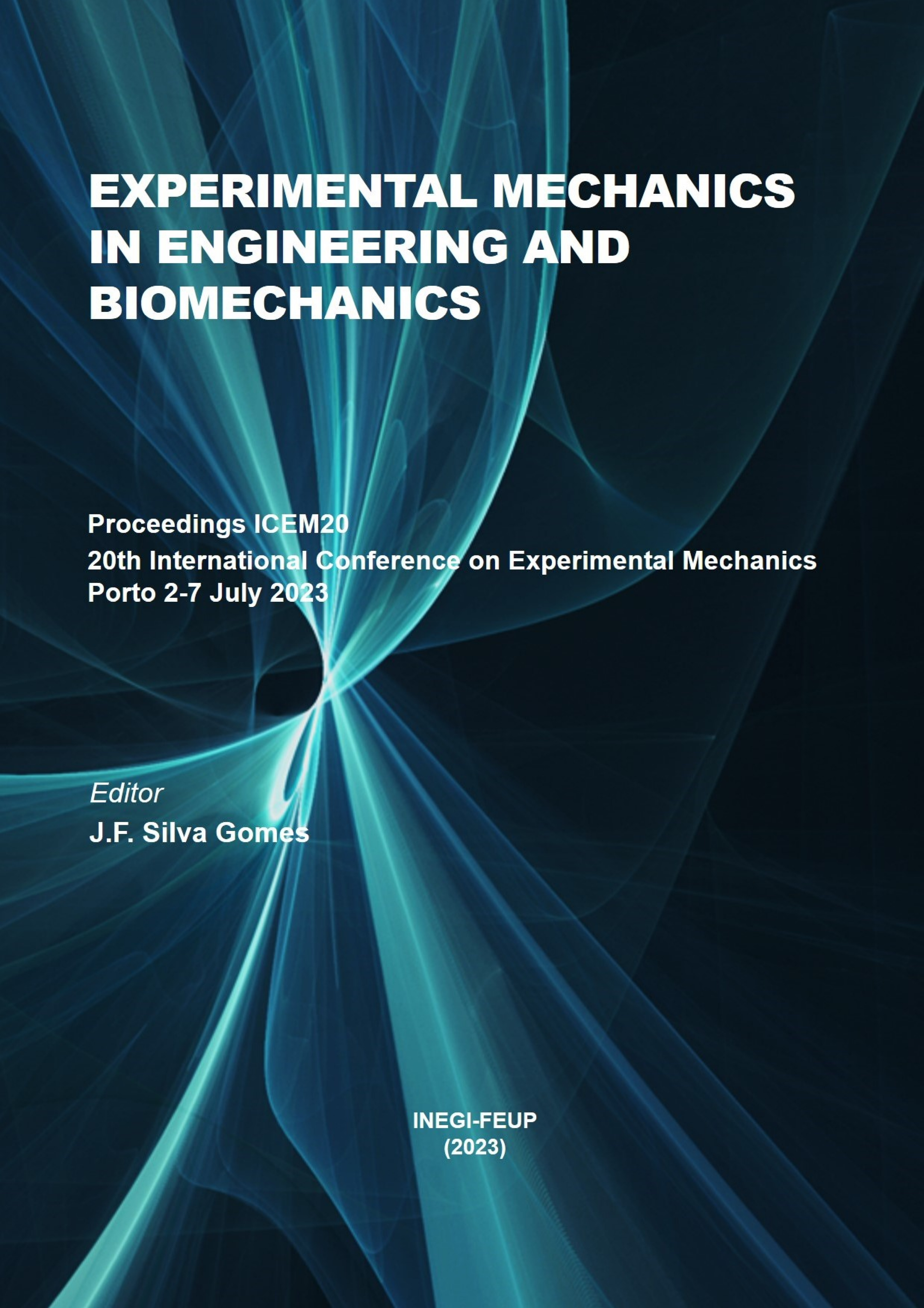

EXPERIMENTAL MECHANICS IN ENGINEERING AND BIOMECHANICS

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NEW HARMONISED PROPOSAL FOR THE FIRE RESISTANCE OF COMPOSITE SLABS WITH STEEL DECK

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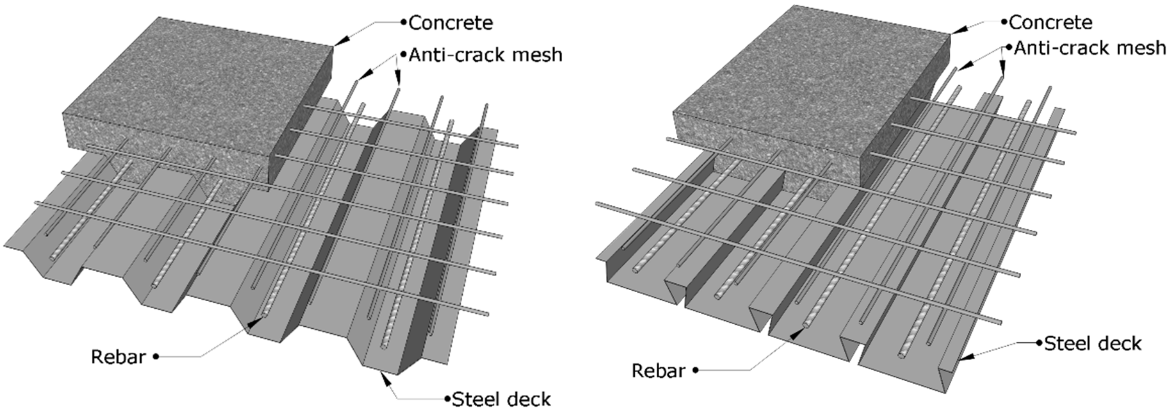
ABSTRACT

The ability to sustain the load (R) of a composite slab during a fire, requires the calculation of the temperature for each load bearing component. The load bearing components that are affected by the temperature are: the bottom flange of the steel deck, the web, the upper flange and the reinforcing bars. The concrete part is not affected by the temperature. The current version of the EN 1994-1-2 presents one simple calculation method that is based on empirical coefficients to determine the average temperature of each component. The effect of the load needs to be compared with the plastic moment of the composite slab for specific fire ratings (60, 90 and 120 min) for the case of the normal weight concrete. Based on a numerical parametric analysis, a new harmonised proposal is presented, including all the main parameters affecting the fire resistance. This new proposal is even safer than the current version.

Keywords: Composite slabs, numerical modelling, fire resistance, MATLAB.

INTRODUCTION

The primary aim of fire safety is to defend human life and property. The importance of safe users while keeping the ability to avoid fire propagation and to sustain the load bearing capacity during a fire is compulsatory. The composite slab with steel deck, see Figure 1, is a structural solution widely used, presenting itself as a more efficient, sustainable, and lighter solution when compared to conventional reinforced concrete slabs.



(a) (b)

Fig. 1 – Usual layout of composite slab profiles: (a) Trapezoidal, (b) Re-entrant.

