SCIENTIFIC
AND DIDACTIC EQUIPMENT

Computational assessment of the load bearing capacity of reinforced concrete slabs in a support area in a fire situation

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ABSTRACT:

The resistance of reinforced concrete slabs, with a thickness of not less than 15 cm, in a fire situation, has been calculated in the document. A standard fire curve was adopted. The calculations have been performed using the simplified Isotherm 500 method. Equilibrium curves that facilitate determination of the fire resistance of the analysed slabs, have been established. The results have been tabulated for use by designers.

Obliczeniowa ocena nośności płyt żelbetowych w strefie przypodporowej w warunkach działania pożaru

Słowa kluczowe: płyta, żelbet, nośność, pożar

STRESZCZENIE:

W pracy obliczono nośność płyt żelbetowych w warunkach działania pożaru o grubościach nie mniejszych niż 15cm. Przyjęto standardową krzywą pożarową. Obliczenia wykonano uproszczoną metodą Izoterma 500. Wyznaczono krzywe równowagi pomocne do wyznaczenia nośności ogniowej analizowanych płyt. Jako pomoc dla projektantów wyniki zebrano tabelarycznie.

INTRODUCTION

In professional practice, a designer is required to ensure appropriate fire resistance of a structure. In the case of reinforced concrete structures such requirements are most often met by placing an appropriately dimensioned design element – this usually means maintaining the required distance of the centre of gravity of the main reinforcement from the slab face, as well as slab cross-section dimensions. The following methods are proposed to meet the fire resistance requirements for EC2 designed buildings [6]:
– tabular method,
– simplified computational models for separate structural elements, such as the Isotherm 500 method or the zone method,
– advanced computational models.
Isotherm 500 [4] allows assessment of the fire resistance in a fire situation of any structural element, which is impossible with tabular restrictions compliant with EC2. The study verified the computational resistance of selected reinforced concrete slabs using the Isotherm 500 method. Comparisons have been performed for many parameters influencing the fire resistance of a structure, such as:
– the distance of the main reinforcement's centre of gravity from the slab face,
– the reinforcement ratio,
– the computational load reduction factor.
The objective of the study is to analyse calculated results, compare them with tabular data specified as safe according to EC2 and create more precise resistance tables. This allowed more economical results from the perspective of an engineer and investor to be obtained.
The study supplements article [1] with resistance of slabs in a support zone in a fire situation.

COMPUTATIONAL ASSUMPTIONS ACCORDING TO ISOTHERM 500

An analysis based on the isotherm 500°C method was used to calculate the resistance.
Assumptions of the method:
– reduction of the steel yield point depending on the calculated temperature in the reinforcement's centre of gravity,
– reduction of the concrete compression zone as determined by the isotherm 500°C range; it has been assumed that concrete in the reduced zone demonstrates compressive strength as per EC2 under normal conditions,
– fire according to the standard fire curve.
Additional restrictions placed by the authors:
– The analysis pertained only to sections reinforced with $f_{yk} = 500\ MPa$ steel, with appropriate ductility allowing deformations of not less than 2% to be obtained at temperatures exceeding $\theta \geq 200^{o}C$,
– Concretes with high compressive strength, i.e. $f_{yk} \leq 50\ MPa$ were not analysed,
– Rectangular cross-sections – the most frequently used cross-section for floor slab structures – have been considered;
– It has been assumed that floor layers provide protection to slabs against fire from above. Screed significantly increases an element's passive protection against the undesirable effects of fire,
– In a fire situation, destruction of the slab due to concrete crushing has been allowed,
– Computational load under a fire situation has been reduced -n_f.
A significant increase in steel deformation caused by its high temperature leads to a decrease in the maximum height of the compressed zone. Therefore, in the case of high reinforcement ratios, the cross-section can be destroyed in a fire situation when the concrete's load-bearing capacity is exhausted. The authors allow for such a situation, as omitting it would result in underestimation of the load-bearing capacity of a structure that under normal circumstances is destroyed by steel yielding to tensile stress, i.e. one properly designed.

