OTPORNOST NA POŽAR ARMIRANOBETONSKIH PLOČA PREMA EC2 I BRANZ TR8

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Rezime:

Betonski elementi su praktično integralni dio svakog građevinskog objekta. Imaju značajno veću otpornost na požar u poređenju sa elementima konstrukcije izrađenih od drugih građevinskih materijala. Međutim, armiranobetonske ploče su najosjetljiviji armiranobetonski elementi u požarnim uslovima u poređenju sa drugim armiranobetonskim elementima. U tom smislu, ovo istraživanje je usmjereno na određivanje otpornosti na požar armiranobetonskih ploča prema Tabelarnom metodu za određivanje otpornosti na požar betonskih elemenata iz BAS EN 1992-1-2:2017, Eurokod 2: Projektovanje betonskih konstrukcija - Dio 1-2: Opšta pravila - Projektovanje otpornosti konstrukcija na djelovanje požara i BRANZ Tehničkoj preporuci br. 8 - Metodu za određivanje otpornosti na požar betonskih greda i međuspratnih konstrukcija. Požarno dejstvo na armiranobetonske ploče je modelirano Standardnim požarom ISO 834 (BAS EN 1991-1-2:2015). U ovom istraživanju razmatra se otpornost na požar armiranobetonskih ploča statičkog sistema proste grede, različitih raspona, debljina i uz varijacuju debljine zaštitnog sloja betona do armature.

Ključne riječi: Armiranobetonske ploče, Otpornost na požar, Zaštitni sloj betona

FIRE RESISTANCE OF REINFORCED CONCRETE SLABS ACCORDING TO EC2 AND BRANZ TR8

Abstract:

Concrete elements are practically an integral part of every construction project and building. They have significantly higher fire resistance in comparison to elements made of other construction materials. However, RC slabs are the most sensitive concrete elements to the effects of fire when compared to all the other reinforced concrete elements. Therefore, this research focuses on determining the fire resistance of RC slabs using Method for determining fire resistance of slabs BAS EN 1992-1-2:2017, Eurocode 2, Design of concrete structures, Part 1-2: Structural fire design (Tabulated Data) and BRANZ Technical recommendation No. 8 – Method for Fire Engineering Design of Structural Concrete Beams and Floor Systems. A fire action to RC slabs is modeled using standard fire ISO 834-1 (BAS EN 1991-1-2:2015). This research considers determining fire resistance of simply supported RC slabs of different spans and different depths with variations of concrete cover.

Keywords: RC slabs, Fire resistance, Concrete cover

1. INTRODUCTION

This research considers determining fire resistance of simply supported RC slabs of different spans (3, 5 and 7 m) and different depths (12, 15 and 17 cm) with variations of concrete cover ranging from 0.5 to 3 cm. Slabs were previously designed according to the BAS EN 1992-1-1:2017, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings [1], with permanent action consisting of slab self-weight and flooring of $1.5 \, kN/m^2$ and variable action of $2 \, kN/m^2$. The determination of fire resistance is conducted according to the Method for determining fire resistance of slabs BAS EN 1992-1-2:2017, Eurocode 2, Design of concrete structures, Part 1-2: Structural fire design (Tabulated Data) [2] and BRANZ Technical recommendation No. 8 – Method for Fire Engineering Design of Structural Concrete Beams and Floor Systems [3].

2. FIRE ACTION TO RC SLABS

The International Standard ISO 834-1, Fire Resistance Tests - Elements of Building Construction from 1999, is internationally accepted in Europe, Australia, New Zealand, and other countries, and it defines the standard temperature – time curve for fire modeling or exposure of test samples in test furnaces.

This standard is also accepted as BAS ISO 834-1 [4] in Bosnia and Herzegovina by the Institute for Standardization of Bosnia and Herzegovina, based upon the proposal of its Technical Committee BAS TC 37 – Fire Safety in Buildings. The curve is defined as:

$$T = 345 \, log_{10}(8t + 1) + 20 \tag{1}$$

where:

T - average temperature in the test furnace in ℃;
t - test time in minutes.

Figure 1. Standard Temperature-Time Curve ISO 834-1 [5]

Table 1 displays values of average furnace temperatures according to the ISO 834-1 temperature-time curve for different test times.

