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PARAMETRIC ANALYSIS ON FIRE RESISTANCE OF ONE WAY SIMPLY SUPPORTED REINFORCED CONCRETE SLABS

Abstract:

The behavior of simply supported reinforced concrete slabs in fire conditions and the influence of certain parameters on their fire resistance is analysed in this paper. The influence of the slab span, concrete cover thickness and the type of reinforcement scheme are analysed. All slabs are exposed to standard fire ISO 834. The analyses are conducted by using the computer program SAFIR2016, which is based on the Finite Element Method, and the simplified procedure given in EN 1992-1-2. For the numerical analyses, two approaches are used: 2D-analysis, when the discretization is performed with beam elements and 3D-analysis, when the discretization is performed with shell elements. The 3D-analyses are performed for a meter width strip and for the real width of the slabs. The width of the slabs is adopted to be the same with the span.

Keywords: RC slab, Fire resistance, 2D and 3D analysis, SAFIR

ПАРАМЕТАРСКА АНАЛИЗА ПОЖАРНЕ ОТПОРНОСТИ СЛОБОДНО ОСЛОЊЕНИХ АРМИРАНО-БЕТОНСКИХ ПЛОЧА НОСИВИХ У ЈЕДНОМ ПРАВЦУ

Сажетак:

Предмет истраживања у овом раду је понашање слободно ослоњених армирано-бетонских плоча у пожарним условима и утицај одређених параметара на њихову пожарну отпорност. Анализиран је утицај распона плоче, дебљине заштитног бетонског слоја и шеме армирања. Све анализиране плоче изложене су стандардном пожару ISO 834. Анализа се врши коришћењем програма SAFIR2016, који се заснива на методу коначних елемената, и помоћу аналитичке методе дате у EN 1992-1-2. За нумеричку анализу се користе два приступа: 2D-анализа, када се дискретизација врши гредним елементима и 3D-анализа, када се дискретизација врши елементима љуске. 3D анализа се врши за траке ширине метар и за стварну ширину плоче.

Кључне ријечи: АБ плоче, пожарна отпорност, 2D и 3D анализа, SAFIR

1. INTRODUCTION

The fire resistance of building members is an important part of any structural and fire safety design. Floor slabs, as horizontal elements, have a very important role in providing bearing capacity, usability and stability of the building as a whole. Their proper selection and design, when they are exposed to different types of loads (mainly: permanent and variable), should provide stable and safe structure during the exploitation period.

In case of fire, floor slabs do not have only load bearing function. In most cases they are used as elements for separating the fire compartment. Where compartmentation is required, the elements forming the boundaries of the fire compartment, including joints, shall be designed and constructed in such a way to maintain their separating function during the relevant fire exposure [1]. This shall ensure, where relevant, that integrity failure does not occur, insulation failure does not occur and thermal radiation from the unexposed side is limited.

Does the floor structure meet the required fire resistance criteria mainly depends on: mechanical and thermal characteristics of the materials used for the construction; initial loading level; support conditions; dimensions of the cross section; steel ratio; concrete cover thickness and fire scenario.

A durable structure shall meet the requirements of serviceability, strength and stability throughout its design life, without significant loss of utility or excessive unforeseen maintenance. In fire conditions, as a result of a large number of real fire tests and corresponding numerical analyses, it was found out that the moment of failure of the floor structure is always followed by significant deformation (deflection). If the structure is close to the limit state, after the cooling phase the residual deflections are so great that it cannot be used without significant rehabilitation. For these reasons, during the fire action, the deformation (deflection) of the slab is limited to prescribed value. According to the ISO standard [2], this limit value is L/30 (L is the span of the slab) [3].

This paper presents the numerically achieved results for the fire resistance of one way simply supported reinforced concrete slabs with different spans, different concrete cover thickness and different reinforcement scheme. 2D-Analyses (beam element) and 3D-Analyses (shell element) by using the computer program SAFIR2016 [4] are conducted. For comparison, the slabs are analyzed by using the simplified method given in EN 1992-1-2 [5].

In order to draw a conclusion how each of the above mentioned parameters affects the fire resistance of one way simply supported reinforced concrete slabs, only the corresponding parameter is varied, and therefore in each case the reinforcement equal to the minimum required is adopted. This means that when adopting the reinforcement, the dimensions of the reinforcement bars that actually exist are not considered.

Based on the numerically achieved results, certain conclusions that can be useful for meeting the prescribed fire resistance criteria for these type of floor structures are given.

2. THERMAL ANALYSIS

Static analysis of the slab at each time interval uses the output data from the thermal analysis of the fire exposed elements, so it should be performed for a compatible finite element mesh, which means the 2D or 3D thermal analysis have to be performed by using compatible FE mesh.

Considering that in reinforced concrete slabs the temperature is changed only in direction of thickness, the cross section is discretized with rectangular elements with a width equal to the cross section of the slab. The results for the temperature distribution in the cross section of the slab are equal in case of 2D or 3D thermal analyses. Figure 1 shows the discretization of the slab cross section in 2D thermal analysis. The width of the cross section is b = 12.5 cm, and the thickness of the slab is h = 16 cm. In Figure 2 the temperature distribution in the cross section of the slab for moment t=3600 sec.=60 min. is presented.

Temperatures at the bottom side, in the middle plane and at the top side of the slab, during action of ISO 834 fire cure, are presented in Figure 3.

