Lecture Notes in Civil Engineering

Paulo A. G. Piloto
João Paulo Rodrigues
Valdir Pignatta Silva *Editors*

Advances in Fire Safety Engineering

Selected Papers from the 5th Iberian-Latin-American Congress on Fire Safety, CILASCI 5, July 15–17, 2019, Porto, Portugal

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Preface

This book gathers selected contributions presented during the 5th Iberian-Latin-American Congress on Fire Safety (CILASCI), held in Porto, Portugal, from 15–17 July 2019. The CILASCI is held once every two years, with the aim of disseminating scientific and technical knowledge in the field of fire safety, attracting different players involved in this area of knowledge.

The 5th Iberian-Latin-American Congress on Fire Safety reflected the new developments achieved in a wide range of application areas. The papers included in this book were selected out of 78 manuscripts (full papers), and five invited lectures, written and presented during six parallel sessions from researchers around the world (Algeria, Australia, Belgium, Brazil, China, Czech Republic, France, Hong Kong, Italy, Mozambique, Portugal, Spain, UK and USA).

The selected papers were peer-reviewed during and after the congress, and this selection process has resulted in new, extended, revised and full original versions covering the experimental analysis of materials and structures, the computational modelling of structures and materials, the fire events in special buildings and spaces, the architectural issues and evacuation topics for fire safety in buildings.

Fire safety has been advancing fast as a result of research, development and innovation worldwide; the new research programmes, the support of new skilled professionals and the existence of advanced training programmes in Fire Science Technology are not only expected to increase the safety level of people, buildings and products, but are also going to produce a positive impact in the economy of each country and society.

The editors gratefully acknowledge the members of the scientific committee and the experts who carried out the reviews of the manuscripts. They are also grateful to the organizing committee from the Polytechnic Institute of Bragança (IPB), the

Faculty of Engineering of the University of Porto (FEUP) and the School of Engineering (ISEP) from the Polytechnic Institute of Porto, and the support from the Luso-Brazilian Association for Fire Safety (ALBASCI) is also acknowledged.

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Contents

Three-Dimensional Numerical Analysis on the Fire Behaviour of Composite Slabs with Steel Deck

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Abstract. A composite steel-concrete slab consists of a concrete topping cast on the top of a profiled steel deck. Normally, the concrete is reinforced with an anti-crack mesh positioned on the upper part and individual reinforcing bars placed within the ribs. Composite slabs play an important role in the overall stability of buildings during a fire, and must be designed in accordance with regulations and standards. Usually, this structural element is rated on the basis of standard fire tests using the standard fire curve ISO 834. The fire resistance should be determined according to three different criteria, namely Load Bearing (R), Integrity (E) and Insulation (I). The Annex D of the EN 1994-1-2 presents a simplified calculation method for the determination of the fire resistance (I) of composite slabs subjected to standard fire exposure from below. During the last two decades, no revisions were made to this method, and there are no proposals for changes in the design formulae for the next version of the EN 1994-1-2. This investigation presents the development of numerical thermal models for three-dimensional analysis of composite slabs under fire conditions in ANSYS and MATLAB. During fire exposure, the steel deck heats up rapidly, expands and may separate from the concrete topping. In order to simulate debonding effects, an alternative thermal model is utilized, presenting an air gap with constant thickness between the steel deck and the concrete topping. The results of the numerical simulations are validated against the results of experimental fire tests, and compared with the simplified calculation method. A new equation is proposed for the calculation of the fire resistance (I) of composite slabs.

Keywords: Composite slabs · Fire resistance · Insulation criterion · Numerical simulation

1 Introduction

A composite steel-concrete slab consists of a concrete topping casted on the top of a profiled steel deck. Normally, the concrete is reinforced with an anti-crack mesh positioned on the upper part and individual reinforcing bars placed within the ribs, see Fig. 1. The steel deck acts as a permanent formwork and the composite action between the steel and concrete is generally achieved by indentations or embossments in the steel

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deck. Due to the reinforcement provided by the steel deck, composite slabs are generally slenderer and more efficient than flat full concrete slabs because they require less additional reinforcement and less concrete as well. The reduction of the construction time, simplicity of installation and reduction/elimination of shoring systems are other advantages of composite slabs that should be highlighted.

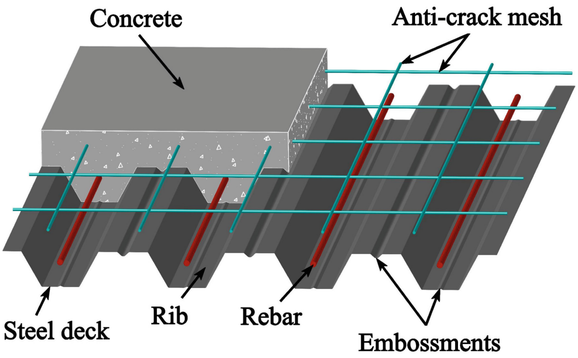


Fig. 1. Typical layout of a composite slab with trapezoidal steel deck.

Since the decade of 1980, a significant increase in the use of composite slabs with steel deck has taken place in Europe. The most popular types of shapes of the profiled steel deck are trapezoidal and re-entrant. Owing to the ease of casting concrete, slabs with trapezoidal steel deck are more popular than re-entrant ones. The overall depth of composite slabs usually varies between 100 and 170 mm, and the steel deck thickness between 0.7 and 1.2 mm. Generally, the steel deck is protected with a zinc layer on both faces in order to prevent corrosion and increase durability.

The steel deck may be directly exposed to accidental fire conditions. Composite slabs have to meet fire-safety requirements in accordance to standards and regulations. Normally, this structural element is rated on the basis of standard fire tests using the standard fire curve ISO 834 [1]. The fire resistance should be determined according to three different criteria, namely Load Bearing (R), Integrity (E) and Insulation (I).

The profiled geometry of the steel deck and the presence of the ribs in composite slabs create an orthotropic profile, resulting in complex thermal gradients hence presenting challenges in numerical modelling [2]. In recent years, several studies have been conducted in order to investigate the fire behaviour of this structural element. In 1983, recognizing the need for a calculation method, the European Convention for Constructional Steelwork (ECCS) [3] published the first instructions applied to the design of composite slabs with profiled steel deck under standard fire conditions. This document introduced simple calculation rules, which were based on the results of fire tests performed on different European laboratories, enabling the fire resistance of composite slabs to be quickly calculated. According to this technical note, for properly designed slabs at room temperature, the explicit fire analysis is not required to achieve a fire resistance of 30 min or less. In addition, it establishes that if the insulation criterion for fire resistance is fulfilled, then the integrity criterion is also fulfilled. At this time, the knowledge about the fire behaviour of composite slabs was incomplete and conservative assumptions were adopted, resulting in uneconomical solutions.

