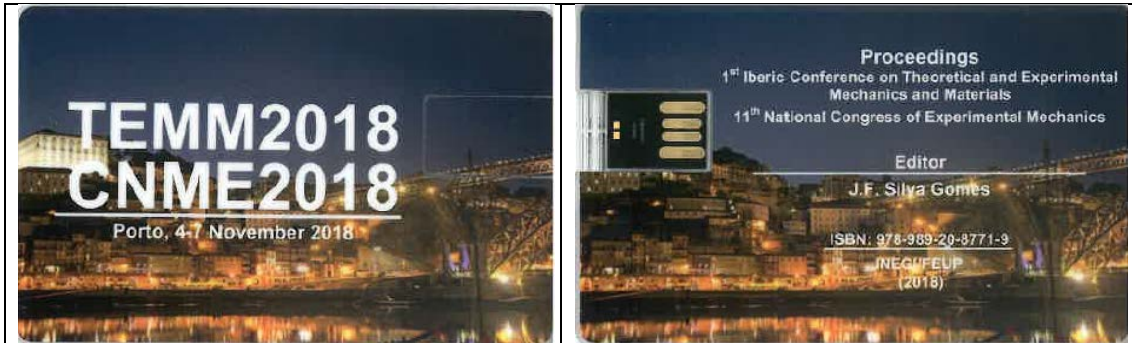


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1<sup>st</sup> Iberic Conference on Theoretical and Experimental Mechanics of Materials

11<sup>th</sup> National Congress of Experimental Mechanics

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# TEMM2018 CNME2018

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Experimental Mechanics and Materials  
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(Porto/Portugal, 4-7 November 2018)

Editor

*J.F. Silva Gomes*

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## PREFACE

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**CNME2018** is the eleventh national gathering of a prestigious series of Experimental Mechanics conferences coordinated by the Scientific Committee of Portuguese Society of Experimental Mechanics (**APAET**). This series of conferences is totally devoted to advances in experimental mechanics, materials, structural integrity and design.

This time, the traditional **CNME2018** congress is jointly organized with **TEMM2018-*The 1st Iberic Conference on Theoretical and Experimental Mechanics and Materials***, institutionally sponsored by the University of Porto, the University of Vigo, and the Portuguese Society of Experimental Mechanics. It is held in Porto/Portugal, from 4 to 7 November 2018

The conference attracted over 80 participants with 124 accepted submissions in English, Portuguese or Spanish languages, involving 416 authors from Portugal, Spain, Brasil and other countries from Latin America. The conference themes which address novel and advanced topics on Theoretical and Experimental Mechanics focused on Automotive, Locomotive, Aerospace, Civil Engineering and Biomechanics, including Experimental Techniques and Instrumentation, Computational Mechanics, Composite and Advanced Materials, Mechanical Design and Maintenance, Civil and Structural Engineering Applications, Biomedical Applications, and Industrial Engineering and Management, among other topics.

We believe that the meeting offered our delegates a forum for the discussion and dissemination of their recent work in assessing the mechanical behaviour of engineering structures, components and systems, fostered research that integrates theoretical and experimental mechanics and materials in the design process, and promoted exchange of ideas and international co-operation among scientists and engineers in this important field of engineering.

We are particularly indebted to the authors and special guests for their presentations. Each of the 124 contributions offered opportunities for thorough discussions with the authors. We acknowledge the excellent contributions of the participants, their innovative ideas and research directions, their novel modeling and experimental techniques, and their invaluable critical comments. We are also indebted to the outstanding keynote speakers who highlighted the conference themes with their contributions and covered the main topics of the conference. We also take this opportunity to thank the members of the International Scientific Committee and the reviewers for their time and helpful suggestions, and the local organising committee for an absolutely superb organization of the meeting in this magnificent city of Porto. To all of you, we offer our deep gratitude.

*J.F. Silva Gomes*

*Porto / Portugal, November 2018.*

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## FIRE RESISTANCE OF COMPOSITE SLABS WITH STEEL DECK: EXPERIMENTAL ANALYSIS AND NUMERICAL SIMULATION

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### ABSTRACT

This work investigates the thermal behaviour of composite slabs with steel deck under controlled test conditions corresponding to a fire from the bottom. This composite solution consists of a concrete topping cast on the top of a steel deck. The concrete is typically reinforced with a steel mesh and may also contain individual rebars. The deck also acts as reinforcement and may be exposed to accidental fire conditions from the bottom. This composite solution is widely used in every type of buildings and requires fire resistance, in accordance to regulations and standards. Composite slabs need to meet fire-safety requirements according to building codes. The fire assessment of this type of elements is normally made using standard fire tests. Two samples are being prepared to be tested and should take into account the criterion for stability (R), Integrity (E) and insulation (I). The scope of this investigation concerns the fire rating for insulation (I). Numerical simulation was performed through Matlab PDE toolbox for the thermal effects of standard fire exposure. The results are also compared with the simplified method proposed by Eurocode, which seems to be unsafe.

