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CALCULATION OF TWO-WAY REINFORCED CONCRETE SLABS SUBJECTED TO FIRE

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Keywords: fire resistance; two-way reinforced concrete slabs; Isotherm 500 °C.

ABSTRACT

Reinforced concrete two-way slabs subjected to fire exposure from the top side or from the bottom side are discussed. The proposed design procedure is based on the method of redistribution of efforts of Prof. A. Gvozdev and simplified calculation method “Isotherm 500 °C” in BDS EN 1992-1-2. A numerical example is developed, on the basis of which conclusions and recommendations are made.

1. Introduction

Reinforced concrete structures should have a certain fire resistance and their members shall comply with criteria for load-bearing capacity (R), for integrity (E) and for insulation (I). The elements are designed to meet the requirements of one or several criteria.

Depending on the type, purpose and category of the building, the regulatory documents provide a minimum period of time during which each element must not reach the limit state of fire resistance. A fully developed fire model described by a standard temperature-time curve is usually used. Floor structures must satisfy all three criteria – R, E and I, during an exposure to fire and this report only considers the determination of the load bearing capacity of two-way slabs under fire exposure.

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2. Standards and methods for evaluating the fire resistance of reinforced concrete two-way slabs

Standards in the Republic of Bulgaria related to the fire protection requirements for reinforced concrete structures are Ordinance Iz-1971 [12] and BDS EN 1992-1-2 [3]. They include the following methods for evaluating the fire resistance of reinforced concrete elements and structures: by tests, by calculation and by comparison.

In Appendix 5 of [12], comparative results of experimental data are presented, through which the fire resistance limit of reinforced concrete slabs can be estimated. They can be used to estimate the fire resistance limit of reinforced concrete slabs. The analysis for two-way slabs can only be performed for concrete grade C16/20 with a limited number of proposed comparative results. No procedure is presented for the calculation of two-way slabs under fire.

In BDS EN 1992-1-2 [3], a tabular method for determining the fire resistance limit of one-way and two-way slabs subjected to standard fire is proposed. From Table 5.8 the minimum dimensions and axial distances a (from the center of gravity of load-bearing reinforcement in the first row to the concrete surface below, which is being heated directly) can be calculated for the limit of fire resistance for simply supported one-way and two-way solid slabs. The values in columns 2 and 4 of this table may also apply to one-way and two-way continuous slabs where the moment redistribution does not exceed 15 % for ambient temperature design. Otherwise, each span of the continuous slab should be assessed as a simply supported slab. In Appendix E of BDS EN 1992-1-2 [3], a simplified calculation procedure for continuous beams and one-way slabs is given, but two-way slabs are not commented on.

In regulatory documents: Brazilian Standard ABNT NBR 15200 [1], American Standard ACI-216.01-97 [2], British Standard BS 8110-2 [4], Indian Standard IS 1642 [7], New Zealand Standard NZS 3101 [11] and others, determination of the fire resistance of reinforced concrete slabs is mainly carried out by tabular methods.

The listed standards do not take into account the specific support conditions of the slab (simply supported end, fixed end or presence of a cantilevered span); the load in a fire situation from permanent (dead) and live loads; the type, quantity, diameter, location and concrete cover of the embedded reinforcement; the grade of concrete; the type of aggregates, etc.

In many scientific studies, the behavior of two-way slabs subjected to fire has been studied, analyzing the above-mentioned conditions unaffected by standards [5, 14, 15, etc]. The Bulgarian experience in evaluating the fire resistance of reinforced concrete slabs is presented in [8 – 10, 16, 17, etc].

This paper proposes a methodology for a more accurate determination of the time from the occurrence of uncontrolled burning to reaching the limit state of load-bearing capacity (R) for two-way slabs, taking into account the above-mentioned conditions.

3. Calculation of two-way slabs under fire exposure

The present proposal for calculation of reinforced concrete two-way slabs subjected to fire exposure and bending is based on the limit equilibrium method, also known as the Method of Redistribution of Efforts (MRE). The method is based on the inelastic behavior of reinforced concrete in ultimate limit state, which affects the distribution of bending moments in the slab. The formation of plastic joints occurs in the most loaded sections (at the supports and the center of the slab) and is caused by the yielding of the steel reinforcement and the rotation around a center located in the compression zone of the two adjacent sections along the crack formed in the tension zone. The calculation of the two-way slabs is complicated, because the support

conditions are usually not symmetrical, the reinforced concrete material is inhomogeneous, there are cracks in service state, etc. In 1944 Prof. A. Gvozdev [6] developed a simplified method for calculating two-way slabs at normal temperature, based on a symmetrical arrangement of the plastic joints in the slab, regardless of the magnitude of the supporting bending moments and cases of fixions.

