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THE AIR GAP EFFECT ON THE FIRE RESISTANCE OF COMPOSITE SLAB WITH STEEL DECK

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Abstract *The fire resistance of composite slabs with steel deck may be defined by experimental tests or using simple calculation methods available in standards, such as EN1994-1-2. The composite slab is made by a concrete topping cast on the top surface of a steel deck, presenting a combination of two different materials (steel and concrete). This work presents the results and the validation of a two dimensional finite element model, used for comparison with experimental results developed by the authors. Results are also compared with the simple calculation method of EN1994-1-2, which seems to be unsafe. The numerical model considers perfect contact between materials, but investigates the effect of the air gap between the concrete slab and the steel deck. The existence of the air gap is usually justified by different expansion coefficients and by the thermal bowing caused by the thermal gradient across the thickness, which leads to the separation of both materials during experimental tests.*

1. INTRODUCTION

Concrete slabs with steel decks are slabs that use steel deck as a permanent formwork and as reinforcement to the concrete placed on top, see Figure 1. This represents one of the advantages of this solution, because it reduces the construction time, requires less concrete, providing slender slabs.

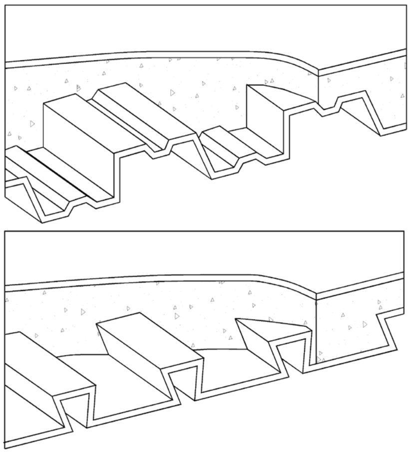


Figure 1– Trapezoidal and re-entrant composite slab with steel deck.

Composite slabs are widely used in buildings, since 1980. The overall depth can vary between 100 to 170 mm. The thickness of the deck can vary from 0.7 to 1.2 or more and this part of the structure is normally galvanized to increase durability [1]. The composite floor is usually made with these plate elements supported by secondary beams (linear elements) and shear studs that are responsible for the composite action between both elements. The fire resistance of both elements is prescribed by the building codes, but this investigation only considers the fire behaviour of the plate element.

In 1983, the European Convention for Constructional Steelwork, ECCS [2], published some calculation rules applied to the practical dimensioning of composite concrete slabs with a profiled steel deck, exposed to a standard fire [3]. This document also presents a resume of several experimental tests developed in different European testing laboratories. According to this document, the explicit fire design calculations for the composite slabs is not required, when the fire requirements are smaller or equal than 30 minutes. The application of this rule would only be applied when the slab was safely design to run at room temperature. For the other cases, simple calculation formulas were presented in a basis of conservative approximations for a safer design procedure. In this technical note, it is also assumed that if the insulation criterion is fulfilled, then the integrity criterion is also fulfilled. The technical note also identified the existence of the membrane effect when the composite slab is relatively well attached to the boundary of the building structure.

Since the initial work published by Hamerlinck *et al* [4], in 1990, many researchers have devoted themselves to evaluate the fire resistance of concrete slabs with steel deck. Some studies focus on experimental tests, such as for instance, Bailey *et al* [5], Abdel-Halim *et al* [6], L. Lim *et al* [7] Guo-Qiang Li *et al* [8].

Experimental fire resistance tests are very important, but they are also very expensive. For this reason, the numerical simulations allow to estimate the fire resistance in a more economical and fast way. Numerical simulations do not always capture all the physical phenomena involved. Consequently, numerical results often differ from experimental results. The search for reliable numerical models has become increasingly important.

In 2017, a numerical study based on detailed and reduced-order models of heat transfer in composite slabs was carried out by Jian Jiang *et al* [9] from NIST. The main objective of this research was to develop a reduced-order modelling approach applicable for both thermal and structural analysis, in order to simplify the analysis of the structural behaviour under fire conditions. Solid elements were used for the concrete slab and shell elements for the steel sheet. Both detailed and reduced-order models were validated against experimental evidence and a parametric study using the detailed model was conducted to evaluate the effect of some components on temperature development such as thermal boundary conditions, thermal properties and slab geometry. In addition, the specific heat of the concrete was modified to better estimate the heat input in the web, and thereafter an equation for the modification was suggested. In order to consider the effects of the change in emissivity of the galvanized steel sheet due to the melting of the zinc layer, a novel method to calculate the temperature-dependent emissivity was proposed. Generally speaking, it was observed that satisfactory results did not require a great refinement of the finite element mesh and temperatures at the unexposed side were mainly affected by the thickness of the concrete topping. The results of the proposed model for emissivity showed better conformity with experimental results than those calculated from EC4.

In previous, work we investigate the thermal performance of composite slabs under standard fire conditions [10]. The key objective of this study was to develop two-dimensional numerical models using the software MATLAB and ANSYS in order to evaluate the fire resistance of different slab configurations according to the insulation criterion. Several numerical simulations were performed with the aim of analysing the effect of both concrete and steel decking thicknesses on the temperatures at the unexposed side. Considering that the thermal behaviour is not influenced by the mechanical behaviour, experimental fire tests were conducted on two unloaded samples. Moreover, the results of numerical simulations were compared against results obtained with the experimental tests as well as the simplified method given in EC4 and NBR 14323. On the whole, the fire resistance ratings obtained from the numerical models were considerably inferior to those measured on the experimental tests and a comparison between the numerical and simplified method results evidenced that present calculation rules were unsafe. According to the numerical results, a new and better approach considering a quadratic dependence between the fire resistance and the effective thickness of the composite slab was proposed.