In 1991, Hamerlinck [4] conducted a numerical and experimental study regarding the thermal and mechanical behaviour of reinforced composite slabs under fire conditions. Both numerical models were experimentally validated with loaded and unloaded tests. Due to the melting of the zinc layer and surface blackening, the resulting emissivity of the galvanized steel deck was calculated as temperature dependent. The testing programme took into consideration the most important parameters for fire resistance and a new computer program was developed, enabling simulations at low computational cost (low time processing). It was concluded that the developed two-dimensional model provided satisfactory results, although not including three-dimensional thermal effects.

In 1998, an investigation was carried out by Both [5] with the main objective of introducing easy to handle calculation rules as well as providing more insight on the fire behaviour and failure mechanisms mainly of continuous composite slabs. The numerical models were validated against the results of experimental tests performed by the author and other researchers. The three-dimensional effects near internal supports, concrete cracking and the melting of the zinc layer of the steel deck were considered. Finally, a parametric study was performed and simple calculation rules were derived from the results using standard regression techniques. It was concluded that the thermal model was able to describe the two and three-dimensional heat flow in composite slabs during fire exposure and the assessment rules for the fire resistance given in Eurocode 4 at that time could be considerably improved, among other conclusions.

In 1999, Abdel-Halim, Hakmi and O'Leary [6] conducted a study with the main goal of providing data about the performance of fire exposed composite slabs adopting a model fire test facility. Two different specimens, one with and another without additional longitudinal reinforcement bars were tested using the standard fire ISO 834 in the University of Salford, UK. Thereupon, the investigation focused on the analysis of the effect of additional bars on the fire resistance as well as on the comparison between the fire resistance of the samples with respect to integrity and insulation criteria. It was concluded that the specimen without reinforcement bars presented a lower rate of temperature rise on the unexposed surface in comparison to the reinforced specimen and consequently, a higher fire resistance in both insulation and integrity criteria. This is explained due to the existence of high conductive material (steel rebar) within the concrete layer of the reinforced specimen.

In 2002, Lim and Wade [7] performed fire tests on six large-scale concrete slabs, comprising three reinforced concrete flat slabs and three composite steel-concrete slabs. The main objective of the tests was to analyse the fire behaviour of unrestrained simply supported slabs in a controlled furnace. The slabs were subjected to a live load and standard fire conditions during three hours. All the slabs resisted the full duration of the tests without collapsing, despite presenting extensive surface cracking on the unexposed surface and large deflections (up to 270 mm). In general, the measured fire resistance was higher than the predictions from normative recommendations. The results evidenced the important effect of membrane action on preserving the structural stability of the slabs under fire conditions.

In 2005, the European Commission for Standardization (CEN), published design rules for composite steel-concrete structures under fire conditions, EN 1994-1-2 [8]. This standard determines that if a composite slab with profiled steel deck, with or without additional reinforcement, is properly designed according to EN 1994-1-1 [9], the fire resistance (R) is at least 30 min. In addition, it also states that the integrity criterion (E) is always fulfilled for composite slabs with steel deck. Regarding the insulation criterion (I), the Annex D presents a simplified calculation method, which depends on the geometry of the steel deck, the thickness of concrete above the steel deck and the view factor of the upper flange.

In 2011, Guo and Bailey [10] executed an experimental investigation with the aim of providing more insight on the behaviour of composite slabs during heating and cooling phases of fire. Nine equal specimens were tested: two of them at room temperature and the others at three different fire scenarios, which were controlled by burners and fans within the furnace. The specimens were loaded with representative values found in practice in order to investigate the structural behaviour. The results showed that the maximum temperature and both heating and cooling rates strongly affected the behaviour of the slabs. For all the tests, the maximum temperatures on the unexposed surface and on the mesh were both higher during the cooling stages, due to the thermal inertial effect, which highlighted that insulation failure is likely to occur not only during heating but also during cooling phase.

In 2018, an investigation about the fire behaviour of composite slabs under standard fire conditions was carried out by Piloto et al. [11]. The key objective of this study was to develop two-dimensional numerical models using the software MATLAB and ANSYS in order to evaluate the fire resistance of different slab configurations according to the insulation criterion (I). Several numerical simulations were performed with the aim of analysing the effect of both concrete and steel deck thicknesses on the temperature development on the unexposed side. Two experimental fire tests were conducted on unloaded specimens. On the whole, the fire resistance (I) obtained from the numerical models was considerably smaller than those measured in the experimental tests. A comparison between the numerical results and the simplified calculation method of Eurocode 4 evidenced that the current design rules are unsafe, that is, the European standard overestimated the fire resistance in comparison to the numerical simulations made with perfect contact and underestimates the fire resistance with respect to the experimental test. According to the numerical results, a new and better approach considering a quadratic dependence between the fire resistance and the effective thickness was proposed.

In 2019, Jiang et al. [2], from the National Institute of Standards and Technology (NIST), conducted a numerical investigation around different parameters that may influence the fire resistance of composite slabs with respect to the thermal insulation criterion (I). An improved algebraic expression for the calculation of the fire resistance that explicitly accounts for moisture content of concrete was proposed. The formulation is applicable to an extended range of geometries in comparison to the limitations of the calculation method presented in the current version of Eurocode 4. A set of 54 composite slabs was selected for the numerical analysis, using an accurate finite element approach. It was concluded that the concrete thickness and the moisture content were the parameters that most influenced the fire resistance. The proposed expression for fire resistance was validated against additional analyses and experimental data, resulting in maximum deviations of 15 and 18 min, respectively.

The scope of this investigation concerns numerical simulations using the standard fire curve ISO 834 [1] in order to evaluate the fire resistance from the thermal insulation standpoint. Three-dimensional thermal models were implemented using ANSYS and MATLAB PDE toolbox.

During fire exposure, the steel deck heats up rapidly, expands and may separate from the concrete topping. Previous studies mention the separation between the steel deck and concrete during fire exposure, which increases the thermal resistance in this interface. In order to simulate the debonding effects, an alternative thermal model is presented, including an air gap with constant thickness between the steel deck and concrete topping.

