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Coimbra, Novembro de 2018

6JORNINC

JORNADAS DE SEGURANÇA AOS INCÊNDIOS URBANOS

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JORNADAS DE PROTEÇÃO CIVIL

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6as Jornadas de Segurança aos Incêndios Urbanos

1as Jornadas de Proteção Civil

Departamento de Engenharia Civil
Faculdade de Ciências e Tecnologia
Universidade de Coimbra

29 e 30 de novembro de 2018

Atas das Comunicações das 6as Jornadas de Segurança aos Incêndios Urbanos e das 1as Jornadas de Proteção Civil

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Primeira edição
novembro, 2018

ISBN: 978-989-96461-9-3

Edição:

ACIV – Associação para o Desenvolvimento da Engenharia Civil

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SESSÃO 4 – SISTEMAS DE SEGURANÇA CONTRA INCÊNDIO

1as Jornadas de Proteção Civil

PALESTRA III - Desastres Naturais e seus Planos de Contingência
JOSÉ LUÍS ZÊZERE

SESSÃO 5 – PROTEÇÃO CIVIL

6as Jornadas de Segurança aos Incêndios Urbanos
1as Jornadas de Proteção Civil
Universidade de Coimbra- Portugal – 29 e 30 de novembro de 2018

FIRE RESISTANCE OF COMPOSITE SLABS WITH PROFILED STEEL DECKING: TRAPEZOIDAL AND RE-ENTRANT NUMERICAL SIMULATION

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ABSTRACT

This work investigates the thermal behaviour of composite slabs with steel deck under standard fire 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 resistance is specified by the loadbearing capacity (R), insulation (I) and integrity (E). The fire rating for (R) and (E) is not in the scope of this investigation. The fire rating for insulation (I) is evaluated by two different methods (numerical simulation and simple calculation). Numerical simulation was performed using Matlab PDE toolbox for the thermal effects of standard fire exposure. The fire rating is calculated for 196 different geometric configurations, in order to evaluate the effect of the thickness of the concrete layer and the thickness of steel deck. The fire resistance (I) increases with the thickness of the concrete, according to the results of both methods. The numerical results are also compared with the simplified method proposed by Eurocode, which appears to be unsafe.

Keywords: Composite slabs; Fire resistance; Insulation; 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. This represents one of the advantages of this solution, because reduces the construction time, requires less concrete, providing slender slabs, see Figure 1 and Figure 2.

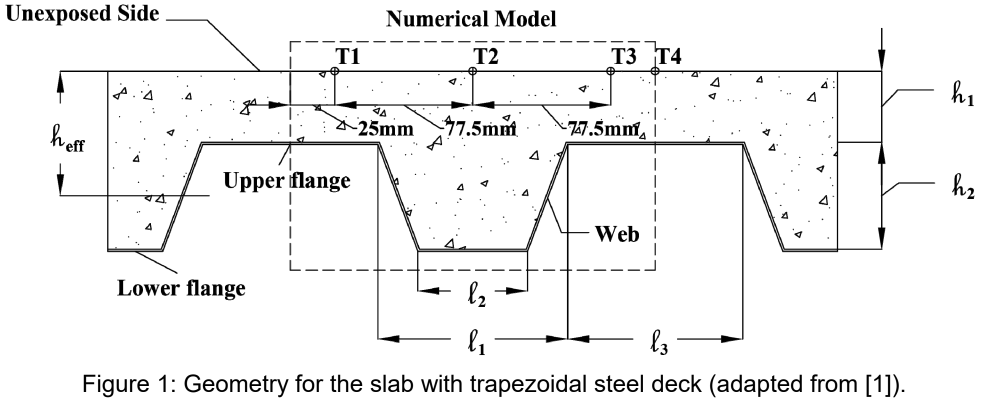

Figure 1: Geometry for the slab with trapezoidal steel deck (adapted from [1]).

