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RESEARCH PAPER

A new calculation method for the temperature of the components of composite slabs under fire

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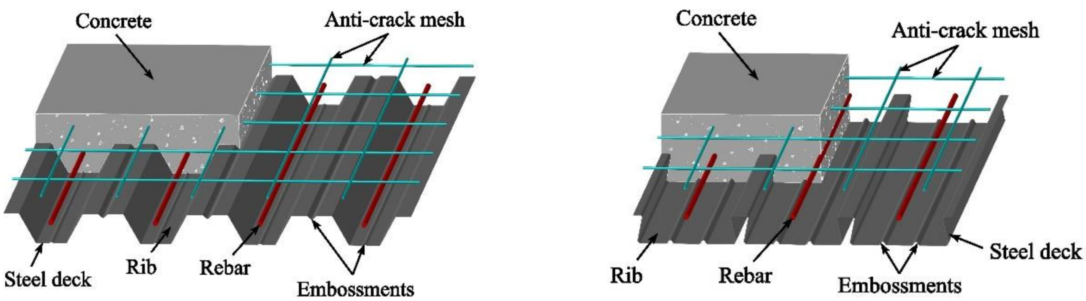
Abstract
Composite steel-concrete slabs are structural elements composed of a profiled steel deck which acts as a permanent formwork to the concrete topping. This layer is commonly reinforced with individual rebars and an anti-crack mesh. The Annex D of the EN 1994-1-2 provides guidelines for the calculation of the temperature of the steel components of composite slabs subjected to the standard fire. However, no revisions were made to these calculation rules during the last years. This paper proposes a new method for the estimation of the temperature of the parts of the steel deck and the rebars as well. The proposed methodology is derived from numerical analyses using a 3-D finite element model, considering perfect thermal contact between the materials.

Keywords: Composite slabs, Fire resistance, Numerical simulation, Calculation method.

Introduction

A composite steel-concrete slab consists of a concrete topping cast on the top of a profiled steel deck. Usually, the concrete is reinforced with an anti-crack mesh positioned on the upper part and individual reinforcing bars placed within the ribs, see figure 1. This type of slab is broadly used in buildings due to its several advantages, such as the reduction or elimination of propping and the simplicity of installation. The most popular types of shapes of the profiled steel deck are trapezoidal and re-entrant. The overall thickness of composite slabs usually varies between 100 and 170 mm, and the steel deck thickness between 0.7 and 1.2 mm.



a) Trapezoidal profile. b) Re-entrant profile.

Figure 1. Typical layout of composite slabs.

Composite slabs need to meet fire-safety requirements in accordance with standards and regulations. Usually, this structural element is fire rated based on standard fire tests, using the standard fire curve ISO 834 [1]. The fire resistance of composite slabs should be determined according to three different criteria, namely load bearing (R), integrity (E) and thermal insulation (I). The profiled geometry of the steel deck in composite slabs creates an orthotropic

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profile, resulting in complex thermal gradients, hence representing challenges in numerical modelling [2].

In recent years, several investigations have been carried out in order to analyse the fire behaviour of this structural element. In 1983, the ECCS (European Convention for Constructional Steelwork) [3] published the first instructions for the practical design of composite slabs under fire conditions. This document introduced simple calculation methods based on criteria for fire resistance of the standard ISO 834, hence inspiring the diffusion of the use of composite slabs.

In 1991, Hamerlinck [4] conducted a numerical and experimental study concerning the thermal and mechanical behaviour of composite slabs under fire conditions. The numerical models were experimentally validated with loaded and unloaded tests. It was observed that the developed two-dimensional model provided satisfactory results on the thermal behaviour of composite slabs although not including three-dimensional thermal effects.

In 1998, Both [5] performed a numerical and experimental study with the main objective of introducing easy to handle calculation rules as well as providing more insight on the fire behaviour and failure mechanisms mainly of continuous composite slabs. It was concluded that the thermal model was able to describe the two and three-dimensional heat flow in composite slabs during fire exposure and the assessment rules for the fire resistance given in the Eurocode 4 at that time could be considerably improved.

