FIRE RESISTANCE OF RC SLABS ACCORDING TO ACI/TMS 216.1 AND EC2 – POSSIBILITY FOR COMPARISON -

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Summary: *RC slabs are the most sensitive concrete elements to the effects of fire in comparison to all other reinforced concrete elements. Therefore, this research focuses on determining the fire resistance of RC slabs using Method for Determining Fire Resistance of Slabs EN 1992-1-2:2004, Eurocode 2, Design of Concrete Structures, Part 1-2: Structural Fire Design (Simplified Method for Beams and Slabs) and ACI/TMS 216.1 – Code for Determining Fire Resistance of Concrete and Masonry Construction Assemblies. A fire action to RC slabs is modeled using standard fire ISO 834-1 for EN 1991-1-2 and ASTM E 119 for ACI/TMS 216.1. 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 focuses on determining the fire resistance of RC slabs using EN 1992-1-2: 2004, Eurocode 2, Design of concrete structures, Part 1-2: Structural fire design (Simplified Method for Beams and Slabs) and ACI/TMS 216.1 – Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies.
A fire action to RC slabs is modeled using standard fires ISO 834-1 and ASTM E 119 E, depending on the method used for fire resistance determination.
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 EN 1992-1-1, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings, with permanent action consisting of slab self-weight and flooring of 1.5 kN/m^2 and variable action of 2 kN/m^2.
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.

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2. MODELLING OF FIRE ACTION

EN 1991-1-2 enables modeling of fire action for determination of fire resistance using Standard temperature-time fire curve according to ISO 834-1.This curve is defined as:

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

where:

T - average temperature in the test furnace in °C,
t - test time in minutes.

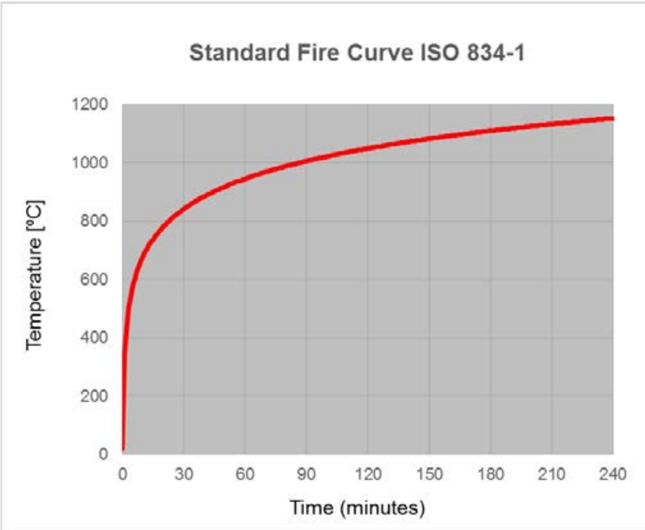

Figure 1 – Standard Temperature-Time Curve ISO 834-1

This fire curve is used in this research as fire action for determination of fire resistance of RC slabs according to the EN 1992-1-2: 2004, Eurocode 2, Design of concrete structures, Part 1-2: Structural fire design, Simplified Method for Beams and Slabs.
The standard fire curve used in the USA is the Standard Fire Curve Temperature-Time ASTM E 119. It is presented with a number of discrete points as shown in the following table. Lie [6] gave several equations that mathematically approximate the ASTM E 119 curve, where the simplest one gives the temperature in function of time through the following relationship:

$$T = 750\left[1 - e^{-3.79553\sqrt{t_h}}\right] + 170.41\sqrt{t_h} + T_0 \tag{2}$$

where
t_h - test time expressed in hours.
Figure 2 illustrates the given relationship.