Table 1. Average Furnace Temperatures for Different Fire Test Times [5]

Time (t) [min]	Average Temperature in Furnace $T-T_0$ [°C]
5	556
10	659
15	718
30	821
60	925
90	986
120	1029
180	1090
240	1133
360	1193

3. EUROCODE 2: DESIGN OF CONCRETE STRUCTURES PART 1-2 – STRUCTURAL FIRE DESIGN - TABULATED DATA

BAS EN 1992-1-2:2017, Eurocode 2, Design of concrete structures, Part 1-2: Structural fire design [2], provides following three methods for determining the fire resistance of concrete structures:

- Tabulated data;
- Simplified calculation methods; and
- Advanced calculation methods. [5]

Fire performance of concrete elements and structures exposed to the nominal fire should be observed through three basic criteria:

- Mechanical resistance, load bearing function (Criterion R);
- Integrity, separating function (Criterion E); and
- Insulation (Criterion I).

BAS EN 1992-1-2:2017 defines that Criterion "R" is assumed to be satisfied when the load bearing function is maintained during the required time of fire exposure. The Criterion "E" (Integrity) is the ability of the separating element of the structure to prevent passing of flame and gases from one side to another side of the element when exposed to the standard fire from one side, thus preventing the occurrence of the flame on the unexposed side during the required time period. Criterion "I" may be assumed to be satisfied when the average temperature rise over the whole of the non-exposed surface is limited to 140 K, and the maximum temperature rise at any point of that surface does not exceed 180 K in consideration of the separating element of the structure when exposed to the standard fire from one side for the required time of fire exposure.

Required criteria for the observed element depend on the element's function in the building. For example, when it comes to slab, it must meet all three criteria R, E and I, while columns are usually expected to satisfy only the load-bearing function - Criterion R.

Tabulated Data method gives recognized design solutions for the standard fire exposure up to 240 minutes and applies to normal weight concrete (2000 to 2600 kg/m^3), made with siliceous aggregates.

The method is based on the determination of the axis distance of the reinforcement to the fire exposed side of the concrete element, and not on the thickness of the concrete cover, depending on the required period of fire resistance and the required function of the element. The following Figure defines the axial distance "a" from the centroid of the reinforcement to the fire exposed concrete face.
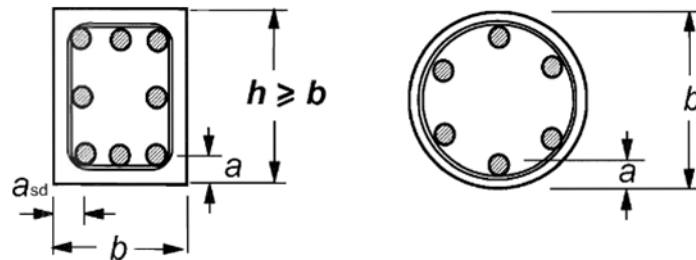

Figure 2. Axis Distance [2]

If calcareous aggregates or lightweight aggregates are used in slabs, minimum dimensions of the cross-section given in tables may be reduced by 10 percent. Minimum requirements tabulated in tables from the aspect of dimensions of the cross-section and the axial distance required to meet Criterion R have their origin from the following equation:

$$E_{d,fi}/R_{d,fi} \leq 1,0 \tag{2}$$

where

$E_{d,fi}$ - design effect of actions in the fire situation; and

$R_{d,fi}$ - design load-bearing capacity (resistance) in the fire situation.

Table 2. Minimum Dimensions and Axis Distance for Simply Supported Concrete Slabs [2]

Standard fire resistance	Minimum dimensions (mm)			
	slab thickness h_s (mm)	axis-distance a	two way:	
		one way	$l_y/l_x \leq 1,5$	$1,5 < l_y/l_x \leq 2$
1	2	3	4	5
REI 30	60	10*	10*	10*
REI 60	80	20	10*	15*
REI 90	100	30	15*	20
REI 120	120	40	20	25
REI 180	150	55	30	40
REI 240	175	65	40	50

l_x and l_y are the spans of a two-way slab (two directions at right angles) where l_y is the longer span.

For prestressed slabs the increase of axis distance according to 5.2(5) should be noted.