**Keywords:** Composite slabs, fire resistance, thermal performance, numerical simulation.

### 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 Figura 1. This represents one of the advantages of this solution, because reduces the construction time, requires less concrete, providing slender slabs.

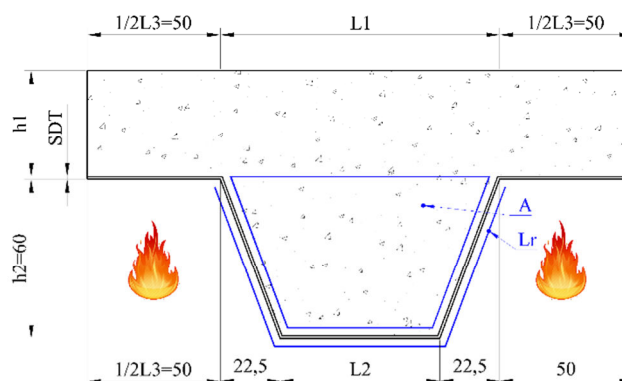


Fig. 1 - Definition of the rib geometry for the cross section of part of the composite slab.

The use of these composite slabs in buildings has become very popular, since 1980. The overall depth ( $h_1+h_2$ ) 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.

Several studies have been conducted to evaluate the fire resistance of concrete slabs with steel deck. In 1990 Hamerlinck et al [2] developed a numerical model that satisfactorily predicted the fire behaviour of different slab geometries. In 1999 Bailey *et al.* [3] 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 [4], 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 developed model presented satisfactory results for most of the tests. In 2002 Lim et al [5] developed fire tests of two-way concrete slabs at the BRANZ fire resistance furnace, six slabs were tested, comprising three reinforced concrete flat slabs and three composite steel-concrete 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 of 3.0 kPa and were heated from the bottom with standard fire ISO 834 during three hours. The slabs supported the full duration of the tests without collapse. The structural fire resistance of the slabs in the tests exceed the predictions of code recommendations.

More recently in 2017, Guo-Qiang Li et al [6], 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 and that could be used for the other geometries, beyond the specified limit. The experiments were developed at Tongji University and the average temperatures of the furnace were below the standard ISO 834 [7]. The temperature at the bottom of the slabs (above the steel deck) were 100 °C on average below furnace temperature. The temperature on the unexposed surface was less than 100 °C during the tests, being the fire rating determined by stability. This research also presents a summary of previous experiments developed on composite floor systems.

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 assessment of this type of elements is normally made using standard fire tests [7]-[9] and should take into account criterion 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 behaviour of composite slabs is generally defined with respect to standard fire exposure from below. Fire exposure at the other side of the slab is less critical [1].

The European recommendations for composite steel and concrete slabs were introduced by the ECCS [10] and a proposal for the assessment of the insulation criterion (I) was made, based on the calculation of the effective thickness of concrete. At this stage, conservative assumptions have been used, leading to uneconomic solutions [1].

The current version of Eurocode 4 [11] proposes a simple calculation method, in Annex D, to define the fire resistance (I), which depends linearly in a set of geometric parameters, but that seems to be over conservative as well.

## 2 SIMPLIFIED METHOD

According to Annex D of Eurocode 4 [11], the fire resistance  $t_i$ , of both simply supported and continuous concrete slabs with profiled steel decks, when submitted to standard fire, may be calculated according to equation (1).

$$t_i = a_0 + a_1 \cdot h_1 + a_2 \cdot \phi + a_3 \cdot A/L_r + a_4 \cdot 1/l_3 + a_5 \cdot A/L_r \cdot 1/l_3 \quad (1)$$

where

$$A/L_r = h_2 (l_1 + l_2) / 2 / \left[ l_2 + 2 \sqrt{h_2^2 + ((l_1 - l_2) / 2)^2} \right] \quad (2)$$

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

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

$a_0$	$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
[min]	[min/mm]	[min]	[min/mm]	[min.mm]	[min]
-28.8	1.55	-12.6	0.33	-735	48

In a previous work [12], 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  $h_1$ . These observations are summarised in Table 2.