TEMPERATURE IN THE REINFORCEMENT

To calculate the resistance, it is necessary to determine the temperature at the centre of gravity of the designed slab reinforcement. In the support zone the temperature of the main reinforcement does not change significantly, as it is protected by floor layers.
Another type of reinforcement employed in the support zone is reinforcement preventing punching of the ceiling. Such reinforcement takes the form of bars perpendicular or oblique in relation to the slab's central axis. Results of numerical simulations of heated reinforced concrete slabs from study [2] make it possible to conclude that the temperature of such rods does not exceed 500°C over most of the length, so their resistance

does not change. For this reason, the impact of fire on the slab reinforcement has been ignored.

FACTORS REDUCING CONCRETE STRENGTH

In line with the assumptions of the Isotherm 500 method, the calculations did not include any factors reducing the concrete's compressive strength. The load-bearing capacity decrease is achieved by reducing the compressed concrete's cross-section as per the trajectory of the isotherm 500 in a fire situation. For an area with a local temperature of $\theta < 500^{o}C$ it has been assumed that $f_{cd,fi} = f_{ck}$, while for areas where $\theta \geq 500^{o}C$ it has been assumed that $f_{cd,fi} = 0$.

CROSS-SECTION REDUCTION

In study [2], once a numerical analysis of the most frequently used reinforced concrete bent elements has been conducted, arbitrary values, such as a_z – the location of Isotherm 500 in reinforced concrete slabs – were recommended. It transpired that for slabs with a thickness of $h \geq 15\ cm$ the location of isotherm 500 is actually independent of the tested element's thickness (Fig. 1).

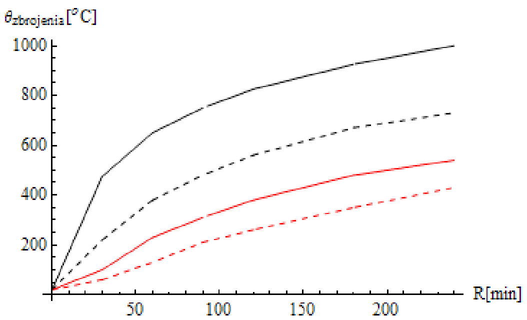

Figure 1 Dependence of the temperature in the reinforcement's centre of gravity on the duration of the fire for different distances from the heated face of the slab, see [2]

RESISTANCE OF THE SLABS

Computational analysis was conducted for the most common floor slabs with a thickness greater than 15 cm. The values assumed were *d* = 12 cm, 15 cm, 22 cm, where *d* is the section's useful height.

COMPUTATIONAL LOAD REDUCTION FACTOR

A fire load is counted among exceptional loads on a structure. When determining the strain on a structure exposed to fire, we often use the ratio of the computational load in a fire situation to the computational load under normal conditions As per EC2 recommendations [6], $n_f = 0.7$ was adopted. For the designer, this is a safe estimate. It needs to be noted that the adoption of lower reduction factor values may significantly increase the fire resistance class of the designed building. Smaller values were also included in the final tables [Tab. 1-2].

Table 1 Fire resistances

n_f	Fire resistance for α < 0.1					
	Minimum d [cm]					
	R30	R60	R90	R120	R180	R240
0.7	-	-	-	-	13.2	15.8
0.6	-	-	-	-	-	13
0.5	-	-	-	-	-	-
0.4	-	-	-	-	-	-
0.3	-	-	-	-	-	-

n_f	Fire resistance for α < 0.2					
	Minimum d [cm]					
	R30	R60	R90	R120	R180	R240
0.7	-	-	-	-	13.6	16.3
0.6	-	-	-	-	-	13.4
0.5	-	-	-	-	-	-
0.4	-	-	-	-	-	-
0.3	-	-	-	-	-	-

n_f	Fire resistance for α < 0.3					
	Minimum d [cm]					
	R30	R60	R90	R120	R180	R240
0.7	-	-	-	-	14	16.7
0.6	-	-	-	-	-	13.9
0.5	-	-	-	-	-	12.1
0.4	-	-	-	-	-	-
0.3	-	-	-	-	-	-

n_f	Fire resistance for α < 0.5					
	Minimum d [cm]					
	R30	R60	R90	R120	R180	R240
0.7	-	-	-	12.1	17.2	20.7
0.6	-	-	-	-	14.4	17.3
0.5	-	-	-	-	12.2	14.7
0.4	-	-	-	-	-	12.6
0.3	-	-	-	-	-	-