In 2019, Jian Jiang et al. [2] carried out a numerical investigation around different parameters that may influence on the fire resistance of composite slabs concerning the thermal insulation criterion (I). An improved algebraic expression for the calculation of the fire resistance that explicitly accounts for moisture content of concrete was proposed. A set of 54 composite slabs was selected for numerical analyses using a high-fidelity finite element approach. It was concluded that the concrete thickness and the moisture content were the parameters that most influenced the fire resistance.

Table 1. Nomenclature.

l_1, l_2, l_3	*Specific dimensions of the trapezoidal or re-entrant steel deck profile (mm)*
A	*Concrete volume of the rib per metre of rib length (mm^3/m)*
L_r	*Exposed area of the rib per metre of rib length (mm^2/m)*
Φ_{up}	*View factor of the upper flange (-)*
u_3	*Distance of the centre of the rebar to the lower flange (mm)*
h_1	*Height of the concrete part of a composite slab above the decking (mm)*
h_2	*Height of the concrete part of a composite slab within the decking (mm)*
h_{eff}	*Effective thickness of a composite slab (mm)*
u_1, u_2	*Shortest distances of the centre of the rebar to any point of the webs of the steel deck (mm)*
α	*Angle of the web (°)*
z_i, z_j	*Distance from the plastic neutral axis to the centroid of the elemental area A_i or A_j (mm)*
$k_{y,\theta,i}$, $k_{c,\theta,i}$	*Reduction coefficients for the yielding stress of steel and the compressive strength of concrete*
$f_{y,i}$	*Nominal yield strength f_y for the elemental area A_i taken as positive on the compression side of the plastic neutral axis and negative on the tension side*
$\gamma_{M,fi}$	*Partial factor for a material property in the fire situation*
α_{slab}	*Coefficient taking into account the assumption of the rectangular stress block when designing slabs*
$f_{c,j}$	*Characteristic strength of concrete part j at 20°C*
$\gamma_{M,fi,c}$	*Partial factor for the strength of concrete in the fire situation*
T	*Temperature of the material*
$\rho_{(T)}$, $Cp_{(T)}$, $\lambda_{(T)}$	*Specific mass; specific heat; thermal conductivity*
α_c	*Convection coefficient*
T_g	*Gas temperature of the fire compartment, considering the standard fire ISO 834*
ε_m, ε_f	*Emissivity of the material; emissivity of the fire (-)*
σ	*Stefan-Boltzmann constant (5.67E-8 W/m^{2}K^4)*

The scope of this study concerns 3-D numerical simulations using the standard fire curve ISO 834 [1] in order to evaluate the temperature of the steel components of composite slabs. A thermal model considering perfect thermal contact between the materials is implemented using ANSYS Mechanical APDL. The perfect contact model has been selected due to the lack of information regarding the thermal resistance between materials (steel deck with concrete and concrete with rebars). The most important thermal resistance is defined between the steel deck and concrete, reason to adopt the air gap effect. The numerical model is validated using the experimental results published by Hamerlinck [4], and the results are also compared to the simplified calculation method of the Eurocode 4 – Part 1-2. Thereafter, a parametric study comprising different steel deck profiles is conducted, and a new calculation method is presented for the temperatures of the parts of the steel deck and the rebars. Table 1 presents the nomenclature used throughout this work.

Simplified Calculation Method of the Eurocode 4 – Part 1-2

The annex D of EN 1994-1-2 [6] presents a simplified calculation method for the determination of the temperature of the parts of the steel deck and the rebars of composite slabs subjected to the standard fire from below. During the last years, no revisions were made to this method. These temperatures are important for the calculation of the sagging moment resistance and the fire resistance according to the load bearing criterion (R). The temperatures of the parts of the steel deck θ_a (°C) should be calculated according to equation 1.

$$\theta_a = b_0 + b_1 \cdot 1/l_3 + b_2 \cdot A/L_r + b_3 \cdot \Phi_{up} + b_4 \cdot \Phi_{up}^2 \tag{1}$$

Table D.2 from the EN 1994-1-2 [6] presents the partial factors bi. The rib geometry factor of the slab A/Lr (mm) and the temperature of the rebars in the rib θ_s (°C) shall be calculated according to equation 2 and equation 3, respectively.