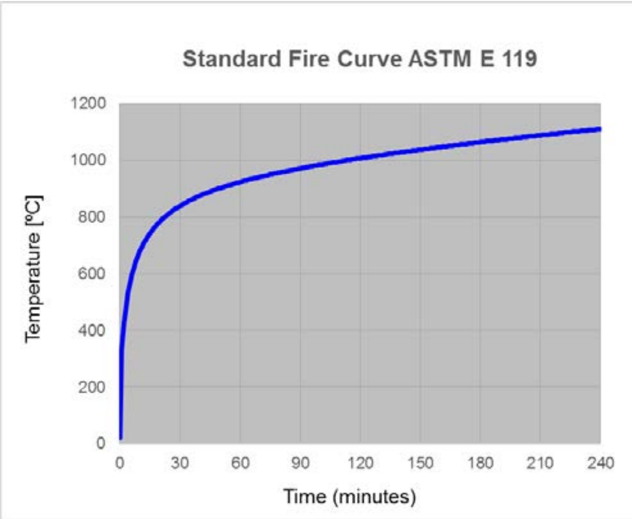

Figure 2 – Standard Temperature-Time Curve ASTM E 119

Standard Temperature-Time Curve ASTM E 119 is used in this research for fire resistance determination according to ACI/TMS 216.1 – Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies.
These two standard fire curves are not identical; however there are no significant differences in temperature development, what can be noticed from Figure 3.

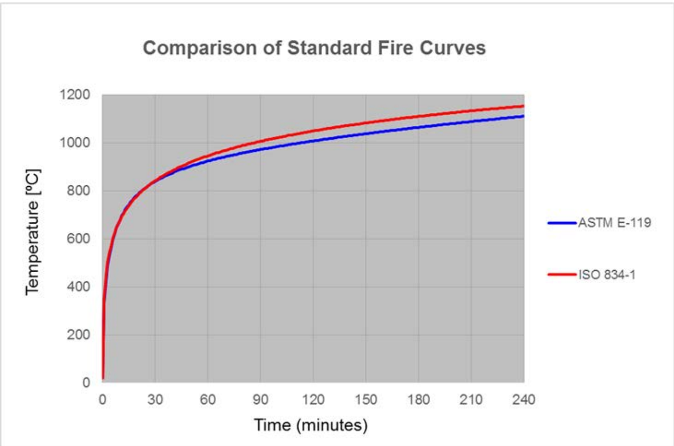

Figure 3 – Compasrison of Standard Temperature-Time Curves ISO 834-1 and ASTM E 119

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

The simplified calculation procedure for beams and slabs given in Eurocode 2, Part 1-2, Annex E, applies to beams and slabs, where the load is predominantly uniformly distributed and where the ambient temperature design is based on a linear analysis or on a linear analysis with limited redistribution.
This method is practically a continuation of the tabular method for beams exposed to the fire on three sides and on slabs in order to determine the bending capacity in situations where the axial distance to the bottom reinforcement is shorter than the one required in the tables.
Steel strength reduction factors used in this method are presented in*Figure 4*.
The main guideline of this procedure is to ensure that the design bending moment in fire conditions is less than or equal to the cross-sectional moment capacity in the fire situation:

$$M_{Ed,fi} \leq M_{Rd,fi} \quad (3)$$

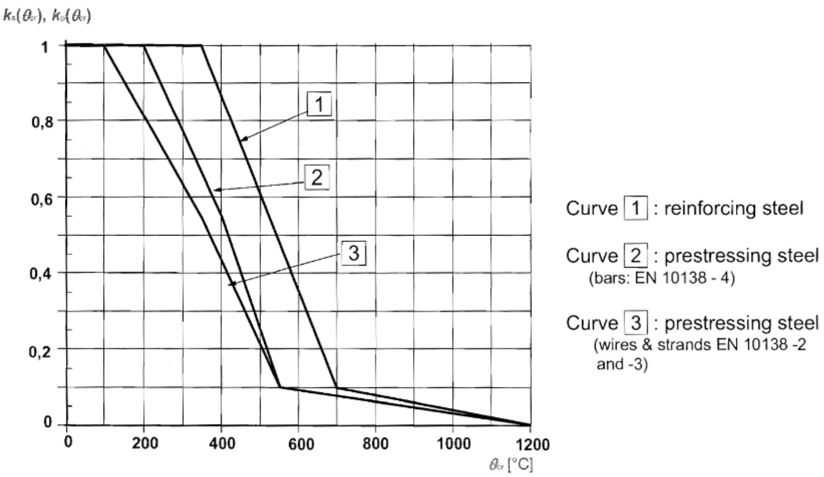

Figure 4 – Steel Strength Reduction Factors [14]