Table 2 Fire resistance with punching shear

n_f	Minimum d [cm]					
	R30	R60	R90	R120	R180	R240
0.7	-	-	-	-	16	19.4
0.6	-	-	-	-	13.4	16.3
0.5	-	-	-	-	-	13.8
0.4	-	-	-	-	-	-
0.3	-	-	-	-	-	-

LOAD-BEARING CAPACITY OF THE SLAB IN A NORMAL SITUATION

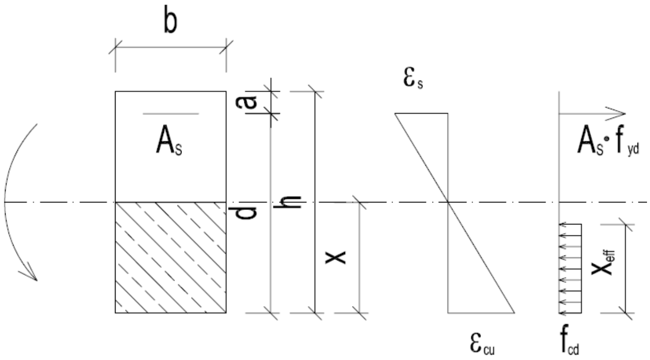

Figure 2 Forces in a section for a normal situation. Support zone

RESISTANCE WHEN BENDING

The load-bearing capacity has been determined using the simplified method of modelling a concrete cross-section, with single reinforcement, only subjected to bending. The equations for the balance of forces and moments (Fig. 2) are as follows [3]:

$$bx_{ff} f_{cd} = A_s f_{yd} \tag{1}$$

$$M_{Rd} = x_{eff} f_{cd} (d - \frac{x_{eff}}{2}) \tag{2}$$

After switching to dimensionless values, we obtain:

$$m_{Rd} = \alpha (1 - \frac{\alpha}{2}) \tag{3}$$

where:

$m_{Rd} = \dfrac{M_{Rd}}{f_{cd} bd^2}$ - dimensionless resistance of the cross-section to bending,

$\alpha = \xi_{eff} = \dfrac{x_{eff}}{d} = \dfrac{A_s f_{yd}}{bdf_{cd}}$ - reinforcement ratio.

In subsequent considerations it has been assumed that the cross-section was designed for 100%, i.e. that $m_{Ed} = m_{Rd}$. Reducing the force by the n_f factor results in a dimensionless load in a fire situation of $m_{Ed,fi} = n_f m_{Ed}$.

RESISTANCE WITH PUNCHING SHEAR

The anti-punching shear reinforcement does not lose its load-bearing capacity in a fire situation. As a result, the resistance with punching shear on the reinforced critical perimeters in a fire situation is the same as in a normal situation, even higher when reduction factors are omitted. Due to this, the article will compare non-reinforced critical perimeters.

According to [5], assuming there are no pre-stressing forces, the punching shear resistance is:

$$V_{Rd,c} = \frac{1}{\beta}\frac{0{,}18}{\gamma_c}\left(1 + \sqrt{\frac{200}{d}}\right)\sqrt[3]{100\rho_l f_{ck}}\, u\, d$$

where:

ρ_l – geometric mean of the reinforcement ratio,

u – critical perimeter length,

$\left(1 + \sqrt{\frac{200}{d}}\right)$ – but not more than 2.

The control perimeter depends on the dimensions of the column inducing punching shear on the ceiling. The larger the column's circumference, the less visible the effect of the useful height reduction is, so it has been assumed that the column exerting punching shear on the ceiling is relatively small and has a diameter of 10 cm, in which case $u = 2\pi(5 + 2d)$ (fig. 3).