One of the physical phenomena observed in all the experimental tests consists of the debonding of the steel deck from concrete top. Debonding can justify the existence of a thermal resistance to the heat flux coming from the bottom. This phenomenon is responsible for the higher temperatures observed in the numerical simulations in comparison to the experimental temperatures. We observe that this temperature difference can be reduced by introducing in the numerical simulations an air gap between the steel deck and the concrete [11].

In this investigation we make several numerical simulations corresponding to the introduction of an air gap, with different thicknesses, between the concrete slab and the steel deck. The existence of the air gap is usually justified by different expansion coefficients and by the thermal bowing cause by the thermal gradient across the thickness, which leads to the separation of both materials during experimental tests. We look for the best numerical model used to validate the experimental results.

2. FIRE RATING

Composite slabs need to meet fire-safety requirements according to building codes. The fire requirements are normally specified by fire rating periods of 30, 60, 90 min or more. The fire rating of this type of building elements is normally made using standard fire tests [12], and should consider the criteria for Stability (R), Integrity (E) and Insulation (I). These tests are expensive and time-consuming, reason why the fire resistance can be evaluated by means of numerical simulation or by the use of simple calculation methods. The fire resistance of the composite slabs is always defined with respect to standard fire exposure from below.

The load bearing resistance for flexural loaded elements (R) is the ability to support the loading during test and the assessment shall be made on the basis of limiting vertical displacement D (D=L2/400d [mm]), or limiting rate of vertical contraction (dD/dt=L2/9000d [mm/min]).

The integrity (E) is the ability to withstand fire in one side and the assessment shall be made on the basis of measuring cracks or openings in excess of given dimensions, or the ignition of a cotton pad, or sustained flaming on the unexposed side. The integrity (E) criterion is usually verified because the floor slab is cast in situ, being the joints adequately sealed. Any cracks which may occur in the concrete during fire exposure are unimportant because the steel profile will prevent the passage of flames or hot gases [2].

The insulation (I) is the ability to withstand fire in one side and the assessment shall be made on the basis of the average temperature rise (Tave) on the unexposed face limited to 140 °C above the initial average temperature, or; made on the basis of the maximum temperature rise (Tmax) at any point limited to 180 °C above the initial average temperature.

3. SIMPLIFIED METHOD

The current version of Eurocode 4 part 1.2 [13] presents a simple calculation method, to define the fire resistance (I), which depends linearly in a set of geometric parameters, but that seems to be over conservative and unsafe. According to the annex D [13], the fire resistance, of both simply supported and continuous concrete slabs with profiled steel deck, may be calculated according to equations (1) and (2).

$$\begin{aligned} t_i &= a_0 + a_1.h_1 + a_2.\phi + a_3.A/L_r + \\ &+ a_4.1/l_3 + a_5.A/L_r\,1/l_3 \end{aligned} \tag{1}$$

The rib geometry factor defined by equation (2), see Figure 2.

$$A/L_r = \frac{h_2\,(l_1 + l_2)/2}{l_2 + 2\sqrt{h_2^2 + ((l_1 - l_2)/2)^2}} \tag{2}$$

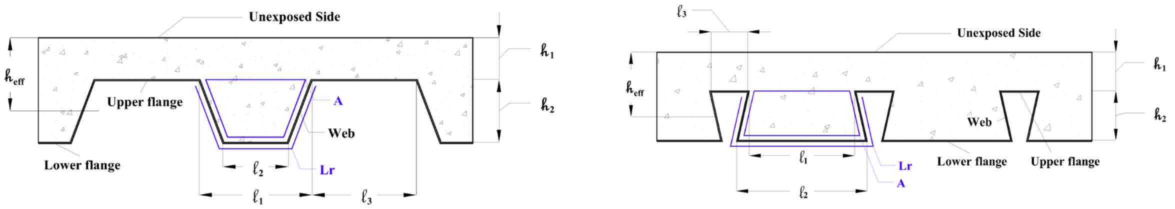


Figure 2. Model for the composite slab with steel deck (trapezoidal and re-entrant shape).

The partial factors are proposed for normal weight concrete (NC), according to Table 1.

a0	a1	a2	a3	a4	a5
[min]	[min/mm]	[min]	[min/mm]	[min.mm]	[min]
-28.8	1.55	-12.6	0.33	-735	48

Table 1. Partial factors used for the calculation of fire resistance (NC).

The view factor (ϕ) specified in the equation (1), quantifies the geometric relation between the surface emitting radiation and the surface receiving, that depends on the surfaces areas and orientations, as well as the distance between them [9]. The view factor at the lower flange of the composite slab is given as $\phi_{lower} = 1$. The view factor of the web ϕ_{web} and of the upper flange ϕ_{upper} of the steel deck are smaller than one, due to the obstruction caused by the ribs of the steel deck. These values can be calculated by Hottel´s crossed-string method, using equations (3) and (4).

$$\phi_{upper} = \frac{\sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2} - \sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}}{l_3} \tag{3}$$

$$\phi_{web} = \frac{\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2} + (l_3 + l_1 - l_2) - \sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2}}{2\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}} \tag{4}$$

In a previous work [14], authors concluded that the fire resistance is also independent of the steel deck thickness and present a quadratic dependence on concrete depth above the deck h1. These observations are summarised in Table 2.