With the aim of validating the approach, the results of the numerical simulations are compared with experimental results published by Lim and Wade [7], Piloto et al. [11], Abdel-Halim, Hakmi, O'Leary [6], and Hamerlinck [4]. In addition, a comparison between the fire resistance obtained numerically, experimentally and analytically (using the Eurocode 4 calculation method [8]) is presented.

This paper is divided into 7 sections. In Sect. 1, an introduction to the research theme and a summary of relevant investigations in the field of study are given. Section 2 presents the definition of the fire resistance criteria. Section 3 deals with the simplified calculation method of Eurocode 4. In Sect. 4, a succinct description of the experimental setup of the four different fire tests is given. Section 5 describes the numerical thermal model and presents the comparison of the results. Section 6 presents a parametric study and the proposed new equation for fire resistance (I). Finally, the conclusions and general observations about the results are given in Sect. 7.

2 Fire Resistance Criteria

Structural elements need to meet fire-safety requirements according to building codes and standards. For composite slabs, the requirements are normally specified by fire ratings of 30, 60, 90 min or more. The fire rating of this type of building elements is usually made using standard fire tests [12, 13] and should consider the criteria of Insulation (I), Integrity (E) and Load Bearing (R). Usually, experimental tests are expensive and time-consuming. As an alternative solution, the fire resistance can be determined by means of numerical simulations and simple calculation methods. The fire resistance of composite slabs is defined with respect to a standard fire exposure from below. In this study, the fire resistance is exclusively investigated with respect to the thermal insulation criterion (I).

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

The integrity criterion (E) is the capacity to withstand fire in one side and resist penetration of hot gases and flames. The assessment should 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. For composite slabs cast in situ, the integrity criterion is normally fulfilled provided that the joints are adequately sealed.

The load bearing resistance for flexural loaded elements (R) is the ability to support the loading during the test without collapsing. The assessment shall be made on the basis of limiting vertical displacement D (D = $L^2/400d$ [mm]), or limiting the rate of vertical displacement (dD/dt = $L^2/9000d$ [mm/min]), being L the clear span of the testing specimen in millimetres and d the distance from the extreme fibre of the cold design compression zone to the extreme fibre of the cold design tensile zone of the structural section, in millimetres.

3 Simplified Calculation Method of Eurocode 4

The Annex D of EN 1994-1-2 [8] presents a simplified calculation method for the prediction of the fire resistance of unprotected composite slabs subjected to the standard fire curve ISO 834 from below. The analytical expressions given in the current version of this standard are based on the study conducted by Both [5] in 1998. During the last years, no revisions were made to this method [2], and there are no proposals for changes in the design formulae for the next version of the EN 1994-1-2. The fire resistance (t_i) with respect to thermal insulation criterion should be determined according to Eq. 1.

$$t_i = a_0 + a_1 \cdot h_1 + a_2 \cdot \phi_{upper} + a_3 \cdot \frac{A}{L_r} + a_4 \cdot \frac{1}{l_3} + a_5 \cdot \frac{A}{L_r} \cdot \frac{1}{l_3} \quad (1)$$

The rib geometry factor of the slab (A/L_r) shall be calculated according to Eq. 2.

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

The fire resistance depends on the geometric parameters of the slab (l_1, l_2, l_3, h_1 and h_2), and also on partial factors (a_i). Table 1 presents the factors for composite slabs with normal weight concrete (NWC).

Table 1. Coefficients for determination of the fire resistance for composite slabs with NWC (adapted from EN 1994-1-2 [8]).

a_0 (min)	a_1 (min/mm)	a_2 (min)	a_3 (min/mm)	a_4 (mm min)	a_5 (min)
−28.8	1.55	−12.6	0.33	−735.0	48.0

The EN 1994-1-2 states that the effective thickness of a composite slab h_{eff} (mm) should be calculated according to Eq. 3a, 3b.

$$h_{eff} = h_1 + 0.5 \cdot h_2 \cdot \left(\frac{l_1 + l_2}{l_1 + l_3}\right) \quad \text{for } h_2/h_1 \leq 1.5, \text{and } h_1 > 40\,\text{mm} \tag{3a}$$

$$h_{eff} = h_1 \cdot \left[1 + 0.75 \cdot \left(\frac{l_1 + l_2}{l_1 + l_3}\right)\right] \quad \text{for } h_2/h_1 > 1.5, \text{and } h_1 > 40\,\text{mm} \tag{3b}$$

The geometric parameters of the slab h_1, h_2, l_1, l_2 and l_3 are illustrated in Figs. 2, 3, 4 and 5. The effective thickness may be adopted as h_1 if $l_3 > 2\ l_1$.

4 Experimental Fire Tests

Four different composite slabs with trapezoidal profile have been selected to perform the numerical validation. These slabs correspond to experimentally tested slabs: slab 1 was tested by Lim and Wade [7] (test number 4), slab 2 was tested by Piloto et al. [11] (test number 1), slab 3 was tested by Abdel-Halim, Hakmi and O'Leary [6] (test number 2), and slab 4 was tested by Hamerlinck [4] (test number 2). The slabs were exposed to the ISO 834 standard fire from below in controlled furnaces. The profiles of slabs 1, 2, 3 and 4 are shown, respectively, in Figs. 2, 3, 4 and 5.

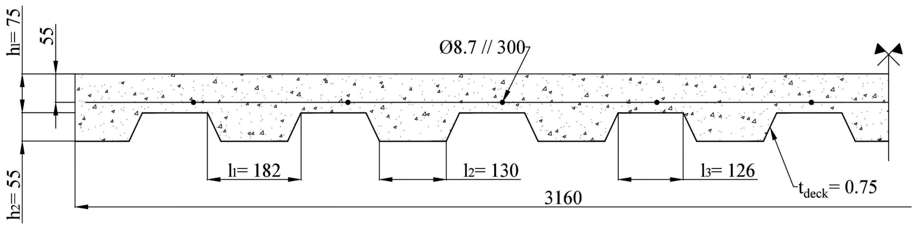


Fig. 2. Profile of slab 1: dimensions in millimetres (Lim and Wade [7]).