The fire resistance can be determined by simple calculation methods, numerical methods, and experimental methods. Previous experimental tests revealed that the current version used for the simplified method [1] is not safe. Consequently, new proposals have been presented to reduce the difference between the results. The numerical model proposed by Piloto and Balsa [2],[3] includes an air gap layer, that was observed in most of the experimental tests, including the tests developed by the same authors [4]. Different finite element models have been used, including the one developed in MATLAB Partial Differential Equations Toolbox (PDE Toolbox).

In 1980, these composite slabs became very popular in the United Kingdom. Although these types of composite structures had been in use in North America since the 1970s, regulating authorities in Europe were concerned due to the lack of data on the fire resistance of composite slabs was insufficient to meet the European fire test requirements [5]. Thus, after 1982, considerable large-scale testing of composite slabs was defined to be performed [4].

The European Standard EN 13501-2 [6] defines these criteria and the fire rating classification of building products and elements. The three criteria (REI) are the classification period during which all criteria are satisfied (R- loadbearing capacity, E- integrity, and I- thermal insulation). Structural elements need to meet fire-safety requirements according to building codes. Regarding the latter point, it is mentioned that traditionally fire resistance is assessed based on experimental tests of single structural elements such as beams, columns, walls, or slabs. The fire rating REI of composite slabs is usually made using standard fire tests and can change between 15 and 240 min [6].

Three-dimensional thermal models are presented in this investigation to simulate the thermal effects of standard fire ISO 834 [7] on composite slabs. The objective is to determine the temperature effect on the components of the steel deck (upper flange, web, lower flange) and the reinforcing bars.

The most expensive and time-consuming approach to determine the fire resistance of a composite slab is the experimental fire test. A few simplified methods are available, such as Annex D of EN 1994-1-2 [1], allowing us to determine the fire resistance using a more straightforward calculation approach. This approach is now out of date because it is based on old studies and does not consider some physical observations. It is based in empirical coefficients that are not providing an accurate estimation of the average temperature of the main components affected by temperature. This can result in a significant overestimation or underestimation of the sagging moment, with important implications in the fire resistance and structural safety of the component or structure. It is recommended to consider more comprehensive and detailed methods, such the advanced calculation methods, to more accurately predict the temperature of structural components under fire. Computer simulations are also quicker and less expensive than performing experimental tests [8].

In 1983, The European Convention for Constructional Steelwork (ECCS) developed a set of design guidelines for composite slabs with profiled steel decks that were exposed to a standard fire [9]. The performance criteria were based on a simplification of the general fire resistance criteria as specified in ISO 834 [7]. As a result, several studies have emerged from developing and improving simplified and numerical calculation models.

Hamerlinck in 1990, developed a numerical computation model to analyse the mechanical and thermal behaviour of composite slabs [10]. Afterward, in 1991, Hamerlinck [11] described separately all the methods used in his development. The experimental investigation was performed to validate the numerical results. The temperature evolution over time and the mechanical responses of the slab were both accounted for in the models. The author of this study concluded that there was no appreciable difference between the expected and actual data.

More recently, various finite element software programs have developed a wide range of thermal and structural models to predict the structural and thermal behaviour of steel-concrete composite slabs under fire conditions. In 2019, Piloto et al. [12], [13] used ANSYS and MATLAB software to perform numerical simulations, on a standard fire-based thermal solution, presenting 3D numerical validation models on load bearing (R) and insulation (I) fire resistance criteria. The purpose of the study was to determine how load affected the resistance criterion (R) and how concrete thickness affected the insulation criterion (I). These authors adopted an alternate model with air gaps between the steel and the concrete due to experimental observations [4]. When the composite slab is exposed to fire from below, the steel plate heats up and expands quickly, causing separation from the concrete. The "Air gap" is the name given to this effect. The authors concluded that the actual fire resistance (R) of the composite slab is overestimated by the current standard for load levels smaller than 40% and underestimated for load levels higher than 40%, when using the air gap model. The insulation fire resistance (I) is underestimated by the numerical model when using the perfect contact between materials.

In 2021, Bolina et al. [14] evaluated the thermal behaviour of composite steel-concrete slabs exposed to standard fire. These authors developed eight full-scale fire tests, that were used to calibrate the numerical models made using ABAQUS software. The numerical results and the analytical method provided by EN 1994-1-2 [4] were compared. The temperature in the steel deck was in good agreement with the analytical and experimental results, but the same was not observed for the temperatures on the rebars and the mesh. A new simplified method was presented for assessing the negative rebar temperatures and new factors for assessing the thermal insulation performance.

In 2021, NIST [15] started a series of large fire compartment tests to assess the fire behaviour of the full-scale composite floor assembled in place with a two-story steel frame. This experimental test showed the composite slab developed large concrete cracks (failure by integrity), before reaching the designed fire rating of 120 min. Large concrete cracks occurred around the hogging moment region in less than 30 min, and the steel deck was exposed through mid-panel concrete cracks along the longitudinal centerline of the fire test bay at 70 min. The steel mesh reinforcement failed in tension (rupture), meaning that the value admissible to the building code (60 mm^2/m) may not be sufficient to keep the integrity of the composite steel deck for 120 min.

To optimize the calculation model presented by EN 1994 1-2 [1], a parametric analysis was developed to determine the temperature distribution along the composite cross sections of the slabs using normal-weight concrete (NWC) in four different types of steel deck. Three-dimensional thermal models are presented to simulate the thermal effects of fire exposure using the standard fire curve ISO 834 [1] on composite slabs using MATLAB Partial Differential Equations Toolbox (PDE Toolbox) [16]. Therefore, with the parametric results, a new proposal is presented for the coefficients of Annex D of EN 1994-1-2 [1] and the analytical method of temperature calculation. Therefore, with the parametric analysis, a new proposal is presented to determine the coefficients of Annex D of EN 1994-1-2 [1], and a new formula is presented for the temperature calculation. Then, a comparison is made between the new improved proposals, and the current simplified methods for: the estimation of the fire resistance (I) and; the estimation of the temperature components of the steel deck and rebars, to proceed to the estimation of the fire resistance (R).

SOLUTION METHOD FOR THERMAL ANALYSIS

A parametric study is conducted to investigate the influence of the concrete thickness h_1 on the temperatures used to determine the fire resistance of composite slabs according to the load-bearing criterion (R), two different solution methods are used: the simplified solution method following the recommendations of EN 1994-1-2 [4] and the advanced solution method. The second one is based on a three-dimensional finite element model using the MATLAB Toolbox, including the effect of additional steel reinforcement bars (rebars). This model was developed to evaluate the thermal behaviour of composite slabs with steel decks subjected to standard fire exposure. The numerical temperatures are compared with those obtained by the simplified solution method, provided in the standard, and then are used to derive a new proposal, an alternative to the simplified solution method, to determine the temperatures in the main components of the composite slabs for better accuracy. The fitting of the analytical model to the numerical data was done by solving the linear least squares problem using singular value decomposition. This method guarantees a better solution that minimizes the square of the deviations.