As the fire develops and the temperature of the materials increases, their strength characteristics are reduced. During the exposure to fire from the bottom surface of a two-way fixed slab, the temperature of the lower reinforcement increases, the bearing capacity of the slab in the middle decreases, and the bending moments are redistributed to the sections with upper reinforcement (Fig. 1a). The process of redistribution depends on the inserted amount of reinforcement and continues until the bending capacity of the support sections of the plate is reached. When the fire is from the upper surface, the occurring processes are analogous, whereas the redistribution is from the support bending moments to the moments in the center of the slab until reaching the bending capacity of the sections (Fig. 1b).

The author has compiled a calculation procedure for the application of MRE for two-way slabs subjected to fire from the bottom and upper sides, based on the method developed by Prof. A. Gvozdev.

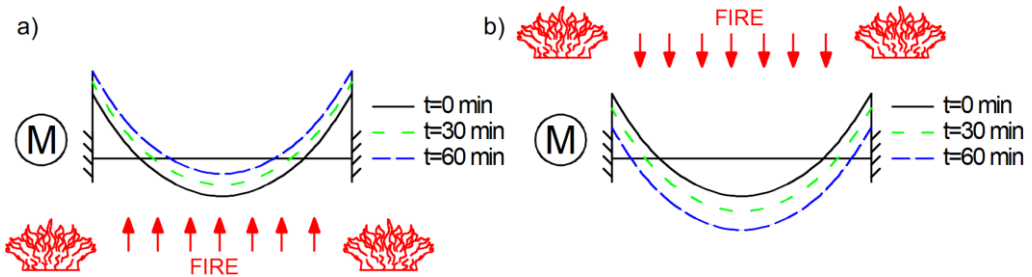


Figure 1. Cross section two-way slab - redistribution of bending moments during an exposure to fire from: a) bottom surface; b) upper surface

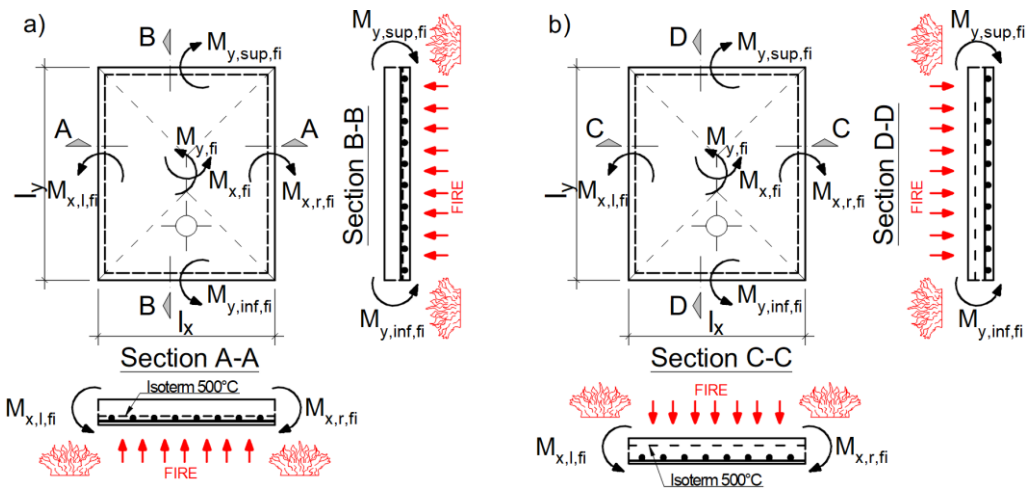


Figure 2. Scheme of two-way slab subjected to fire from: a) the bottom surface; b) the upper surface