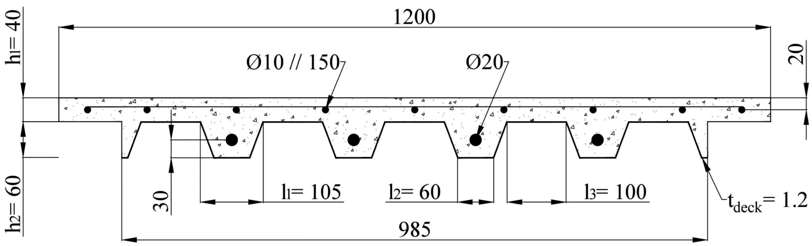


Fig. 3. Profile of slab 2: dimensions in millimetres (Piloto et al. [11]).

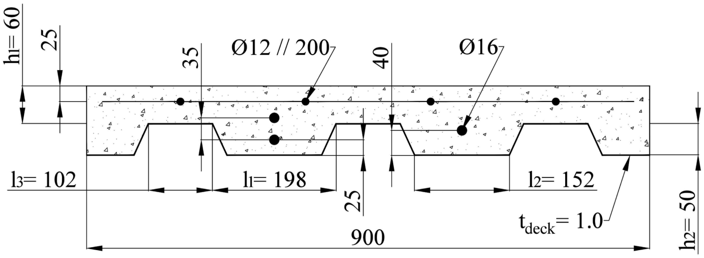


Fig. 4. Profile of slab 3: dimensions in millimetres (Abdel-Halim, Hakmi and O'Leary [6]).

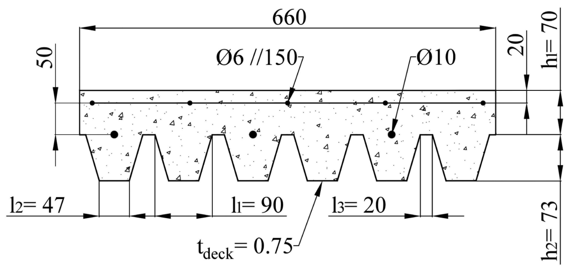


Fig. 5. Profile of slab 4: dimensions in millimetres (Hamerlinck [4]).

For slab 1 (clear span of 3160 mm wide by 4160 mm long), normal weight concrete with siliceous aggregates was used and the moisture content amounted to 5.6% by weight. The initial bulk temperature was of 13 °C. For slab 2 (clear span of 985 mm wide by 916.8 mm long), normal weight concrete was used and the moisture content was approximately 3.0% by weight. The initial bulk temperature amounted to 20 °C. For slab 3 (clear span of 900 mm wide by 1200 mm long), normal weight concrete was used and prior the test, the specimen was conditioned with the aim of reducing the moisture to air dry condition. The initial bulk temperature was of 20 °C. For slab 4 (clear span of 660 mm wide by 3200 mm long), normal weight concrete was used and the moisture content amounted to 3.5% by weight. The initial bulk temperature amounted to 20 °C. For all the slabs, debonding of the steel deck from the concrete topping was observed during the tests.

5 Numerical Modelling

In the following section, the methodology used to model and numerically determine the thermal effects of standard fire exposure on composite slabs is outlined. Thereby, a brief description of the finite elements, thermal properties of materials, boundary conditions and convergence criterion are presented. Finally, a comparison between the numerical, experimental and analytical results is presented.

5.1 Thermal Model

The composite slab is meshed to solve a nonlinear transient thermal analysis, using 3-D models from ANSYS and MATLAB. The finite element method (FEM) requires the solution of Eq. 4 in the domain and the definition of the boundary conditions in Eq. 5 on the exposed and unexposed side of the slab.

$$\nabla\left(\lambda_{(T)} \cdot \nabla T\right) = \rho_{(T)} \cdot Cp_{(T)} \cdot \partial T/\partial t \tag{4}$$

$$\lambda_{(T)} \cdot \nabla T \cdot \vec{n} = \alpha_c \cdot \left(T_g - T\right) + \phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot \left(T_g^4 - T^4\right) \tag{5}$$

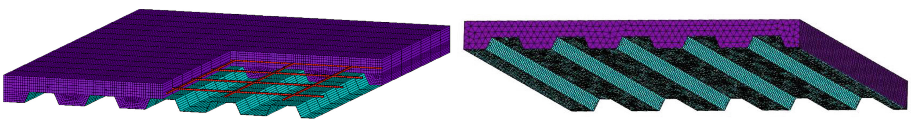
In the equations above: T represents the temperature of each material; $\rho_{(T)}$ is the specific mass; $Cp_{(T)}$ is the specific heat; $\lambda_{(T)}$ is the thermal conductivity; α_c is the convection coefficient. T_g represents the gas temperature of the fire compartment, using the standard fire ISO 834 applied on the bottom part of the slab; ϕ is the view factor; ε_m is the emissivity of each material; ε_f represents the emissivity of the fire and σ represents the Stefan-Boltzmann constant.

The view factor (ϕ) quantifies the geometric relation between the surface emitting radiation and the surface receiving radiation. The view factor of the lower flange of composite slabs (ϕ_{low}) is given as 1. Owing to the obstruction to direct exposure caused by the ribs of the steel deck, the view factors of the web (ϕ_{web}) and upper flange (ϕ_{upper}) are smaller than one. These view factors can be calculated as function of the geometric parameters of the slab, as follows.

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

$$\phi_{web} = \frac{\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2} + (l_3 + l_1 - l_2) - \sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2}}{2\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}} \tag{7}$$

The finite element method is applied to solve numerically the heat transfer equation using the software ANSYS and MATLAB. For slab 1, the respective 3-D meshes developed in ANSYS and MATLAB are presented in Fig. 6.

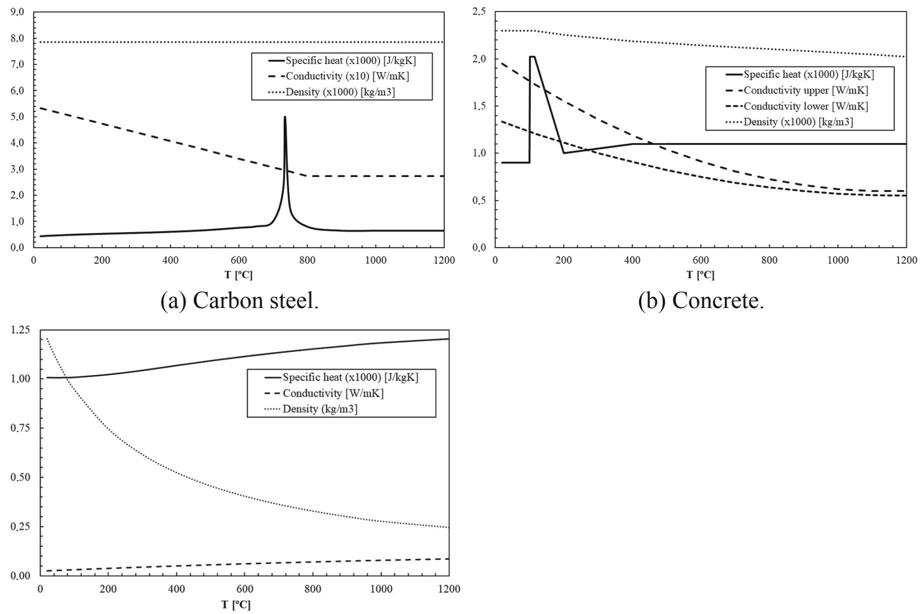


(a) ANSYS. (b) MATLAB.

