FIRE RESISTANCE OF COMPOSITE SLABS WITH STEEL DECK: FROM EXPERIMENTS TO NUMERICAL SIMULATION

RESISTÊNCIA AO FOGO DE LAJES MISTAS COM CHAPA COLABORANTE: DOS ENSAIOS À SIMULAÇÃO NUMÉRICA

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ABSTRACT

This work investigates the thermal insulation behaviour of composite slabs with steel deck under standard fire test conditions. This composite slab consists of a concrete topping cast on the top of a steel deck. The concrete is usually reinforced with a steel mesh on the top and may also be reinforced using individual rebars. The steel deck also acts as reinforcement and may be directly exposed to fire conditions. This composite solution is widely used in every type of buildings which require fire resistance, in accordance to regulations and standards. The fire rating of this type of elements is determined by standard fire tests. Two samples were tested using standard fire conditions ISO834 to evaluate the Integrity (E) and insulation (I). The scope of this investigation concerns the fire rating for insulation (I). Numerical thermal simulation was also developed using Matlab PDE toolbox and ANSYS to compare the results and to find out the thermal effects of standard fire exposure. The results are also compared with the simplified method proposed by Eurocode 4-part 1.2, which seems to be unsafe.

RESUMO

Este trabalho investiga o comportamento ao fogo padrão de lajes mistas com chapa de aço colaborante. Esta laje mista resulta da cobertura de betão no topo de uma chapa perfilada em aço. O betão é geralmente reforçado com uma malha de aço na parte superior e também pode ser reforçado usando varões de aço individuais. A chapa de aço também funciona como reforço, podendo ser exposta diretamente às condições de incêndio. Esta solução mista é amplamente utilizada em todos os tipos de edifícios, que requerem um determinado nível de resistência ao fogo, de acordo com os regulamentos e normas. A classificação de resistência destes elementos é determinada por testes de incêndio padrão ISO834. Duas amostras foram testadas nestas condições para avaliar a integridade (E) e o isolamento (I). O objetivo desta investigação diz respeito à classificação de resistência para o isolamento (I). A simulação térmica numérica também foi desenvolvida usando os programas Matlab PDE e ANSYS para comparar os resultados e descobrir os efeitos térmicos da exposição ao fogo padrão. Os resultados também são comparados com o método simplificado proposto pelo Eurocódigo 4-parte 1.2, que parece ser inseguro.

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 Fig. 1. This fact represents one of the main advantages of this building solution, because reduces the construction time, requires less concrete, providing slender slabs.

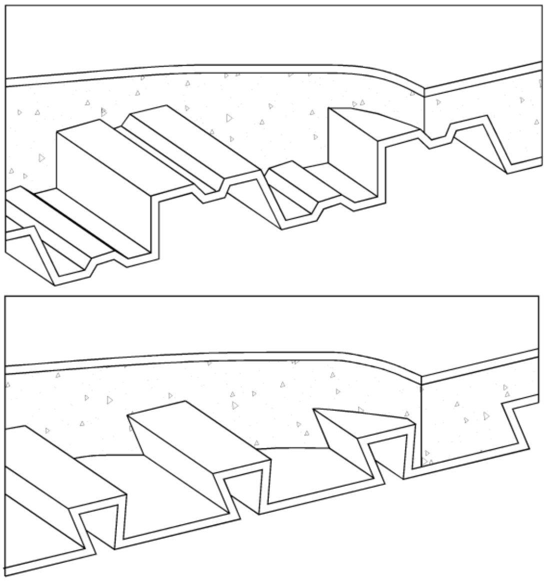


Fig. 1 - Trapezoidal and re-entrant composite slab with steel deck.

The use of these composite slabs in buildings has become very popular, since 1980. The overall depth can vary between 100 to 170 mm. The thickness of the steel deck can vary from 0.7 to 1.2 or more and this part of the element is normally galvanized to increase durability [1].

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 deign 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.