Table 2 - Fire resistance in completed minutes (insulation criterion).

Geometry	$h_1$ [mm]	40	50	60	70	80	90	100	110
L1/L2=84/40	$t_i$ [min]	34	50	65	81	96	112	127	143
L1/L2=105/60	$t_i$ [min]	38	53	69	84	100	115	131	146

This study intends to analyse the model with  $h_1=40$  mm and  $L1/L2=105/60$ , with an expected fire resistance of 38 min, according to the simplified method.

## 3 NUMERICAL SIMULATION METHOD

### 3.1 Heat transfer equation

A two dimensional model was used for the numerical simulations. The cross section of the slab is meshed to solve a nonlinear transient thermal analysis. The finite element method requires the solution of equation (3) in the domain of the cross section ( $\Omega$ ) and equation (4) for the boundary conditions exposed to fire ( $\partial\Omega$ ).

$$\nabla(\lambda_{(T)} \cdot \nabla T) = \rho_{(T)} \cdot C_{p(T)} \cdot \partial T / \partial t \quad (\Omega) \quad (3)$$

$$\lambda_{(T)} \cdot \nabla T \cdot \rho = \alpha_c (T_g - T) + \phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot (T_g^4 - T^4) \quad (4)$$

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;  $\alpha_c$  specifies the convection coefficient;  $T_g$  represents the gas temperature of the fire compartment, using standard fire ISO 834 [6] to be applied to the lower part of the slab,  $\phi$  specifies the view factor;  $\varepsilon_m$  represents the emissivity of each material (in both cases equals 0.7);  $\varepsilon_f$  specifies the emissivity of the fire;  $\sigma$  represents the Stefan-Boltzmann constant.

### 3.2 Matlab PDE toolbox

The PDE toolbox from Matlab was used for the analysis of this thermal model, using the finite element method [13]. The maximum size of the finite element mesh is 0.01m, see Figure 2. The thermal properties (specific heat, density and conductivity) of the materials (concrete and steel) are temperature dependent. The exposed side is submitted to a heat flux by convection and radiation, using different view factors and a bulk temperature following the standard fire. The unexposed side is submitted to a convective heat flux (including the radiation heat flux), using a constant bulk temperature of 20°C. The model considers 1.2 mm for the thickness of the steel deck, the geometric ratio L1/L2 is equal to 105/60 and the concrete depth above the deck measures h1=40 mm. The mesh uses triangular finite elements with 3 nodes and one degree of freedom per node (temperature). The interpolating functions are linear. 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.

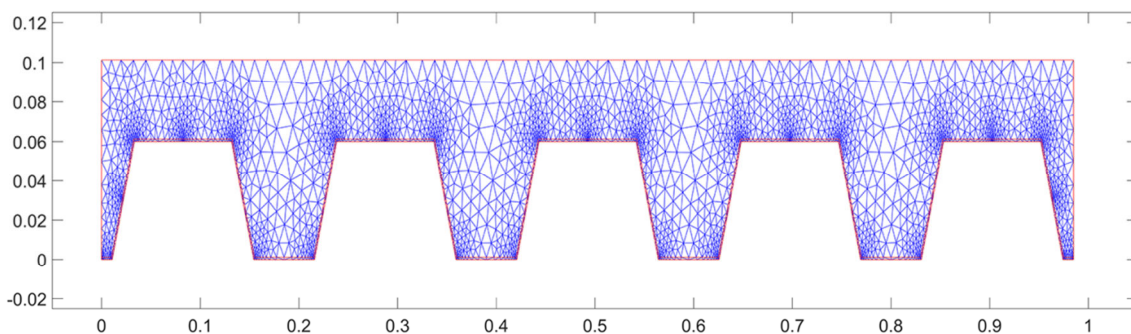


Fig. 2 - Finite element mesh used for the slab (L1/L2=105/60mm/mm, h1=40 mm, SDT=1.2mm).

### 3.3 View Factor

The view factor ( $\phi$ ) specified in the equation (4), quantify the geometric relation between the surface emitting radiation and the receiving surface, that is dependent of the surfaces areas and orientations, as the distance between them [14].