Fig. 6. Finite element mesh (slab 1).

A 3-D model of the slab is generated, which is composed by subdomains that correspond to the different materials: the concrete topping, steel deck, rebars and steel mesh in ANSYS; and concrete topping and steel deck in MATLAB. A parametric study performed by the authors evidenced that the steel components within the concrete topping do not affect the fire resistance with respect to the thermal insulation criterion. Therefore, by means of simplification, these components are not included in the MATLAB numerical model. An alternative thermal model is created, using an air gap with constant thickness (1 mm for slab 1, 3 mm for slab 2, 2 mm for slab 3, and 1 mm for slab 4), included between the steel deck and the concrete topping in order to simulate the debonding effects. The thicknesses of the air layer used in the air gap model for the four slabs were determined from a parametric analysis, selecting the values that best fit with the experimental data for each slab. Through the air gap, only heat flow by conduction is considered, due to the very small thickness of this layer.

The thermal properties of the materials are temperature dependent and vary according to the standards used for composite slabs [8], steel structures [14] and concrete structures [15]. The thermal properties of steel, concrete and air are presented in Fig. 7. Presently, there is no standard which specifies the thermal properties of air. However, computer programs and experimental tests provide reliable data for numerical analyses. This work considers the thermal properties of air at 1 atm pressure [16]. Regarding the conductivity of concrete, the upper limit was selected for the numerical simulations. The specific heat of concrete presents a peak value related to 3% of moisture content of concrete weight. The extrapolation method was used to update higher moisture contents.



(a) Carbon steel.

(b) Concrete.

(c) Air.

Fig. 7. Thermal material properties.

In ANSYS, three different finite elements are used: SHELL131, SOLID70 and LINK33. The SHELL131 element has four nodes with up to 32 degrees of freedom (temperature) per node, depending on the number of layers (one layer). This element presents linear interpolation functions in the plane of the element, using full Gauss integration method (2×2) and linear interpolation functions through the layer thickness (three Gauss points). The shell element is used to model the steel deck of the composite slab. The bottom temperature of shell element nodes is assumed to be equal to the temperature of solid element nodes, when both nodes are coincident. The SOLID70 element presents eight nodes with a single degree of freedom (temperature) at each node. Linear interpolation functions are used for this element and the full Gauss integration method is also applied ($2 \times 2 \times 2$). This finite element is used to model the concrete topping and, in the alternative model, the air gap volume. The LINK33 element has two nodes with a single degree of freedom (temperature) per node. This uniaxial element presents linear interpolation functions and exact integration. The LINK33 element is used to model the anti-crack mesh and the rebars.

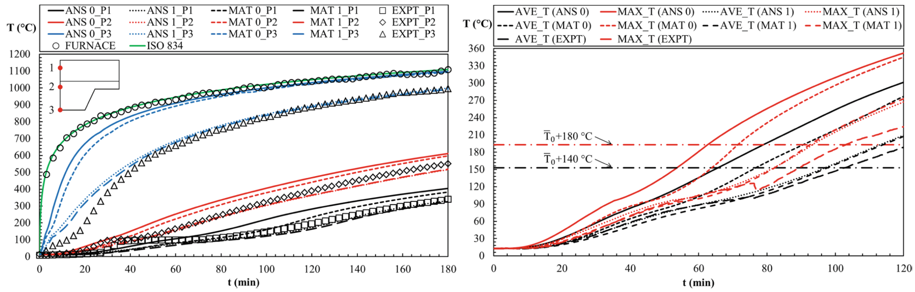
In MATLAB, the geometry is meshed in the Partial Differential Equation Toolbox (PDE) with only linear tetrahedral (solid) elements. The toolbox does not support meshes with elements of different types. This element has four nodes (one node at each corner) and a single degree of freedom (temperature) at each node. Linear interpolation functions are used for this element.

According to the measured initial average temperatures, see Sect. 4, all the nodes are set with an initial condition for temperature of 13 °C on slab 1, and with 20 °C on slabs 2, 3 and 4. The exposed side is submitted to a heat flux by convection and radiation, see Eq. 5, using different values for view factors and a bulk temperature following the standard fire. This boundary surface of the steel deck is subjected to standard fire conditions using a convection coefficient of 25 W/m^2K and an emissivity of fire equal to 1. The unexposed side is subjected to a convective heat flux (including the radiation heat flux), using a constant bulk temperature of 13 °C for slab 1 and 20 °C for slabs 2, 3 and 4. A convective coefficient of 9 W/m^2K is applied on this boundary surface of the composite slab in order to include the radiation effect [17].

With respect to the convergence criterion, the heat flow criterion is applied in ANSYS, using a tolerance value of 0.001 and a minimum reference value of 10^{-6}. In MATLAB, a value of 10^{-2} is set to the absolute tolerance and 10^{-1} to the relative tolerance, using a maximum number of Gauss-Newton iterations of 15.

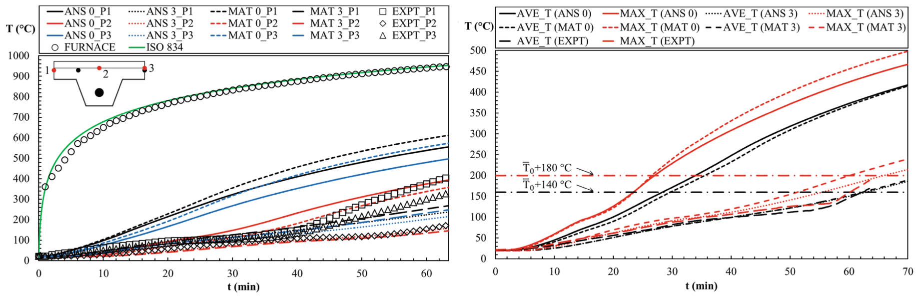
5.2 Results

Figures 8, 9, 10 and 11 present the temperature development (numerical and experimental) at different selected points, as well as the average and maximum temperatures on the unexposed surface for each slab. The curves “ANS x_Py” and “MAT x_Py” refer to the results from ANSYS and MATLAB, respectively; where x is the thickness of the air gap and y is the number of the point. The curves “AVE_T” and “MAX_T” refer to the average and maximum temperature, respectively, on the unexposed surface of the slab. “EXPT” represents the experimental results.