The determination of bending moments is carried out by equalizing the work of external forces and internal efforts. The bending moment in the middle of the slab under the impact of fire $M_{x,fi}$ is determined by the other moments or their relations (Fig. 2):

$$M_{x,fi} = \frac{M_{o,fi} - \sum M_{xi,fi} - \sum M_{yi,fi} / \lambda}{m_{x,l,fi} + m_{x,r,fi} + 2 + (m_{y,sup,fi} + m_{y,inf,fi} + 2) \cdot c / \lambda}, \quad (1)$$

where:

$$M_{0,fi} = p_{fi} \cdot l_x / \alpha;$$

$M_{xi,fi}$ and $M_{yi,fi}$ are known support moments in between $M_{x,l,fi}$; $M_{x,r,fi}$; $M_{y,sup,fi}$;

$M_{y,inf,fi}$;

p_{fi} – full load on fire combination;

$$\alpha = 12 \cdot \lambda / (3 \cdot \lambda - 1) \text{ at } \lambda \geq 1; \alpha = 12 / \lambda \cdot (3 - \lambda) \text{ at } \lambda < 1;$$

$$m_{x,l,fi} = M_{x,l,fi} / M_{x,fi}; \quad m_{x,r,fi} = M_{x,r,fi} / M_{x,fi}; \quad m_{y,sup,fi} = M_{y,sup,fi} / M_{y,fi};$$

$$m_{y,inf,fi} = M_{y,inf,fi} / M_{y,fi}; \quad c = M_{y,fi} / M_{x,fi} = 1 / \lambda^2;$$

$$\lambda = l_y / l_x \text{ – ratio to the distances of the slab.}$$

When calculating for normal temperature, the ratios between the support bending moments and the moments in the center of the slab $m_{x,l}$; $m_{x,r}$; $m_{y,sup}$ и $m_{y,inf}$ are recommended to be in the range between 0,50 ÷ 2,0. It is expedient that the difference between the obtained results and those from elastic analysis is up to 30 %. When designing slabs for fire impact it is not necessary to limit the vertical deformations in the middle of the slab, as well as to control the rotation of the sections in the plastic joints, therefore the parameters $m_{x,l,fi}$; $m_{x,r,fi}$; $m_{y,sup,fi}$ and $m_{y,inf,fi}$ are not limited.

Bending design is performed according to the simplified calculation method “Isotherm 500 °C”, presented in BDS EN 1992-1-2 [3]. The method is based on the hypothesis that concrete with temperature higher than 500 °C is damaged and is ignored when calculating the bearing capacity of the section, and concrete with temperature below 500 °C is assumed to retain its full strength equal to that at temperature of 20 °C. The thickness of the damaged concrete a_z , from the directly heated surface of the section, is determined for the middle position of the isotherm 500 °C, using the temperature profiles given in Appendix A of [3] or in other specialized literature. The characteristic yield strength of the reinforcing steel at elevated temperatures $f_{sy}(\theta)$ is calculated based on the temperature θ_s at the center of gravity of the reinforcing bars and the reduction factor $k_s(\theta)$, which is determined according to [3]:

$$f_{sy}(\theta) = k_s(\theta) \cdot f_{yk}. \quad (2)$$

Design for bending moments of rectangular sections reinforced with single tensile reinforcement under fire impact from the lower or upper surface is carried out according to Fig. 3 and Fig. 4. The reduced yield strength of the reinforcing steel is taken into account in the calculations. The recommendations presented in [9], as well as the corresponding limit values in Table 1 of [9] are also taken into account.