In 1990 Hamerlinck *et al* [4] developed a numerical model that satisfactorily predicted the thermal and the mechanical behaviour of different slab geometries under fire conditions. The authors used old approximations for the thermal properties, which can partially justify the differences between the nodal temperatures that they found.

In 1999 Bailey *et al* [5], presented the results of 2 experimental full-scale tests (complete building), demonstrating that the performance of the structure under fire differed from that was expected from fire codes and demonstrated that they were also conservative. Both tests also demonstrated that the element behaviour is different from what is normally obtained from standard small-scale fire tests.

In 2001 Lamont *et al* [6], performed an analysis of the heat transfer in composite slabs of the Cardington building. Four tests were performed in different floors of the building. An adaptive heat transfer model was used to estimate the temperatures through the slab. The code was able to model the moisture evaporation from the pores of the concrete by assuming a phase change for temperature equal to 100ºC. The developed model presented satisfactory results for most of the tests.

In 2002 Lim *et al* [7], developed six fire tests of two-way concrete slabs, comprising three reinforced concrete flat slabs and three composite steel-concrete slabs. The main objective was to investigate the behaviour of unrestrained simply supported slabs. The three flat slabs had different amount of reinforcing steel to investigate their effect on controlling crack widths to insure integrity. The slabs were submitted to a live load and standard fire during three hours. All the slabs presented extensive surface cracking and loss of moisture. The amount of concrete damage was related with the amount of reinforcement. The slabs supported the full duration of the tests without collapse. The fire resistance of the slabs in the tests exceed the predictions of the code recommendations. The tests were able to demonstrate the tensile membrane action effect during fire, despite the significant loss of flexural strength.

More recently in 2017, Guo-Qiang Li *et al* [8], performed 4 tests in composite slabs with steel decking, which were fire rated with 90 minutes and concluded that Eurocode 4 design calculations are conservative. The slabs were tested with different combinations for secondary beams, direction of the ribs and location of the rebars. The experiments revealed that the temperatures of the furnace were below the standard ISO834. The temperature at the bottom of the slabs (above the steel deck) were 100 °C on average below furnace temperature, after 100 min. The temperature on the unexposed surface was less than 100 °C, for the same time duration. From the point of view of insulation, the predicated fire resistance was 93 min, which means that for this particular condition, the simple calculation method is conservative. The fire rating was determined by the loadbearing capacity of the element. Debonding was also observed in all experiments, which can justify the existence of a thermal resistance to the heat flux coming from the bottom.

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 [9]-[10], 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 ($D=L^2/400d$ [mm]), or Limiting rate of vertical contraction ($dD/dt=L^2/9000d$ [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 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 on the unexposed face limited to 140 °C above the initial average temperature, or; made on the basis of the maximum temperature rise at any point limited to 180 °C above the initial average temperature.

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].

3. SIMPLIFIED METHOD

The current version of Eurocode 4 part 1.2 [11] 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 [11], the fire resistance, t_i, 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 Fig. 2.

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

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

The view factor (ϕ) specified in the equation (1), quantifies the geometric relation between

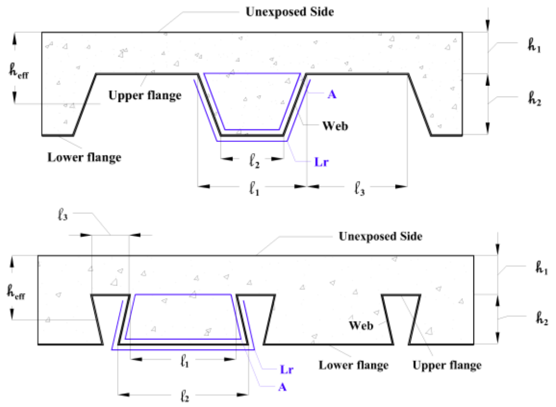


Fig. 2 – Model for the composite slab with steel deck (trapezoidal and re-entrant shape).

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

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

the surface emitting radiation and the surface receiving, that depends on of the surfaces areas and orientations, as well as the distance between them [12]. 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).