SIMPLIFIED SOLUTION METHOD

The simplified solution method for composite slabs with steel deck is available in the Annex D of EN 1994 Part 1-2 [1] to determine the fire resistance. This standard enables the temperature for each steel deck component (upper flange, web, and lower flange) and rebar, to determine the bending moment resistance of the composite slab (sagging moment). According to annex D, the temperatures of the components may be calculated according to the following equations. For the case of the steel deck components, see Equation (1).

$$\theta_a = b_0 + b_1 \cdot \frac{1}{l_3} + b_2 \cdot \frac{A}{L_r} + b_3 \cdot \Phi + b_4 \cdot \Phi^2 \ [°\mathrm{C}] \qquad (1)$$

and the rebar component (θ_s) by Equation (2).

$$\theta_s = c_0 + c_1 . \frac{u_3}{h_2} + c_2 \cdot z + c_3 \cdot \frac{A}{L_r} + c_4 \cdot \alpha + c_5 \cdot \frac{1}{l_3} \ [°\mathrm{C}] \qquad (2)$$

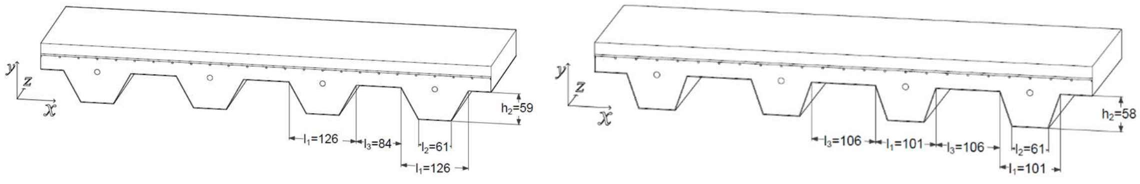
The empirical coefficients b_i and c_i refer are given by EN 1994 1.2 [1], but they depend on the type of concrete used and on the fire rating of the element. The factor Φ corresponds to the view factor of the upper flange, and the partial coefficients b_i are coefficients depending on the type of concrete. The temperature θ_a represents the average temperature in each of the steel deck components and θ_s represents the temperature in the rebar [°C]. The parameter l_3 is the distance within the ribs, u_3 represents the distance from the middle of the rebar to the lower flange in [mm], h_2 is the height of the rib in [mm], the z-factor represents the average position of the rebar concerning the rib geometry in [$mm^{0.5}$], α corresponds to the angle formed between the web component of the steel deck and the horizontal direction in degrees.

ADVANCED SOLUTION METHOD

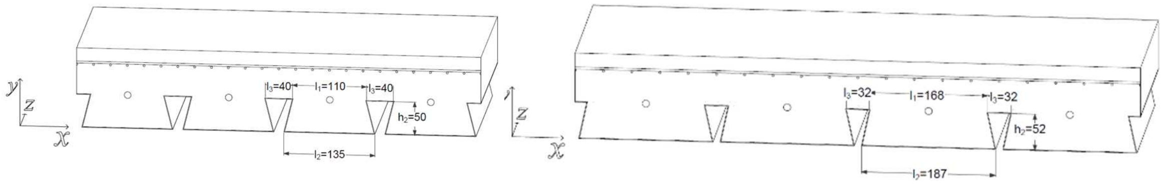
This section presents all the steps necessary to develop the finite element thermal model, which will be used to solve the nonlinear transient thermal problems. The heat transfer problem in this study must be solved in the multi-domain body corresponding to the composite slab, assuming the incremental and iterative solution method. The heat flux applied to unexposed surfaces is determined by the convection, assuming the ambient (20 ºC) bulk temperature, while the heat flux applied to the exposed surfaces considers the convection and radiation of the flames, using the ISO 834 temperature curve for both bulk temperatures [17].

Physical domain, materials and models

The three-dimensional (3D) transient heat transfer problem will be solved on four composite slabs with different geometries, as shown in Figure 2. Two composite slabs with trapezoidal geometry were selected: Confraplus 60 and Polydeck 59 s. For this category, the following values were adopted for the $h1$ thickness: 50, 70, 90,110, and 125 [mm]. However, for the other two slabs with re-entrant geometry (Multideck 50 and Bondek) the following thicknesses $h1$ were used: 60, 70, 90, 110, and 125 [mm]. The 3D models were created following a realistic representation of the physical model of the slabs, where the geometry of the models considers the approximate shape of the surfaces based on a representative volume of the slab. The cross-section was selected as the side edges bounded by the centroid of the top flange and comprised a rib with a sample length of 200 [mm].



(a) Polydeck 59S (b) Cofraplus 60



(c) Multideck (d) Bondeck

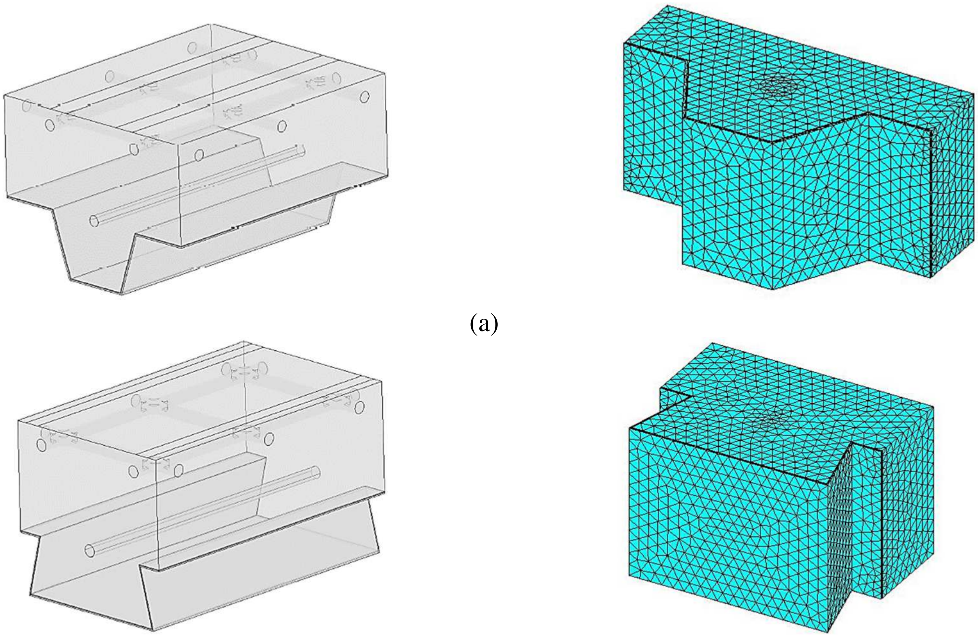
Fig. 2 – Composite slabs geometric characteristics and dimensions [mm].

These geometries have been selected based on the geometric difference and current use. The following table resumes the ranges of the investigated parameters.

Table 1 – Parameters of the parametric study.