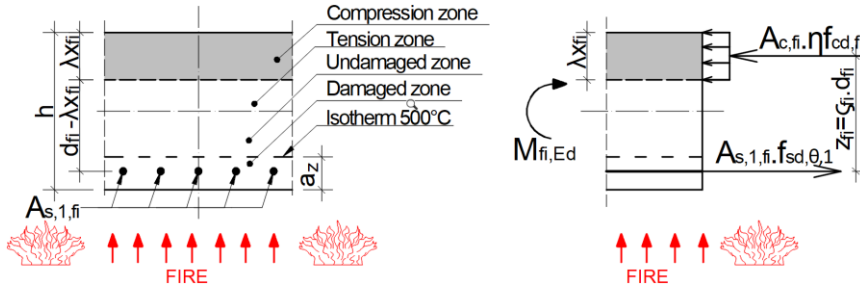


Figure 3. Bending design of a slab under fire exposure from the bottom surface

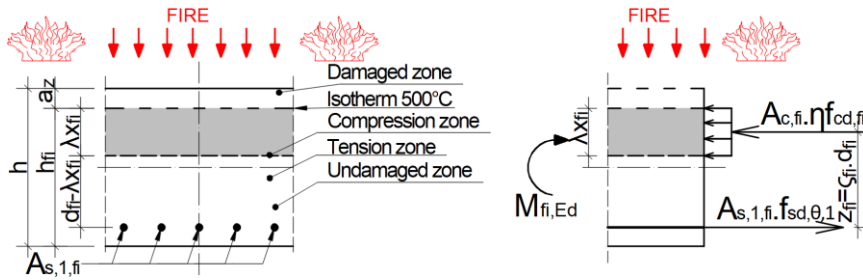


Figure 4. Bending design of a slab under fire exposure from the upper surface

The determination of the required steel reinforcement for a rectangular cross-section in fire condition is calculated by the formula:

$$A_{s,req,fi} = \frac{M_{i,fi}}{\zeta_{fi} \cdot d_{i,fi} \cdot f_{sy}(\theta)}, \quad (3)$$

where ζ_{fi} is reported by [13] for $m_{Ed,fi} = \frac{M_{i,fi}}{b_{fi} \cdot d_{i,fi}^2 \cdot f_{cd,fi}}$, and $d_{i,fi}$ is effective depth of the slab for lower or upper reinforcement layers.

The stresses in reinforcing steel are determined, taking into account the required $A_{s,req,i,fi}$ and inserted $A_{s,i,prov}$ amount of reinforcing steel:

$$\sigma_{sy,i}(\theta) = f_{sy,i}(\theta) \cdot \frac{A_{s,req,i,fi}}{A_{s,prov,i}}. \quad (4)$$

The compiled program procedure determines the coefficients $m_{x,l,fi}$, $m_{x,r,fi}$, $m_{y,sup,fi}$ and $m_{y,inf,fi}$ through iterations, and in order to simplify the calculations, the same value of all parameters is assumed. The limiting condition for determining their value is:

$$\sigma_{sy,i}(\theta) \leq f_{sy,i}(\theta). \quad (5)$$

In addition to bending design of the slab, it is necessary to carry out checks to determine the load-bearing capacity of shear under fire according to [3, 10].

4. Numerical example

The bearing capacity of a four-sided fixed slab subjected to standard fire impact from the bottom and separately from the upper surfaces is investigated with developed iterative procedure for 90 min. The clear dimensions in plan are $\ell_x = 500$ cm and $\ell_y = 600$ cm, and the thickness of the slab is 12 cm. The embedded reinforcement in the slab is presented in Fig. 5. The total characteristic dead loads from the slab's self-weight $g_{k,1}$ and super dead loads $g_{k,2}$ are $g_k = g_{k,1} + g_{k,2} = 3,00 + 1,50 = 4,50$ kPa, and live loads $-q_k = 5,00$ kPa. The coefficient for combining live loads in a fire situation is $\psi_2 = 0,60$. The reinforcement inserted in the slab is determined for long-term and short-term calculation situations (design at normal temperature – DNT), and is presented in Fig. 5, the concrete cover of the outer row of bars is 25 mm. The materials used are: concrete grade C20/25 and reinforcing steel grade B500.

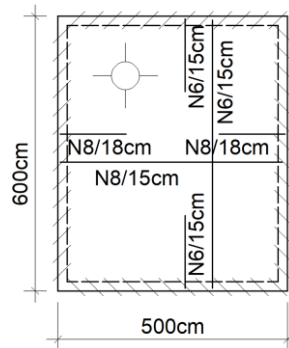


Figure 5. Embedded reinforcement $A_{s,prov,i}$

Based on the above procedure, the numerical example was calculated and the results are presented in Table 1 and Table 2.