The axis distance *a* in Column 4 and 5 for two way slabs relate to slabs supported at all four edges. Otherwise, they should be treated as one-way spanning slab.

* Normally the cover required by EN 1992-1-1 will control.

Tabulated data are based on the reference load level $\eta_{fi} = 0.7$ unless otherwise stated. In order to ensure necessary axis distances in tensile zones of simply supported slabs, Table 3, Column 3 (one way), are based on a critical steel temperature of $\theta_{cr} = 500$ °C. This assumption corresponds approximately to $E_{d,fi} = 0.7\ E_d$ and $\gamma_s = 1,15$, where E_d denotes the design effect of actions according to BAS EN 1992-1-1:2017. The minimum slab thickness h_s given in Table 2 ensures adequate separating function (Criteria E and I).

4. BRANZ TECHNICAL RECOMMENDATION NO. 8 - METHOD FOR FIRE ENGINEERING DESIGN OF STRUCTURAL CONCRETE BEAMS AND FLOOR SYSTEMS

BRANZ – The Building Research Association of New Zealand, Technical Recommendation No. 8 from 1991 [3], provides a model for determining fire resistance of load-bearing beams and slabs made of reinforced or pre-stressed concrete, influenced by elevated temperatures. The basic design procedure was developed and verified through a large number of fire resistance tests of reinforced concrete elements sponsored by the Portland Cement Association - PCA. The significance of this method for determining fire resistance of concrete elements lies in its combination of the principles for determining the fire resistance given in ACI 216.1-97/ TMS 0216.1-97 [6], but also applies the standard temperature-time curve according to BAS ISO 834-1[4], for distinction from ACI 216.1-97/TMS 0216.1-97 which is based exclusively on the standard fire curve according to ASTM E 119 [7].

The foundation of this method is as follows: if the bending moment capacity of the slab is greater than or equal to the maximum applied bending moment $M_\theta^+ \geq M_a$, the slab has the required fire resistance; however, if the bending moment capacity of the slab is less than the maximum applied bending moment $M_\theta^+ < M_a$, then the slab does not fulfill requirements for the required fire resistance period.

Determination of the bending moment capacity M_θ^+ of the slab cross section, given after the required time of exposure to the fire is carried out according to the following equation:

$$M_\theta^+ = A_s \cdot f_{y\theta} \cdot \left(d_\theta - \frac{a_\theta}{2}\right) \tag{3}$$

where

M_θ^+ - bending moment capacity of the slab cross section;
A_s - cross sectional area of tensile reinforcing steel provided;
$f_{y\theta}$ - yield stress of reinforcing steel at the temperature θ;
d_θ - width of the compression stress block (1.0 m for slabs); and
a_θ - depth of the compression stress block.

Based on the nominal temperature of the tensile steel (θ), the yield strength of reinforcing steel at elevated temperatures is determined using the next equation:

$$\frac{f_{y\theta}}{f_y\ (20\ °C)} = \begin{cases} 1.0 & for\ \theta \leq 250\ °C \\[2mm] 1,53 - \dfrac{\theta}{470} & for\ \theta > 250\ °C \end{cases} \tag{4}$$

Since all methods for determining the fire resistance of reinforced concrete elements assume that the temperature of concrete and the temperature of the reinforcement are identical at the same position, diagram in Figure 3 can be used to determine the temperature of concrete and nominal temperature of tensile steel (θ).
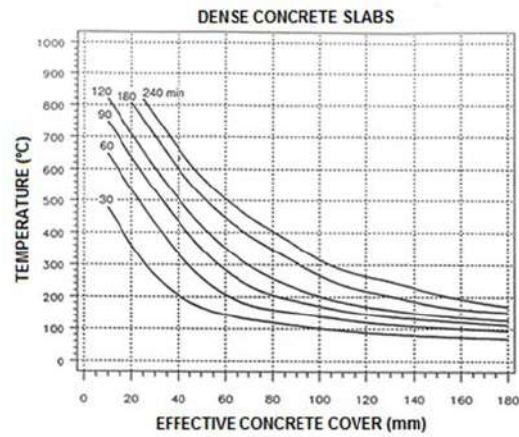

Figure 3. Determination of the Temperature of Reinforcing Steel [3]

Since the compression zone of slabs is not exposed to the fire, the width of compression block is equal to 1.0 m for slabs. The depth of the equivalent rectangular stress block a_θ is:

$$a_\theta = \frac{A_s \cdot f_{y\theta}}{0.85 \cdot f'_{c\theta} \cdot d_\theta}$$

(5)

where

$f'_{c\theta}$ - reduced compression strength of concrete at the temperature θ.