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

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

In a previous work [13], 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.

This experimental study intends to analyse 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.

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

Trapezoidal Geometry	ℓ_1/ℓ_2= 84/40	ℓ_1/ℓ_2= 105/60
h1 [mm]	t_i [min]	t_i [min]
40	34	38
50	50	53
60	65	69
70	81	84
80	96	100
90	112	115
100	127	131
110	143	146

4. EXPERIMENTAL METHOD

Two composite steel-concrete slab specimens were tested. 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 Fig. 3.

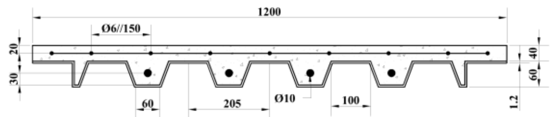


Fig. 3 – Composite slab model made with H60 trapezoidal steel deck.

Normal weight concrete is used for the specimens. The compressive strength of the concrete is 30 MPa and the yield strength of the rebars is higher than 500 MPa.

The fire resistance test is governed by the general standard EN1363-1 [9] and by the specific standard EN1365-2 [10]. 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 in the top of the furnace, see Fig. 4.

The test ran up to the critical time, expected by the insulation criterion, monitoring the temperature evolution in the unexposed side.

The thermocouple 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. The thermocouples are identified in Fig. 5, 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 in the unexposed surface (T1 up to T11).

The results for both specimens are presented in the next Fig. 6. The temperature readings were divided into two graphs for better understanding and clarity. The average

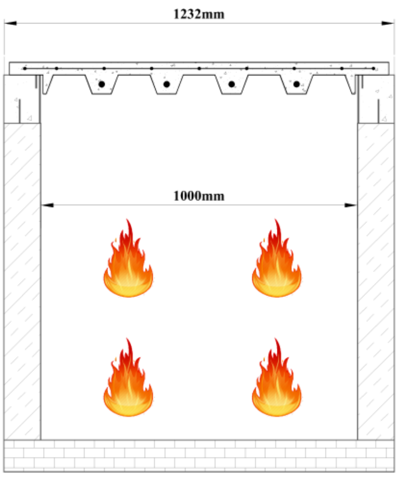


Fig. 4 – Specimen installed in the furnace.

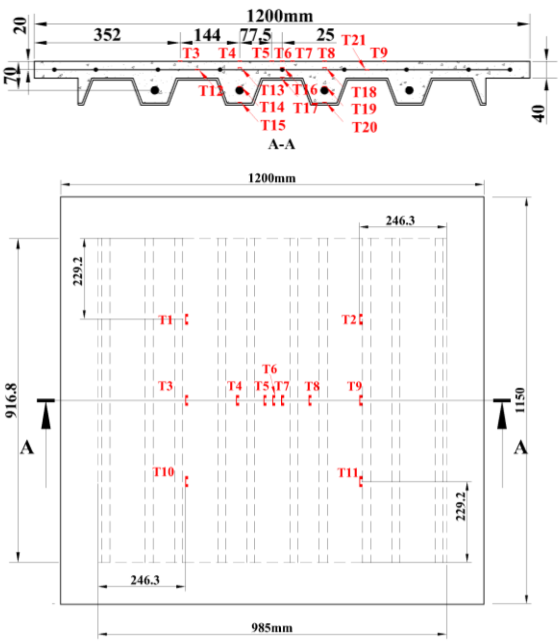
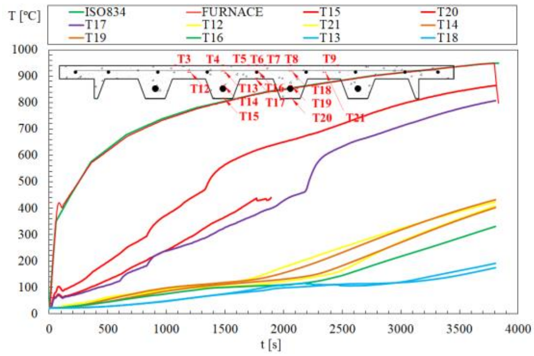
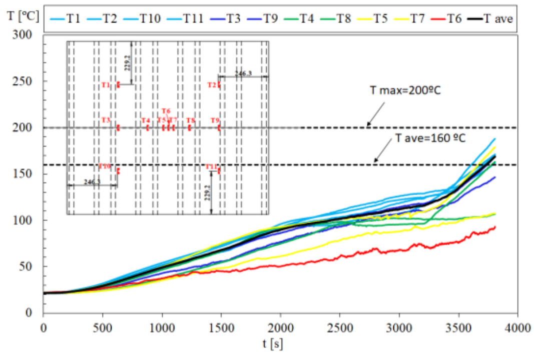