The view factor at the lower flange of the composite slab is given as  $\phi_{inf} = 1$ . The view factor of the web and of the upper flange of the steel deck are smaller than one, due to the

obstruction caused by the ribs of the steel deck. This values can be calculated by Hottel’s crossed-string method [15]. This method is also used by the Eurocode 4. The resulting equations for the web ( $\phi_{web}$ ) and upper flange ( $\phi_{upper}$ ) view factors are calculated according to equations (5) and (6), being the geometric parameters represented in the Figure 3.

$$\phi_{upper} = \frac{ad + cb - ab - cd}{2ab} = \frac{\sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2} - \sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}}{l_3} \quad (5)$$

$$\phi_{web} = \frac{ac + cd - ad}{2ac} = \frac{\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2} + (l_3 + l_1 - l_2) - \sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2}}{2\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}} \quad (6)$$

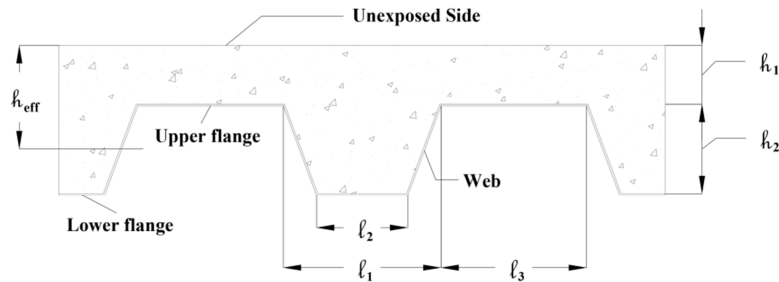


Fig. 3 - Symbols for trapezoidal sheeting (adapted from [11])

### 3.4 Material Properties

The thermal proprieties are temperature dependent and vary according the standards used for composite slabs, steel and concrete [11], [16], [17]. Both properties are depicted in Figura 4 and Figure 5. 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.

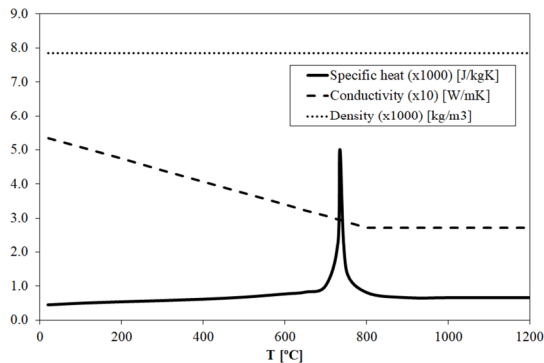


Fig. 4 - Thermal properties for carbon steel.

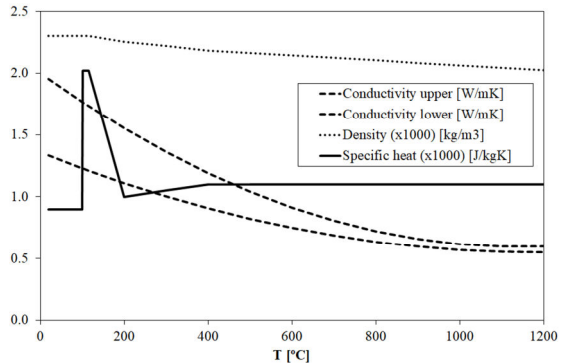


Fig. 5 - Thermal properties for concrete.

### 3.5 Boundary Conditions

An initial uniform temperature is applied to all the nodes (20°C). The lower part of the deck is submitted to standard fire conditions, using a convection coefficient of 25 [W/m<sup>2</sup>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<sup>2</sup>K] to include the radiation effect [18].

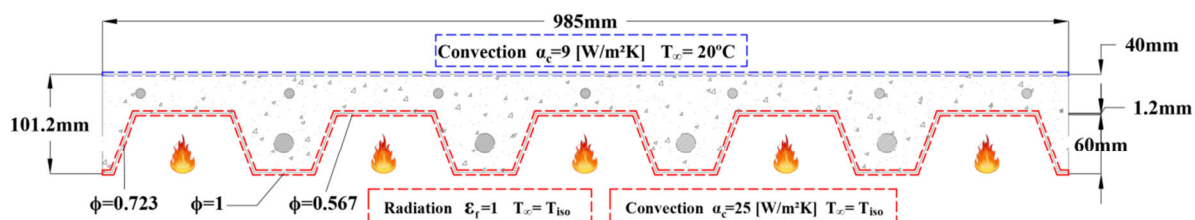


Fig. 6 - Definition of the slab geometry and display of the boundary conditions and different view factors, that have effect in each part of the slab.