Trapezoidal Geometry	ℓ1/ℓ2= 84/40	ℓ1/ℓ2= 105/60	Re-entrant Geometry	ℓ1/ℓ2= 108/135	ℓ1/ℓ2= 112/135
h1 [mm]	t_i [min]	t_i [min]	h1 [mm]	t_i [min]	t_i [min]
40	34	38	40	51	54
50	50	53	50	66	69
60	65	69	60	82	85
70	81	84	70	97	100
80	96	100	80	113	116
90	112	115	90	128	131
100	127	131	100	144	147
110	143	146	110	159	162

Table 2. Fire resistance of trapezoidal composite slabs in completed minutes (insulation criterion).

This experimental study analysed the fire behaviour of the trapezoidal composite slab, using h1=40 mm and L1/L2=105/60. According to the simple calculation method, the expected fire resistance is 38 min.

4. NUMERICAL SIMULATIONS

In a previous work developed by the authors [14], smaller numerical models were used to determine the fire resistance, using representative ribs from the composite slabs. The numerical models were developed using ANSYS and the PDE toolbox from Matlab. Both results agreed very well with each other. Two dimensional models were used for the numerical simulations. The cross sections of the slab were meshed to solve a nonlinear transient thermal analysis. The finite element method requires the solution of equation (5) in the domain of the cross section (Ω) and equation (6) for the boundary conditions exposed to fire (∂Ω).

$$\nabla\left(\lambda_{(T)}.\nabla T\right)=\rho_{(T)}.Cp_{(T)}.\partial T/\partial t \tag{5}$$

$$\lambda_{(T)}.\nabla T.\vec{n}=\alpha_c\left(T_g-T\right)+\phi.\varepsilon_m.\varepsilon_f.\sigma.\left(T_g^4-T^4\right) \tag{6}$$

In these equations: T represents the temperature of each material; $\rho_{(T)}$ defines the specific mass; $Cp_{(T)}$ defines the specific heat; $\lambda_{(T)}$ defines the thermal conductivity; α_c specifies the convection coefficient; T_g represents the gas temperature of the fire compartment, using a standard fire ISO834, applied to the bottom part of the slab, ϕ specifies the view factor; ε_m represents the emissivity of each material (in both materials equal to 0.7); ε_f specifies the emissivity of the fire and σ represents the Stefan-Boltzmann constant.

The two dimensional simulation allow for the verification of the fire resistance (insulation). The thicknesses of the slabs were fixed to h1=40 mm. The 2D geometry of the composite slab is depicted in Figure 3.

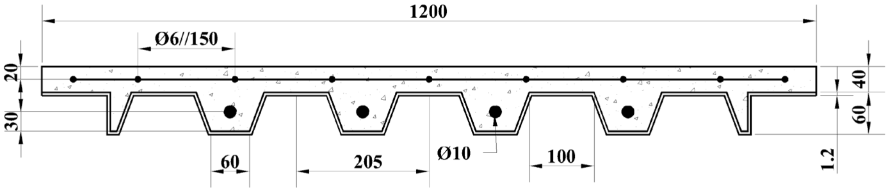


Figure 3. Composite slab model made with H60 trapezoidal steel deck

In this investigation, the full model was developed, using the mesh presented in Figure 4. The maximum finite element size used for the mesh was 0.01m. The finite element has linear interpolation functions with full integration.

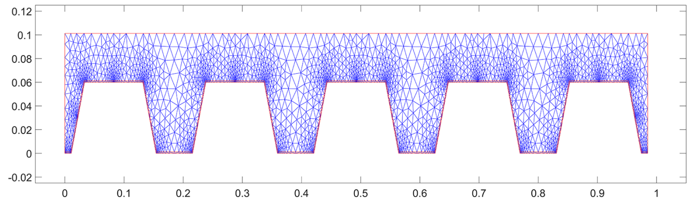
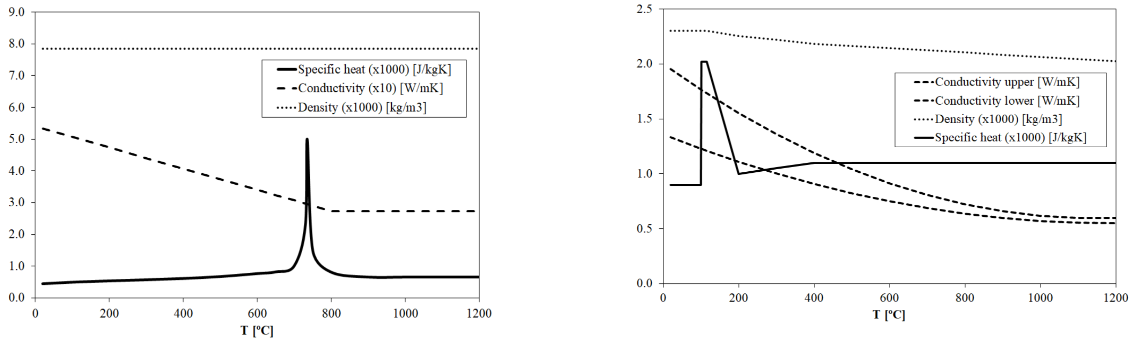