$$A/L_r = h_2 \cdot \left(\left(l_1 + l_2\right)/2\right) \Big/ \left(l_2 + 2\sqrt{h_2^2 + \left(\left(l_1 - l_2\right)/2\right)^2}\right) \tag{2}$$

$$\theta_s = c_0 + \left(c_1 \cdot u_3/h_2\right) + \left(c_2 \cdot z\right) + \left(c_3 \cdot A/L_r\right) + \left(c_4 \cdot \alpha\right) + \left(c_5 \cdot 1/l_3\right) \tag{3}$$

The partial factors ci are given in Table D.3 from the EN 1994-1-2 [6]. The z-factor should be calculated according to equation 4.

$$1/z = 1/\sqrt{u_1} + 1/\sqrt{u_2} + 1/\sqrt{u_3} \tag{4}$$

The simplified calculation method also provides general rules for the determination of the load bearing capacity of composite steel-concrete slabs. Based on a global plastic analysis, the design for bending resistance should be determined using equation 5.

$$M_{fi,t,Rd} = \sum_{i=1}^{n=4} A_i \cdot z_i \cdot k_{y,\theta,i} \cdot \left(\frac{f_{y,i}}{\gamma_{M,fi}}\right) + \alpha_{slab} \cdot \sum_{j=1}^{m=1} A_j \cdot z_j \cdot k_{c,\theta,j} \cdot \left(\frac{f_{c,j}}{\gamma_{M,fi,c}}\right) \tag{5}$$

The coefficient $k_{y,\theta,i}$ may have different values, according to the type of steel (cold-formed carbon steel for the design of class 4 sections at elevated temperatures [6] and cold-formed carbon steel for rebars [7]). The model assumes no reduction for concrete.

The neutral axis under fire conditions can be defined by the equilibrium of equation 6 [6]. This axis modifies its position during fire, moving from the hot region to the cold region, assuming different positions for R60, R90 and R120.

$$\sum_{i=1}^{n=4} A_i \cdot k_{y,\theta,i} \cdot \left(\frac{f_{y,i}}{\gamma_{M,fi}}\right) + \alpha_{slab} \cdot \sum_{j=1}^{m=1} A_j \cdot k_{c,\theta,j} \cdot \left(\frac{f_{c,j}}{\gamma_{M,fi,c}}\right) = 0 \qquad (6)$$

Numerical Thermal Model

In this section, the methodology used to numerically determine the thermal effects of standard fire exposure on composite slabs is outlined. The composite slab is meshed to solve a nonlinear transient thermal analysis, using a 3-D model from ANSYS. The finite element method (FEM) requires the solution of equation 7 in the domain and the definition of the boundary conditions in equation 8 on the exposed and unexposed surface of the slab.

$$\nabla\left(\lambda_{(T)} \cdot \nabla T\right) = \rho_{(T)} \cdot Cp_{(T)} \cdot \partial T/\partial t \qquad (7)$$

$$\lambda_{(T)} \cdot \nabla T \cdot \vec{n} = \alpha_c \cdot \left(T_g - T\right) + \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot \left(T_g^4 - T^4\right) \qquad (8)$$

The view factor (Φ) quantifies the geometric relation between the surface emitting radiation and the surface receiving radiation. The view factor of the lower flange of composite slabs (Φ_{low}) is given as 1. Owing to the obstruction to direct fire exposure caused by the ribs of the steel deck, the view factors of the web (Φ_{web}) and upper flange (Φ_{up}) are smaller than one. These view factors can be calculated according to equation 9 and equation 10.

$$\Phi_{up} = \left[\sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2} - \sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}\right] \Big/ l_3 \qquad (9)$$

$$\Phi_{web} = \left[\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2} + \left(l_3 + l_1 - l_2\right) - \sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2}\right] \Big/ 2\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2} \qquad (10)$$

The finite element mesh for the slab of the validation model is presented in figure 2.