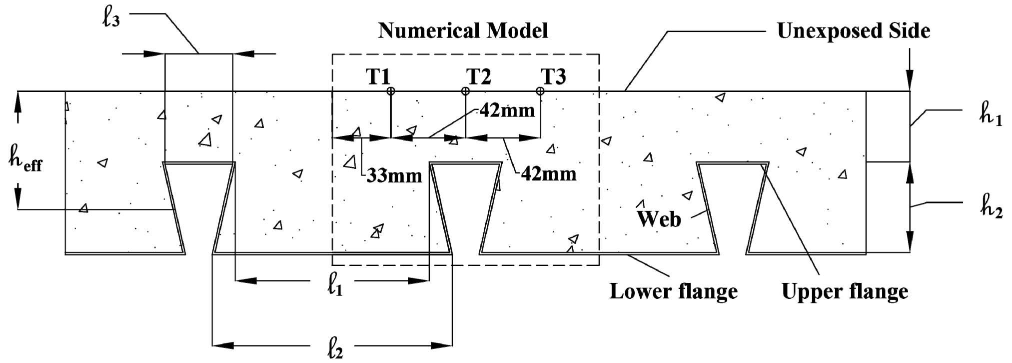

Figure 2: Geometry for the slab with re-entrant steel deck (adapted from [1]).

The use of these composite slabs in buildings has become very popular, since 1980. The overall depth (h1+h2) can vary between 100 to 230 mm. The thickness of the deck can vary from 0.7 to 1.2 mm or more and this part of the structure is normally galvanized to increase durability [2]. 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 insulation (I) behaviour of the composite slab.

Several studies have been conducted to evaluate the fire resistance of concrete slabs with steel deck. In 1990 Hamerlinck *et al.* [3] developed a numerical model that satisfactorily predicted the fire behaviour of different slab geometries. In 1999 Bailey *et al.* [4] 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.* [5], performed an analysis of the heat transfer in composite slabs for 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 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 but 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 the 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 [2]. 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 [2]. The current version of Eurocode 4 [1] 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 unsafe as well.

2 SIMPLIFIED METHOD

According to Annex D of Eurocode 4 [1], 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). This method was firstly proposed by Cornelis Both in his PhD thesis [11].

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

where

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

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 h1. These observations are summarised in Table 2.

Table 2: Fire resistance of trapezoidal deck in completed minutes (insulation criterion).

Geometry	h1 [mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=84/40	t_i [min]	34	50	65	81	96	112	127	143	158	174	189	205	220	236
L1/L2=105/60	t_i [min]	38	53	69	84	100	115	131	146	162	177	193	208	224	239

The fire resistance was also calculated to the re-entrant geometry using the Eurocode 4 [1] recommendations, see Table 3.

Table 3: Fire resistance of re-entrant deck in completed minutes (insulation criterion).

Geometry	h1 [mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=112/135	t_i [min]	54	69	85	100	116	131	147	162	178	193	209	224	240	255
L1/L2=108/135	t_i [min]	51	66	82	97	113	128	144	159	175	190	206	221	237	252

This study intends to analyse two different slab models with different steel deck geometries. One trapezoidal geometry (Figure 1) with h1 varying from 40 mm to 170mm, using the geometry L1/L2=84/40 and L1/L2=105/60, and one re-entrant geometry (Figure 2) with the same variation for h1, but using the geometry L1/L2=112/135 and L1/L2=108/135.

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 (Ω) and equation (4) for the boundary conditions exposed to fire (∂Ω).

$$\nabla\left(\lambda_{(T)}.\nabla T\right) = \rho_{(T)}.Cp_{(T)}.\partial T/\partial t \qquad (\Omega) \qquad (3)$$

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

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; α_c specifies the convection coefficient; T_g represents the gas temperature of the fire compartment, using a standard fire ISO 834 [7], applied to the bottom part of the slab, ϕ specifies the view factor; ε_m represents the emissivity of each material (in both cases equals 0.7); ε_f specifies the emissivity of the fire and σ 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 domain is discretized in a mesh using linear triangular elements with a maximum size equal to 0.01m, see Figure 3 and Figure 4. Equation (3) is solved through an implicit scheme with a maximum time step set to 1s. The thermal properties (specific heat, density and conductivity) of the materials (concrete and steel) are temperature dependent. Consequentially, in each time step the values of these properties are determined through an iterative process based on the heat flow calculation. The convergence criterion is based on the absolute tolerance, set to 10^{-6}, or based on the relative tolerance, set to 10^{-3}, and on a maximum number of iterations equal to 25.

The exposed side is submitted to a heat flux by convection and radiation, using different view factors and a bulk temperature following the temperature of the standard fire. The unexposed side is submitted to a convective heat flux (including the radiation effect), using a constant bulk temperature of 20ºC. The model considers 0.7mm, 0.8mm, 1.0mm and 1.2 mm for the thickness of the steel deck for the trapezoidal sheeting deck, and a thickness of 0.9mm, 1.0mm and 1.2mm for the re-entrant sheeting decks.