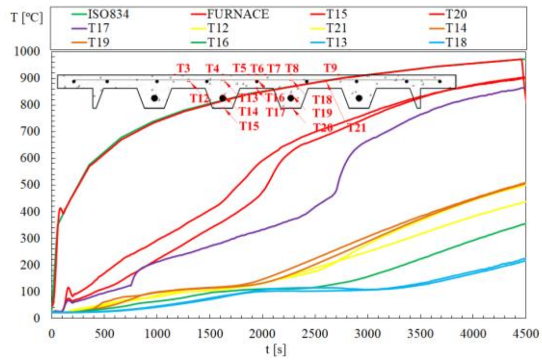
Fig. 5 – Thermocouples in the specimen.



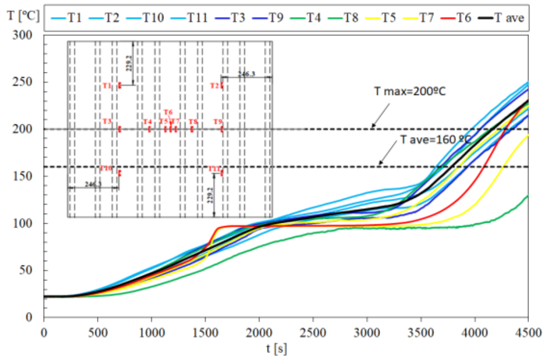
a) Specimen 01: Temperature measurements from below and inside the slab.



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.

Fig. 6 – Temperature reading from both tests (specimen 01 and specimen 02).

and the maximum temperature was calculated based on the temperature readings from the unexposed side.

The thermocouple T15 from specimen 01 was lost during the test, probably due to the separation of the steel deck. 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 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.

Fig. 7 presents two time instants during fire tests, one for each specimen.

a) Specimen 01: Photo from inside furnace.

b) Specimen 02: Photo from inside furnace.

Fig. 7 – Photographs during experiments (specimen 01 and specimen 02).

Both slabs were cured with the same time and prepared with the same conditions, but the temperature plateau for dehydration is better stablished in slab 2, see Fig. 6.

5. NUMERICAL SIMULATIONS

In a previous work developed by the authors [13], 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).

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

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

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.

In this investigation, the full model was developed, using the mesh presented in Fig. 8. The maximum finite element size used for the mesh was 0.01m. The finite element has linear interpolation functions with full integration.

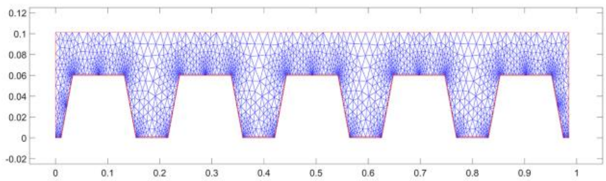
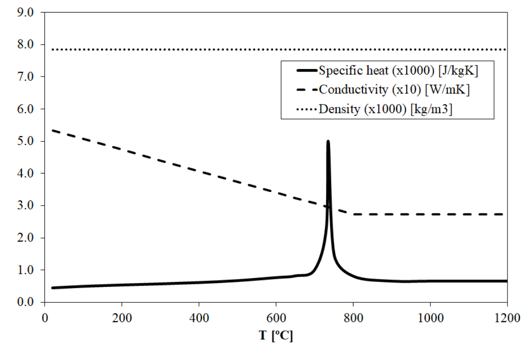