For determining the concrete strength at elevated temperatures, the diagram in next Figure can be used, where bilinear diagram "a" is for normal weight concrete and bilinear diagram "b" is for lightweight concrete.
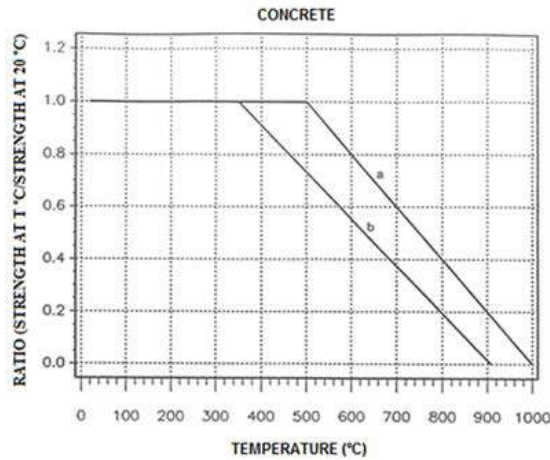
Figure 4. Ratio of Concrete Compression Strength at Elevated Temperatures [3]

According to this Technical Recommendation, but also many other regulations, the partial safety coefficient for permanent action in the fire environment is equal to 1.0. The safety factor for the variable action in case of fire for floors (domestic, office, parking and trafficable roofs) is 0.4; for floors in storages and other structures, it is 0.6, and 0 for non-trafficable roofs. Thus, design action in fire conditions is:

$$w = 1{,}0 \cdot g + \gamma_p \cdot p \tag{6}$$

where:

w - design action of the slab;
g - permanent action of the slab;
γ_p - safety factor for variable action in fire conditions;
p - variable action of the slab.

Then, the maximum applied bending moment to the simply supported slab with uniformly distributed load is:

$$M_a = \frac{w \cdot l^2}{8} \tag{7}$$

where

M_a - maximum applied bending moment to the simply supported slab with
     uniformly distributed load;
w - design action of the slab;
l - effective span of the slab.

5. FIRE RESISTANCE DETERMINATION OF RC SLABS

For the researching purposes, simply supported RC concrete slabs with spans of 3.0 m, 5.0 m, and 7.0 m were considered. Depths of slabs are 12, 15 and 17 cm respectively. All

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slabs were designed according to BAS EN 1992-1-1:2017, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings [1]. Actions taken into consideration are self-weight of slabs, flooring (1.5 kN/m^2), and variable load of 2 kN/m^2. Different concrete classes were used for each slab: C 20/25, C 30/37 and C 40/50. A concrete cover was also variated for each slab: 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 cm. It should be noted that thicknesses of the concrete cover of 0.5 and 1.0 cm are not allowed for slabs according to Eurocode 2, Part 1-1 [1]. However, given the construction situation in Bosnia and Herzegovina, it is not rare to encounter very thin concrete covers, or virtually no concrete covers at all in the actual construction practice, due to failure of the contractor involved, or poor site inspection of the construction sites, so it is interesting to assess the fire resistance of such slabs.

All slabs were reinforced by welded ribbed meshes made of steel grade B500A, Ductility Class A, Yield = Re 500 MPa, or by straight ribbed bars made of steel grades B500A or St-500-b.

All slabs were exposed to the Standard Fire Curve ISO 834-1 [4] for determining fire resistance according to BAS EN 1992-1-2:2017, Eurocode 2, Design of concrete structures, Part 1-2: Structural fire design - Tabulated data [2] and BRANZ Technical Recommendation No. 8 – Method for Fire Engineering Design of Structural Concrete Beams and Floor Systems [3].

The results of fire resistance of RC slabs according to different methods are presented in Tables 3-11.