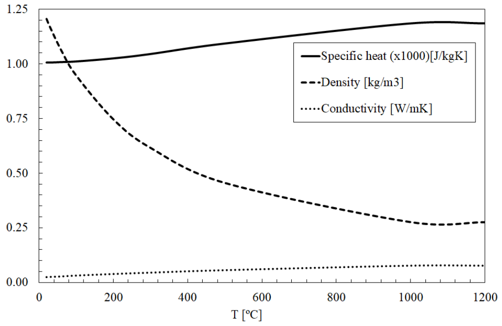
Figure 4. Finite element mesh used for the slab (L1/L2=105/60mm/mm, h1=40 mm, SDT=1.2mm).

The thermal properties (specific heat, density and conductivity) of all the materials (concrete and steel) are temperature dependent, and they change according the standards used for composite slabs, steel and concrete [13,15,16], see Figure 5.



a) Thermal properties for carbon steel.

b) Thermal properties for concrete.



c) Thermal properties for air.

Figure 5. Thermal properties for the materials of the composite slabs.

The conductivity of the steel decreases with temperature and the specific heat has a strong variation due to the allotropic phase transformation. The specific mass and the conductivity of the concrete decrease with temperature, being the upper value used for these simulations. The specific heat of concrete presents a peak value related with 3% in moisture content of concrete weight. Figure 5 also depicts the thermal properties for air. These properties are also temperature dependent and were used to simulate the interface between the steel deck and the bottom surface of the concrete. Previous investigations mention the separation between the steel deck and the concrete, allowing for the creation of a thermal resistance in this interface.
The solution method is incremental and iterative. The time increment is smaller than 1 s. The convergence criterion is based on the heat flow calculation, for an absolute tolerance of 10^{-6}, a relative tolerance of 10^{-3}, a residual tolerance of 10^{-4}, using a maximum number for iterations equal to 25. An initial uniform temperature is applied to all the nodes (20ºC). The lower part of the deck is submitted to standard fire conditions, using a convection coefficient of 25 [W/m^{2}K] and an emissivity of the fire equal to 1. These parameters are depicted in the Figure 6. The upper part of the slab is submitted to a convective coefficient of 9 [W/m^{2}K] to include the radiation effect, according to EN1991-1-2 [17].

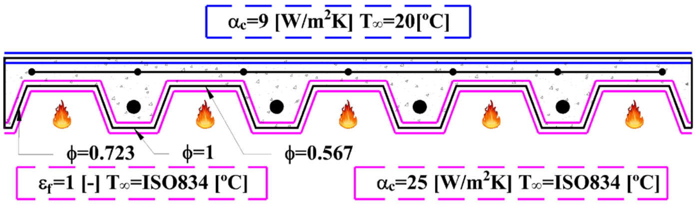
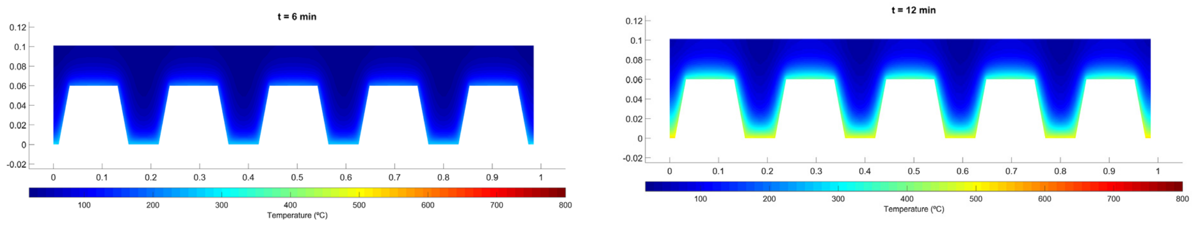


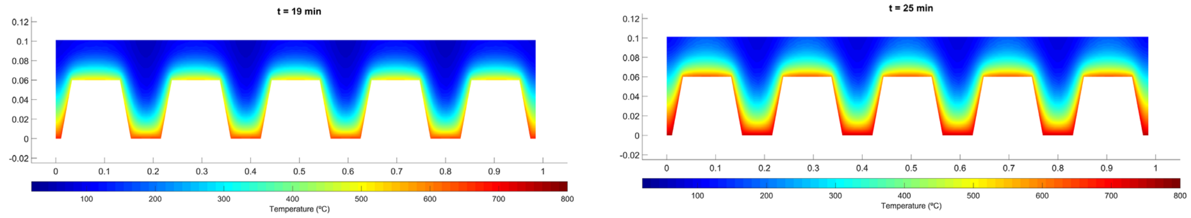
Figure 6. Boundary conditions for the composite slab.

The time history results allow the calculation of the temperature in the unexposed side of the slab and inside the slab. The average (Tave) rise on the unexposed surface is based on the arithmetic calculations, using a specific number of nodal temperatures. The contour of the nodal temperature is presented in Figure 7, for different time instants. The results were obtained on the hypothesis of perfect contact between the materials (steel deck and concrete).



a) Temperature field after 6 min

b) Temperature field after 12 min



c) Temperature field after 19 min

d) Temperature field after 25 min

Figure 7. Contour of nodal temperatures during fire exposure (perfect contact).