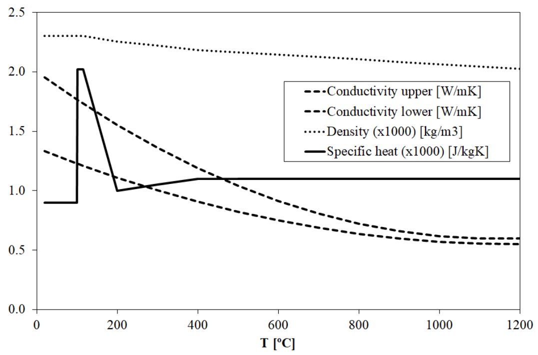
Fig. 8 - Finite element mesh used for the slab (L1/L2=105/60mm/mm, h1=40 mm, SDT=1.2mm).

The thermal properties (specific heat, density and conductivity) of both materials (concrete and steel) are temperature dependent, and they change according the standards used for composite slabs, steel and concrete [11] [14] [15], see Fig. 9.

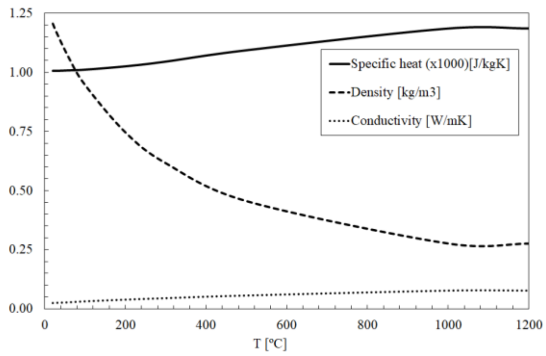
The conductivity of the steel decreases with temperature and the specific heat has a strong variation due to the allotropic phase transformation. The specific mass and the conductivity of the concrete decrease with temperature, being the upper value used for these simulations. The specific heat of concrete presents a peak value related with 3% in moisture content of concrete weight. Fig. 9 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.



a) Thermal properties for carbon steel



b) Thermal properties for concrete



c) Thermal properties for air

Fig. 9 - Thermal properties for the materials of the composite slabs.

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 Fig. 10. 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 [16].

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 Fig. 11, for different time instants. The results were obtained on the hypothesis of perfect contact between the materials (steel deck and concrete).

A second model was generated with an interface model for gas (air) that is expected to be generated during fire exposure. 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

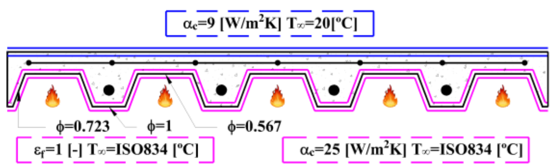
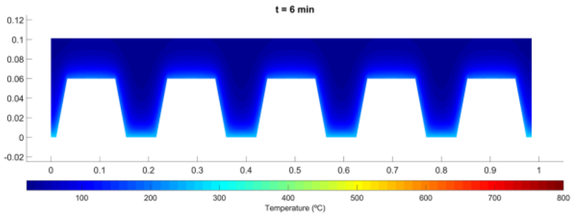
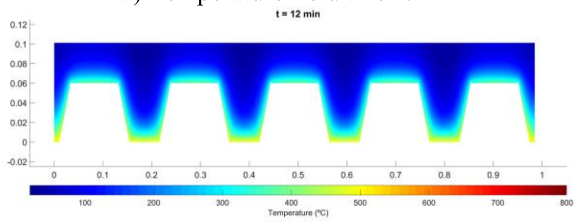


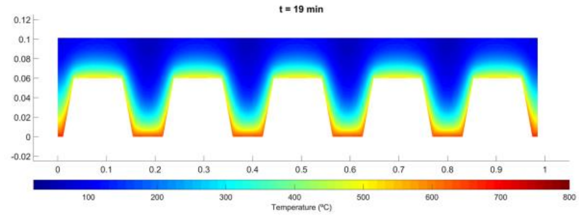
Fig. 10 - Boundary conditions for the composite slab.