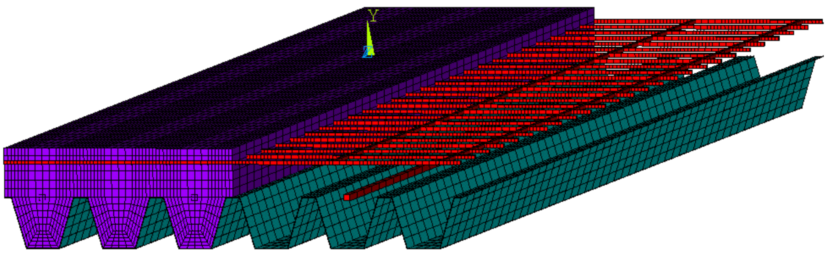
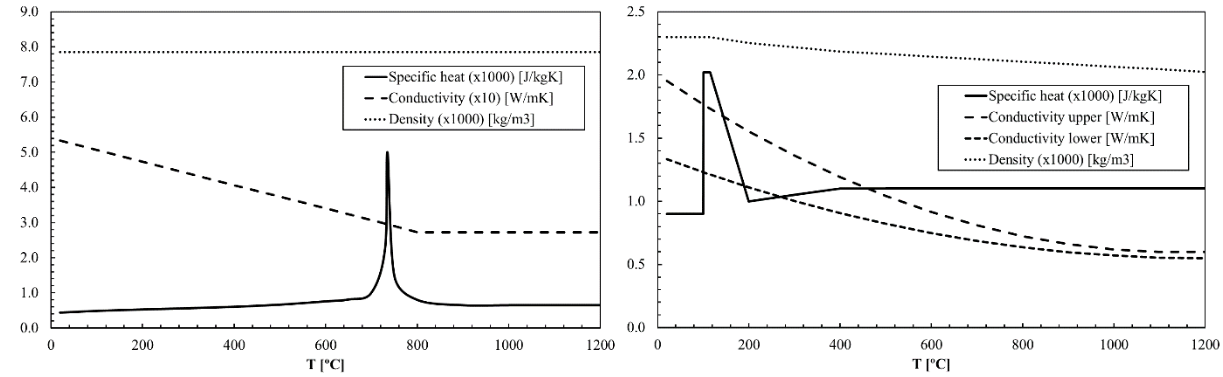


Figure 2. Finite element mesh (ANSYS).

A three-dimensional model of the slab is generated, which is composed by subdomains that correspond to the different materials: the concrete topping, steel deck, rebars and steel mesh. Perfect thermal contact between all the materials is considered.

The thermal properties of the materials are temperature dependent and vary according to the standards used for composite structures, steel structures and concrete structures. The thermal properties of carbon steel and concrete are presented in figure 3. Regarding the conductivity of concrete, the upper limit has been selected for the numerical simulations. According to the note 2, point 9, from section 3.3.2 of the EN 1994-1-2 [6], the upper limit has been derived from tests of steel-concrete composite structural elements, and the use of the upper limit is recommended. The specific heat of concrete presents a peak value related to 3% of moisture content of concrete weight. The extrapolation method was used to update higher moisture contents.



a) Carbon steel. b) Concrete.

Figure 3. Thermal material properties.

Three different finite elements are used. The SHELL131 element has four nodes with up to 32 degrees of freedom per node. This element presents linear interpolation functions in the plane of the element and through the layer thickness, using full Gauss integration method (2x2). This element is used to model the steel deck. The bottom temperature of shell element nodes is assumed to be equal to the temperature of solid element nodes when both nodes are coincident. The SOLID70 element presents eight nodes with a single degree of freedom per node. Linear interpolation functions are used for this element and the full Gauss integration method is also applied (2x2x2). This element is used to model the concrete topping. The LINK33 element has two nodes with a single degree of freedom per node. This element presents linear interpolation functions and exact integration. The LINK33 element is used to model the anti-crack mesh and the rebars.

All the nodes are set with an initial condition for temperature of 20°C. The exposed side is submitted to heat flux by convection and radiation considering different values for view factors and the bulk temperature following the standard fire, see equation 8. The unexposed side is subjected to a convective heat flux, using a constant bulk temperature of 20 ºC. The lower part of the steel deck is subjected to standard fire exposure using a convection coefficient of 25 W/m²K and an emissivity of fire equal to 1. A convective coefficient of 9 W/m²K is applied on the upper part of the slab to include the radiation effect. Perfect thermal contact between all the materials is considered, and the heat flow criterion is applied as convergence criterion, using a tolerance value of 10^{-3} and a minimum reference value of 10^{-6}.