A second model was generated with an interface model for gas (air) that is expected to be generated during fire exposure, see Figure 8 for the central ribs. This second model assumed the existence of an additional thermal resistance, using 1, 2 and 3 mm thickness of air gap. The thermal barrier considers only the heat flow by conduction, neglecting the heat flow by radiation and convection. This hypothesis is based on the existence of a very small gap thickness, that most of the researchers used to justify the difference between the experimental and numerical results.

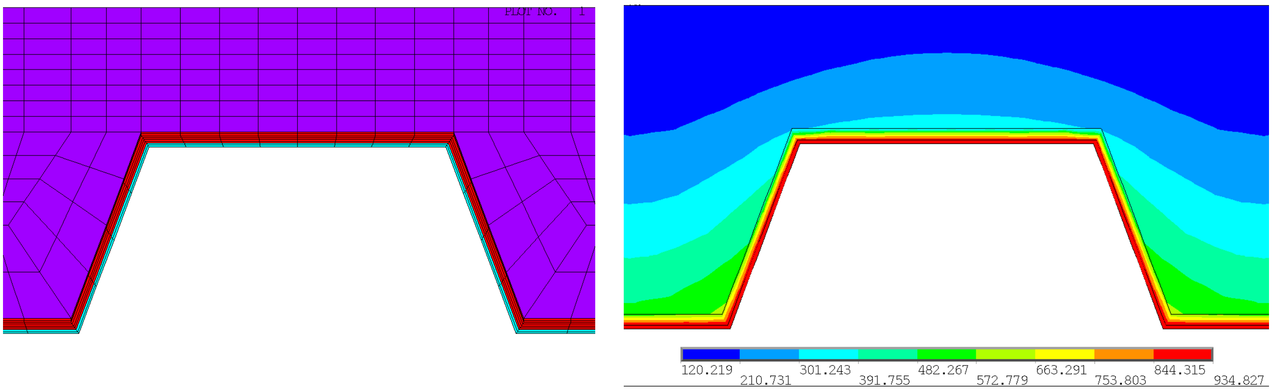


Figure 8. Model with 3mm of air gap and the temperature field for the critical time (T ave) of 62 minutes.

The additional air gap with 1 mm thickness (air 1) is responsible for an increase of 10 minutes of fire resistance, the model with 2 mm thickness (air 2) is responsible for an increase of 25 minutes and the model with 3 mm (air 3) increased the fire resistance in 40 minutes, see Figure 9.

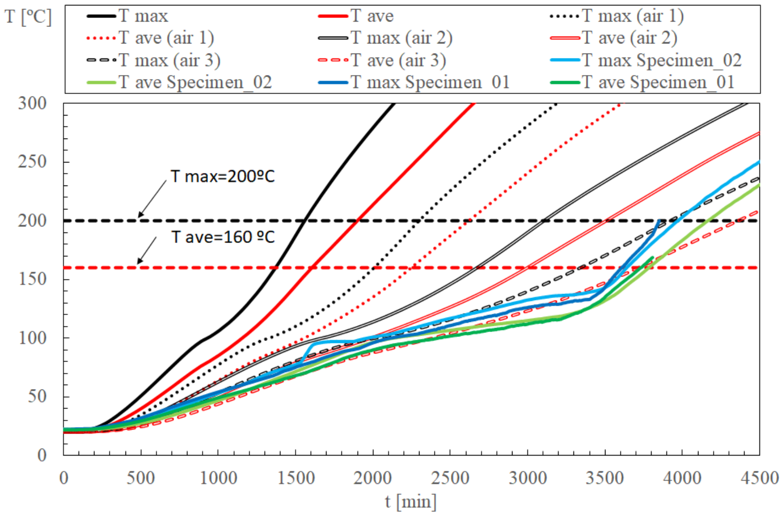


Figure 9. Experimental and numerical results with perfect contact and with air gap (1, 2 and 3 mm).

5. EXPERIMENTAL TESTS

We present here a summary description of the tests carried out with two specimens of composite slabs. More details on these tests can be obtained in [11]. Both samples represent

only one part of normal slab dimensions. These specimens allow for the verification of the fire resistance (insulation). The length of each slab is 1.15 m wide and 1.2 m long. The thicknesses of the slabs were fixed to h1=40 mm. The composite slabs used the same proportion and quantity of reinforcement steel as used for the normal slab dimensions. The composite slab was built with the steel deck model H60 from O-FELIZ, see Figure 3.
Normal weight concrete is used for the specimens. The furnace runs in natural gas, with 4 burners, with 90 KW maximum power each, located in different planes and vertical positions. Each sample is mounted in a special frame, locate on the top of the furnace, see Figure 10.