Steel deck profile	h_1 **[mm]**	t_d **[mm]**	$Ø_{reb}$ **[mm]**	**Steel mesh [mm//mm]**
ArcelorMittal Polydeck 59S (Trapezoidal)	50,70,90,110,125	1.00,1.25	10,16	Ø6//50
ArcelorMittal Cofraplus 60 (Trapezoidal)	50,70,90,110,125	1.00, 1.25	10, 16	Ø6//50
Kingspan Multideck (Re-entrant)	60,70,90,110,125	1.00, 1.20	10, 16	Ø6//50
Lysaght Bondeck (Re-entrant)	60,70,90,110,125	0.75, 1.00	10, 16	Ø6//50

The developed multi-domain consists of four sub-domains: the steel deck, the airgap, the concrete, and the rebar. Thus, the materials that make up the physical subdomains are carbon steel (steel deck and rebars), concrete (concrete topping), and air (to simulate the debonding effect between the steel deck and concrete).



(a)

(b)

Fig. 3 – Examples of the composite slab models; (a) Composite slab Geometry volumes and Finite Element Mesh – Trapezoidal Profile; (b) Composite slab Geometry and Finite Element Mesh – Re-entrant Profile.

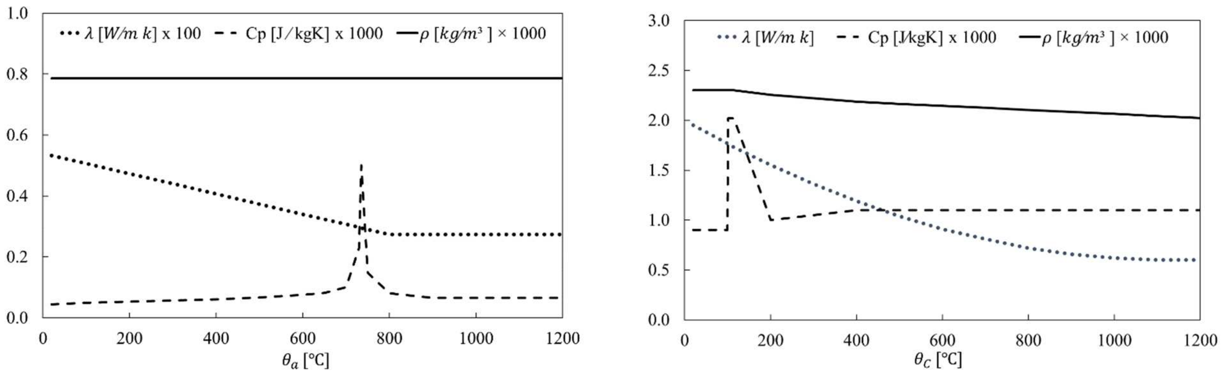
The heat conduction inside the physical domain is mathematically modelled by the energy conservation Equation (3).

$$\rho(\theta)C_p(\theta)\frac{\partial\theta}{\partial t} = \nabla\cdot(\lambda(\theta)\nabla\theta) \qquad (3)$$

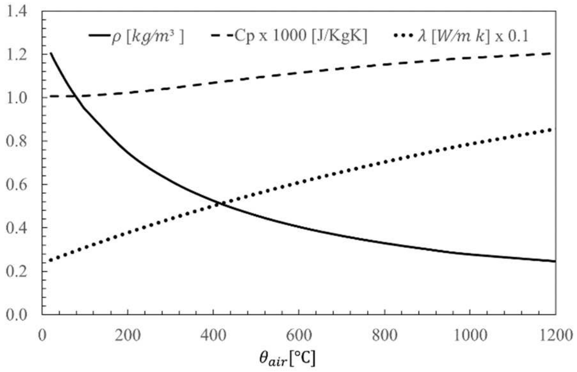
Where θ represents the respective material temperature [℃], $\rho(\theta)$ is the specific mass $[kg/m^3]$, $C_p(\theta)$ is the specific heat $[J/kgK]$, $\lambda(\theta)$ is the thermal conductivity $[W/mK]$, t is the time in [s] and $\nabla = (\partial_x, \partial_y, \partial_z)$ is the gradient.

Figure 4 depicts the thermal properties of the three different types of materials that should be considered in this analysis. The thermal properties of the materials used in the numerical model follow the formulas of Eurocode 2 and 3, being the steel and concrete properties specified in EN 1993-1-2 [18] and EN 1992-1-2 [19]. The air gap is included between the steel plate and the concrete and follows the material properties given by Cengel [20].

The thermal properties of the materials should be viewed as close to reality and temperature dependent as feasible to achieve the best results in the thermal model. The nonlinearity of heat transfer along the cross section can be regarded as the primary characteristic of this type of slab, assuming that the composite slab is a globally and locally heterogeneous structure taking specific elements into account. As a result, the temperature variation during the fire period implies changes in the material thermal properties, such as: the specific heat, the thermal conductivity, and the density.



(a) Carbon steel. (b) NWC



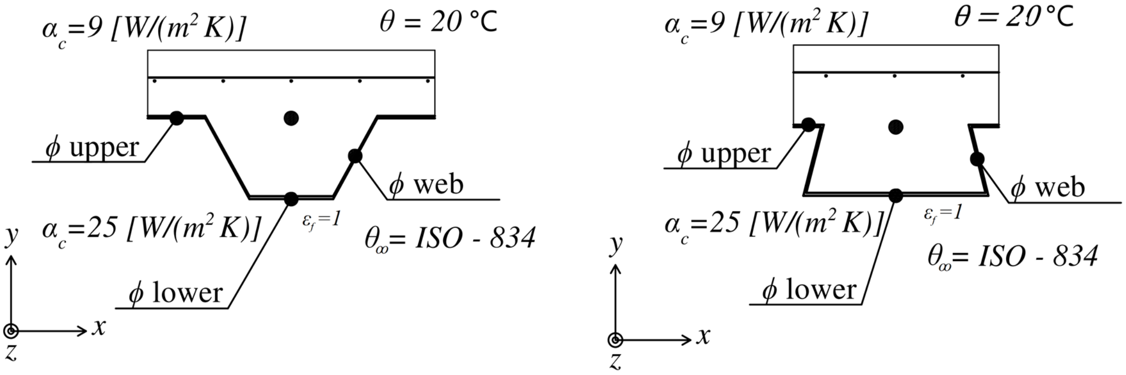
(c) Air.

Fig. 4 – Thermal properties as a function of temperature variation.

To obtain the correct solution to the problem, it is necessary to apply the boundary conditions according to EN 1991-1-2 [17] and the ISO-834 [7] fire curve.

Boundary Conditions

The boundary conditions in any numerical analysis are crucial in limiting the temperature and locations of actions and responses sparked by thermal loads. This work includes boundary conditions that affect how heat is transferred through composite slabs. The composite slabs are exposed to three main boundary conditions: exposed surfaces, unexposed surfaces, and adiabatic surfaces. The EN 1991-1.2 [17] guidelines for the standard boundary conditions are depicted in Figure 5.