Experimental fire testing

A fire test conducted by Hamerlinck [4] (test no. 2) has been selected for the validation of the numerical model. The simply supported slab was exposed to the ISO 834 standard fire from bellow in a controlled furnace. The specimen had a clear span of 660 mm wide by 3200 mm long. Normal weight concrete was used, and the moisture content amounted to 3.5% by weight.

The initial bulk temperature was of 20 °C. Figure 4 shows the cross section of the composite slab.

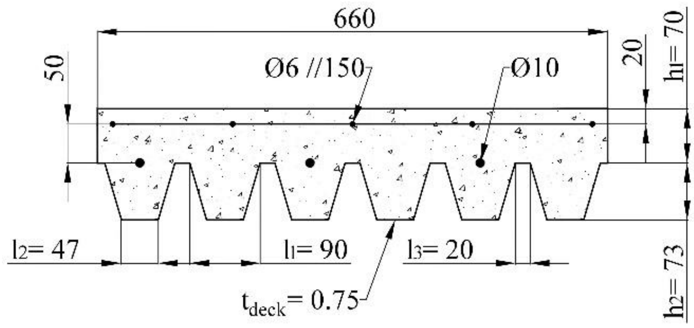
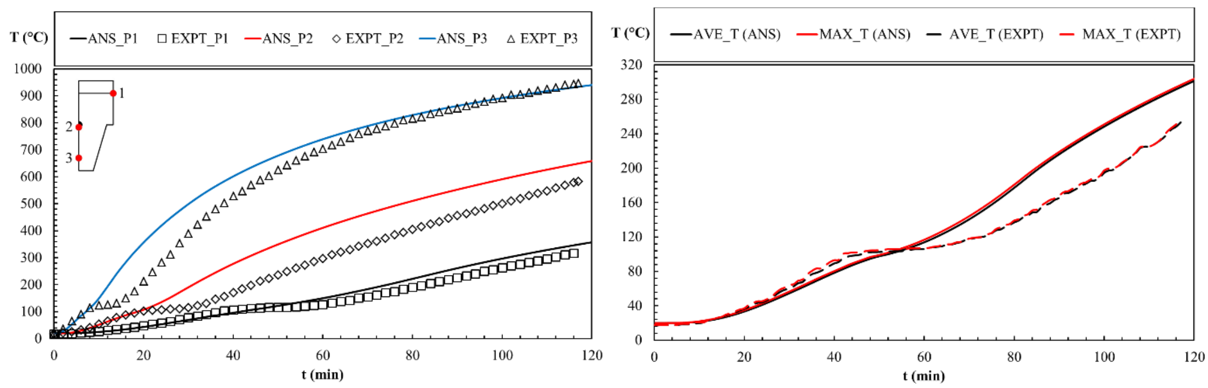


Figure 4. Cross section of the tested slab: dimensions in millimetres [2].

Validation of the thermal model

Figure 5 shows the temperature development (numerical and experimental) at different selected points, as well as the average and maximum temperatures on the unexposed side of the slab.



a) Selected points. b) Unexposed side.

Figure 5. Numerical and experimental results – Points 1, 2 and 3 at distance 20, 74 and 123 mm from the top.

