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The Structural Adequacy of a Reinforced Concrete Element Exposed to Fire

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Abstract

This paper summarizes an example of a beam fire check using tabulated data and the isotherm 500 °C method. This beam is subjected principally at bending moment. This analysis shows that the reinforced beams may have strength reserves. The correct evaluation of those reserves leads eventually to elaborate the appropriate solution to reconstruct and/or to consolidate the structures affected by fire. There are presented different evaluation formulae, regarding the estimation of a reinforced concrete beam capacity, under fire. For better understanding of the fire effect on a beam, an experimental study should be carried out, but a real fire progress is difficult to be set in laboratory conditions.

Rezumat

Această lucrare prezinta un exemplu de verificare a unei grinzi, solicitată preponderent la moment încovoietor, folosind datele prezentate sub formă de tabele şi metoda izotermei 500 °C. Analiza demonstrează că grinzile din beton armat pot avea rezerve de rezistenţă. Evalauarea corectă a acestor reserve de rezistenţă duce în final al elaborarea unor soluţii potrivite de refacere şi/sau consolidare a structurilor afectate de acţiunea incendiilor. Sunt prezentate diferite ecuaţii de evaluare a capacităţii portante a grinzilor, sub acţiunea focului. Pentru o înţelegere mai exactă a efectelor incendiilor asupra grinzilor trebuie efectuat un studiu experimental, dar dezvoltarea reală a unui incendiu este dificil de realizat în condiţii de laborator.

Keywords: reinforced concrete, bending fire capacity, design, modeling, eurocode.

1. Introduction

When checking the fire adequacy of a structure or of a structural member, the first steps to take should be:

- select the appropriate fire scenario;
- determine the temperature profile.

The fire analysis can be performed on:

- a specific structural element (ELEM);
- part of a structure (PART);
- the entire structure (STRUCT).

In Australia (Australian Standards), in the European countries (Eurocodes) and in the Japanese

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Standards (Building Standards Law of Japan) there are provided several methods of fire design:

- using tabulated data (for ELEM);
- simplified calculation methods (for PART);
- advanced calculation methods (for: ELEM+PART+STRUCT).

Nominal fire is the most commonly used.

This example sight the bending capacity of a simply supported beam in fire conditions.
The beams characteristics: bxh= 300x600mm, span length: 5000mm.
Concrete class: C20/25.
Type of reinforcement Bst 500S.
The required fire strength: R60(t=60minutes), R90(t=90minutes), R120 (t=120minutes).

2. Actions

When evaluating the external actions on the element, it can be used the following general equation:

$$w = \gamma_G \cdot G_k + \gamma_Q \cdot Q_k \qquad (1)$$

Table 1**:** Stress evaluation

Conditions	γ_G **[-]**	G_k **[kN/m]**	γ_Q **[-]**	Q_k **[kN/m]**	**w [kN/m]**	$\mathbf{M_{Ed}}$ **[kN•m]**
Cold	1.35	20	1.5	60	117	365
Fire	1.0	20	0.3	60	38	119

3. Material characteristics

3.1 Concrete

Table 2: Concrete strength and safety factors

Cold			**Fire**
γ_c **[-]**			γ_M **[-]**
1.5			1.00
f_{ck} **[Mpa]**	f_{ctm} **[Mpa]**	f_{cd} **[Mpa]**	f_{cd} **[Mpa]**
20	1.5	13.33	20

3.2 Steel in cold conditions

Table 3: Steel yield strength and safety factor for cold conditions

Cold	
γ_s **[-]**	
1.15	
f_{yk} **[MPa]**	f_{yd} **[MPa]**
500	435

4. Cold design

4.1 Reinforcement design

[1] Determine:

$$k = \frac{M_{Ed}}{b \cdot d^2 \cdot f_{ck}} = 0.21 \leq k'. \tag{2}$$

Computing the lever arm using the equation given in [1]:

$$z = \frac{d}{2} + [1 + \sqrt{1 - 3.53k}] = 400.84[mm] < 0.95 \cdot d = 508 \qquad [mm]. \tag{3}$$

The provided reinforcement aria:
$A_{s\ prov}$=25.13 cm^2, the equivalent of 8ø20.

4.2 The bending strength

$$M_{Rd,cold} = A_{s,prov} \cdot f_{yd} \cdot \left(d - 0.5 \cdot \frac{A_{s,prov} \cdot f_{yd}}{0.85 \cdot f_{cd} \cdot b} \right) = 583 \quad [kN \cdot m] \tag{4}$$

$$M_{Rd,cold} = 583[kN \cdot m] > M_{Ed,cold} = 365[kN \cdot m] \tag{5}$$

5. Fire design

5.1 Fire design using tabulated data

Eurocode 2[2], states the minimum requirements of the cross-sectional dimensions of the elements. The same requirements can be found in the Australian Building Code (AS 3600-2009)[3] and in Building Standards Law of Japan (BSLJ)[4]. This tabulated data are summarized in table 4.