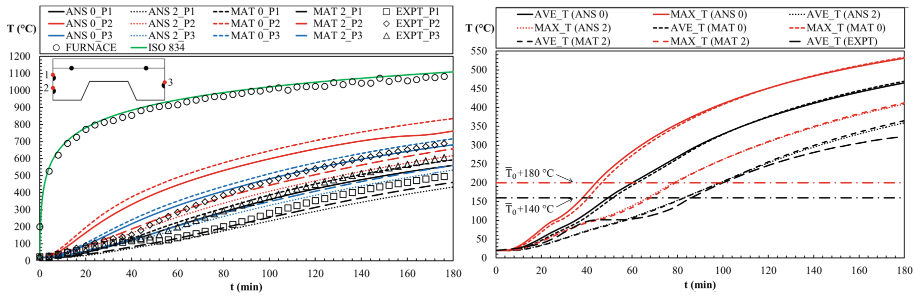
(a) Selected points. (b) Unexposed side.

Fig. 8. Numerical and experimental results for slab 1 - Points 1, 2 and 3 at distance 20, 70 and 130 mm from the top.



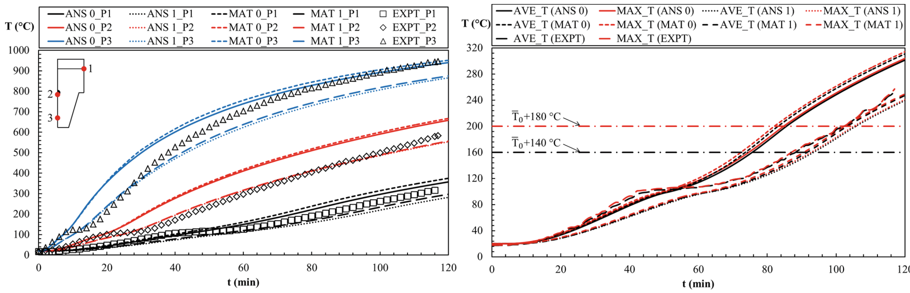
(a)Selected points. (b) Unexposed side.

Fig. 9. Numerical and experimental results for slab 2 - Points 1, 2 and 3 at distance 20, 15 and 15 mm from the top.



(a) Selected points. (b) Unexposed side.

Fig. 10. Numerical and experimental results for slab 3 - Points 1, 2 and 3 at distance 50, 85 and 70 mm from the top.



(a) Selected points. (b) Unexposed side.

Fig. 11. Numerical and experimental results for slab 4 - Points 1, 2 and 3 at distance 20, 74 and 123 mm from the top.

From the results of slab 1, a reasonable agreement is observed between the furnace temperature and the standard fire curve ISO 834. For both perfect contact models ANS 0 and MAT 0, a considerable difference to experimental results (EXPT) can be observed in the first stages of heating. The numerical results from MATLAB are slightly closer to experimental results than the results from ANSYS. The air gap models ANS 1 and MAT 1 (air gap thickness of 1 mm) provide a good agreement to measured temperatures for all selected points. With respect to the unexposed surface, a big difference between the results of the perfect contact models and the air gap models is verified. For the models ANS 1 and MAT 1, the agreement between the computed and measured temperatures is very good for both average and maximum temperatures until 76 min. After that, some differences are noticed, probably due to experimental deviations such as the furnace temperature, for example. In general, the results of the air gap models ANS 1 and MAT 1 are closer to each other in comparison to the perfect contact models ANS 0 and MAT 0. Small differences between the results of ANSYS and MATLAB models are observed, with exception of the average and maximum temperatures on the unexposed surface for the perfect contact models ANS 0 and MAT 0.

Regarding the slab 2, the furnace temperature is very close to the standard fire curve ISO 834, although presenting a small deviation in the first minutes of fire exposure. For the perfect contact models ANS 0 and MAT 0, the temperatures are higher than the experimental results (EXPT) throughout the entire duration of the test. The results of the air gap models ANS 3 and MAT 3 (air gap thickness of 3 mm) are considerably smaller than the perfect contact models and present satisfactory agreement with measured temperatures, principally for point 2 and average temperature on the unexposed side. For points 1 and 3, the results of the air gap models present good agreement with measured temperatures until the first 42 min of fire. Some differences are observed between the results of ANSYS and MATLAB models, being greater for the perfect contact models (ANS 0 and MAT 0).

For slab 3, it is noteworthy that the furnace temperature is under the standard fire curve ISO 834, which was used for the numerical simulations. Consequently, the numerical results should be higher than experimental results. For the perfect contact models ANS 0 and MAT 0, a good agreement with experimental results (EXPT) is observed for point 1 until the first 44 min of fire. After that, better results are obtained using the air gap models ANS 2 and MAT 2 (air gap thickness of 2 mm). This is because during a fire, the debonding of the steel deck from concrete occurs after a period of time. A delay in the rate of temperature increase is observed in the last minutes of fire on curve ANS 0_P2. It can be justified by the coincidence of two different materials (steel and concrete) on the same node and the abrupt change in the specific heat of steel for temperatures between 700 °C and 800 °C, see Fig. 7(a). In general, the results of the air gap models present a better agreement with measured temperatures in comparison to the results of the perfect contact models. For the selected points, models ANS 0 and MAT 2 present better agreement with experimental results when compared to models MAT 0 and ANS 2, respectively. Considerable differences between ANSYS and MATLAB models are evident, mainly for curves ANS 0_P2 and MAT 0_P2. On the other hand, the results of these models are very close to each other on the unexposed surface.