(a) (b)

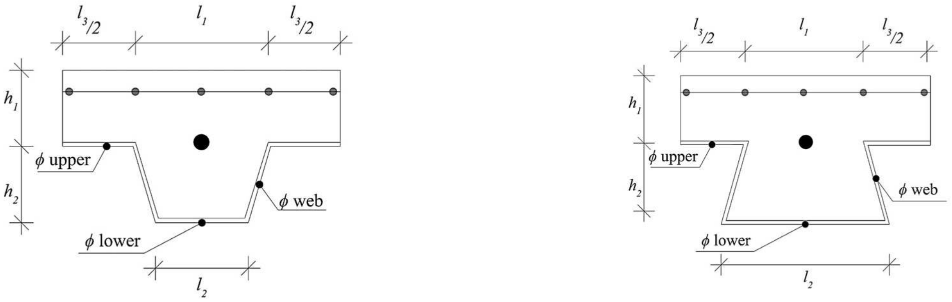
Fig. 5 – Boundary conditions: (a) Trapezoidal profile, (b) Re-entrant profile.

In the exposed side of the composite slab, the boundary conditions comprise the heat transfer by convection and radiation and are given by Equation (4).

$$\lambda(\theta)\nabla\theta\cdot\vec{n} = \propto_c (\theta_\infty - \theta) + \Phi\varepsilon_m\varepsilon_f\sigma\left({\theta_\infty}^4 - \theta^4\right) \tag{4}$$

where $\vec{n}$ is the unitary vector normal to the external face, Φ is the view factor, $\propto_c$ is the convection coefficient, ε_m is the emissivity of the material, ε_f is the emissivity of fire, σ is the Stefan-Boltzmann constant and θ_∞ is the gas temperature of the fire compartment, that in the case of standard fire is given by ISO 834 [7]. This equation represents the amount of heat flux that arrives at the steel deck by radiation and convection based on the gas bulk temperature, which will be transferred through the slab by conduction.

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 $\alpha_c = 25[\mathrm{W}/m^2K]$, the emissivity of steel is $\varepsilon_m = 0.7$, and the fire emissivity is $\varepsilon_f = 1$. The view factor defined in EN 1994 1-2 [1], is based on Hottel's crossed-string method developed in 1950 [20]. For composite slab geometries, the view factor of the lower flange of steel decking is typically taken as one $\Phi_{low} = 1.0$. Figure 6 depicts the main dimensions used to determine the view factor for the web (not considered in EN 1994-1-2) and the view factor for the upper flange of the steel deck (included in the EN 1994-1-2).



(a) (b)

Fig. 6 – Parameters for determining the view factors: (a) Trapezoidal profile, (b) Re-entrant profile.

Equations (5) and (6) provide the mathematical relations to determine this view factor as a function of the geometric characteristics.

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

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

The fire resistance of a building element is defined as the time during standard exposure to fire, expressed in completed minutes, until failure occurs under one of the criteria applicable to the element, according to ISO 834 [7] and the more updated standard used for testing EN 1363-1 [21]. In Equation (7), θ represents the gas temperature in [°C], and t is the time elapsed in minutes.

$$\theta = 345 \cdot log_{10} \cdot (8t + 1) + 20 \tag{7}$$

According to the recommendations of standard EN 1991-1-2 [17], the top part of the slab (unexposed side) is submitted to a convective coefficient of 9 [W/m^2K] to include the radiation effect. The unexposed surface of the composite slab is also an important side to determine the temperature evolution, especially to determine the ability to keep this temperature below a certain level, avoiding fire to spread. After all, it will determine the ability to transfer heat from the compartment below the composite slab to the above compartment.

The boundary condition in the unexposed surface of the composite slab is given by Equation 8.

$$\lambda(\theta)\nabla\theta \cdot \vec{n} = \propto_c (\theta - \theta_\infty) \tag{8}$$

The θ_∞ is the bulk temperature (room). The other four surfaces of the slab (front, back, left, right) are considered adiabatic surfaces. That is, the null heat flux condition applied to these surfaces is given by Equation 9.

$$\lambda(\theta)\nabla\theta \cdot \vec{n} = 0 \tag{9}$$

THE NEW PROPOSAL

The finite element method has been used to follow the second-order partial differential energy equation. An incremental and iterative solution has been applied to determine the temperature field in the 3D domain. The temperature has been collected from the unexposed side to determine a new proposal to determine the fire resistance by insulation (I).

The temperature has also been averaged from the affected four components to define the new proposal for the temperature calculation over the main fire ratings (30, 60, 90 and 120 min). These temperatures can be used to determine the fire resistance by load (R), see Figure 7.

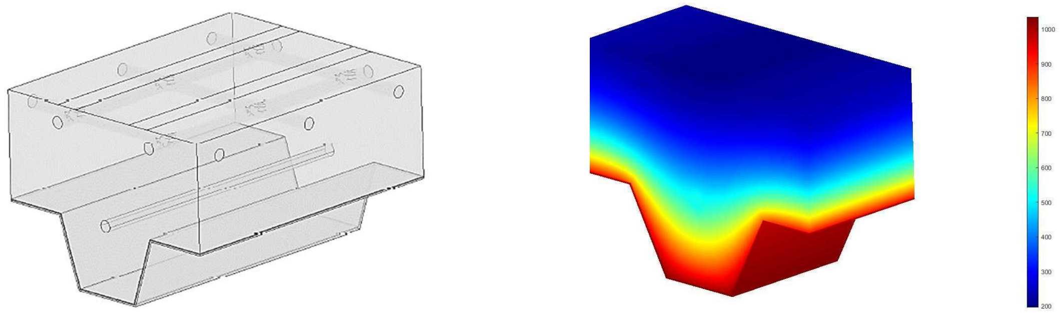


Fig. 7 – Solid model and finite element results after 120 min for Polydeck 59S with concrete cover h1 = 90 [mm].

Equation 10 represents the ability to sustain the temperature on the unexposed side below the criteria defined by the standard EN 1363-1 [21]. The fire resistance of the slab t_{fi}, is given in [min], where the effective thickness of the composite slab h_{eff} and the air gap layer t_a are given in [mm]; with the following limits: $70 \leq h_{eff} \leq 150$ [mm] and $0 \leq t_a \leq 3$ [mm]. According to several numerical validations (standard and natural fire), the best fit is obtained with the t_a=0.5 [mm] [22] [23] [24] [25].

$$t_{fi} = 0.0059 \cdot {h_{eff}}^2 + 0.1127 \cdot h_{eff} - 5.8065 + \left(0.1424 \cdot h_{eff} + 2.4672\right) \cdot t_a \tag{10}$$

Equation 11 and Equation 12 establish new optimized coefficients for both trapezoidal and re-entrant composite slabs, including the new parameter for the "fire rating" t [min] and the usual geometric parameters (l_3, A/L_r), the view factor Φ of the upper flange, the new parameter for the concrete thickness h_1 and the new parameter for the diameter of the rebar $\emptyset_{reb}$. The empirical coefficients were determined by fitting the mathematical model, which minimizes the sum of the squared difference between the numerical results and the analytical.

$$\theta_a = \mathrm{b}_0 + \mathrm{b}_1 \frac{1}{\mathrm{l}_3} + \mathrm{b}_2 \frac{\mathrm{A}}{\mathrm{L}_\mathrm{r}} + \mathrm{b}_3 \cdot \Phi + \mathrm{b}_4 \cdot \Phi^2 + b_5 \cdot h_1 + b_6 \cdot t + b_7 \cdot \emptyset_{reb} \tag{11}$$

$$\theta_s = c_0 + c_1 \frac{u_3}{h_2} + c_2 \cdot z + c_3 \frac{A}{L_r} + c_4 \cdot \alpha + c_5 \frac{1}{l_3} + c_6 \cdot h_1 + c_7 \cdot t + c_8 \cdot \emptyset_{reb} \tag{12}$$

The new proposals give satisfactory results for the temperature behaviour and fire resistance. Based on the simulation results, the new proposal establishes new optimized coefficients b_i and c_i that are proposed for the simplified model, to be used for both geometries indifferently (trapezoidal and re-entrant). That is, it allows the analysis to be performed independently of the slab geometry.