When simplified calculation method, given in EN 1992-1-2, is used, the temperature profile in the slab may be defined by formula given in literature [3,6]. The Standard fire curve ISO834 is given by Eq. 1, the surface temperature by Eq. 2, while the temperature at distance *d* from the slab surface is defined by Eq. 3.

$$T_f = 20 + 345 \cdot \log(8t + 1) \quad (1)$$

$$T_w = [1 - 0.0616 \cdot t_h^{-0.88}] \cdot T_f \quad (2)$$

$$T_d = [0.18 \cdot \ln{(t_h/d^2)}] \cdot T_w \quad (3)$$

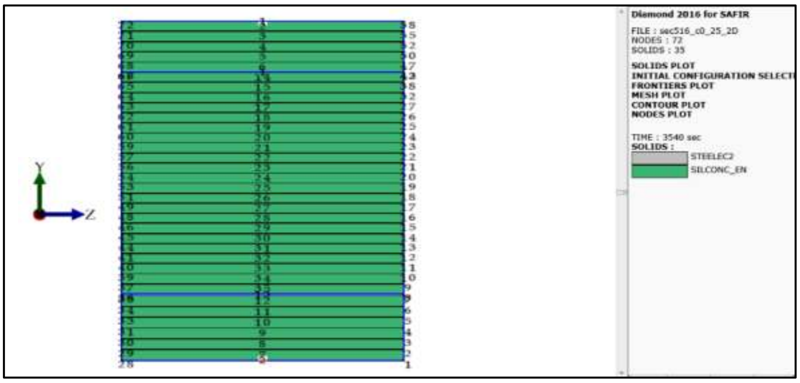


Figure 1. *Discretization of the slab cross section in 2D thermal analysis*

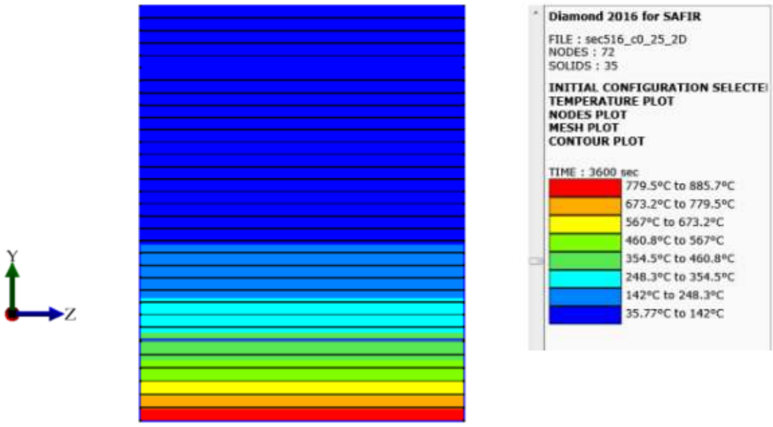
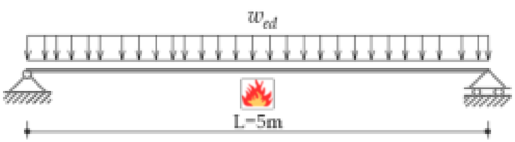


Figure 2. *Temperature distribution in the cross section of the slab for moment t=60 min.*

3. STATIC ANALYSIS

3.1. Description of the rc slab

The purpose of the analyses is to define the effect of the concrete cover thickness, the reinforcement scheme and the slab span on the fire resistance of one way simply supported slab, as one of the most important parameters that influence the fire resistance of RC slabs [7-16]. For the numerical analyses, two approaches are used: 2D-analyses, when discretization is performed with beam elements and 3D-analyses, when discretization is performed with shell elements. In case of 3D-analyses, a meter width strip is analysed and the real width of the slab is analysed. The width of the slab is adopted to be the same with the span. The analyzed RC slab is described in Figure 3. For the design actions recommendations given in EN 1992-1-2 [5] are used.



Permanent action

(self-weight is included): G_k= 5.5 kN/m^2

Variable action: Q_k= 4 kN/m^2

Slab thickness: h = 16 cm

Concrete grade: f_{ck} =30 Mpa

Steel grade: f_{yk}=500 Mpa

Figure 3. *Description of the slab geometry, load intensity and material properties*

- The design action for ambient temperature:

$$w_{Ed} = g_k \cdot \gamma_g + q_k \cdot \gamma_q = 5.5 \cdot 1.35 + 4 \cdot 1.5 = 13.425 kN/m \quad (4)$$

- The design action in case of fire:

$$w_{Ed,fi} = g_k \cdot \gamma_g + q_k \cdot \psi_1 = 5.5 \cdot 1.0 + 4 \cdot 0.6 = 7.9 kN/m \quad (5)$$

In practice, one way simply supported slabs are reinforced by placing the main reinforcement in the bottom part of the section, while only 50% of the main reinforcement is adopted as negative reinforcement and placed above the supports. The analysis has shown that, when a part of the negative reinforcement is extended along the entire span, as presented in Figure 4, better fire resistance is achieved. In this case, for 3D analysis, the slab is additionally reinforced in the middle part of the upper zone with 25% of the required positive reinforcement (Figure 4).

In case of 2D analysis, when beam elements are used, 10% of the main reinforcement is adopted as negative reinforcement.