Table 3. Fire Resistance of RC Slab, Span 3 m, Depth 12 cm, C20/25

FIRE RESISTANCE OF SLAB depth 12 cm, span 3 m, C 20/25 $q_{Ed} = 9.075$ kN/m^2						
Concrete cover (cm)	a_S (cm)	$M_{Ed,fi}$ (kNm/m')	Reinforcement	Bar diameter (mm)	EN 1992-1-2 Tabulated data	BRANZ TR8
0.5	0.825		R 221	6.5	R$_\varnothing$	0 min
1.0	1.275		R 238	5.5	R 30	30 min
1.5	1.850	7.14	R 257	7.0	R 30	30 min
2.0	2.350		R 257	7.0	R 60	60 min
2.5	2.800		R 283	6.0	R 60	60 min
3.0	3.325		R 332	6.5	R 90	90 min

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Table 4. Fire Resistance of RC Slab, Span 3 m, Depth 12 cm, C30/37

FIRE RESISTANCE OF SLAB depth 12 cm, span 3 m, C 30/37 $q_{Ed} = 9.075$ kN/m^2						
Concrete cover (cm)	a_S (cm)	$M_{Ed,fi}$ (kNm/m')	Reinforcement	Bar diameter (mm)	EN 1992-1-2 Tabulated data	BRANZ TR8
0.5	0.825		R 221	6.5	R$_\infty$	0 min
1.0	1.275		R 238	5.5	R 30	30 min
1.5	1.850		R 257	7.0	R 30	30 min
2.0	2.350	7.14	R 257	7.0	R 60	60 min
2.5	2.800		R 283	6.0	R 60	60 min
3.0	3.325		R 332	6.5	R 90	90 min

Table 5. Fire Resistance of RC Slab, Span 3 m, Depth 12 cm, C40/50

FIRE RESISTANCE OF SLAB depth 12 cm, span 3 m, C 40/50 $q_{Ed} = 9.075$ kN/m^2						
Concrete cover (cm)	a_S (cm)	$M_{Ed,fi}$ (kNm/m')	Reinforcement	Bar diameter (mm)	EN 1992-1-2 Tabulated data	BRANZ TR8
0.5	0.825		R 221	6.5	R$_\infty$	0 min
1.0	1.275		R 238	5.5	R 30	30 min
1.5	1.775		R 238	5.5	R 30	30 min
2.0	2.350	7.14	R 257	7.0	R 60	60 min
2.5	2.800		R 283	6.0	R 60	60 min
3.0	3.300		R 283	6.0	R 90	60 min

Table 6. Fire Resistance of RC slab, Span 5 m, Depth 15 cm, C20/25

FIRE RESISTANCE OF SLAB depth 15 cm, span 5 m, C 20/25 $q_{Ed} = 10.08$ kN/m^2						
Concrete cover (cm)	a_S (cm)	$M_{Ed,fi}$ (kNm/m')	Reinforcement	Bar diameter (mm)	EN 1992-1-2 Tabulated data	BRANZ TR8
0.5	0.950		R 636	9	R$_\infty$	30 min
1.0	1.450		R 636	9	R 30	30 min
1.5	0.195		R 636	9	R 30	30 min
2.0	2.450	22.03	R 636	9	R 60	60 min
2.5	3.000		R 785	10	R 90	60 min
3.0	3.500		R 785	10	R 90	90 min

Table 7. Fire Resistance of RC Slab, Span 5 m, Depth 15 cm, C30/37

FIRE RESISTANCE OF SLAB depth 15 cm, span 5 m, C 30/37 $q_{Ed} = 10.08$ kN/m²						
Concrete cover (cm)	a$_S$ (cm)	M$_{Ed,fi}$ (kNm/m')	Reinforcement	Bar diameter (mm)	EN 1992-1-2 Tabulated data	BRANZ TR8
0.5	0.95		R 636	9	R$_\emptyset$	30 min
1.0	1.45		R 636	9	R 30	30 min
1.5	1.95	22.03	R 636	9	R 60	30 min
2.0	2.50		R 785	10	R 90	90 min
2.5	3.00		R 785	10	R 90	90 min
3.0	3.50		R 785	10	R 90	90 min