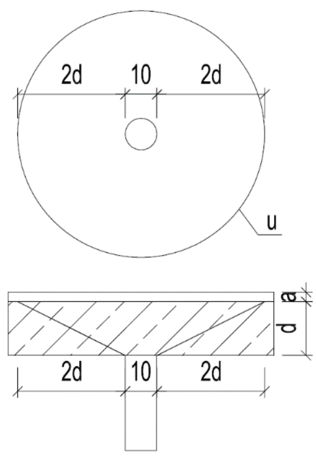

Figure 3 Computational critical perimeter for a round centre column of 10 cm. Punching of the ceiling under normal conditions

In subsequent considerations it has been assumed that the cross-section was designed for 100%, i.e. that $V_{Ed} = V_{Rd,c}$. Reducing the force by the n_f factor results in a dimensionless load in a fire situation $V_{Ed,fi} = V_{Ed} n_f$.

RESISTANCE OF THE SLAB IN A FIRE SITUATION

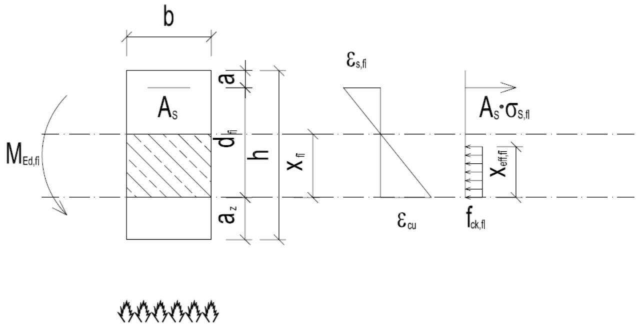

Figure 4 Forces in a section for a fire situation. Support zone

RESISTANCE WHEN BENDING

Similarly, for a fire situation (Fig. 4):

$$b\, x_{eff,fi}\, f_{ck} = A_s \sigma_{s,fi}; \quad \sigma_{s,fi} = p\, f_{yd,fi};$$

$$f_{yd,fi} = f_{yk}; \quad d_{fi} = d - a_z$$

$$M_{Rd,fi} = b\, x_{eff,fi}\, f_{ck} \left(d_{fi} - \frac{x_{eff,fi}}{2} \right)$$

After switching to dimensionless values, we obtain:

$$m_{Rd,fi} = \alpha\, \gamma_s\, p \left(1 - \frac{a_z}{d} - p\, \frac{\alpha\, \gamma_s}{2\, \gamma_c} \right)$$

where:

$m_{Rd,fi} = \dfrac{M_{Rd,fi}}{f_{cd} b d^2}$ – dimensionless resistance of the cross-section to bending in a fire situation,

$\sigma_{s,fi}$ – stresses in the reinforcement in a fire situation $p \in$,

p – reinforcement ratio use in a fire situation, ,

γ_c – concrete partial factor under normal conditions (according to EC2 = 1.4),

γ_s – steel partial factor under normal conditions (according to EC2 = 1.15).

The following set of equations was solved to determine p:

$$\begin{cases} \varepsilon_{s,fi} = \dfrac{\varepsilon_{cu} \left(d - a_z - \dfrac{x_{eff,fi}}{0,8} \right)}{\dfrac{x_{eff,fi}}{0,8}} \\ \sigma_{s,fi} = p\, f_{yk} \\ x_{eff,fi} = \alpha\, \dfrac{\gamma_s}{\gamma_c}\, p\, d \\ \sigma_{s,fi} = E\, \varepsilon_{s,fi} \end{cases}$$

RESISTANCE WITH PUNCHING SHEAR

According to [5], assuming there are no prestressing forces, the punching shear in a fire situation is as follows:

$$V_{Rd,c,fi} = \frac{1}{\beta} \frac{0,18}{1} \left(1 + \sqrt{\frac{200}{d - a_z}} \right) \sqrt[3]{100 \rho_l f_{ck}}\, u_{fi}\, (d - a_z)$$

The control perimeter depends on the dimensions of the column inducing punching shear on the ceiling. The larger the column's circumference, the less visible the effect of the useful height reduction is, so it has been assumed that the column exerting punching shear on the ceiling is relatively small and has a diameter of 10 cm, then $u = 2\pi\big(5 + 2(d - a_z)\big)$ (fig. 5).