For slab 4, it can be observed that the temperature development on the selected points is quite similar between the experimental results EXPT and the perfect contact models ANS 0 and MAT 0 at the first minutes of heating. After that, better results are obtained using the air gap models ANS 1 and MAT 1 (air gap thickness of 1 mm), with exception to point 3. Regarding the temperature development on point 2, the air gap models present good agreement with experimental results for temperatures over 100 °C. For point 3, at the last minutes of heating, the perfect contact model presents better agreement with measured temperatures in comparison to the air gap model. Concerning the temperature development on the unexposed surface, the maximum and average temperature curves are very close to each other for all the models. In this case, better agreement with the experimental results is observed using the air gap models.

Tables 2, 3, 4 and 5 present the results obtained for the fire resistance according to the insulation criterion with respect to the average temperature rise (t_{fi} Ave) or the maximum temperature rise (t_{fi} Max) on the unexposed surface for each slab.

Table 2. Fire resistance of slab 1 (criterion I): experimental, numerical and analytical results.

	Model ANS 0	Model MAT 0	Model ANS 1	Model MAT 1	EXPT result	EN 1994-1-2
t_{fi} Ave (min)	65.6	76.7	97.0	97.7	*102.7*	*95.8*
t_{fi} Max (min)	*62.6*	*71.4*	*93.3*	*92.5*	103.0	

Table 3. Fire resistance of slab 2 (criterion I): experimental, numerical and analytical results.

	Model ANS 0	Model MAT 0	Model ANS 3	Model MAT 3	EXPT result	EN 1994-1-2
t_{fi} Ave (min)	28.3	29.7	*62.8*	62.3	*62.2*	*38.0*
t_{fi} Max (min)	*27.0*	*26.5*	65.9	*60.1*	–	

Table 4. Fire resistance of slab 3 (criterion I): experimental, numerical and analytical results.

	Model ANS 0	Model MAT 0	Model ANS 2	Model MAT 2	EXPT result	EN 1994-1-2
t_{fi} Ave (min)	49.4	51.4	82.6	82.9	*80.0*	*73.9*
t_{fi} Max (min)	*44.1*	*46.5*	*78.3*	*79.1*	–	

Table 5. Fire resistance of slab 4 (criterion I): experimental, numerical and analytical results.

	Model ANS 0	Model MAT 0	Model ANS 2	Model MAT 2	EXPT result	EN 1994-1-2
t_{fi} Ave (min)	*75.6*	*73.6*	*93.5*	*91.6*	*88.2*	*106.5*
t_{fi} Max (min)	84.8	82.0	105.1	102.5	102.1	

The results obtained with the air gap models underestimate the fire resistance for slab 1, with a relative error of 9.2% for ANSYS and 9.9% for MATLAB. Better approximation to experimental results is observed for the EN 1994-1-2 provisions, with a relative error of 6.7%.

With respect to the slab 2, a good agreement between the fire resistance obtained with the air gap models and experimental results is achieved, resulting in a relative error of 1.0% for ANSYS and 3.4% for MATLAB. An underestimated value is obtained using the EN 1994-1-2 provisions, with a relative error of 38.9%.

Regarding the slab 3, the results evidence that the fire resistance obtained using the air gap models is slightly underestimated, with a relative error of 2.1% for ANSYS and 1.1% for MATLAB. In addition, a good agreement between EN 1994-1-2 calculations and experimental data is also observed, resulting in a relative error of 7.6%.

According to the results for slab 4, it can be concluded that the air gap models slightly overestimated the fire resistance, with a relative error of 6.0% for ANSYS and 3.9% for MATLAB. A bigger discrepancy is obtained using the perfect contact models, with a relative error of 14.3% for ANSYS and 16.6% for MATLAB. The EN 1994-1-2 provisions overestimated the fire resistance, providing an unsafe result with a relative error of 20.7%.

In all experimental fire tests, the air layer which appears due to debonding of the steel deck from concrete does not have constant thickness. This means that the air gap is 0 mm thick at the beginning of the test (perfect contact) and as the specimen is heated, the steel deck separates slowly from the concrete, hence increasing the air gap thickness. By means of simplification, this work assumes that the air gap has constant thickness throughout the whole duration of the simulations.

6 Parametric Study

A parametric study has been conducted in order to evaluate the influence of the thickness of the concrete topping (h_1) and the air gap (t_a) on the fire resistance (I) of composite slabs. A total of 40 numerical simulations have been carried out, of which 32 performed in ANSYS, using the perfect contact model and the air gap model; and 8 performed in MATLAB, using the air gap model. In ANSYS, the air layer is divided into elements with 0.5 mm through the thickness.

The "O Feliz H60" trapezoidal steel deck profile (slab 2) has been selected to perform the numerical analyses. A representative portion of 1 m by 1 m of each slab has been considered to perform the thermal analyses. Table 6 presents the ranges of investigated parameters for the numerical simulations performed in ANSYS and MATLAB.

Table 6. Investigated parameters of the parametric study.

	h_1 (mm)	t_a (mm)
ANSYS	50, 60, 70, 80, 90, 100, 110, 120	0 (perfect thermal contact), 1, 2, 3
MATLAB	50, 60, 70, 80, 90, 100, 110, 120	3

Figure 12 presents the results for the fire resistance (I) obtained through the thermal models (ANSYS and MATLAB); experimental fire tests (EXPT); and simplified calculation method presented in Sect. 3. The experimental results were published in 1983 by the ECCS [3].

A model with quadratic dependence between the fire resistance t_i and the effective thickness h_{eff} is chosen to fit the results of the numerical simulations. A linear relationship between the effective thickness and the thickness of the air gap t_a is considered in order to consider the increase in fire resistance. The proposed new equation for the fire resistance of composite slabs is given in Eq. 8.

$$t_i = 0.0059 \cdot h_{eff}^2 + 0.1127 \cdot h_{eff} - 5.8065 + \left(0.1424 \cdot h_{eff} + 2.4672\right) \cdot t_a \qquad (8)$$

Where t_i is given in minutes, and h_{eff} and t_a are given in millimetres; with the following limits: $70 \leq h_{eff} \leq 150$ mm and $0 \leq t_a \leq 3$ mm.

Figure 12 illustrates the results obtained with the application of Eq. 8 (New Eq) for different air gap thicknesses.

Analysing the Fig. 12, a good agreement is observed between the results of the proposed new equation and the numerical results. A satisfactory agreement between the results of the EN 1994-1-2 and the numerical simulations is obtained using an air gap thickness of 2 mm. Good agreement between experimental and numerical results is observed considering an air gap thickness of 3 mm.

The thickness of the air gap t_a depends on the geometry of the profiled steel deck among other parameters. Further numerical analyses should be performed considering different geometries to define an optimal air gap thickness for composite slabs with several steel deck profiles.