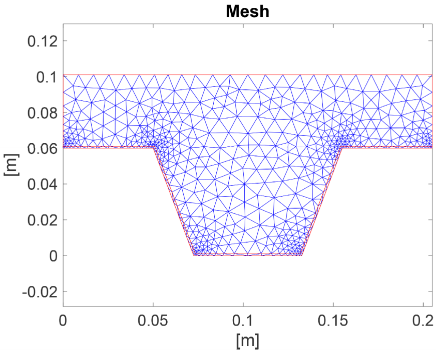

Figure 3: Finite element mesh used for the trapezoidal slab (L1/L2=105/60mm/mm, h1=40 mm, SDT=1.2mm).

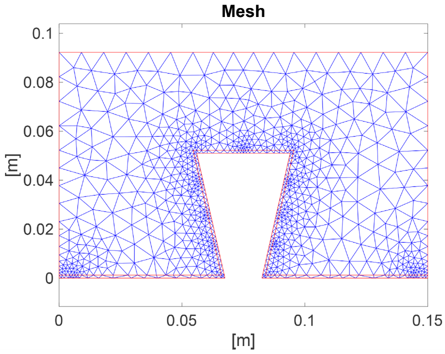

Figure 4: Finite element mesh used for the re-entrant slab (L1/L2=112/135mm/mm, h1=40 mm, SDT=1.2mm).

3.3 View Factor

The view factor (ϕ) specified in the equation (4), quantifies the geometric relation between the surface emitting radiation and the surface receiving, that depends on of the surfaces areas and orientations, as well as the distance between them [14].

The view factor at the lower flange of the composite slab is given as $\phi_{lower}=1$. 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. These values can be calculated by Hottel´s crossed-string method [15]. This method is also used by the Eurocode 4. The view factors for the web (ϕ_{web}) and upper flange (ϕ_{upper}) should be calculated according to equations (5) and (6), see Table 4, being the geometric parameters represented in the Figure 1 and Figure 2.

$$\phi_{upper} = \frac{\sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2} - \sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}}{l_3} \tag{5}$$

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

Table 4: Calculated view factors.

Geometry	ϕ_{lower}	ϕ_{web}	ϕ_{upper}
L1/L2=84/40	1	0.563	0.720
L1/L2=105/60	1	0.567	0.723
L1/L2=112/135	1	0.094	0.137
L1/L2=108/135	1	0.102	0.160

3.4 Material Properties

The thermal proprieties are temperature dependent and vary according the standards used for composite slabs, steel and concrete [1, 16, 17]. Both properties are depicted in Figure 5 and Figure 6. 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 of the conductivity used for these simulations. The specific heat of concrete presents a peak value related with 3% in moisture content of concrete weight.

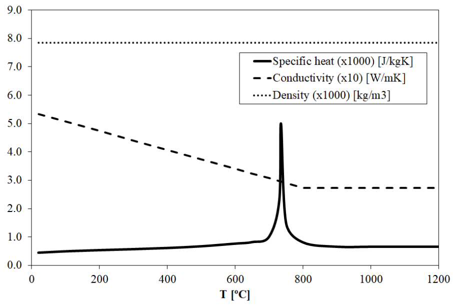

Figure 5: Thermal properties for carbon steel.

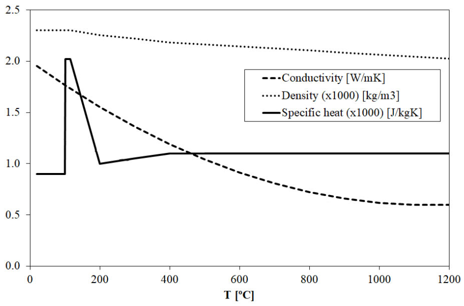

Figure 6: Thermal properties for concrete.

3.5 Boundary Conditions

An initial uniform temperature is applied to all the meshed 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 7 and Figure 8. The upper part of the slab is submitted to a convective coefficient of 9 [W/m^{2}K] to include the radiation effect [18].