In the focus of this research are simply supported reinforced concrete one-way slabs, thus, fire design moment for predominantly uniformly distributed load is:

$$M_{Ed,fi} = w_{Ed,fi} \cdot l_{eff}^2/8 \quad (4)$$

where

$w_{Ed,fi}$ - uniformly distributed load in the fire situation;
l_{eff} - effectivelength of the slab.
For the simply supported slab, the moment of resistance in the fire situation is determined according to the following relationship:

$$M_{Rd,fi} = (\gamma_s/\gamma_{s,fi}) \cdot k_s(\theta) \cdot M_{Ed} \cdot (A_{s,prov}/A_{s,req}) (5)$$

where

γ_s - the partial safety factor for steel used in EN 1992-1-1;

$\gamma_{s,fi}$ - the partial safety factor for steel in fire conditions;

$k_s(\theta)$- a steel strength reduction factor for the given temperature θ for the required time of fire resistance;

M_{Ed} - the applied moment for ambient temperature design according to EN 1992-1-1;

$A_{s,prov}$ - the cross-sectional area of tensile steel provided; and

$A_{s,req}$ - the cross-sectional area of tensile steel required for the design at the ambient temperature according to EN 1992-1-1.

In this calculation, ratio $A_{s,prov}/A_{s,req}$ should not be greater than 1.3.

Fordetermining the steel strength reduction factor $k_s(\theta)$ at the temperature θ for the required fire resistance period, it is necessary to establish the temperature of the reinforcement θ first. [5] Considering that the temperature of the steel reinforcement is assumed to be the same as the temperature of concrete in the observed fiber of the cross section, then the temperature of steel θ can be determined based upon temperature profiles for slabs given in Annex A, EN 1992-1-2: 2004, shown in the following *Figure*.

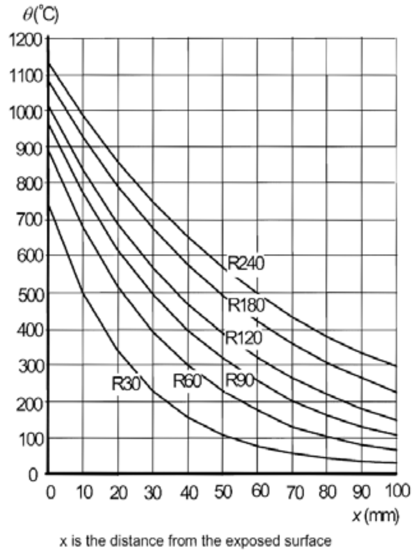

Figure 5 – Temperature Profiles for Slabs (height 200 mm)[14]

4. ACI/TMS 216.1 - CODE REQUIREMENTS FOR DETERMINING FIRE RESISTANCE OF CONCRETE AND MASONRY CONSTRUCTION ASSEMBLIES

If the reinforcement is straight and equal along the entire span of the slab, then the moment capacity is also equal along the entire span of the slab, and it is:

$$M_n = A_s \cdot f_y \cdot \left(d - \frac{a}{2}\right) \quad (6)$$

where

A_s – cross sectional area of reinforcement provided;

f_y – characteristic yield strength of the reinforcing steel;

d - is the distance between the centroid of the reinforcing steel to the extreme compressive fiber;

a - is the depth of the equivalent rectangular compressive stress block at ultimate load.

The depth of the equivalent rectangular compressive stress block at the ultimate load can be determined as:

$$a = A_s \cdot f_y \cdot (0.85 \cdot f_c' \cdot b) (7)$$

where

f_c' - characteristic cylinder compressive strength of concrete;

b- 1.0 m for slabs.