## 4 EXPERIMENTAL METHOD

Two composite steel-concrete slab specimens are to be tested. Both samples represent only one part of normal slab dimensions. This specimens allow for the verification of the fire insulation behaviour. Each slab presents 1.15 m wide and 1.2 m long. The thicknesses of the slabs were fixed to 40 mm. The slabs used the same proportion and quantity of reinforcement steel as used for the normal slab dimensions. The slab model H60 is presented in Figure 7, where one can observe the geometry of this model.

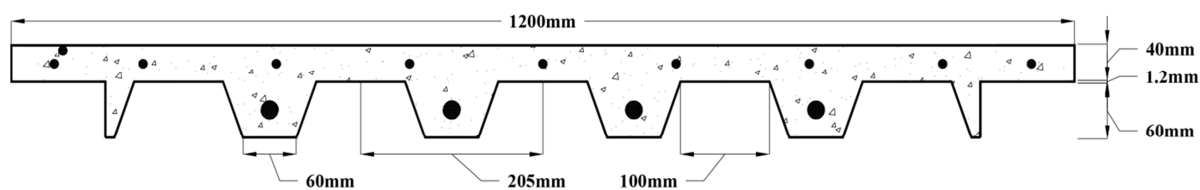


Fig. 7 - Model of the slab and the respective geometry.

Normal weight concrete is used for the specimens. The compressive strength of the concrete is 30 MPa. The compressive strengths of the concrete is to be determined by cylinder crushing tests conducted 7 days and 28 days after the concrete is cast. After the material characterization, the specimens need casted, prepared and instrumented. The tests should be conducted to a maximum of one hour or before the final time, if the slab is deformed to a point impend of structural collapse, which may lead to damage of the furnace. The test should also be stopped before this period if the insulation criteria is achieved, and critical time can be determined [5].

### 4.1 Furnace

The fire tests are predicted to be conducted in a natural gas furnace with maximum power of 360 kW. The furnace has 4 burners located in different planes and positions. The geometry of

the furnace is depicted in Figure 8, as well as the relative position of the slab. This slab is mounted in a special frame. This furnace is running with standard fire ISO834 [7].

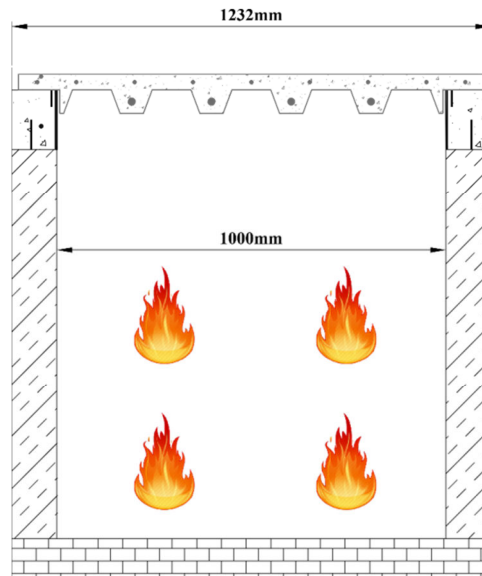


Fig. 8 - Furnace geometry.

## 4.2 Thermocouples

The thermocouple layout was based on standards for testing EN 1363-1 [8] and the EN 1365-2 [9], with additional thermocouples for numerical validation. More thermocouples were included through the depth of the slab to obtain more results during the test duration. Sensors are identified in Figure 9 and Figure 10 for all 21 thermocouples.