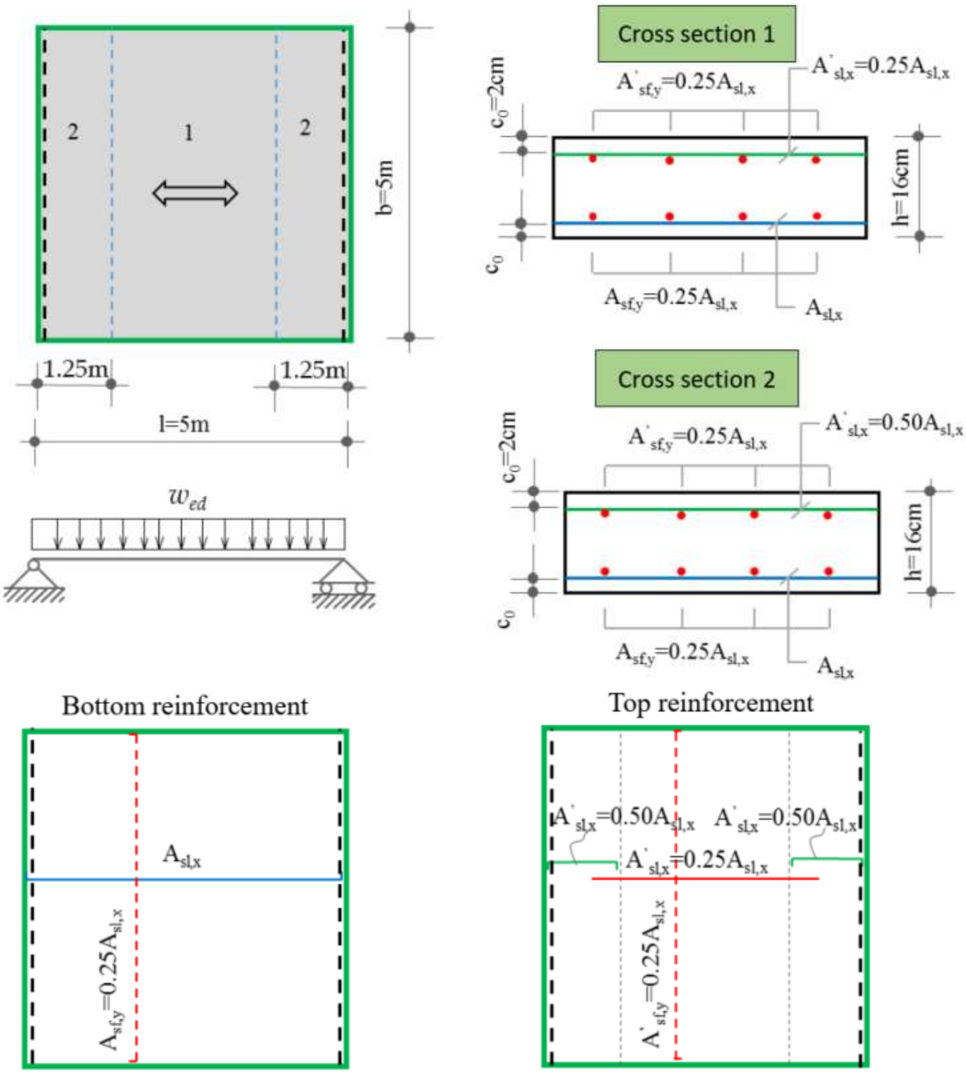


Figure 4. *Reinforcement schema for the one way simply supported slab, in case of 3D analysis*

For 3D analysis, the slab is discretized with 80 shell elements, when only a 1m wide strip is analysed, or 256 shell elements, when the slab is analysed with a real width of 5 m. The boundary conditions are shown in Figure 5.

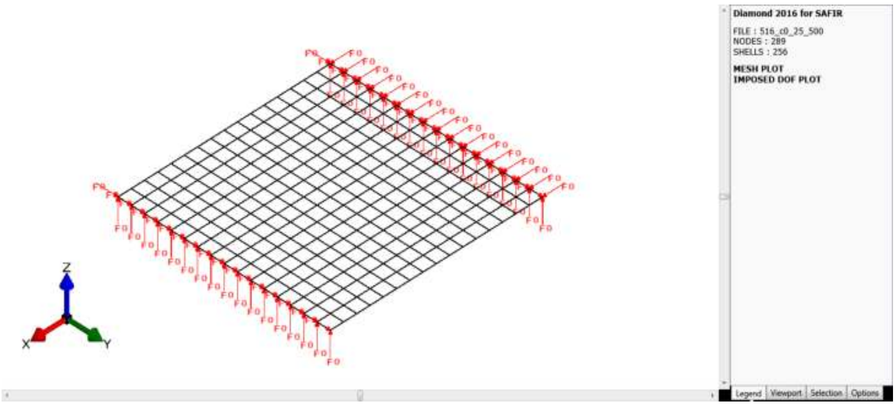


Figure 5. *3D model and boundary conditions of one way simply supported slab*

3.2. Fire resistance as function of concrete cover thickness

The concrete cover protects the reinforcement from high temperatures and has a positive effect on the fire resistance of structural elements. In case of one way simply supported slab, for analyzing these positive effects, three different values for the concrete cover thickness on the side of the fire (bottom side of the slab) are used: c_0 = 20 mm; c_0= 25 mm and c_0= 30 mm, while the concrete cover for the top reinforcement is c_0= 20 mm.

By changing the concrete cover, the lever arm of the cross section is also changed. Therefore, in order to find out the real influence of the concrete cover on the fire resistance of the analyzed slabs, the adopted reinforcement area is equal to the required one, Table 1. In such a way, the initial stresses in the reinforcement are the same for all three cases.

Table 1. *Main reinforcenet area as function of different concrete cover thickness*

Concrete cover thickness, c_0 (cm)	Adopted main reinforcement, $A_{sl,x}$ (cm^2)
2.0	7.778
2.5	8.136
3.0	8.532

The fire resistance of the one way simply supported slab mostly depends on the yield strength of the steel, i.e. the reinforcement, which is significantly reduced when the temperature is increased. The reduction coefficients are given in EN 1992-1-2 [4]. The influence of the concrete cover thickness on the reinforcement temperature is presented in Figure 6. It is obvious that as the thickness of the concrete cover increases, the temperature in the reinforcement decreases, which contributes to a smaller reduction of the yield strength of the steel and a higher bearing capacity of the slab.