From Eurocode 2[2], the minimum required axis distance of the reinforcement bar and the nearest concrete face is a_{min}=55mm.

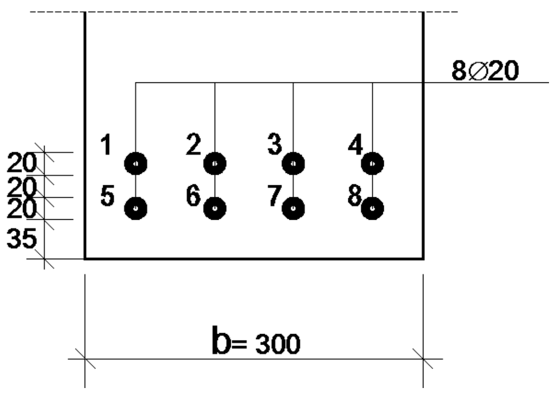


Figure 1. The reinforcement arrangement in the cross-section of the beam. Dimensions used to determine the average distance, a_m .

Table 4: Structural adequacy for different concrete elements according to Eurocode 2[2], AS 3600-2009[3] and BSLJ[4].

Standard	**Fire exposure & characteristics**		**Dimension**		**Fire resistance class**					
					R30	**R60**	**R90**	**R120**	**R180**	**R240**
Column										
EC2	Exposed on 4 sides	$\mu_{fi}\leq 0.5$	Cross-sectional dimension [mm]	b_{min}*)	200	250	300	450	500	600
				a_{min}	30	35	45	50	60	70
		$\mu_{fi}\leq 0.7$		b_{min}*)	200	350	500	500	600	>600
				a_{min}	30	40	50	60	75	-
AS 3600-2009	Exposed on more than 1 sides and N_f*/N_u=	0.2		b_{min}*)	200	200	200	300	250 350	350
				a_{min}	25	25	31	25	40 35	61
		0.5		b_{min}*)	200	200 300	300	400	350 450	350 450
				a_{min}	25	36 31	45	38	45 40	63 75
		0.7		b_{min}*)	200 300	250 350	350	450	350 450	450
				a_{min}	32 27	46 40	53	40	57 51	70
BSLJ	Not specified			b_{min}*)	-	-	-	120	400	-
				a_{min}	-	30	-	50	60	-
Simply supported and continuous beam										
EC2 & AS 3600-2009	Not specified	Simply supported & continuous	Cross-sectional dimension [mm]	$b_{w.min}$	80	120	150	200	240	280
		Simply supported		a_{min}	25	40	55	65	80	90
		continuous		a_{min}	15	25	35	45	60	75
BSLJ	Not specified			$b_{w.min}$	-	-	-	-	-	-
				a_{min}	-	-	-	50	60	-
Slabs										
EC2 & AS 3600-2009	Not specified	All types of slabs	Cross-sectional dimension [mm]	$h_{f.min}$	60	80	100	120	150	175
BSLJ	Not specified			$h_{f.min}$	-	70	-	100	-	-
				a_{min}	-	-	-	30	-	-
Simply supported slabs										
EC2 & AS 3600-2009	Not specified	One way	Cross-sectional dimension [mm]	a_{min}	10	20	30	40	55	65
		Two way $\ell_y/\ell_x\leq 1{,}5$		a_{min}	10	10	15	20	30	40
		Two way $\ell_y/\ell_x\leq 1{,}5$		a_{min}	10	15	20	25	40	50
				a_{min}	10	15	20	25	40	50
Continuous slabs										
EC2	Not specified		Cross-sectional	a_{min}	10	15	20	25	40	50
AS 3600-2009	Not specified			a_{min}	10	10	15	20	30	40

Where:
$\mu_{fi} = N_f^*/N_u$, degree of utilization in fire situation;
N_f^*= design axial load in fire conditions;
N_u = ultimate strength in compression, or tension, at a cross-section of an eccentrically loaded compression or tension member respectively;
$b_{min}^{*)}$= smaller cross-sectional dimension of a rectangular column;
$b_{w,min}$= minimum width of the beam;
a_{min}= the minimum required average distance from the reinforcement centroid to the nearest exposed surface;

The average effective distance is:

$$a_m=(\sum A_{si}a_i)/\sum A_{si}=65.96 \quad [mm] \tag{6}$$

which is grater that the required a_{min}.

A_{si}= cross-sectional area of the reinforcement bar.
a_i = distance from the reinforcement centroid to the nearest exposed surface.

5.2 The isotherm 500°C

All the equations are using the reduced section. This method considers that the concrete having a temperature higher that 500°C is not capable to bear compression.