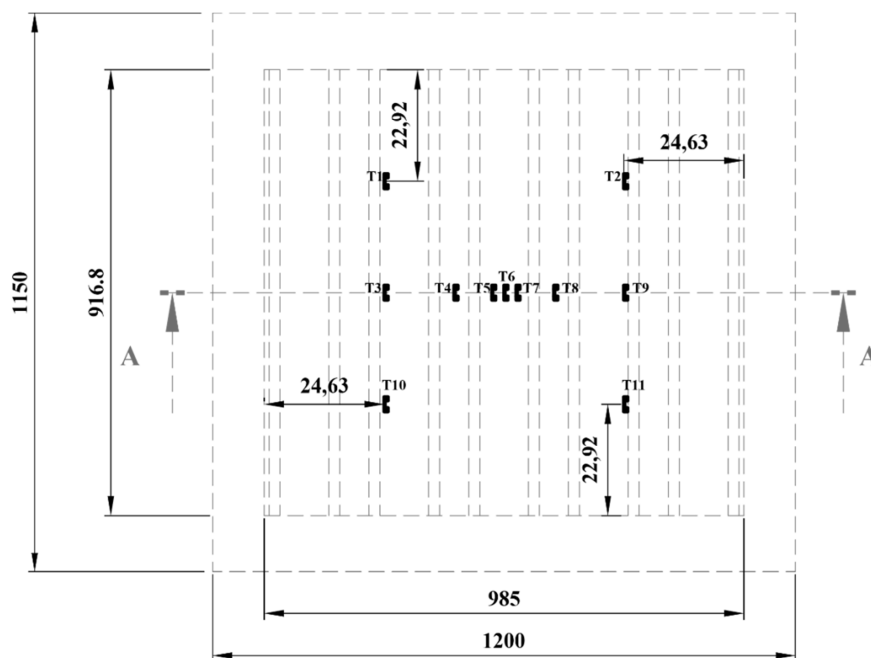


Fig. 9 - Top view of the thermocouples locations.

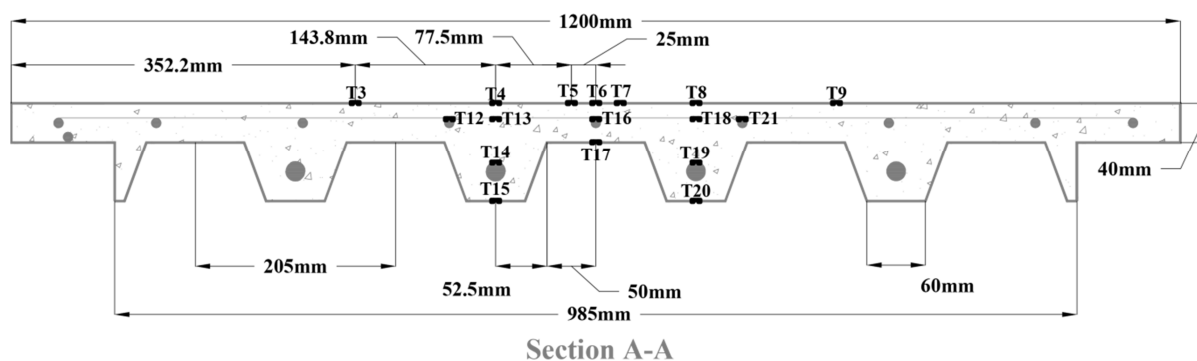


Fig. 10 - Thermocouples locations in the section A-A.

### 4.3 Fire resistance criteria

To prevent fire propagation into adjacent compartments, slabs must meet the requirements for fire resistance, preventing the propagation of fire and limiting the temperature of the unexposed surface in the fire compartment. The insulation criterion (I) for fire resistance of this construction element depends on the temperature evolution at the unexposed surface. The performance level used to define insulation shall be the average temperature rise on the unexposed surface limited to 140 °C above the initial average temperature, or, with the maximum temperature rise at any point limited to 180 °C above the initial average temperature [8]. A temperature increase of 140 °C at the unexposed side is usually taken as the limiting insulation criterion [10], but the other condition for the maximum temperature can also be a limiting condition.

For concrete slabs with steel decks, the integrity criterion (E) is easily verified, because concrete slab is cast in situ, assuring that joints are correctly sealed. Possible cracks that may occur during the tests due to fire exposure are protected by the steel deck, preventing the penetration of flames and hot gases through the slab.

## 5 RESULTS

The time history for the temperature evolution was calculated in the some expected locations for the experimental measurements. The results are plotted into two separated graphs; according to the locations for measurements (see Figure 11 for the unexposed locations and Figure 12 for intermediate locations). The temperature of the unexposed side is characterized by T1, T2, T3, T4, T5, T6, T7, T8, T9, T10 and T11, while the temperature for intermediate measurements are characterized by T12, T13, T14, T16, T18, T19 T21, T15, T20 and T17.

The average and the maximum temperature rise on the unexposed surface is based on measurements obtained from disk thermocouples, located at or near the centre of the section and at or near the centre of each quarter section [8], see thermocouples T1, T2, T6, T10 and T11. The maximum temperature was determined by the highest temperature registered by any of the unexposed thermocouples. Figure 13 represents the average (T\_AVE) temperature and maximum temperature (T\_MAX) evolution in the composite slab.