If the slab is uniformly loaded, the moment diagram will be parabolic with a maximum value at midspan:

$$M = \frac{w \cdot l^2}{8} (8)$$

where l is the span length and w is defined according to the Appendix C2.5 from ASCE 07, Minimum Design Loads for Buildings and Other Structures. This proposes load combinations for checking the capacity of a structure or structural element to withstand the effect of extraordinary events such as fires, which is characterized by low probability of occurrence and usually short duration. Load combinations include the following cases [1]:

1.2 Dead + (0.5) Live or 0.2 Snow (9)

(0.9 or 1.2) Dead + 0.2 Wind. (10)

It is generally assumed that during the fire, dead and live loads remain constant. However, the strength of materials is reduced so that the retained nominal moment strength is

$$M_{n\theta} = A_s \cdot f_{y\theta} \cdot \left(d - \frac{a_\theta}{2}\right) (11)$$

in which θ signifies effects of elevated temperatures. Note that A_s and d are not affected, but $f_{y\theta}$ is reduced. Similarly, a_θ is reduced, but the concrete strength at the top of the slab f'_c is generally not significantly reduced.

It can be assumed that the flexural failure occurs when $M_{n\theta}$ decreases to M, and the conclusion is that the time of fire resistance depends on the load intensity and the behavior of the concrete reinforcement at high temperatures. In conclusion, the period of fire resistance of the observed slab depends on the time required to reach the critical temperature of the steel, which again depends on the applied protection of the reinforcement. The most commonly used protection is the concrete cover.

Fire resistance of simply supported slabs depends on the type of reinforcement used, the type of concrete depending on the aggregate, the intensity of the bending moment applied, and the distance of the reinforcement centroid from the fire exposed side of concrete denoted by "u". If the reinforcement is uniformly arranged along a tensile zone, the value "*u*" is determined as the average distance of individual bars from the fire exposed side of concrete.Taking into account that the reinforcement index is

$$\omega = A_s \cdot f_y / (b \cdot d \cdot f_c') \quad (12)$$

and determining the ratio M/M_n, and also using "*u*", it is possible to determine the period of fire resistance of the slab from the diagram presented in *Figure 6*.

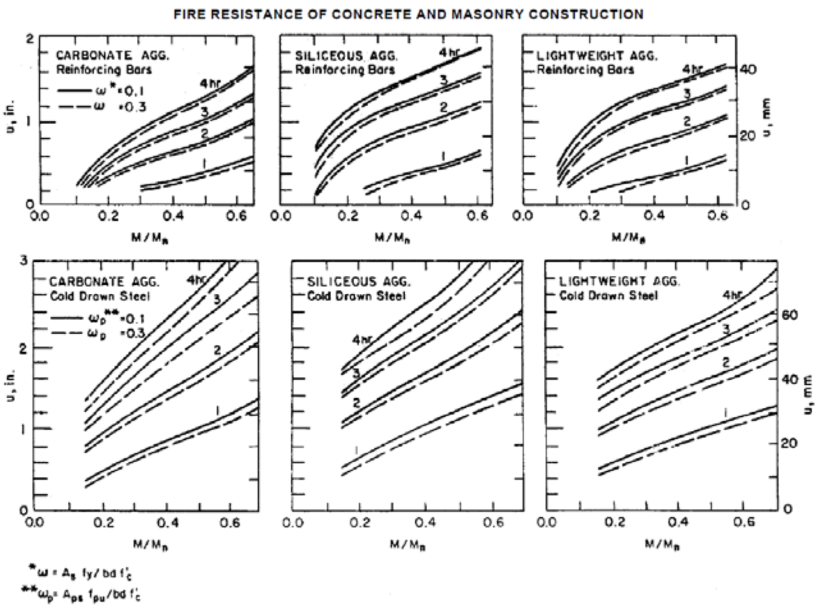

Figure 6 – Fire Resistance of Concrete Slabs as Influenced by Aggregate Type, Reinforcing Steel Type, Moment Intensity, and "u" [8]

5. FIRE RESISTANCE DETERMINATION OF RC SLABS

This study considers fire resistance determination of RC slabs using two different methods: EN 1992-1-2:2004, Eurocode 2, Design of concrete structures, Part 1-2: Structural fire design - Simplified calculation method for slabs, and ACI/TMS 216.1 – Code Requirements for Determining Fire Resistance of Concrete and Masonry Assemblies.