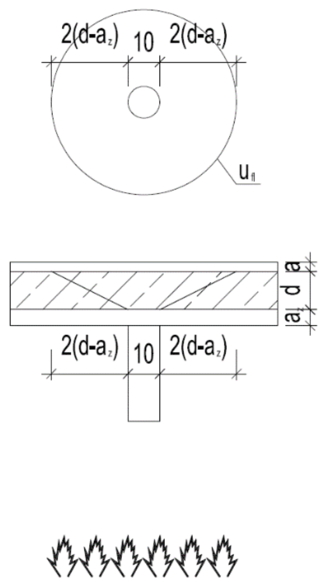

Figure 5 *Computational critical perimeter for a round centre column of 10 cm. Punching shear on the ceiling under a fire situation*

ANALYSIS RESULTS

Resistance under bending

Solving the system of equations (10) has resulted in resistance diagrams (Figs. 6-8) for usable slab heights of 12 cm, 15 cm and 22 cm. The horizontal axis indicates dimensionless reinforcement ratios, while the vertical axis denotes the dimensionless load-bearing capacity of the cross-section. If load-bearing capacity at a particular time in the fire, as represented by different colours of the diagrams, exceeds the charted maximum load, this indicates that a particular section has at least that level of fire resistance.

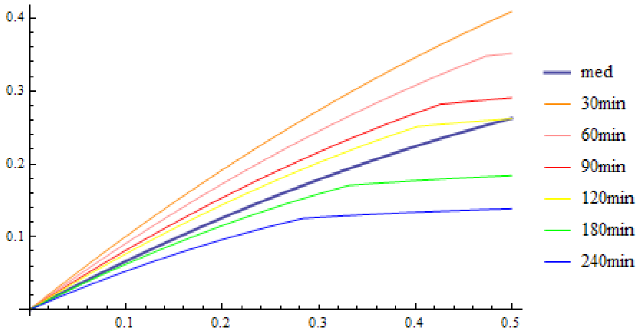

Figure 6 Fire resistance for d = 12 cm

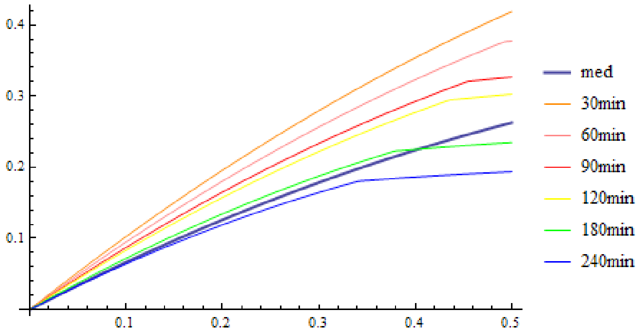

Figure 7 Fire resistance for d = 15 cm

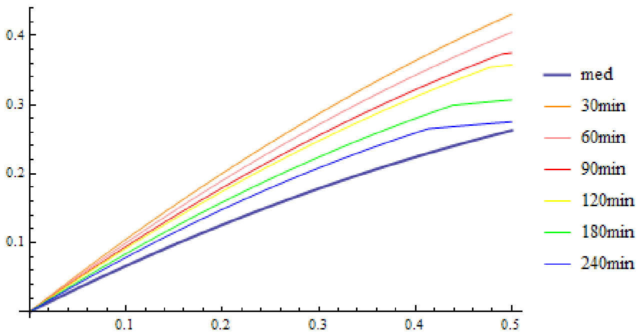

Figure 8 Fire resistance for a = 22 cm

The charts clearly show that for lower reinforcement ratios the cross-section belongs to a higher fire resistance class. To facilitate the use of the charts, tables (Tab. 1) showing the minimum useful heights allowing for a slab to be classified in a particular fire resistance class for given reinforcement ratios, have been prepared. Given that the assumed $n_f = 0.7$ is very restrictive, especially in the case of reinforced concrete slabs, for which the weight of the structure itself is significant, the resistance has also been distinguished for different values of this aforementioned factor.