Table 1. Fire results from the bottom surface

	Stresses in the longitudinal reinforcement [MPa]				
	DNT	$t = 0$ min	$t = 30$ min	$t = 60$ min	$t = 90$ min
1	2	3	4	5	6
Bottom reinforcement in "X" direction	337,8	180,9	180,9	180,9	144,2
Bottom reinforcement in "Y" direction	414,3	224,1	224,1	224,1	178,9

Maximum stress for bottom reinforcement	434,8	500,0	405,1	298,0	179,3
Top reinforcement in "X" direction	411,5	220,3	259,2	295,5	424,7
Top reinforcement in "Y" direction	414,3	224,1	263,1	299,3	427,1
Maximum stress for top reinforcement	434,8	500,0	500,0	500,0	500,0

Table 2. Fire results from the upper surface

	Stresses in the longitudinal reinforcement [MPa]				
	DNT	$t = 0$ min	$t = 30$ min	$t = 60$ min	$t = 90$ min
1	2	3	4	5	6
Bottom reinforcement in "X" direction	337,8	180,9	212,8	242,6	350,1
Bottom reinforcement in "Y" direction	414,3	224,1	263,1	299,3	428,9
Maximum stress for bottom reinforcement	434,8	500,0	500,0	500,0	500,0
Top reinforcement in "X" direction	411,5	220,3	220,3	220,3	174,6
Top reinforcement in "Y" direction	414,3	224,1	224,1	224,1	177,8
Maximum stress for top reinforcement	434,8	500,0	405,1	298,0	179,3

From the results presented in Table 1 and Table 2, it is observed that the stresses in the reinforcing steel in long-term and short-term calculation situations, i.e. in the calculation combination $1,35 \cdot g_k + 1,50 \cdot q_k$ (design for normal temperature – DNT), are lower than the calculation stresses at the yield point $f_{sd} = 434,8$ MPa. At the time of occurrence of the fire impact ($t = 0$ min), the stresses in the reinforcing steel have significantly smaller values, due to the reduced loads in case of fire calculation combination – $1,00 \cdot g_k + 0,60 \cdot q_k$. After the start of the fire, the stresses in the reinforcement from the heated surface remain constant during a 60-minute fire exposure. As the fire develops and reaching the maximum stresses $f_{sy,i}(\theta)$ for the corresponding steel temperature, the compiled procedure determines the values of the coefficients $m_{x,l,fi}$, $m_{x,r,fi}$, $m_{y,sup,fi}$ and $m_{y,inf,fi}$ through iterations so that condition (5) is satisfied. The stresses in the steel on the unheated surface increase as the fire progresses due to compromising the concrete on the compression zone and reducing effective depth of the slab. Upon reaching the maximum stresses in the heated reinforcement and the subsequent redistribution of the bending moments in the system, the stresses in the reinforcement from the unheated surface increase.

From the data presented in Table 1 and Table 2, it can be concluded that the plate satisfies the criteria for load-bearing capacity for 90 min standard fire impact from the lower or upper surface.

6. Conclusions and recommendations

On the basis of the present research, the following main conclusions and recommendations can be made for the design of two-way slabs in case of fire:

- the standards [3 and 12], offer tabular data and comparative analysis for quick and easy determination of the fire resistance limit of two-way slabs, but these methods do not take into account the specific support conditions of each support on the slab

(simply supported end, fixed end or presence of a cantilevered span); the load in a fire situation from permanent (dead) and live loads; the type, quantity, diameter, location and concrete cover of the embedded reinforcement; the grade of concrete; the type of aggregates, etc.

- if there is a need for increased accuracy in determining the fire resistance limit of two-way slabs under fire impact from the upper or lower surfaces, the proposed procedure developed on the basis of the MRE of Prof. A. Gvozdev [6] and the “Isotherm 500 °C” method, given in BDS EN 1992-1-2 [3], can be applied.

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ИЗСЛЕДВАНЕ НА КРЪСТОСАНО АРМИРАНИ ПЛОЧИ, ПОДЛОЖЕНИ НА ПОЖАРНО ВЪЗДЕЙСТВИЕ

Хр. Нешев¹

Ключови думи: *пожарно въздействие; стоманобетонни кръстосано армирани плочи; Изотерма 500 °C.*

РЕЗЮМЕ

В настоящия доклад е изготвено предложение за процедура за изчисляване на кръстосано армирани плочи, подложени на пожарно въздействие откъм горната или откъм долната повърхност. Оразмерителната процедура е базирана на метода на преразпределение на усилията (МПУ) на проф. А. Гвоздев и метод „Изотерма 500 °C“, който е представен в БДС EN 1992-1-2. Решен е изчислителен пример и са направени изводи, сравнения и препоръки за практическо приложение.

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