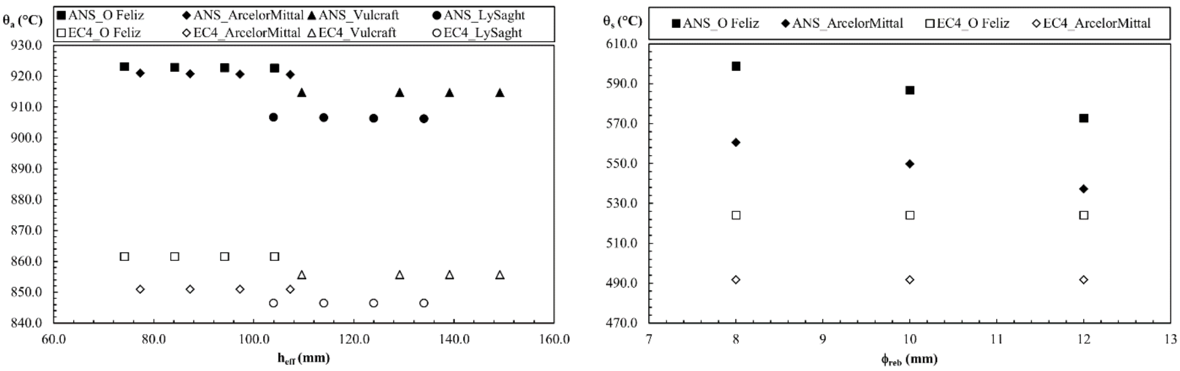
It can be observed that the temperature development on points 2 and 3 is quite similar between the experimental (EXPT) and the perfect contact model (ANS) in the first minutes of heating. After that, larger differences are observed probably due to localized moisture concentrations, and/or debonding of the steel deck from the concrete topping when the moisture evaporation starts in the experimental test. These phenomena are not taken into consideration in the numerical model. The moisture migration inside concrete was not considered in the model (in experiments this mass transfer occurs). The effect of evaporation has been considered in the model through the use of effective thermal property (specific heat).

For point 1, a satisfactory agreement between numerical and experimental results is obtained for the entire duration of the test. On the unexposed surface, the average and maximum temperature curves are very close to each other for both numerical and experimental results. A good agreement between the numerical and experimental results is observed for both average and maximum temperatures until the first 60 minutes of heating.

Other differences may arise due to the existence of different boundary conditions between experimental tests and numerical simulations (adiabatic condition from the lateral surfaces, existence of different values for the convective coefficient and emissivity, for example). All these effects may justify the differences between the model and the experimental measurements.

Parametric Study

A parametric study comprising slabs with commercial steel deck profiles has been conducted in order to analyse the influence of the steel components on the temperature of the parts of the steel deck (lower flange, web and upper flange) and the rebars as well. A total of 208 numerical simulations have been conducted in ANSYS considering perfect thermal contact between the materials and all the parameters are compared separately. The ranges of selected parameters comprise commonly used values. A representative portion of 1 m by 1 m of each slab is selected to perform the thermal analyses considering standard fire conditions. Figure 6 presents the numerical results obtained in ANSYS (ANS) and the Eurocode 4 provisions (EC4) for the temperatures of the lower flange and the rebars, for the fire resistance class R60.



a) Temperature of the lower flange b) Temperature of the rebars (trap. profiles).

Figure 6. Comparison between the numerical results and EN 1994-1-2 provisions for the fire resistance class R60.

It can be observed that the results from the EN 1994-1-2 for both the temperature of the lower flange and the rebars are considerably lower in comparison to the numerical results. This means that the calculation rules of the European standard are on the unsafe side. In addition, it is noteworthy that the simplified calculation method of the standard does not include the effect of the diameter of the rebars ϕ_{reb} (mm) on its temperature. In this regard, a new equation considering this effect is proposed, see equation 11. Furthermore, new coefficients are proposed for the calculation of the temperature of the steel components of composite slabs with normal weight concrete (NWC), see Table 2 and Table 3.

$$\theta_s = c_0 + (c_1 \cdot u_3/h_2) + (c_2 \cdot z) + (c_3 \cdot A/L_r) + (c_4 \cdot \alpha) + (c_5 \cdot 1/l_3) + (c_6 \cdot \phi_{reb}{}^2) + (c_7 \cdot \phi_{reb}) \tag{11}$$

Table 2. Proposed new coefficients for the temperature of the parts of the steel deck for slabs with NWC.

Standard fire resistance	Part of the steel deck	b0 (°C)	b1 (°C mm)	b2 (°C mm)	b3 (°C)	b4 (°C)
R60	Lower flange	1015	-1197	-2.32	86.4	-147.5
	Web	725	600	-2.00	537.7	-356.0
	Upper flange	474	1300	-1.95	1148.4	-777.0
R90	Lower flange	939.5	95.0	1.00	93.0	-78.3
	Web	848.0	345.0	-2.21	464.9	-308.6
	Upper flange	641.5	854.0	-1.55	700.0	-315.0
R120	Lower flange	1106.0	-995.0	-1.55	46.7	-82.8
	Web	920.0	300.0	-1.82	344.2	-199.0
	Upper flange	764.0	660.0	-1.67	592.6	-271.0

Table 3. Proposed new coefficients for the temperature of the rebars in the rib for slabs with NWC.