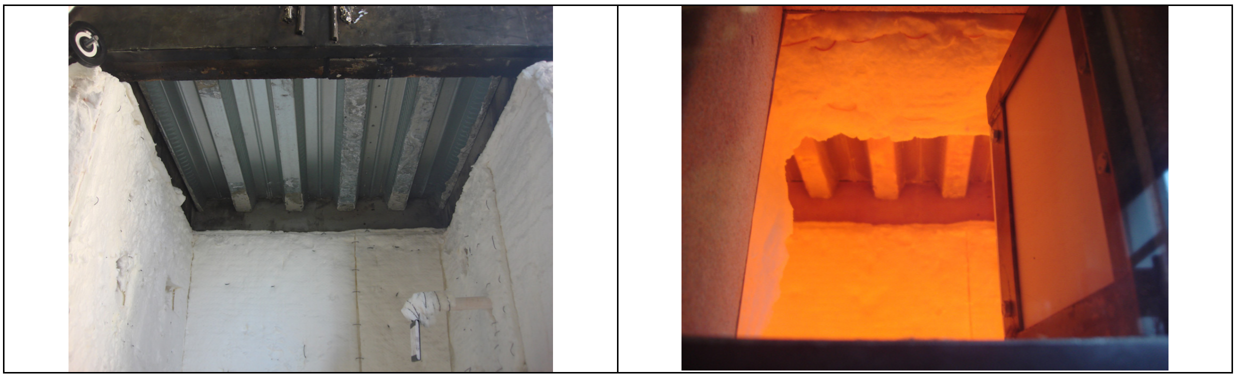


Figure 10. Fire resistance test of specimen 01. Before and during test.

The thermocouples position was based on standards with additional thermocouples for numerical validation. More thermocouples were included through the depth of the slab to validate the numerical model, see Figure 11.

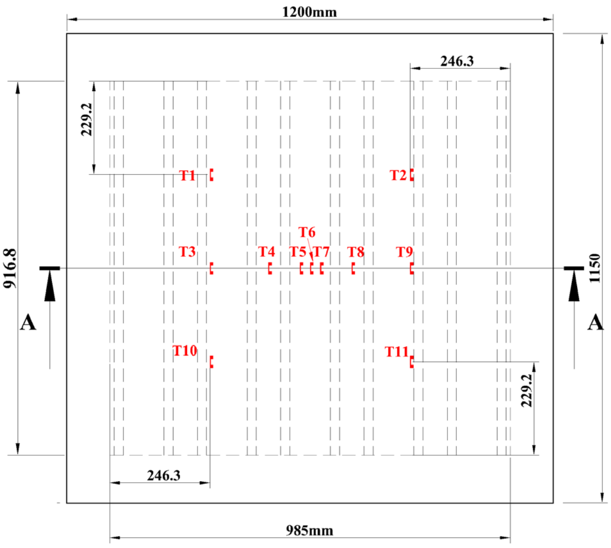
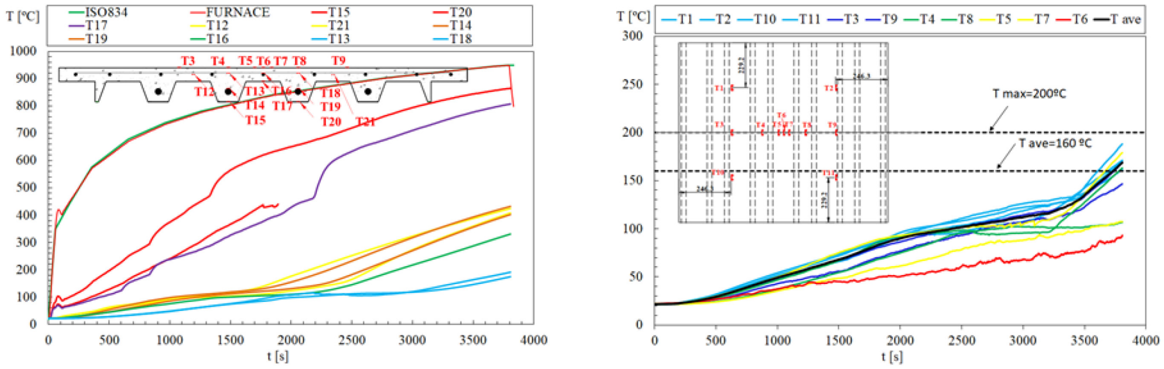


Figure 11. Thermocouples in the specimen

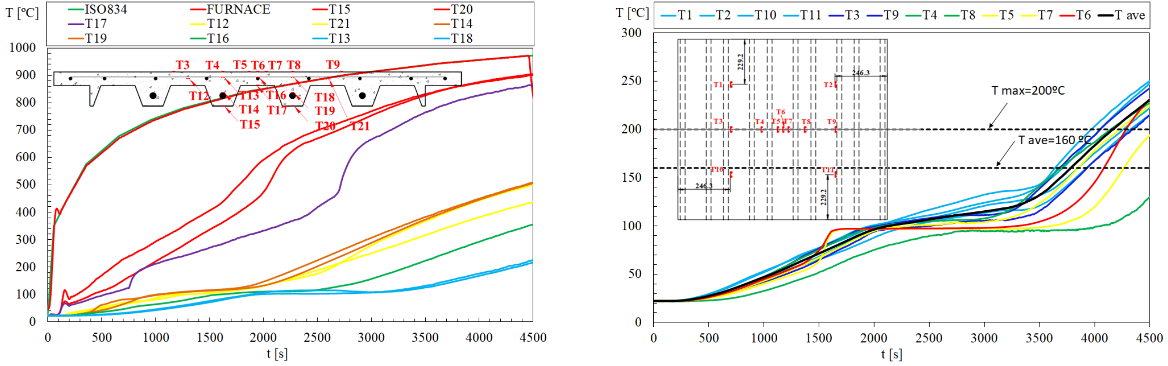
The thermocouples are identified in, being some of them welded to the steel deck (T15,T17,T20), others are welded to the steel mesh (T12,T16,T21) and rebars (T14,T19). Other thermocouples were placed inside concrete (T13,T18) using a steel nut, and finally, the copper disk thermocouples were placed over the unexposed surface (T1 up to T11).