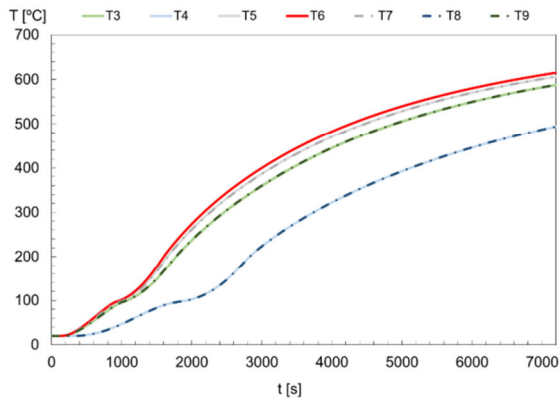


Fig. 11 - Temperature evolution of the unexposed side

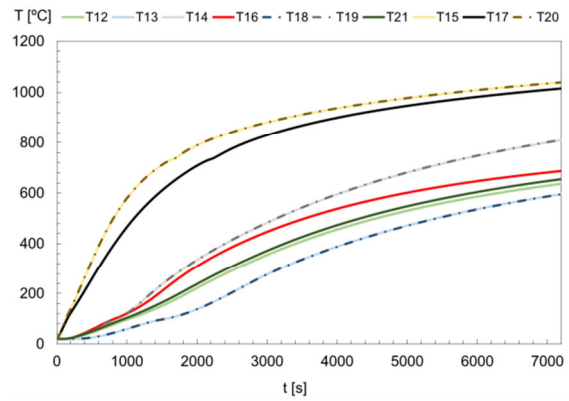


Fig. 12 - Temperature evolution for intermediate locations.

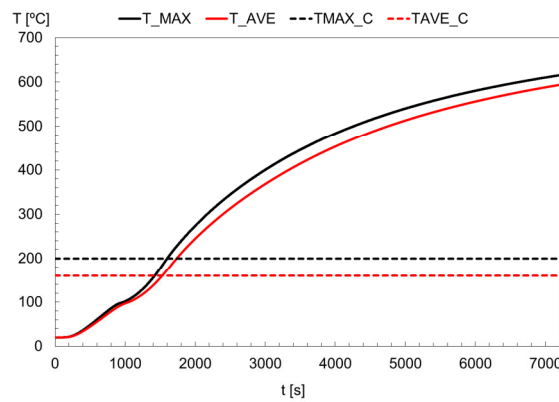


Fig. 13 - Unexposed temperature evolution (T\_MAX and T\_AVE).

Figure 13 also presents the performance criteria for the fire insulation rating ( $T_{MAX\_C}=180+20$  °C or  $T_{AVE\_C}=140+20$  °C). The maximum temperature is obtained through the time history of the thermocouple T6 that is the one that presents the highest temperature during the simulation. Five thermocouples were used for the calculation of T\_AVE (T1, T2, T6, T10 and T11). The expected fire resistance is equal to 1528 s that corresponds to 25 min complete minutes. This value is smaller than 38 min, which is the value determined by the simplified model proposed in the Eurocode (see Table 2).

The temperature field is plotted for time equal to 6, 12, 19 and 25 minutes, see graphs from Figure 14 to Figure 17.

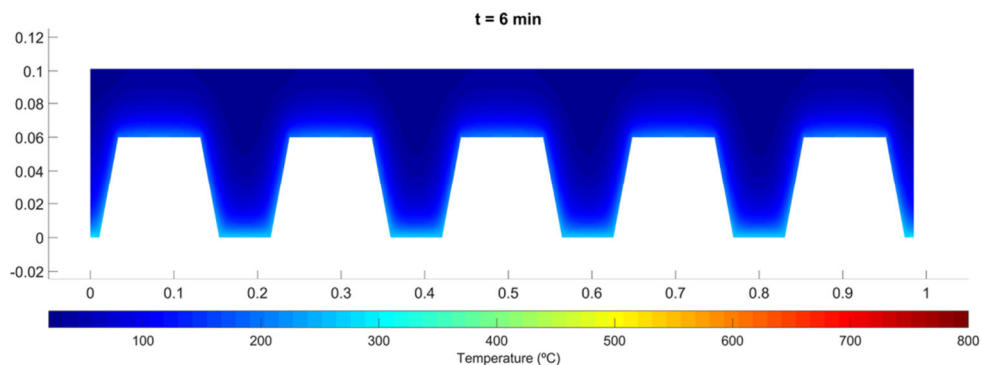


Fig. 14- Temperature field after 6 min, for the slab geometry ( $L1/L2=105/60$ ,  $h1=40$  mm,  $SDT=1.2$ mm).