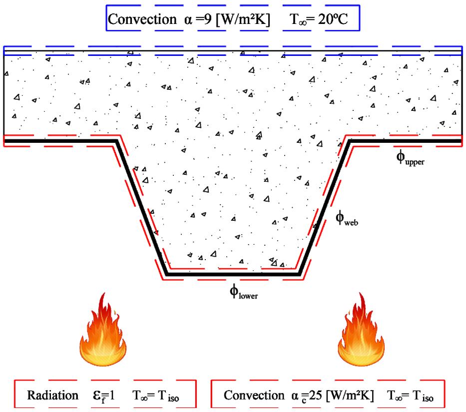

Figure 7: Boundary conditions for the slab with the trapezoidal steel deck.

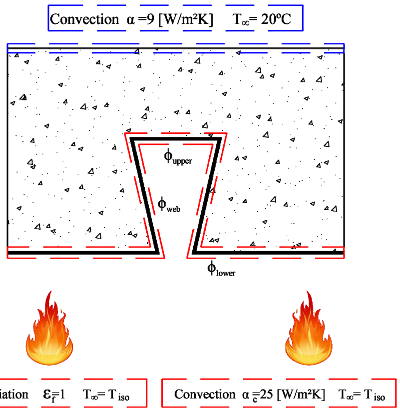

Figure 8: Boundary conditions for the slab with re-entrant steel deck.

3.6 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.

4 RESULTS

The values for average temperature were obtained through a weighted average of the temperatures determined at nodes T1, T2 and T3 shown in the Figure 1 and Figure 2. The values for the nodal positions T2 and T4 were used for the calculation of the maximum temperature on both geometries. Figure 9 to Figure 12 represent the average temperature (T_AVE) and maximum temperature (T_MAX) evolution in the composite slab, according to the first to be achieved for each simulation. The simulations were developed to a final time of 7200s, and if none of the fire resistance criteria was achieved the simulations were redone to a final time of 14400s.

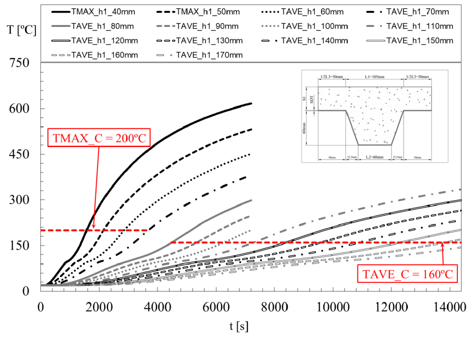

Figure 9: Unexposed temperature evolution at the trapezoidal slab (L1/L2=105/60mm/mm).

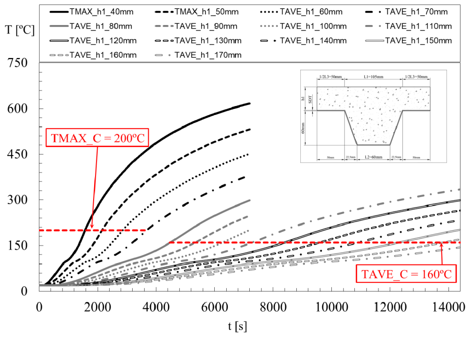

Figure 10: Unexposed temperature evolution at the trapezoidal slab (L1/L2=84/40mm/mm).

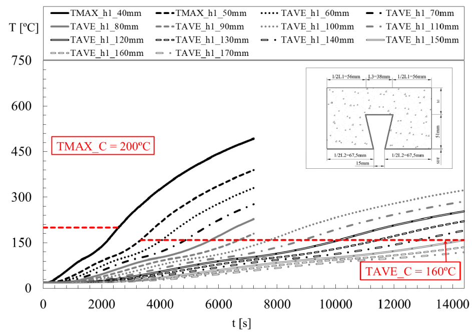

Figure 11: Unexposed temperature evolution at the re-entrant slab (L1/L2=112/135mm/mm).

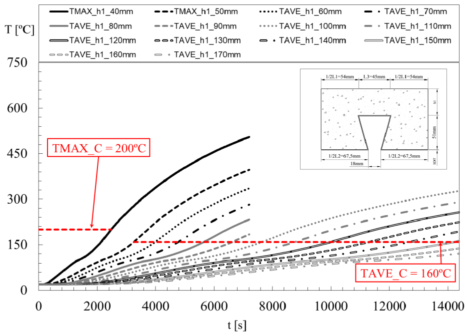

Figure 12: Unexposed temperature evolution at the re-entrant slab (L1/L2=108/135mm/mm).

The simulated fire resistance for all the trapezoidal sheeting slabs are presented in the Table 5. The results for the re-entrant sheeting slabs are presented in the Table 6. Since the maximum time for simulations was set to be 14400s, some slabs did not reach the fire resistance criteria during this period (ti > 240 min).