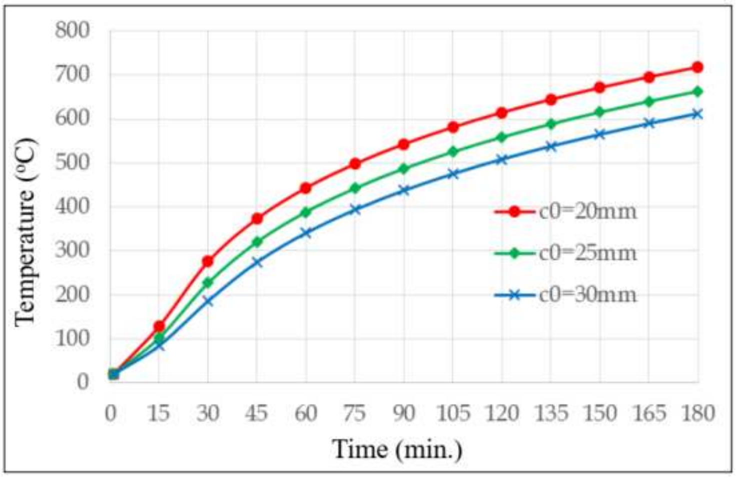


Figure 6. *Reinforcement temperature as function of the concrete cover thickness*

The vertical displacements in the middle of the span, when concrete cover thickness is 20 mm, obtained by 2D and 3D analyses, are presented in Figure 7. The time when the slab collapses is adopted as a criterion for the fire resistance and in that moment the program interrupts the calculation. Additionally, the fire resistance of the slab is determined by the simplified method given in EN 1992-1-2, and the obtained fire resistance is lower than in case of numerical analysis.

The diagrams from all three analyses show that, from the aspect of failure time, the slab has approximately the same fire resistance. In case of 3D analysis with real width of the slab, larger displacements are obtained than in case of 2D analysis, which is realistic, because the 3D analysis includes the effect of membrane forces. When the 3D analysis is performed on a strip with a width of 1 m, the number of finite elements is smaller, the time required for the analysis is shorter, but the effect of membrane forces cannot be expressed, consequently the vertical displacements are smaller than in case of 3D analysis when the real width of the slab is analysed.

From the aspect of load-bearing capacity, in order to shorten the calculation time, the fire resistance analyses can be performed on a 2D model that gives acceptable results even from the aspect of the vertical displacements. Only at moments before the failure, when the vertical displacements are significantly higher than *l/30* (criterion for maximum acceptable deflection) and the slab begins to function as a chain, the difference in displacements obtained by the two approaches decreases.

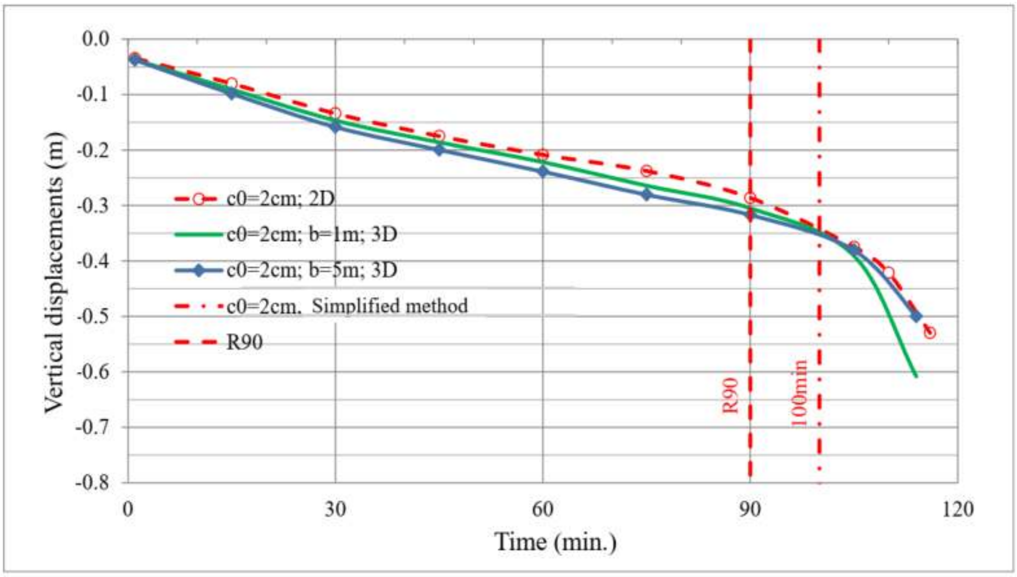


Figure 7. *Vertical displacements of one way simply supported slab with concrete cover thickness c_0=20 mm, according to 2D and 3D analyses and simplified method*

Temperature and time dependent vertical displacements of one way simply supported slab for different values of the concrete cover thickness, obtained with 2D analysis, 3D analysis for real width of the slab, and with the simplified method given in EN 1992-1-2, are presented in Figure 8. It is evident that the concrete cover thickness has a great influence on the fire resistance of the slab and on the value of the vertical displacements (deformations).