The results for both specimens are presented in the next Figure 12. The temperature readings were divided into two graphs for better understanding and clarity. The average and maximum temperature was calculated based on the temperature readings from the unexposed side.



a) Specimen 01: Temperature measurements from below and inside the slab.

b) Specimen 01: Temperature measurements from the unexposed side.



c) Specimen 02: Temperature measurements from below and inside the slab.

d) Specimen 02: Temperature measurements from the unexposed side.

Figure 12. Temperature reading from both tests (specimen 01 and specimen 02).

The thermocouple T15 from specimen 01 was lost during the test, probably due to the separation of the steel deck (debonding). For both tests, the temperature in the upper flange (T17) is smaller than the temperature from the bottom flange (T15,T20), as expected. The unexposed side was monitored by thermocouples T1-T10.

The fire resistance of slab 1, considering the insulation criterion, was determined in 62 min., by the average temperature value of the unexposed side, while the fire resistance time for slab 2 was 63 min, also determined by the average temperature.

6. COMPARISON OF RESULTS

We begin by presenting the comparison of the experimental results with the numerical results. Taking into consideration the experimental fire resistance (62 and 63 min), the best approximation achieved by numerical simulation is 62 min, using the average value for the unexposed side (see Figure 9). Table 3 presents the comparison between the unexposed temperature rise between the experimental tests and the best fir of the numerical model (air 3). The relative error is 0.3% for the maximum temperature (Tmax) and 0.4% for the average temperature (Tave).

Specimen / Model	t_i [sec] for Tmax	t_i [min] for Tmax	t_i [sec] for Tave	t_i [min] for Tave
Specimen 01	3850	64	3732	62
Specimen 02	3971	66	3784	63
Specimen average	3910	65	3758	62.5
Num. model (air 3)	3922	65	3742	62
Error Num. model (air 3)	0.3 %	0%	0.4%	

Table 3 - Fire resistance of trapezoidal composite slabs (insulation criterion).

The results of experimental tests and numerical simulations are also compared with existing experimental results and with previous recommendation to determine the fire resistance for the concrete slabs with steel decks. The fire resistance is plotted against the effective thickness in Figure 13.

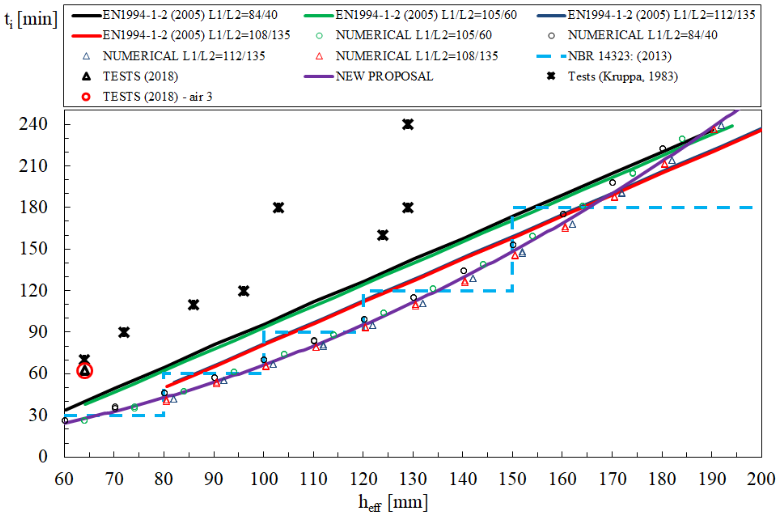


Figure 13. Comparison of results.

The effective thickness is an arithmetical average of the thickness that takes into account the shape of the slab, according to equation (7).

$$h_{eff} = h_1 + h_2 / 2 .((l_1 + l_2)/(l_1 + l_3)) \tag{7}$$

The fire resistance obtained by numerical simulation, assuming perfect contact, is smaller in comparison with the other results. This means that the proposal from Eurocode 4 – Part 1.2 may be unsafe. According to the numerical results, there is a nonlinear dependence between the fire resistance and the effective thickness, which is not included in equation (1). A quadratic dependence can be proposed to take this behaviour in to consideration, resulting a perfect correlation coefficient of 1, equation (8).

$$t_i = 0.0058 \times h_{eff}^2 + 0.1071 \times h_{eff} - 6.997 \tag{8}$$

Numerical modelling of similar structural elements [18, 19], demonstrate that experimental measured temperatures at the exposed surface during a fire are usually smaller than those resulting from numerical simulation. These researchers mention that this behaviour is probably caused by the buckling deformed shape of steel deck and also due to the debonding in the interface between the concrete and the steel deck, creating the extra insulation layer. These two facts may explain the lower experimental temperature values on the unexposed surface, which is the same to say, explains the higher fire resistance time in experiments.
More recently, Jian Jiang et al. [20] propose an improved algebraic formula for the calculation of the fire resistance (criterion I) that explicitly considers the effect of the moisture content and is applicable to an extended range of slab geometries. The proposed expression is also developed based on simulations obtained from a validated finite element model.