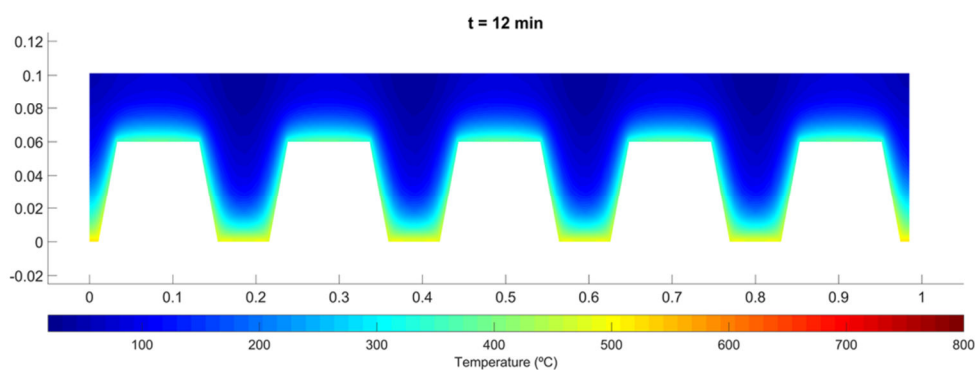


Fig. 15 - Temperature field after 12 min, for the slab geometry ( $L1/L2=105/60$ ,  $h1=40$  mm,  $SDT=1.2$ mm).

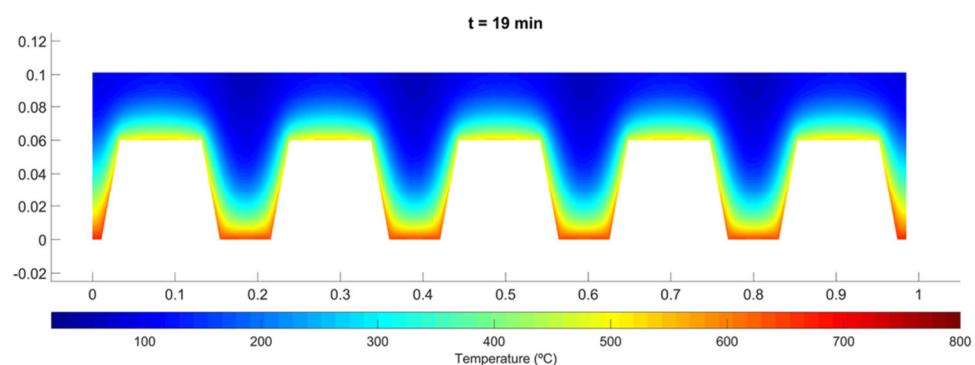


Fig. 16 - Temperature field after 19 min, for the slab geometry ( $L1/L2=105/60$ ,  $h1=40$  mm,  $SDT=1.2$ mm)

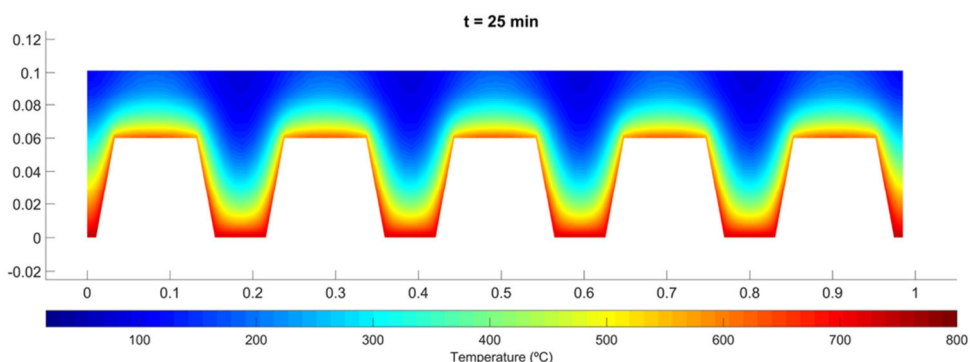


Fig. 17- Temperature field for the critical time (25min), for the slab geometry ( $L1/L2=105/60$ ,  $h1=40$  mm,  $SDT=1.2$ mm).

## 6 CONCLUSIONS

The numerical simulation of the thermal effects caused by a fire on a composite concrete slab with steel deck is presented. This simulation allows to determine the fire resistance of this structural element with regard to the insulation criterion. The numerical simulation predicts lower fire resistance (I) when compared to actual standards, based on the simple calculation method. This fire resistance was defined by the average temperature rise in the unexposed side of the slab. The fire resistance obtained with the simple calculation method, proposed in the Eurocode, 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, by carrying out experimental tests according to standards, as specified in this work.

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