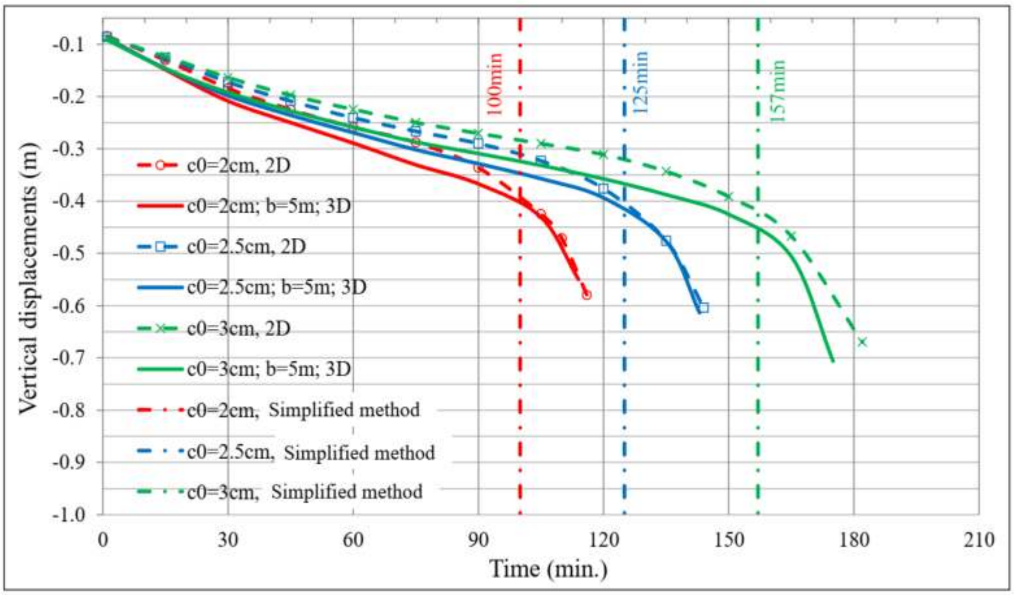


Figure 8. *Comparison of the vertical displacements of the simply supported slab exposed to fire from the bottom side, as function of the concrete cover thickness, according to 2D and 3D analyses and simplified method*

The results from the simplified calculation method, for the slab with concrete cover thickness c_0=20 mm, are presented in Figure 9. The reduction of the load bearing capacity of the slab is defined as function of the temperature of the bottom reinforcement. The moment when the load bearing capacity of the slab is equal to the bending moment for the design actions in case of fire (Equation 5), the slab collapses and this time expressed in minutes is the fire resistance of the slab.

$$M_{Ed,fi} \leq M_{Rd,fi} \quad (6)$$

In this case the fire resistance is 100 min., that means the slab satisfies the criterion R90.

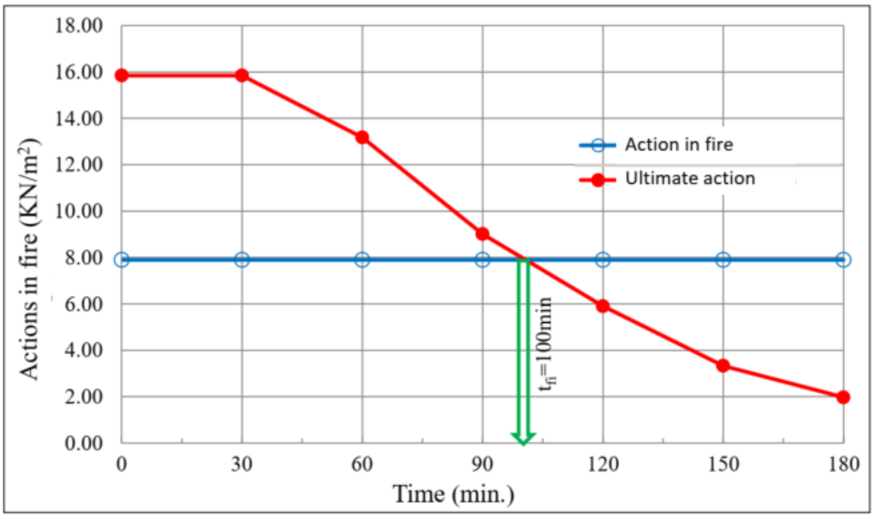


Figure 9. *Fire resistance of a one way simply supported slab with span L = 5 m and concrete cover thickness c_0=20 mm, according to simplified method given in EN 1992-1-2*

Taking under consideration that a simply supported slab is a statically determined girder, failure occurs at the moment when the maximal bending moment from external loads is equal to the bearing capacity of the slab which, as a result of high temperatures, decreases in time. The load-bearing capacity of the slab directly depends on the yield strength of the steel, i.e. the reinforcement in the lower zone of the slab which is exposed to high temperatures, For these reinforcement bars the strength and stiffness reduction is significant.

An overview of the influence of the concrete cover thickness on the fire resistance of simply supported slabs, exposed to fire from the bottom side, is presented in Table 2 and in Figure 10. The results from the aspect of bearing capacity and from the aspect of the slab vertical displacements are presented, i.e. the time when the vertical displacements reach the maximum allowed value *l / 30* (16.667 cm) is given, as a criterion for usability.