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 slabs were designed according to EN 1992-1-1, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. 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. However, given the construction situation in Balkans, 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 contractorinvolved, 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 for determining fire resistance according to EN 1992-1-2:2004, Eurocode 2, Design of concrete structures, Part 1-2: Structural fire design - Simplified calculation method for slabs.To determine fire resistance according to the ACI/TMS 216.1 – Code Requirements for Determining Fire Resistance of Concrete and Masonry Assemblies, fire exposure is assumed according to ASTM E 119.

The results of fire resistance of RC slabs of 5 m span according to these two different methods are presented in *Tables 1-3.* The results for fire resistance of RC slabs of spans 3 and 7 m are not presented in this paper due to limitation of the paper length.

Table 1. Fire Resistance of Slab, Depth 15 cm, Span 5 m, 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 Simplified Method for Slabs**	**ACI/TMS 216.1**
0.5	0.950	22.03	R 636	9	R 30	< 60 min
1.0	1.450		R 636	9	R 30	< 60 min
1.5	1.950		R 636	9	R 60	< 60 min
2.0	2.450		R 636	9	R 60	< 60 min
2.5	3.000		R 785	10	R 60	60 min
3.0	3.500		R 785	10	R 90	60 min

Table 2. Fire Resistance of Slab, Depth 15 cm, Span 5 m, C30/37

FIRE RESISTANCE OF SLAB depth 15 cm, span 5 m, C 30/37 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 Simplified Method for Slabs**	**ACI/TMS 216.1**
0.5	0.95	22.03	R 636	9	R 30	< 60 min
1.0	1.45		R 636	9	R 30	< 60 min
1.5	1.95		R 636	9	R 60	< 60 min
2.0	2.50		R 785	10	R 90	60 min
2.5	3.00		R 785	10	R 90	60 min
3.0	3.50		R 785	10	R 120	60 min

Table 3. Fire Resistance of Slab, Depth 15 cm, Span 5 m, C40/50

FIRE RESISTANCE OF SLAB depth 15 cm, span 5 m, C 40/50 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 Simplified Method for Slabs	ACI/TMS 216.1
0.5	0.95	22.03	R 636	9	R 30	< 60 min
1.0	1.45		R 636	9	R 30	< 60 min
1.5	1.95		R 636	9	R 60	< 60 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 120	60 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 60 minutes;
- Standard Method for Determining Fire Resistance to Concrete and Masonry Structures ACI/TMS 216.1, using diagrams from *Figure 6*was not sufficiently sensitive for determining fire resistance periods of slabs as other method was. Differences were up to 60 minutes, and there was not a clear determination of fire resistance period below 60 minutes. It is also necessary to highlight that results obtained using ACI/TMS 216.1 were not fully comparable with other method, since the fire exposure of Standard Fire (ASTM E 119) was not the same as Standard Fire ISO 834-1, although without significant differences in temperatures. The reason this method was considered in this research was its wider and holistic meaning of the term “fire resistance”, where fire resistance and structures did not recognize borders, countries, or different standards;
- 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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ОТПОРНОСТ НА ПОЖАР АРМИРАНОБЕТОНСКИХ ПЛОЧА ПРЕМА ACI/TMS 216.1 И EC2 – МОГУЋНОСТ ПОРЕЂЕЊА

Резиме: *Армиранобетонске плоче су најосјетљивији армиранобетонски елементи у случају пожара. Стога је ово истраживање усмјерено на одређивање отпорности на пожар армиранобетонских плоча према EN 1992-1-2:2004, Еврокод 2, Пројектовање бетонских конструкција, Део 1-2: Пројектовање конструкција на дејство пожара (Поједностављени метод за греде и плоче) и ACI TMS 216.1 – Код за одређивање отпорности на пожар бетонских и зиданих склопова. Пожарно дејство на армиранобетонске плоче се моделује преко Стандардног пожара ISO 834-1 за EN 1992-1-2: 2004 и ASTM E 119 за ACI/TMS 216.1. У овом истраживању разматра се отпорност на пожар слободно ослоњених армиранобетонских плоча различитих распона, различитих дебљина, те са варијацијом дебљине заштитног слоја бетона до арматуре.*

Кључне речи: *Армиранобетонске плоче, Отпорност на пожар, Заштитни слој бетона*