Table 8. Fire Resistance of RC slab, Span 5 m, Depth 15 cm, C40/50

FIRE RESISTANCE OF SLAB depth 15 cm, span 5 m, C 40/50 $q_{Ed} = 10.08$ kN/m²						
Concrete cover (cm)	a$_S$ (cm)	M$_{Ed,fi}$ (kNm/m')	Reinforcement	Bar diameter (mm)	EN 1992-1-2 Tabulated data	BRANZ TR8
0.5	0.95		R 636	9	R$_\emptyset$	30 min
1.0	1.45		R 636	9	R 30	30 min
1.5	1.95	22.03	R 636	9	R 30	30 min
2.0	2.50		R 636	9	R 60	60 min
2.5	3.00		R 785	10	R 90	60 min
3.0	3.50		R 785	10	R 90	90 min

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Table 9. Fire Resistance of RC Slab, Span 7 m, Depth 17 cm, C20/25

			FIRE RESISTANCE OF SLAB **depth 17 cm, span 7 m, C 20/25** $q_{Ed} = 10.76 \text{ kN/m}^2$				
Concrete cover (cm)	**a_S (cm)**	**$M_{Ed,fi}$ (kNm/m')**	**Reinforcement**	**Bar diameter (mm)**	**EN 1992-1-2 Tabulated data**	**BRANZ TR8**
0.5	1.10		R 1130	12	R 30	30 min
1.0	1.60		R 1130	12	R 30	30 min
1.5	2.20		Ø14/12,5 cm	14	R 60	60 min
2.0	2.70	46.12	Ø14/12,5 cm	14	R 60	60 min
2.5	3.20		Ø14/10 cm	14	R 90	90 min
3.0	3.70		Ø14/10 cm	14	R 90	90 min

Table 10. Fire Resistance of RC Slab, Span 7 m, Depth 17 cm, C30/37

			FIRE RESISTANCE OF SLAB **depth 17 cm, span 7 m, C 30/37** $q_{Ed} = 10.76 \text{ kN/m}^2$				
Concrete cover (cm)	**a_S (cm)**	**$M_{Ed,fi}$ (kNm/m')**	**Reinforcement**	**Bar diameter (mm)**	**EN 1992-1-2 Tabulated data**	**BRANZ TR8**
0.5	1.10		R 1130	12	R 30	30 min
1.0	1.60		R 1130	12	R 30	30 min
1.5	2.20		R 1130	12	R 60	30 min
2.0	2.70	46.12	Ø14/12,5 cm	14	R 60	60 min
2.5	3.20		Ø14/12,5 cm	14	R 90	60 min
3.0	3.70		Ø14/10 cm	14	R 90	90 min

Table 11. Fire Resistance of RC Slab, Span 7 m, Depth 17 cm, C40/45

FIRE RESISTANCE OF SLAB depth 17 cm, span 7 m, C 40/50 $q_{Ed} = 10.76$ kN/m^2						
Concrete cover (cm)	a_S (cm)	$M_{Ed,fi}$ (kNm/m')	Reinforcement	Bar diameter (mm)	EN 1992-1-2 Tabulated data	BRANZ TR8
0.5	1.10		R 1130	12	R30	30 min
1.0	1.60		R 1130	12	R 30	30 min
1.5	2.10		R 1130	12	R 60	30 min
2.0	2.60	46.12	R 1130	12	R 60	60 min
2.5	3.20		Ø14/12,5 cm	14	R 90	60 min
3.0	3.70		Ø14/10 cm	14	R 120	90 min

6. CONCLUSION

This parallel comparison research for determining fire resistance of reinforced concrete slabs of different spans and depths, made of three different concrete classes, with variations of concrete covers ranging from 0.5 m to 3.0 cm, using two different methods, provided the following results:

- Fire resistance periods of RC slabs considered and determined by two different methods were similar, but not the same. However, maximum difference in fire resistance periods was up to 30 minutes;
- In majority of cases, BRANZ TR 8 had the same fire resistance periods as determined by EN 1992-1-2 Tabulated Data Method. The difference was not more than 30 minutes, but mainly was more conservative when using BRANZ TR8;
- The research also confirmed the fact that concrete class had minor influence on the fire resistance period of slabs, while thickness of concrete cover significantly affected the period of fire resistance of slabs;
- Maximum fire resistance period of slabs observed in this research was 120 minutes.

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