Table 2. *Fire resistance of one way simply supported slabs, according to the load-bearing criterion and the deformation criterion l / 30*

c_0 (cm)	t_{ult} (3D Analysis) (min)	t_{ult} (2D Analysis) (min)	Simplified method (min)	Displacements l/30 (min) (3D Analysis)	Displacements l/30 (min) (2D Analysis)
2.0	114	116	100	32	41
2.5	143	144	125	36	48
3.0	175	182	157	39	56

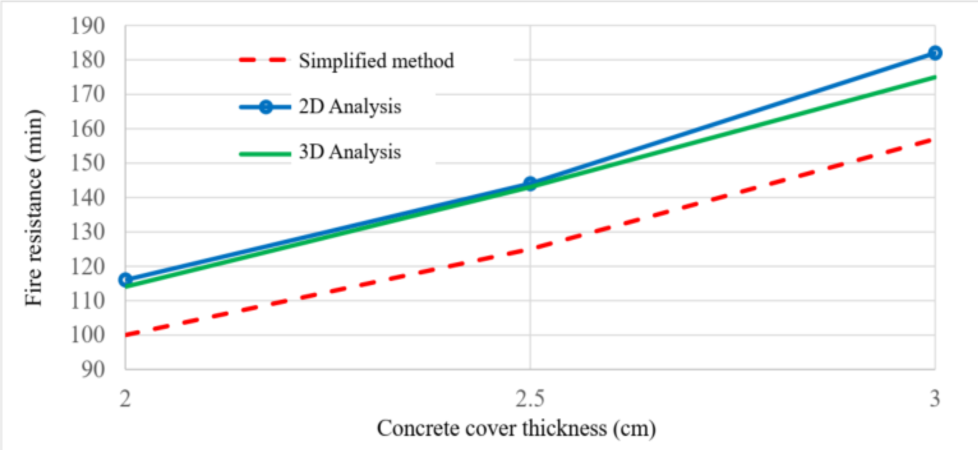


Figure 10. *Fire resistance of one way simply supported slab as function of the concrete cover thickness, according to 2D and 3D analyses and simplified method given in EN 1992-1-2*

3.3. Fire resistance as function of the reinforcement scheme

The aim of the analyses presented in this part is to clarify the influence of the nominal longitudinal reinforcement in the top zone (negative reinforcement) of the one way simply supported slab exposed to fire from the bottom side. The analyses are performed on a slab with a concrete cover thickness 25 mm. Three schemas for the top reinforcement are analysed, Figure 11.

In case of the first schema, the slab is not reinforced in the middle top zone, the schema that is most often used in practice for this type of slabs. In case of the second schema, the middle top zone is reinforced with 25% and above the support with 50% of the required main reinforcement (positive reinforcement). In case of the third schema, the top zone along the entire span is reinforced with 50% of the required main positive reinforcement. The distribution bars in all three schemas are adopted as 25% of the required main positive reinforcement. The scheme of the positive reinforcement in the bottom part of the section is the same in all three models, as it is shown in Figure 4.

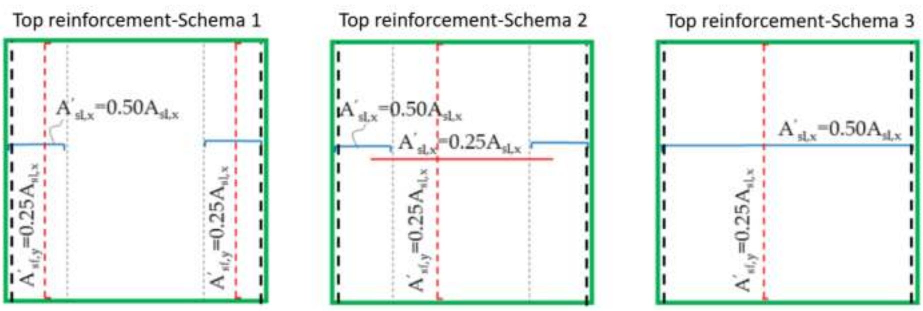


Figure 11. *Different reinforcement schemas for the top reinforcement of one way simply supported slab*

Figure 12 compares the vertical displacements in time for all three reinforcement schemas, obtained by 3D analyses with real width of the slab. The conducted analyses show that for all three reinforcement schemas, the slab shows the same behavior for up to 2 hours of fire exposure. At this time, the slab reinforced according to the second and third schema shows a slightly better behavior. The top reinforcement, although nominal, if placed along the entire span, increases the fire resistance of simply supported slabs. The reason for the better behavior of the slabs is the activation of the top nominal reinforcement for receiving the membrane forces which, at the moments when the vertical displacements are extremely large, i.e. when the slab works like a chain, grow rapidly.

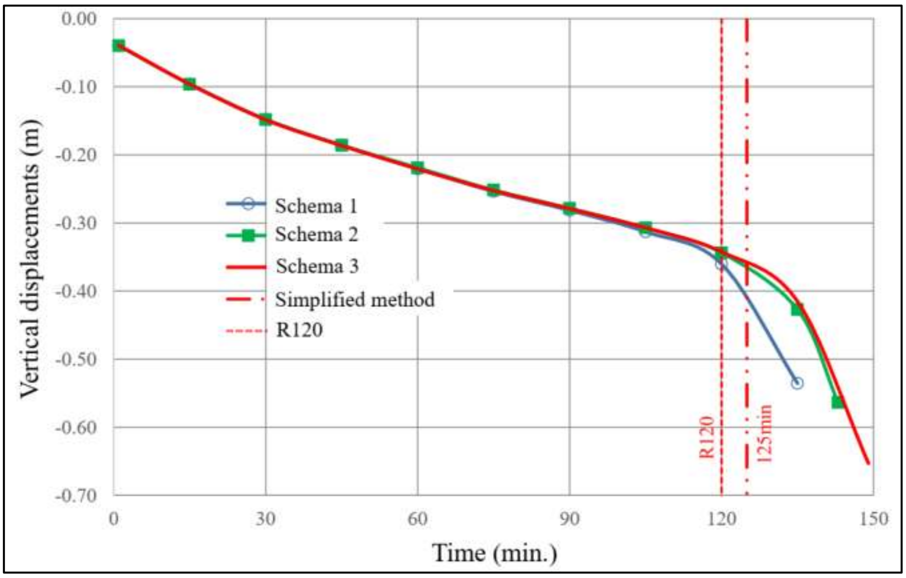


Figure 12. *Comparison of the vertical displacements of one way simply supported slabs, in case of three different reinforcement schemas for the top reinforcement*

The fire resistance of the slab, obtained by the simplified method given in EN 1992-1-2, is also presented in Figure 12, but in this calculation the load-bearing capacity of the top reinforcement is not taken into account.