The reduced cross-section dimensions are:

$$b_{fi}=b-2\bullet t_{fi} \tag{7}$$
$$h_{fi}=h-t_{fi} \tag{8}$$
$$d_{fi}=d \tag{9}$$

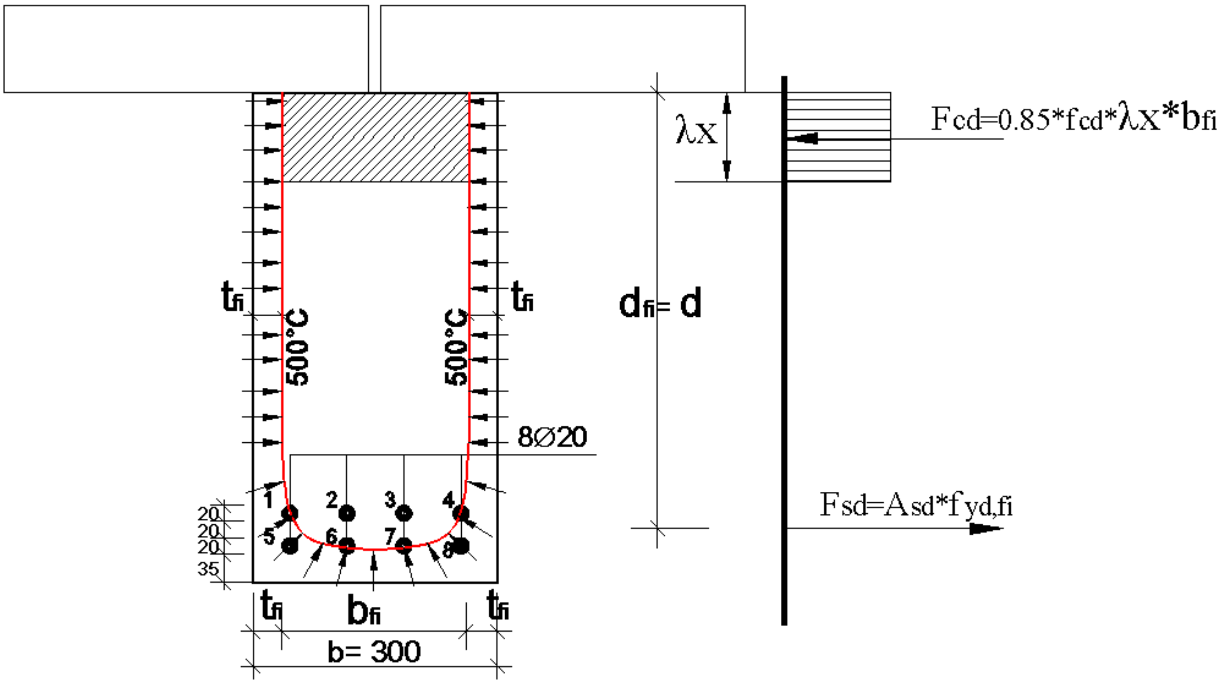
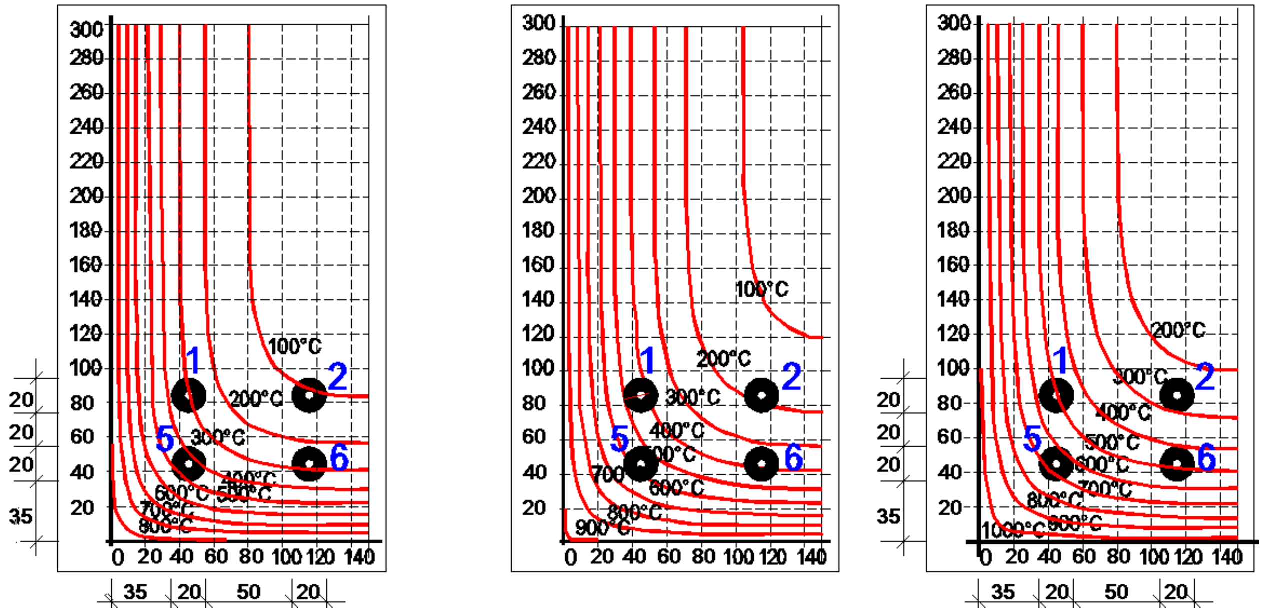