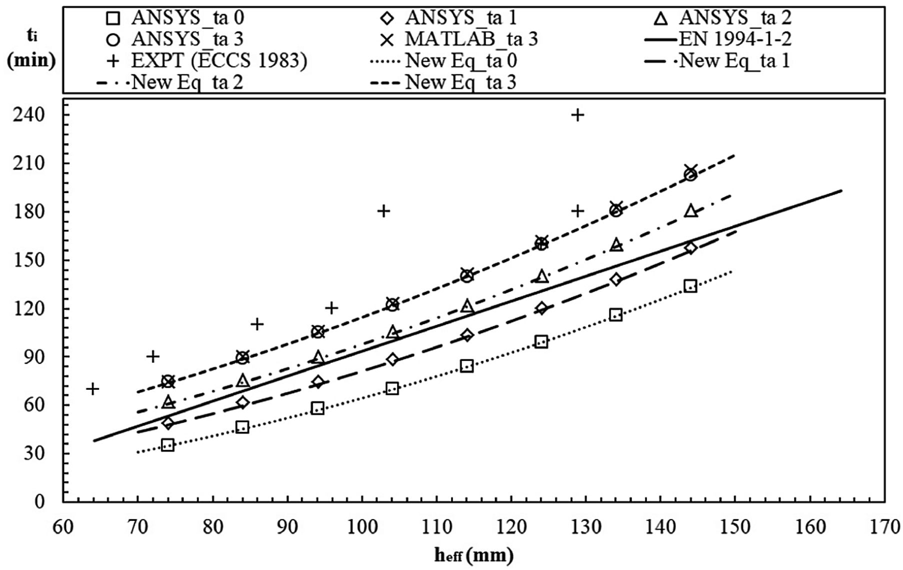


Fig. 12. Results of the proposed new equation for the fire resistance (I) of composite slabs.

7 Conclusions

This study presented a discussion around the results of three-dimensional thermal analyses performed in ANSYS and MATLAB for different composite slabs. The fire resistance according to thermal insulation criterion (I) was evaluated and compared to experimental results and simple calculation method of Eurocode 4 as well. With the aim of simulating the effects of debonding of the steel deck from concrete, an alternative thermal model was used, in which an insulating layer (air gap) with constant thickness was introduced between the concrete topping and steel deck.

For the experimental results of the four slabs, a plateau at about 100 °C (due to moisture evaporation) should be highlighted, consisting of a decrease in the rate of temperature increase. The results of the numerical simulations do not present this pronounced plateau, probably because localized moisture concentrations in the tests were higher than the uniform moisture content introduced in the thermal models for each slab.

The maximum temperature rise criterion was decisive to determine the fire resistance according to thermal insulation criterion for most of the simulations. With respect to the experimental results, the average temperature rise criterion governed the fire resistance. The Eurocode 4 provisions underestimated the fire resistance for all the slabs, and for slab 2 in particular, a considerable difference was observed. The perfect contact models underestimate the fire resistance. Therefore, it is evident that the air gap models provide much better results for fire resistance from the thermal insulation standpoint when compared to the perfect contact models, reducing the temperature rise on the selected points and unexposed surface as well. However, in order to determine the thickness of the air gap t_a, it is necessary to resort to experimental data. In this regard, further thermal analyses should be conducted to better understand the effect of the air gap on different slab profiles.

In some cases, the results of ANSYS and MATLAB models presented noticeable differences for the same situation, that is, for a same point and type of model (perfect contact or air gap model). These differences can be justified by the presence of the steel components within the concrete layer (rebar and mesh) in the ANSYS model which are not included in the MATLAB model. Although not significantly affecting the fire resistance (I), these components can affect the temperature development on particular points.

Based on the numerical results, a new formula has been proposed for the calculation of the fire resistance (I), depending on the effective thickness of the composite slab and the air gap thickness. This proposed model presents good agreement with numerical results and considers parameters which are not included in the current calculation rules of standards.

References

1. International Standard ISO 834: Fire-resistance tests - Elements of building construction (1999)
2. Jiang, J., Pintar, A., Weigand, J.M., Main, J.A., Sadek, F.: Improved calculation method for insulation-based fire resistance of composite slabs. Fire Saf. J. **105**, 144–153 (2019)
3. European Convention for Constructional Steelwork - 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, Brussels (1983)
4. Hamerlinck, R.: The behaviour of fire-exposed composite steel/concrete slabs. Eindhoven University of Technology (1991)
5. Both, C.: The fire resistance of composite steel-concrete slabs. Delft University of Technology (1998)
6. Abdel-Halim, M.A.H., Hakmi, M.R., O'Leary, D.C.: Fire resistance of composite floor slabs using a model fire test facility. Eng. Struct. **21**(2), 176–182 (1999)
7. Lim, L., Wade, C.: Experimental fire tests of two-way concrete slabs. Christchurch (2002)
8. 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 (2005)
9. CEN- European Committee for Standardization, EN 1994-1-1: Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings. CEN - European Committee for Standardization, Brussels (2004)
10. Guo, S., Bailey, C.G.: Experimental behaviour of composite slabs during the heating and cooling fire stages. Eng. Struct. **33**, 563–571 (2011)
11. Piloto, P.A.G., Prates, L.M.S., Balsa, C., Rigobello, R.: Numerical simulation of the fire resistance of composite slabs with steel deck. Int. J. Eng. Technol. (UAE) **7**(2.23), 83–86 (2018). (2018/04/206), ISSN 2227-524X. https://doi.org/10.14419/ijet.v7i2.23.11889
12. CEN - European Committee for Standardization, EN 1363-1: Fire resistance tests - Part 1: General Requirements. Brussels (2012)
13. CEN - European Committee for Standardization, EN 1365-2: Fire resistance tests for load bearing elements - Part 2: Floors and roofs (Withdrawal). Brussels (2014)

14. CEN - European Committee for Standardization, EN 1993-1-2: Design of steel structures - Part 1-2: General rules - Structural fire design. Brussels (2005)
15. CEN - European Committee for Standardization, EN 1992-1-2: Design of concrete structures - Part 1-2: General rules - Structural fire design. Brussels (2004)
16. Çengel, Y.A., Ghajar, A.J.: Heat and Mass Transfer: Fundamentals & Applications, 5th edn. McGraw-Hill Education, New York (2015)
17. CEN - European Committee for Standardization, EN 1991-1-2: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire. Brussels (2002)