Considering that the vertical displacements of the slab reinforced according to the second and third schema are the same, and that the third reinforcement schema gives only 6 minutes higher fire resistance, and the second schema is more economical, it is recommended to reinforce one way simply supported slabs by using the second reinforcement schema.

Simply supported slabs are statically determined girders and there is no redistribution of bending moments as a result of thermal actions. From this reason the effect of negative reinforcement is small, but positive.

3.4. Fire resistance as function of the slab span

In practice, in buildings, the floor slabs are usually constructed with different spans. Considering that the slabs are most often constructed with constant thickness, it is of interest to define the influence of the ratio between the thickness and the lab span on its fire resistance. In this part, one way simply supported slabs with span: l = 4 m, l = 5 m, l = 6 m, and thickness h = 16 cm, are analysed. The concrete cover for all three slabs is c_0 = 2 cm.

The loads and the material properties are presented in Figure 3. The adopted main reinforcement area is equal to the required one, which enables the initial stresses in the reinforcement to be equal in all three cases. In this way, the real influence of the ratio between the thickness and the slab span is obtained. Table 7.3 shows the adopted reinforcement area for the simply supported slabs with different spans.

Table 3. *Adopted main reinforcement area in case od different slab spans*

Slab span, L (m)	4	5	6
Adopted reinforcement are, $A_{sl,req}$ (cm^2)	*4.831*	*7.778*	*11.668*

Vertical displacements in time, up to failure, for simply supported slabs with different thickness/spam ratio, according to 2D and 3D analyses, are presented in Figure 13. It is obvious that decreasing the thickness/spam ratio results in greater deformations, but the fire resistance of the slabs is almost the same.

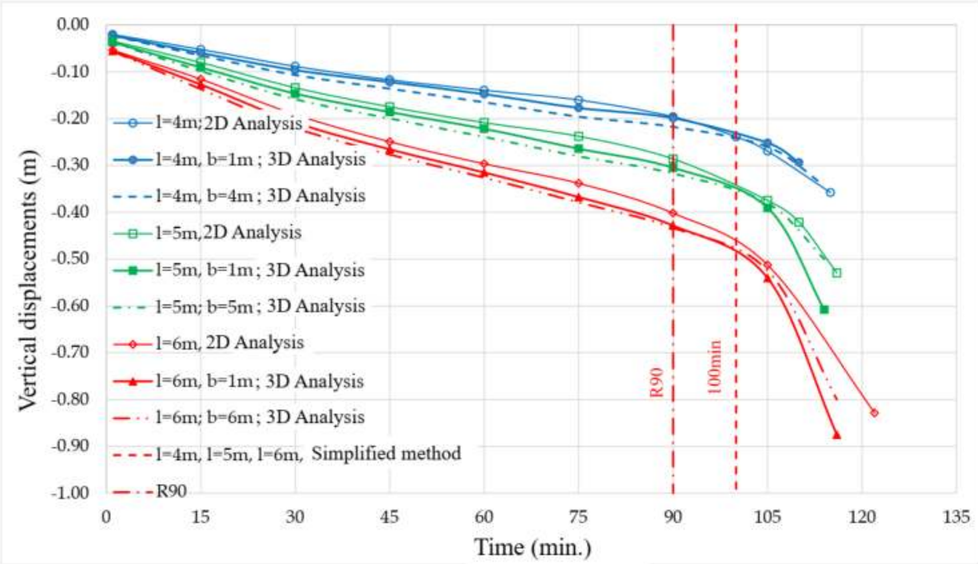


Figure 13. *Vertical displacements of simply supported slabs with spans: l = 4m, l = 5m, l = 6m, concrete cover c_0 = 2 cm, exposed to Standard fire ISO834, according to 2D and 3D analyses and according to the simplified method*

An overview of the effect of the span on the fire resistance of simply supported slabs is given in Table 4, Figure 14 and Figure 15. The fire resistance is defined according to two criteria: the load-bearing criterion (Figure 14) and the criterion based on maximum permitted deformations of the slab in case of fire (Figure 15).

From aspect of load-bearing capacity, the slabs collapse at same time. This is a result of the fact that the initial stresses in the reinforcement are the same in all three analysed slabs. As a result of same concrete cover thickness, the reinforcement temperatures are the same and the steel undergoes the same reduction of tensile strength. Having in mind that the simply supported slab is a statically defined girder, the increased and non-uniform temperature distribution in the slab cross section does not change the internal forces, i.e. the bending moments, consequently the slabs undergo the same reduction of the bearing capacity and collapse at the same time.

According to the criterion for maximum permitted vertical displacements, by increasing the span the thickness/span ration is decreased and consequently the fire resistance of the slab is decreases as a result of larger deformations (Figure 13).

The fire resistance of simply supported slabs according to the criterion for permitted deformations is significantly lower in relation to the fire resistance according to the load-bearing criterion. This is based on the fact that, due to changes in the "σ-ε" diagram for concrete and steel at high temperatures, structures in fire become more ductile and can survive significantly larger dilatations before failure than in case of ambient temperatures.