Figure 2. The reduced cross-section of the beam.



a) R60 b) R90 C) R120

Figure 3. Steel temperature according to the charts of EN 1992-1-2:2006[2].

Using the design charts of EN 1992-1-2:2006[2], the depth of 500^{0}C isotherm, t_{fi}, is recorded in table 5.

Table 5**:** The geometrical characteristics of the reduced cross-section

Conditions	**t_{fi} [mm]**	**b_{fi} [mm]**	**h_{fi} [mm]**
R60	21.3	257.3	578.7
R90	29.9	240.2	570.1
R120	35.1	229.8	564.9

Steel temperature is determined using the charts of EN 1992-1-2:2006[2] and considering the reinforcement determined in the section 4.1. of this paper. The charts used are presented in figure 3 and the considered temperature values for each reinforcement bar are recorded in table 6.

Where:
Θ- is the steel temperature;
k_Θ – is the reduction factor for a strength or deformation property dependent on the material temperature Θ, according to EN 1992-1-2:2006[2] ;
$f_{yd,fi,i}$ – is the reduced yield stress for each reinforcement bar.

For the average reduced design yield stress it may be considered the following expression:

$$f_{yd,fi} = \frac{\sum f_{yd,fi,i} \cdot A_{s,i}}{\sum A_{s,i}} \qquad \text{[MPa]} \qquad (10)$$

The bending strength in fire conditions:

$$M_{Rd,fire} = A_{s,prov} \cdot f_{yd,fi} \cdot \left(d - 0.5 \frac{A_{s,prov} \cdot f_{yd,fi}}{0.85 \cdot f_{cd,fi} \cdot b_{fi}} \right) \qquad \text{[kN·m]} \qquad (11)$$

Table 6: Steel temperature, reduction factor and reduced yield stress for each reinforcement bar

Variables	Reinforcement no. 1&4	2&3	5&8	6&7
R60				
Θ_{R60}	300	111.42	437.97	280.62
$k_{\Theta,R60}$ [-]	1.00	1.00	0.9164	1.00
$f_{yd,fi,i,R60}$ [MPa]	500	500	458.2	500
R90				
Θ_{R90}	431.41	189.76	565.84	383.36
$k_{\Theta,R90}$ [-]	0.93	1.00	0.576	1.00
$f_{yd,fi,i,R90}$ [MPa]	465	500	288	500
R120				
Θ_{R120}	505	290	670	480
$k_{\Theta,R120}$ [-]	0.76	1.00	0.30	0.824
$f_{yd,fi,i,R120}$ [MPa]	380	500	150	412

Table 7: Average reduced yield stress for steel and bending capacity

	$f_{yd,fi}$ [MPa]	$M_{Rd, fire}$ [kN·m]	$M_{Ed,fire}$ [kN·m]
R60	489.55	485.22	119
R90	438.25	440.75	
R120	360.50	379.66	

6. Conclusions

The following conclusions can be drown from this study:

1. The nominal fire scenario is easy to use.
2. Tabulated data is an empirical method, which leads to unreliable results.
3. Performance based methods are more appropriate to capture the true behavior of a reinforced concrete element.
4. Develop a model that reflects the true fire scenario and the real behavior of reinforced concrete element exposed to fire.
5. The temperature rate or the fire intensity is an important element on a realistic analysis.
6. The real fire duration, must be considered.
7. The load-bearing characteristics should be evaluated.
8. The load variation- before, during and after fire- has to be established.
9. The methods of cooling (the materials that are use, such as: water, foam etc.) and the cooling rate may affect the load variation and chemically aggress the concrete element.
10. The thermal behavior analysis of the material, that takes in account the interaction between the steel reinforcement and concrete, at high temperature in a reinforced element, must be performed.
11. The mechanical characteristics of concrete and steel reinforcement at high temperature, such as compression and tension strength, modulus of elasticity, etc., may change.
12. Concrete thermal expansion and spalling affects the reinforced concrete element behavior, when exposed to fire.

7. References

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