Obviously, a responsible designer never designs a slab for 100% load, so the graphs can also be used and the fire resistance of the slab calculated using the formula $M_{Rd,fi} = m_{Rd,fi} f_{cd} bd^2$ and compared to the load in a fire situation equal to $M_{Ed,fi} = n_f M_{Ed}$. Given the iterative nature of the calculations (checking the maximum moment the cross-section is capable of transferring for subsequent minutes of exposure to fire), this is much more time-consuming and not recommended. It is recommended to assume an appropriate distance to the reinforcement's centre of gravity.

Resistance with punching shear

The complexity of the formulas means a decision has been made not to use dimensionless coordinates. Instead, the ratio of the punching shear in a fire situation versus the punching shear

$$\frac{V_{Rd,c,fi}}{V_{Ed,fi}}$$

was set at 1 (Figures 9-11). The graphs were prepared for a usable slab height of 12 cm, 15 cm and 22 cm. The horizontal axis denotes the time from the start of the fire, while the vertical axis shows the ratio of resistance to load.

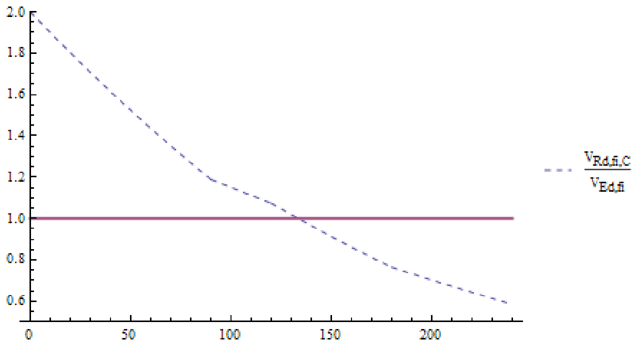

Figure 9 Fire resistance to load ratio for d = 12 cm

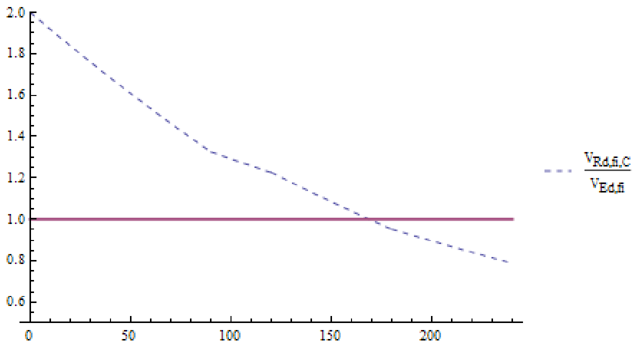

Figure 10 Fire resistance to load ratio for d = 15 cm

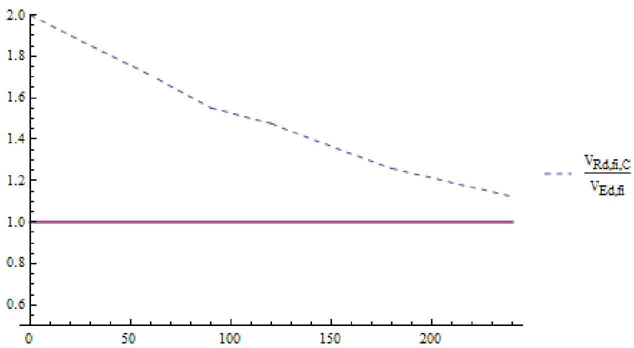

Figure 11 Fire resistance to load ratio for d = 22 cm

In order to facilitate the use of the charts, tables (Table 2) showing the maximum slab reinforcement ratios for a particular fire resistance class have been prepared. Given that the assumed $n_f = 0.7$ is very restrictive, especially in the case of reinforced concrete slabs, for which the weight of the structure itself is significant, the resistance has also been distinguished for different values of this aforementioned factor.

CONCLUSIONS

The study shows that fire resistance calculated according to the Isotherm 500 method largely corresponds to the tabular method given in EC [6]. More precise tables have been proposed, allowing for consideration of the reinforcement ratio that affects the fire resistance.
However, the analysis of the slabs along with the study [1] is complete.

LITERATURE

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