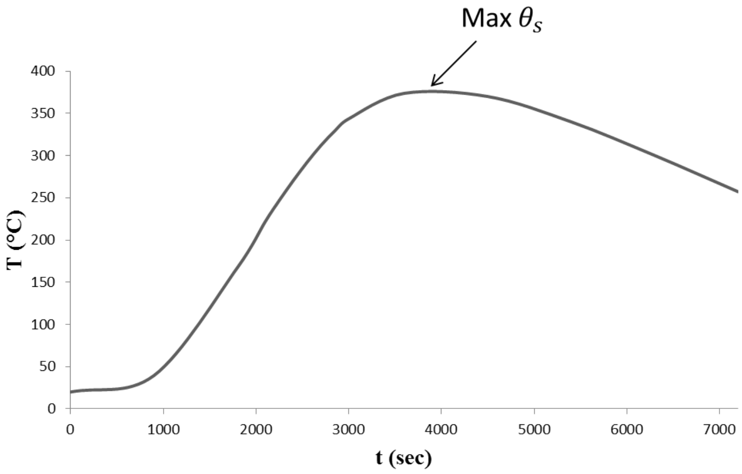


Fig. 8 Temperature-time diagram of the reinforcement bar (office)

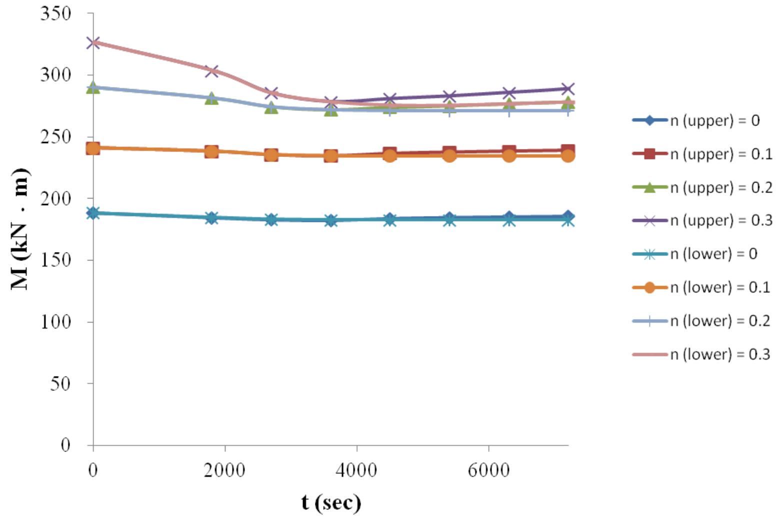


Fig. 9 Maximum permitted bending moment of columns during the fire in the case of the dwelling (n≤ 0.3)

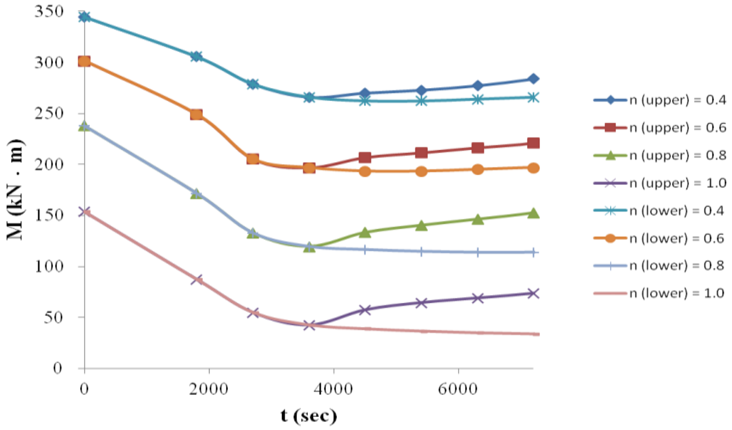


Fig. 10 Maximum permitted bending moment of columns during the fire in the case of the dwelling (n > 0.3)