7. CONCLUSIONS

The numerical simulation of the thermal effects caused by the fire on a composite concrete slab with steel deck is presented. This simulation allows to determine the fire resistance of this structural element from the point of view of the insulation criterion. The numerical simulation predicts lower fire resistance (I) when compared with the simple calculation method used for the actual standards, when using perfect contact. The fire resistance obtained with the simple calculation method, proposed in the Eurocode 4 – part 1.2, seems to be unsafe because it gives a critical time value quite higher to the one obtained with the numerical simulation. Experimental results are important to validate the numerical results, as presented in this investigation. The best numerical model used to validate the experimental results should be the one presenting an equivalent air gap of 3 mm (air 3). A new design formula is proposed to define the fire resistance of the composite slabs made with steel deck, taking into consideration different geometric parameters.

REFERENCES

[1] A. F. Hamerlinck, “The behaviour of fire-exposed composite steel/concrete slabs,” Eindhoven University of Technology, 1991.

[2] ECCS - Committee T3 - Fire Safety of Steel Structures, “Calculation of the fire resistance of composite concrete slabs with profiled steel sheet exposed to the standard fire”, ECCS: Publication 32. ECCS, Committee T3 - Fire safety of steel structures, technical note, p. 48, 1983.

[3] International Organization for Standardization, “ISO 834-1: Fire Resistance Tests - Elements of Building Construction - Part 1: General Requirements.” International Organization for Standardization, Switzerland, p. 25, 1999.

[4] R. Hamerlinck and J. W. B. Stark, “A numerical model for fire-exposed composite steel / concrete slabs,” in 10th International Specialty Conference on Cold-Formed Steel Structures - International Specialty Conference on Cold-Formed Steel

Structures. 5., 1990, pp. 115–130.

[5] C. G. Bailey, T. Lennon, and D. B. Moore, “The behaviour of full-scale steel-framed buildings subjected to compartment fires,” Struct. Eng., vol. 77, no. 8, pp. 15–21, 1999.

[6] M. A. H. Abdel-Halim, M. R. Hakmi, and D. C. O’Leary, “Fire resistance of composite floor slabs using a model fire test facility,” Eng. Struct., vol. 21, no. 2, pp. 176–182, 1999.

[7] L. Lim and C. Wade, “Experimental Fire Tests of Two-Way Concrete Slabs - Fire Engineering Research Report 02/12,” Christchurch, New Zealand, 2002.

[8] G.-Q. Li, N. Zhang, and J. Jiang, “Experimental investigation on thermal and mechanical behaviour of composite floors exposed to standard fire,” Fire Saf. J., vol. 89, pp. 63–76, 2017.

[9] J. Jiang, J. A. Main, F. Sadek, and J. M. Weigand, “Numerical modeling and analysis of heat transfer in composite slabs with profiled steel decking,” 2017.

[10] L. M. S. Prates, “Numerical Simulation of the Fire Behaviour of Composite Structures (Slabs) [in portuguese],” MSc thesis, Instituto Politécnico de Bragança, 2018.

[11] Paulo A. G. Piloto, Lucas M.S. Prates, Carlos Balsa, Ronaldo Rigobello, “Fire resistance of composite slabs with steel deck: experimental analysis and numerical simulation”, proceedings of the 1st Iberic Conference on Theoretical and Experimental Mechanics and Materials / 11th National Congress on Experimental Mechanics, ISBN 978-989-20-8771-9, full paper on USB flash drive, pp. 309-320, Porto, Portugal, 4-7 November 2018

[12] CEN- European Committee for Standardization, EN 1363-1: Fire resistance tests Part 1 : General Requirements, CEN-Europ. Brussels: CEN- European Committee for Standardization, 2012.

[13] CEN- European Committee for Standardization, EN 1994-1-2: Design of composite steel and concrete structures. Part 1-2: General rules - Structural fire design. Brussels: CEN- European Committee for Standardization, 2005.

[14] P. A. G. Piloto, L. M. S. Prates, C. Balsa, and R. Rigobello, “Numerical simulation of the fire resistance of composite slabs with steel deck,” Int. J. Eng. Technol., vol. 7, no. 2.23, pp. 83–86, 2018.

[15] CEN- European Committee for Standardization, EN 1993-1-2: Design of steel structures - Part 1-2: General rules - Structural fire design Eurocode. Brussels: CEN - European Committee for Standardization, 2005.

[16] CEN- European Committee for Standardization, EN 1992-1-2: Design of concrete structures - Part 1-2: General rules - Structural fire design, vol. EN 1992. Brussels: CEN - European Committee for Standardization, 2004.

[17] CEN- European Committee for Standardization, EN 1991-1-2, Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire. Brussels: CEN- European Committee for Standardization, 2002.

[18] S. Lamont, A. S. Usmani, and D. D. Drysdale, “Heat transfer analysis of the composite slab in the Cardington frame fire tests,” Fire Saf. J., vol. 36, no. 8, pp. 815–839, Nov. 2001.

[19] L. Lim, A. Buchanan, P. Moss, and J. Franssen, “Numerical modelling of two-way reinforced concrete slabs in fire,” Eng. Struct., vol. 26, pp. 1081–1091, 2004.

[20] 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 – in press (2019), doi: https://doi.org/10.1016/j.firesaf.2019.02.013.