Table 4. *Fire resistance of one way simply supported slabs, according to the load-bearing criterion and the deformation criterion l / 30, as function of the span*

Fire resistance (min.)					
L (m)	t_{ult} (2D Analysis)	t_{ult} (3D Analysis)	t_{ult} (EN 1992-1-2)	Deflection *l/30* (2D Analysis)	Deflection *l/30* (3D Analysis)
4	115	114	100	55	43
5	116	114	100	41	32
6	122	116	100	32	26

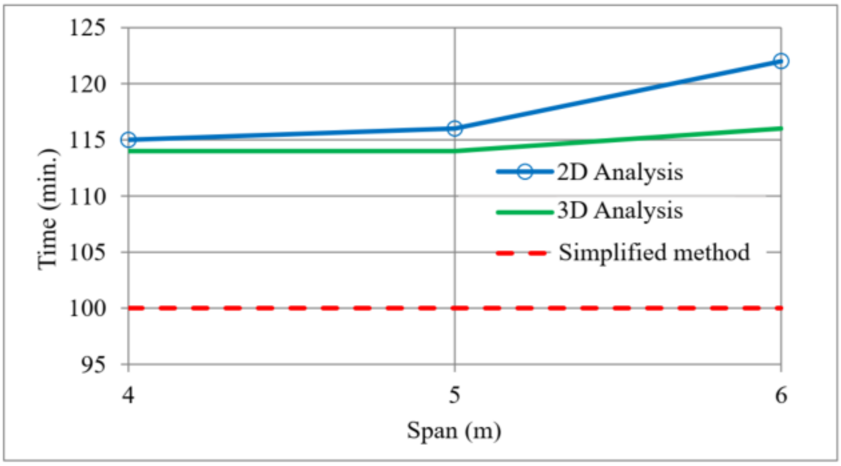


Figure 14. *Fire resistance of one way simply supported slabs, for different spans, according to 2D and 3D analyses, and according to EN 1992-1-2 simplified method*

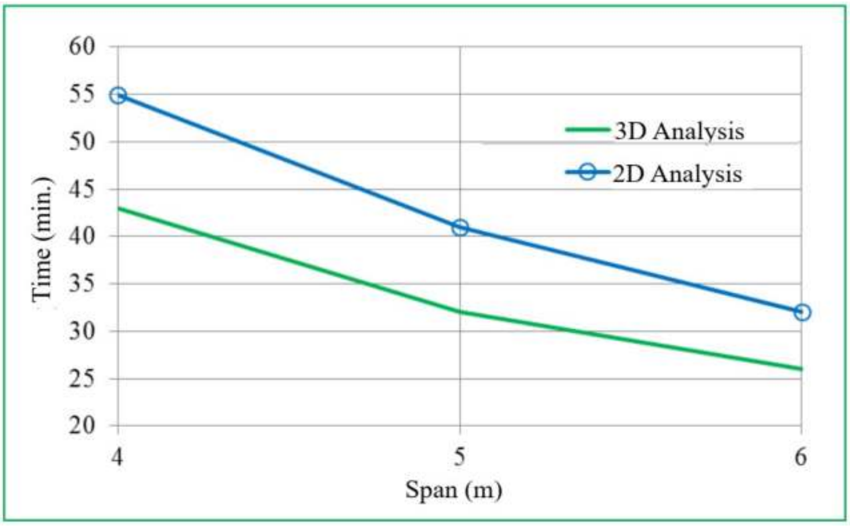


Figure 15. *Time when the vertical displacements at the mid span of the slabs with different spans reach the value l / 30, according to 2D and 3D analysis*

4. CONSLUSIONS

From the aspect of failure time, the results obtained by 2D analyses, 3D analyses for 1 m strip and 3D analyses for the real width of the slabs, are almost equal. In case of 3D analysis with real width of the slab, larger displacements are obtained than in case of 2D analysis, which is realistic, because the 3D analysis includes the effect of membrane forces. When the 3D analysis is performed on a strip with a width of 1 m, the number of finite elements is smaller, the time required for the analysis is shorter, but the effect of membrane forces cannot be expressed, consequently the vertical displacements are smaller than in case of 3D analysis for real width of the slab.

From the aspect of load-bearing capacity, in order to shorten the calculation time, the fire resistance analyses of the slabs can be performed on a 2D model that gives acceptable results even from the aspect of the vertical displacements. Only at the moments before the failure, when the vertical displacements are significantly higher than *l/30* (criterion for maximum acceptable deflection) and the slab begins to function as a chain, the difference in displacements between the two approaches decreases.

The fire resistance obtained with the simplified method given in EN 1992-1-2 is lower and is always on the side of safety. It is easy for use, but does not provide data for the vertical displacements.

Based on the parametric analyses, the following conclusions are drawn:

- The concrete cover thickness has a great influence on the load-bearing capacity of the slabs. If the concrete cover is increased by 0.5 cm, the fire resistance can be increased by up to 30 minutes, depending on the thermal characteristics of the concrete.
- The reinforcement schema for the negative reinforcement has small positive effect on increasing the fire resistance of the one way simply supported slabs. The reason for the better behavior of the slabs is the activation of the top nominal reinforcement for receiving the membrane forces which, at the moments when the vertical displacements are extremely large, i.e. when the slab works like a chain, grow rapidly.
- The span of one way simply supported slabs has an impact on their fire resistance only from the aspect of the criterion for permitted deformations, which in defining the fire resistance of structures is not taken as relevant, because the main goal is the structure to survive the fire for the prescribed time of fire action.

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