In this new proposal, the concrete thickness h_1 is multiplied by the coefficient b_5, in the case of the steel deck temperatures, and by c_6, in the case of the rebar temperature. The rebar diameter $\emptyset_{reb}$ is multiplied by the coefficient b_7 in the case of the steel deck temperatures and by the c_8 the coefficient in the case of the rebar temperature. This new proposal allows performing the simplified analysis, with the specification of the fire rating time *t*. The resulting coefficients used to determine both temperatures on the steel deck and rebar are presented in Table 2 and Table 3, respectively.

Table 2 – Coefficients of the new proposal to determine the temperature of the steel deck components.

Profile	**Flange**	$\mathbf{b_0}$	$\mathbf{b_1}$	$\mathbf{b_2}$	$\mathbf{b_3}$	$\mathbf{b_4}$	$\mathbf{b_5}$	$\mathbf{b_6}$	$\mathbf{b_7}$
Trapezoidal or Re-entrant	Lower	271.56	-1865.90	1.20	271.56	271.56	-0.09	2.08	-1.23
	Web	777.23	-21.44	-5.33	194.38	-18.33	-0.07	2.47	-0.07
	Upper	1212.30	550.22	-15.65	-2824.10	3619.40	-0.29	2.76	0.99

Table 3 – Coefficients of the new proposal to determine the rebar temperature.

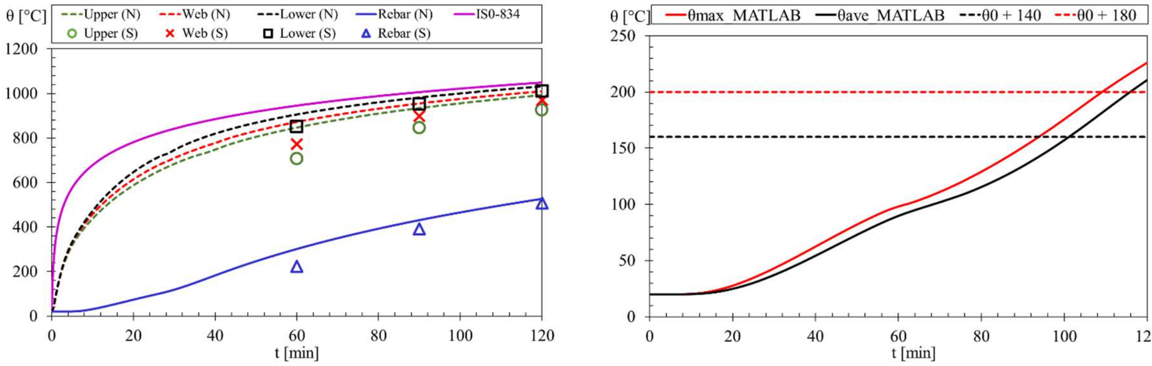
Profile	$\mathbf{c_0}$	$\mathbf{c_1}$	$\mathbf{c_2}$	$\mathbf{c_3}$	$\mathbf{c_4}$	$\mathbf{c_5}$	$\mathbf{c_6}$	$\mathbf{c_7}$	$\mathbf{c_8}$
Trapezoidal or Re-entrant	1366.20	1366.20	-2565.40	155.36	-3.90	-2340.70	-0.28	3.44	-0.29

NUMERICAL AND ANALYTICAL RESULTS

The numerical results were compared with those obtained by Annex D of EN 1994-1-2 [1], when using the current version of the simplified calculation method (S). Figures 8-11 show the temperature development (numerical (N) and analytical (S)) at different selected points, as well as the average and maximum temperatures on the unexposed surface (numerical results). The numerical results are identified by the name of the components and the results determined by the simplified method are identified by the additional (S) for each load-bearing component affected by temperature.

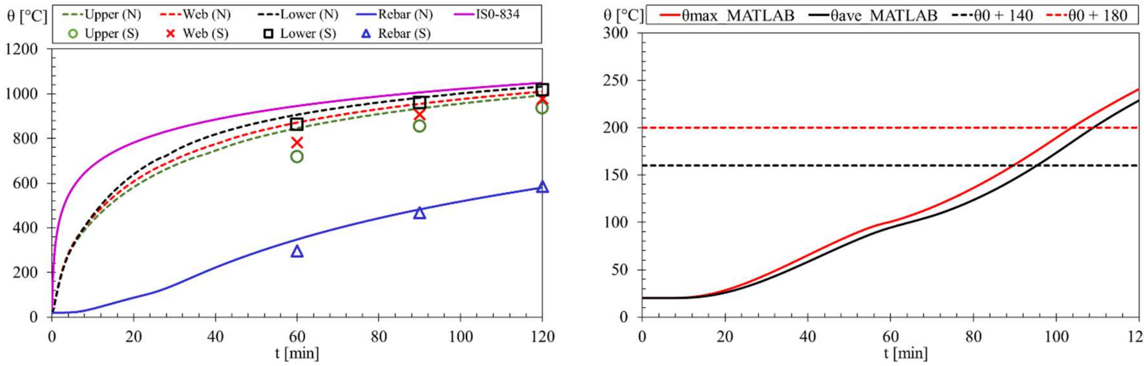
A total of 80 numerical simulations were carried out, using the air gap of t_a=0.5 [mm]. This air-gap value has been determined and optimized through the previous analyses [2], [12], [13], [22]. All simulations were done for NWC. All composite slabs were submitted to numerical simulations of fire exposure for 2 hours of fire exposure.

The curves θ_AVE and θ_MAX refer to the average and maximum temperature, respectively, on the unexposed surface of the slab. The results presented herein are related to slabs with rebar diameter $\emptyset_{\text{rebar}}$ of 10 [mm] and the thickness of the steel deck t_s of 1.0 [mm], with a concrete cover h_1 equal to 90 [mm].