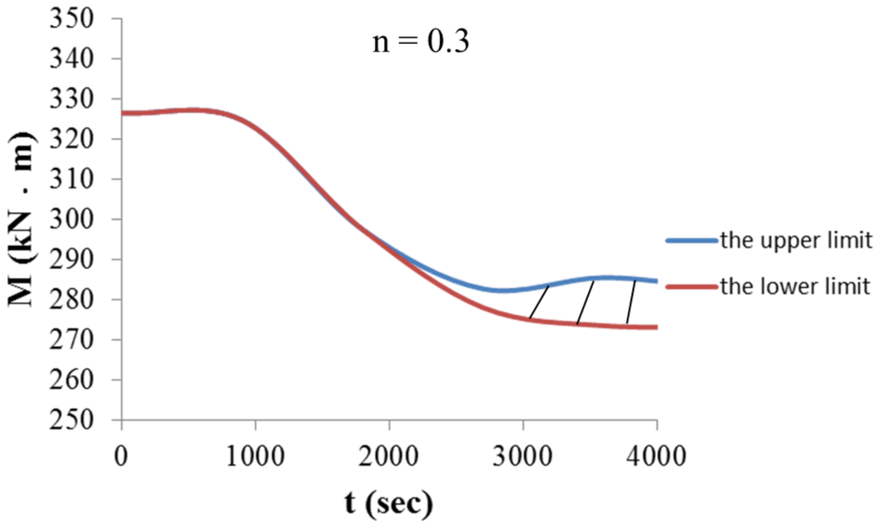


Fig. 11 Range of maximum permitted bending moment during the natural fire when n = 0.3

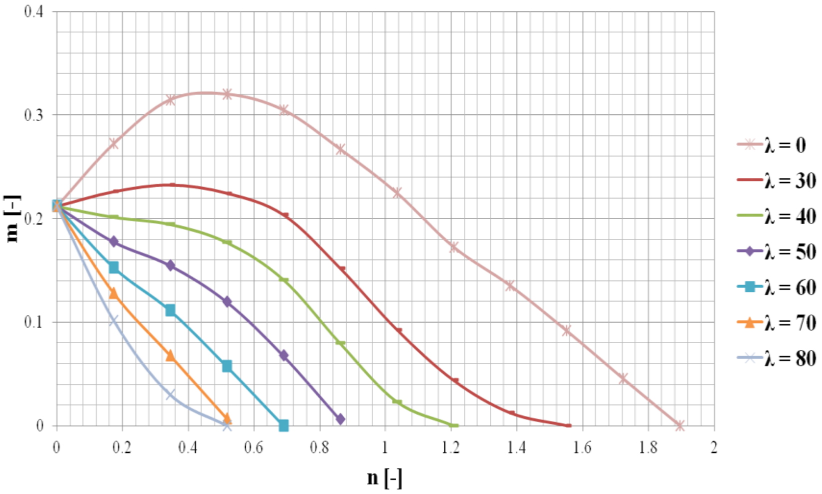


Fig. 12 Interaction curves of columns at 75 min of fire (dwelling)

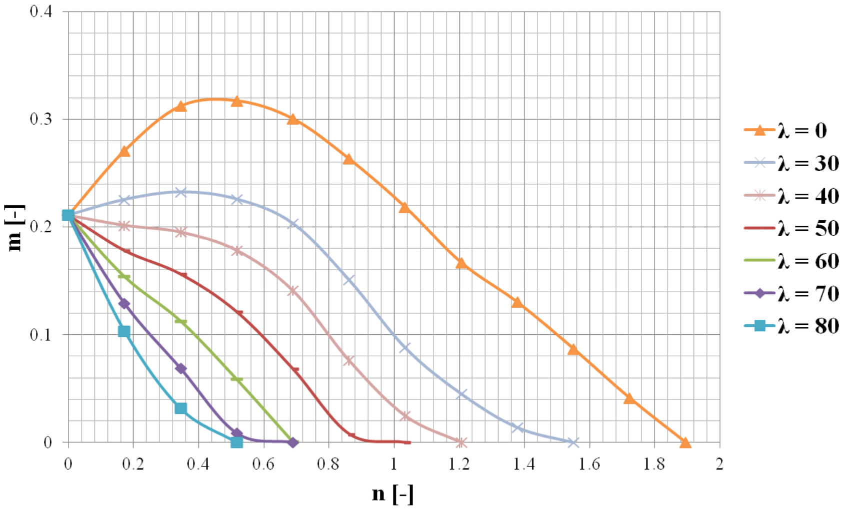


Fig. 13 Interaction curves of columns at 60 min of fire (office)