Steel deck	Fire resistance	c0 (°C)	c1 (°C)	c2 (°C mm0.5)	c3 (°C mm)	c4 (°C/°)	c5 (°C mm)	c6 (°C/mm2)	c7 (°C/mm)
Trapezoidal	R60	1294.90	-250	-240	-5.01	1.04	-925	-0.2425	-1.700
	R90	1406.81	-256	-235	-5.30	1.39	-1267	-0.1938	-1.608
	R120	1407.65	-238	-227	-6.80	2.85	-1326	-0.7544	5.169
Re-entrant	R60	1269.67	-250	-240	-5.01	1.04	-925	-0.160	-0.005
	R90	1363.63	-256	-235	-5.30	1.39	-1267	-0.1425	-0.215
	R120	1382.02	-238	-227	-4.79	1.68	-1326	-0.1413	-0.288

A comparison between this new proposal and the original version of EN 1994-1-2 was made for the composite slab under validation [4]. A reduction on the sagging moment resistance is verified according to this new proposal, see Table 4. The difference is in between 17 and 26%, being the calculation method from EN 1994-1-2 on the unsafe side.

Table 4: Comparison between the calculation method from EN 1994-1-2 and the new proposal for the sagging moment resistance.

Fire Resistance	$M^{+}_{fi,r,Rd}$ (EN 1994-1-2) (N m)	$M^{+}_{fi,r,Rd}$ (New Proposal) (N m)	Difference (%)
R60	11256	8933	26
R90	8296	7071	17
R120	5519	4516	22

Conclusion

This paper presented a discussion around the results of 3-D thermal analyses performed in ANSYS for different composite slabs. The numerical model has been successfully validated with the fire test. Regarding the experimental results, a plateau at about 100 °C (due to moisture evaporation) should be highlighted, consisting of a decrease in the rate of temperature increase.

The results of the numerical simulations do not present this pronounced plateau, probably because localized moisture concentrations in the tests were higher than the uniform moisture content introduced in the thermal model. With respect to the results obtained through the EN 1994-1-2, the temperature of the steel components was on the unsafe side for most of the analyses, which can lead to the unsafe design of composite structures under fire.

A new calculation method has been proposed for the determination of the temperature of the steel components of the composite slab. This new method presents good agreement with numerical results and considers parameters which are not included in the current calculation rules of the European standard. According to this new proposal, the fire resistance is reduced in comparison to the calculation method of the current version of Eurocode 4 – Part 1-2.

References

[1] ISO, ISO 834-1 Fire-resistance tests - Elements of building construction, International Standard Oganization, 1999.

[2] J. Jiang, A. Pintar, J. M. Weigand, J. A. Main, F. Sadek, Improved calculation method for insulation-based fire resistance of composite slabs, *Fire Safety Journal*, Vol. 105, pp. 144-153, 2019.

[3] ECCS, Calculation of the Fire Resistance of Composite Concrete Slabs with Profiled Steel Sheet Exposed to the Standard Fire, *Fire Safety of Steel Structures*, European Convention for Constructional Steelwork - Committee T3, 1983.

[4] R. Hamerlinck, *The behaviour of fire-exposed composite steel/concrete slabs*, Thesis, Technische Universiteit Eindhoven, Eindhoven, 1991.

[5] C. Both, *The fire resistance of composite steel-concrete slabs*, Thesis, Delft University Press, Delft, 1998.

[6] CEN, EN 1994-1-2: Design of Composite Steel and Concrete Structures. Part 1-2: General Rules - Structural Fire Design, European Committee for Standardization, 2005.

[7] CEN, EN 1993-1-2: Design of Steel Structures. Part 1-2: General Rules - Structural Fire Design, European Committee for Standardization, 2005.