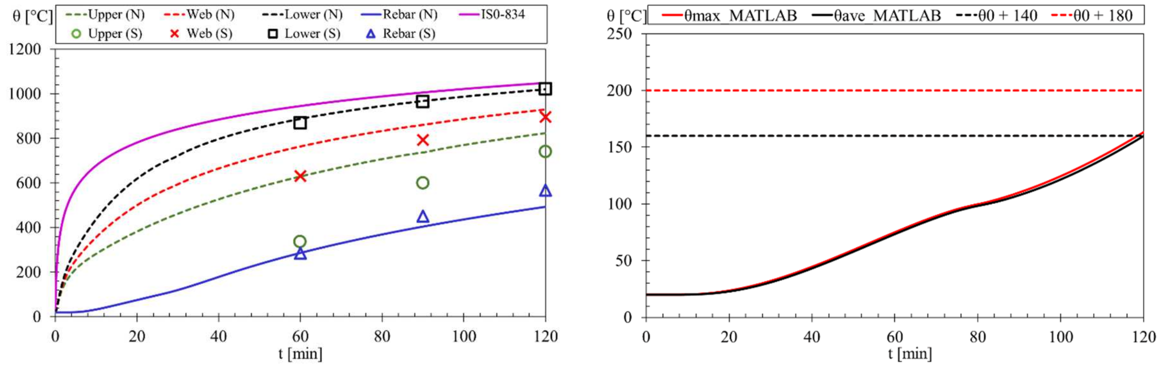
(a) Selected Points (b) Temperature on the unexposed side (N)

Fig. 8 – Polydeck 59S. (a) Temperature evolution: (N) stands for numerical and (S) for the simplified method. (b) Unexposed temperature evolution.



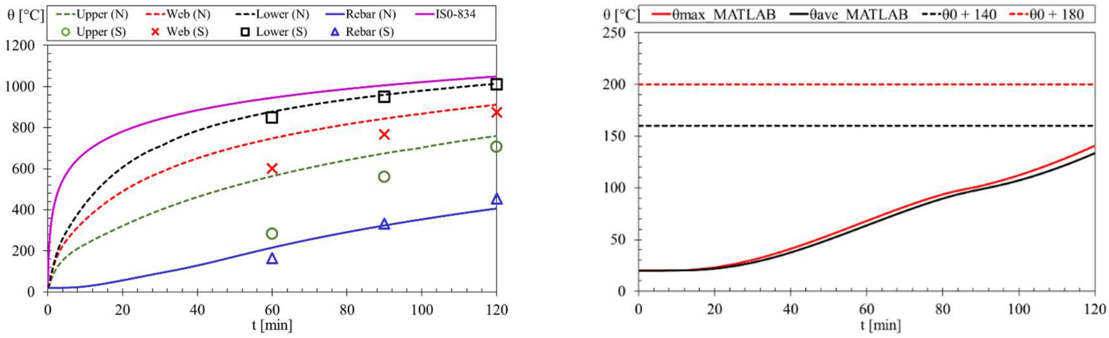
(a) Selected Points (b) Temperature on the unexposed side (N)

Fig. 9 – Cofraplus 60. (a) Temperature evolution: (N) stands for numerical and (S) for the simplified method. (b) Unexposed temperature evolution.



(a) Selected Points (b) Temperature on the unexposed side (N)

Fig. 10 – Multideck. (a) Temperature evolution: (N) stands for numerical and (S) for the simplified method. (b) Unexposed temperature evolution.



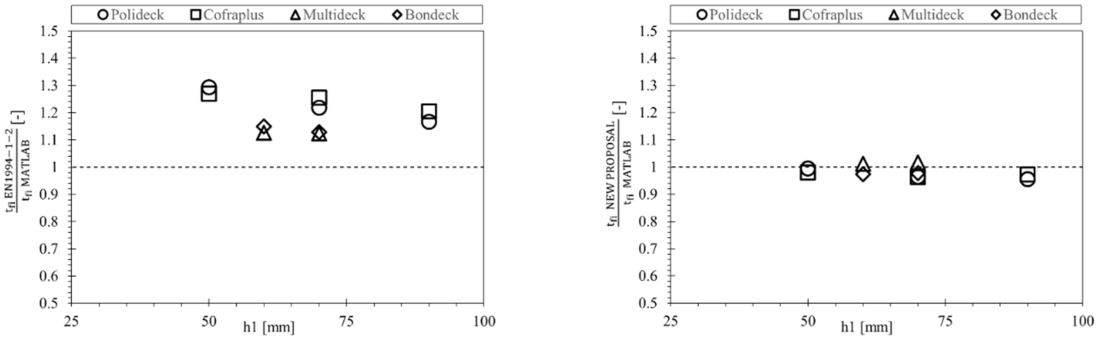
(a) Selected Points (b) Temperature on the unexposed side (N)

Fig. 11 – Bondeck. (a) Temperature evolution: (N) stands for numerical and (S) for the simplified method. (b) Unexposed temperature evolution.

COMPARISON OF RESULTS

The temperature rise at the unexposed surface of composite slabs is a significant concern from the thermal insulation standpoint. Controlling the temperature rise in this region is essential to prevent the ignition of any materials and avoid the spread of fire.

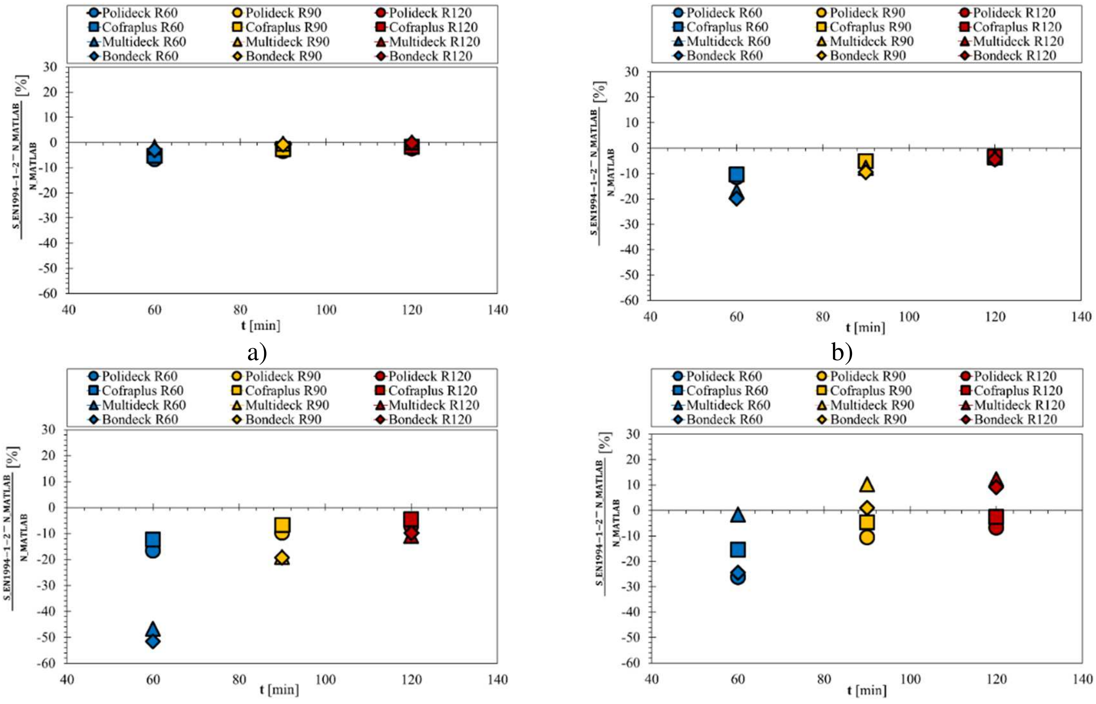
Figure 12 a) presents the comparison between numerical results and results obtained with the simplified calculation method of EN 1994- 1-2 for fire resistance (I), when changing the value of the concrete layer h_1. Figure 12 b) shows that, in general, the results from MATLAB and the new proposal are quite similar, with a variation smaller than 5 %, being most of the results on the safe side. The smallest and largest relative error between the MATLAB results and those obtained with the new proposal is 1.24% and 4.44% respectively. In contrast, the minimum and maximum values of the relative error, when using the current version of the EN 1994- 1-2, are 12.38% and 29.40%. With this, it is demonstrated that the current version of the EN 1994-1-2 method is not accurate.