The temperature field is plotted in Figure 13 and Figure 14 for the critical time of one model of the trapezoidal steel deck slab (L1/L2=105/60, h1=40 mm and SDT=1.2mm) and for one model of the re-entrant steel deck slab (L1/L2=112/135, h1=40 mm and SDT=1.2mm).

Table 5: Fire resistance (numerical) of trapezoidal deck in completed minutes (I criterion).

Geometry	h1 [mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=84/40	t_i [min]	26	36	46	57	70	84	99	115	134	153	175	198	222	>240
L1/L2=105/60	t_i [min]	26	36	47	61	74	88	104	121	139	159	181	205	229	>240

Table 6: Fire resistance (numerical) of re-entrant deck in completed minutes (I criterion).

Geometry	h1 [mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=112/135	t_i [min]	42	55	67	80	95	111	129	147	168	190	214	239	>240	>240
L1/L2=108/135	t_i [min]	40	53	65	79	93	109	126	145	165	187	211	236	>240	>240

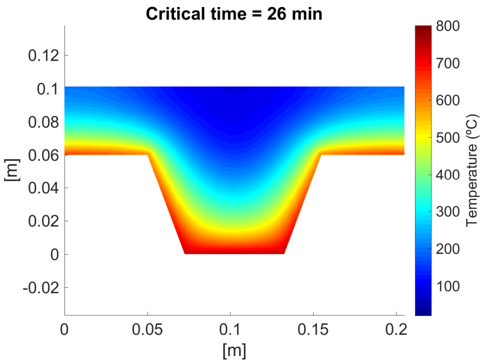

Figure 13: Temperature field for the critical time in the trapezoidal model (L1/L2=105/60, h1=40 mm, SDT=1.2mm).

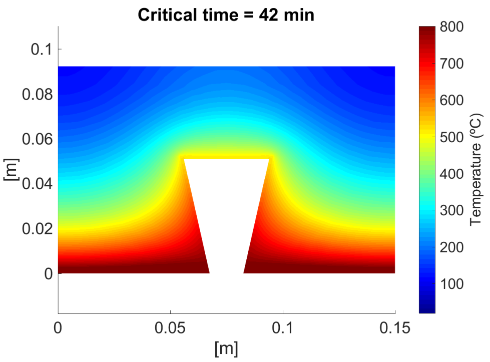

Figure 14: Temperature field for the critical time in the re-entrant model (L1/L2=112/135, h1=40 mm, SDT=1.2mm).

Figure 15 and Figure 16 represent the comparison of the fire resistance between both solution methods (Matlab toolbox and simplified method proposed by the Eurocode 4) by the progression of h_{eff} , see equation (7). Values smaller than 1 should be considered unsafe.

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

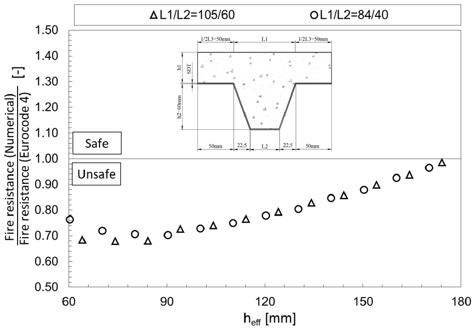

Figure 15: Results for trapezoidal steel deck

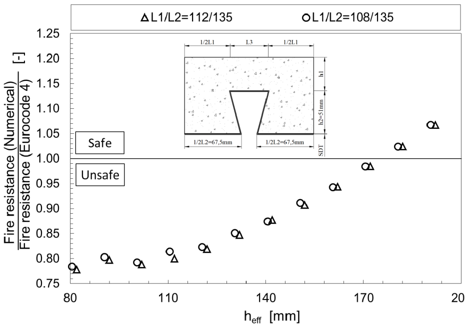

Figure 16: Results for re-entrant steel deck

5 CONCLUSIONS

The numerical simulations allows to determine the fire resistance of this structural element, with regard to the insulation criterion, and predicts lower fire resistance (I) when compared to actual standards, based on the simple calculation method. This fire resistance was defined by the 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 considering that 93% of the cases studied in this paper had critical time values smaller than the ones obtained with Eurocode 4, see Figure 16 and . New simple formula should be proposed to evaluate the fire resistance of composite slabs.

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