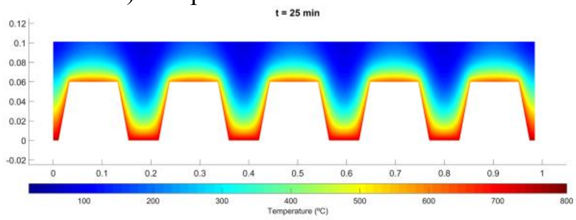
a) Temperature field after 6 min



b) Temperature field after 12 min



c) Temperature field after 19 min



d) Temperature field after 25 min

Fig. 11 - Contour of nodal temperatures during fire exposure (perfect contact).

existence of a very small gap thickness, that most of the researchers used to justify the difference between the experimental and numerical results. 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 increased the fire resistance in 40 minutes, see Fig. 12.

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. Table 3 presents the comparison between the unexposed temperature rise between the experimental tests and the best fit of the numerical model (air 3). The relative error is 0.3% for the maximum temperature and 0.4% for the average temperature.

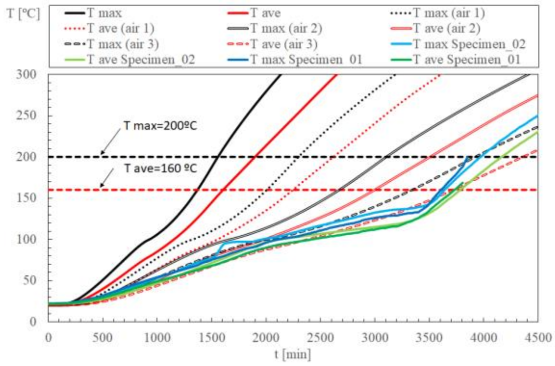


Fig. 12 - Fire resistance: experimental results and numerical results with perfect contact and with air gap (1, 2 and 3 mm).

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

Specimen / Model	t_i [sec] for T max	t_i [min] for T max	t_i [sec] for T ave	t_i [min] for T ave
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 %		0.4%	

6. COMPARISON OF RESULTS

The results of both methods are 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 Fig. 13.

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

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

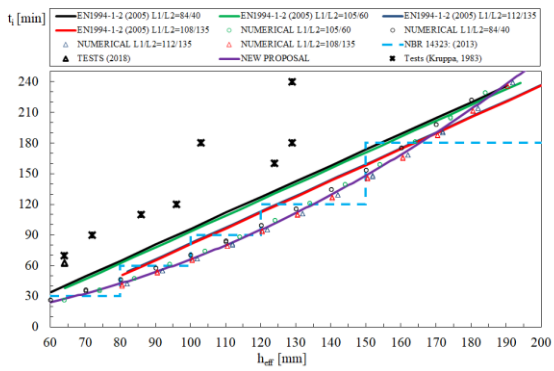


Fig. 13 - Comparison of results.

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).

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

Numerical modelling of similar structural elements [6] [17], 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 higher fire resistance time in experiments.

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 [11] [18], 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.

ACKNOWLEDGMENTS

Special thanks are due to the Portuguese companies: O –Feliz and David & Nuno.

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] 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.

[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, no. November, pp. 63–76, Apr. 2017.

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

[10] CEN - European Committee for Standardization, *1365-2: Fire resistance tests for loadbearing elements - Part 2: Floors and roofs (Withdrawal)*, CEN-Euro. Brussels: CEN - European Committee for Standardization, 2014.

[11] 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.

[12] 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, NIST TN-1958," 2017.

[13] 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.

[14] 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.

[15] 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.

[16] 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.

[17] 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.

[18] Comissão de Estudo de Estruturas de Aço, *ABNT NBR 14323: Projeto de estruturas de aço e de estruturas mistas de aço e concreto de edifícios em situação de incêndio*. 2012.