(a) (b)

Fig. 12 – (a) Comparison between the numerical results and the EN 1994-1-2 to the fire resistance (I). (b) Comparison between the numerical results and the New Proposal to fire resistance (I).

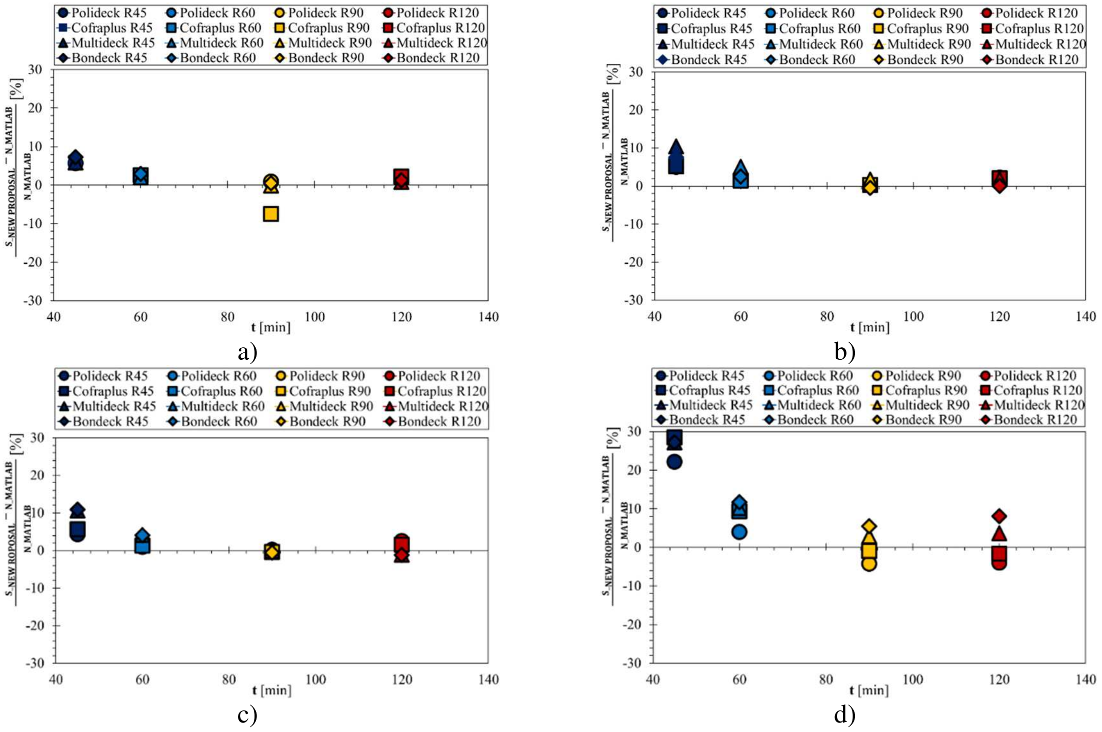
In order to verify the differences between the results proposed by the simplified model (S) presented in EN 1994-1-2 [1] and the numeric results (N), comparison graphs were developed, assuming the concrete topping $h_1 = 70$ [mm] and different fire ratings, R60, 90, and 120, see Figure 13 and Fig. 14. A measurement of the relative errors between the numerical results and those obtained by Annex D of EN 1994-1-2 is presented. Figure 13 illustrates a comparison between the results obtained numerically (MATLAB) and those obtained by the EN 1994-1-2 [1] for the fire resistance (R). The biggest error was found for the upper flange component, with more than 50% difference (for both re-entrant models).



a) b) c) d)

Fig. 13 – Measurement of relative errors for EN 1994-1-2 and the Numerical Results concerning resistance times 45,60,90, and 120 min. For the components a) Lower flange, b) Web, c) Upper flange and d) Rebar.

Figure 14 presents a comparison between the results of the new proposal and numerical results (N). These results were selected for the same concrete cover $h_1 = 70$ [mm] and one additional fire rating R45.



a) b) c) d)

Fig. 14 – Measurement of relative errors for Numerical Results and New Proposal concerning resistance times 45,60,90, and 120 min. For the components a) Lower flange, b) Web, c) Upper flange and d) Rebar.

Regarding the new proposal, higher errors are expected in the rebars for the fire rating 45 min, where the relative error is 22.20% in the Polideck slab, 28.51% in the Cofraplus slab, 27.22% in the Multideck slab and 27.25% in the Bondeck slab. The other components can be predicted with smaller errors (less than 10%).

Overall, the new proposal generated satisfactory results for the fire behaviour of the composite slabs and good agreement with the numerical results describing the three-dimensional heat flow in both the steel deck components and the reinforcing bar. The new proposal includes parameters that are not considered by the current version of EN 1994-1-2. This results in a much more complete proposal in terms of parameters affecting the fire performance, allowing a much more straightforward analysis for the designer.

CONCLUSIONS

In this work, a series of heat transfer analyses were conducted to determine the adequacy of the prescriptive codes for the fire safety of composite slabs. To simulate the thermal behaviour of composite slabs under standard fire conditions, new and more realistic computer models have been created. The steel-concrete interface includes the air gap effect. The parametric analysis results allow us to determine the temperatures for different slab geometries and compare them with those provided by the simplified calculation method of EN 1994-1-2.

To optimize the simplified calculation method, a new proposal has been developed to determine the temperature in the steel deck components and the rebars. The new proposal establishes new optimized coefficients determined by fitting the new proposal to the numerical results by non-linear least-squares for both steel deck geometries.

For the load bearing components affected by the temperature, the new proposal includes the previous parameters provided by the current version of the EN 1994-1-2, but also includes additional parameters. The new parameters include the effect of the concrete thickness h_1, the rebar diameter $\emptyset_{reb}$ and the fire rating time *t,* which makes the analysis even more simplified and straightforward. When comparing the new proposal with the numerical results, it was possible to obtain much smaller errors, resulting in better approximations.

Future work should carry out more parametric studies comprising a series of different steel deck geometries, for both normal weight and lightweight concrete.

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