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**CONGRESSO DE  
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**TEMAS ESPECIAIS  
INTELIGÊNCIA ARTIFICIAL  
ENERGIA**

Editores  
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Paulo Vila Real  
Filip Ljubinković  
Jorge Conde  
Rohola Rahnavard  
Luís Figueiredo Silva



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## Atas do XV Congresso de Construção Metálica e Mista e I Congresso de Engenharia de Fachadas

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## **XV Congresso de Construção Metálica e Mista e I Congresso de Engenharia de Fachadas**

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## Prefácio

O XV Congresso de Construção Metálica e Mista e I Congresso de Engenharia de Fachadas representam um momento de grande relevância para o setor em Portugal, reunindo especialistas, investigadores e empresas num espaço comum de partilha de conhecimento. Nesta décima quinta edição, o Congresso de Construção Metálica e Mista reafirma a maturidade e solidez de um percurso iniciado há mais de duas décadas, consolidando-se como o principal evento técnico-científico nacional dedicado à construção metálica e mista. O crescimento contínuo do número de participantes, comunicações e empresas envolvidas testemunha o reconhecimento da sua importância e o papel que tem desempenhado na promoção da inovação, na disseminação prática do conhecimento e na aproximação entre a academia e a indústria.

Regista-se com satisfação o envolvimento excecional do setor empresarial. O Congresso conta com 80 patrocinadores e uma exposição técnica com 77 stands, números que revelam a confiança e o entusiasmo das empresas na valorização da construção metálica e mista e das fachadas, bem como no papel agregador que este evento desempenha no panorama nacional. No plano técnico-científico, foram submetidos 99 artigos e proferidas 28 palestras, refletindo a intensidade e qualidade da participação da comunidade académica e profissional. A todos expressamos o nosso reconhecimento.

É neste cenário de continuidade, progresso e consolidação que se integra, com especial significado, o I Congresso de Engenharia de Fachadas, que surge como resposta natural à evolução tecnológica do setor e à necessidade de um espaço próprio para discutir temas específicos associados à envolvente dos edifícios. Este novo congresso afirma definitivamente a Engenharia de Fachadas no panorama nacional, como área multidisciplinar, inovadora e essencial para a construção sustentável do futuro, refletindo o avanço das soluções construtivas, a crescente complexidade dos sistemas de fachada e o reconhecimento de que o desempenho do edifício depende, cada vez mais, da qualidade e integração destes elementos.

Num contexto em que a construção enfrenta novos desafios – desde a descarbonização e economia circular, até à necessidade de sistemas construtivos mais eficientes, industrializados e tecnologicamente avançados – este encontro conjunto mostra a capacidade do tecido técnico e industrial português para responder com soluções maduras, competitivas e orientadas para o futuro. A diversidade de comunicações recebidas e a forte participação académica e empresarial atestam o dinamismo do setor e reforçam a importância do diálogo contínuo entre investigação, projeto e indústria.

A fundação em 2025 da EdF – Associação Portuguesa de Engenharia de Fachadas, concretiza uma ambição longamente amadurecida por diversos profissionais e instituições. A EdF nasce para promover o conhecimento técnico, contribuir para a evolução normativa e potenciar a qualidade e visibilidade do trabalho português, dentro e fora do país. Este passo representa não apenas a criação de uma nova entidade, mas a consolidação de uma comunidade empenhada em reforçar competências e abrir novos horizontes à tecnologia de fachadas.

Por fim, a publicação de livro de atas testemunha a vitalidade técnica e científica do Congresso. Reúne trabalhos que refletem o que de mais recente se investiga e pratica, oferecendo um registo permanente do conhecimento aqui partilhado e convidando à reflexão sobre os caminhos que ainda temos por trilhar. Que estas páginas sirvam de referência, inspiração e instrumento de progresso para engenheiros, arquitetos, investigadores, estudantes e todos quantos contribuem para a evolução do setor.

Luís Simões da Silva

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XV Congresso de Construção Metálica e Mista e I Congresso de Engenharia de Fachadas

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## FIRE RESISTANCE OF PROTECTED COMPOSITE SLAB WITH A STIFFENED LOWER FLANGE STEEL DECK

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**Abstract.** This study developed a simplified method to evaluate the fire resistance of composite slabs with steel decking protected by a novel steel shield. A numerically validated model, incorporating experimental data, demonstrated that the steel shield increases insulation failure time by approximately 25% (criterion I) and significantly reduces temperatures in critical zones. New empirical coefficients ( $b_i$ ,  $c_i$ ) were calibrated for use with the EN 1994-1-2 simplified method, enabling accurate prediction of the thermal and structural behaviour of this system. Mineral wool insulation provided even superior performance. The research offers a practical design tool for engineering more efficient and fire-safe composite slabs.

### 1. Introduction

Composite slabs with steel decking represent a highly efficient and lightweight structural system, widely adopted in modern steel-framed and high-rise buildings [1]. These slabs comprise a cold-rolled steel deck profile, acting as permanent formwork and tensile reinforcement, upon which concrete is cast, often with additional anti-crack mesh or rebar.

A significant vulnerability of this system is its performance under fire conditions. The direct exposure of the steel deck to heat leads to a rapid degradation of its strength and stiffness, critically compromising the slab's load-bearing capacity (criteria R) and its role as a fire compartment barrier [2]. Consequently, ensuring adequate fire resistance is paramount for life safety, property protection, and preventing progressive collapse.

Current design guidance, notably the simplified method in EN 1994-1-2 [3], is considered to overestimate fire resistance in some cases [4] and does not account for critical phenomena observed in modern studies. Recent research highlights that structural failures can occur during the cooling phase of a fire [5, 6, 7], and that connection failures may trigger slab collapse, facilitating fire spread between floors [8, 9]. These findings underscore the necessity for more refined design tools.

In response to this challenge, Fourie [10] proposed an innovative active insulation method. This solution involves attaching a ‘steel shield’ to the lower flanges of the deck ribs, creating a protected zone that mitigates direct fire exposure. Experimental tests demonstrated that this shield significantly reduces temperatures on the unexposed slab surface by 16% to 41% [10], thereby enhancing insulation performance (criteria I) and contributing to material efficiency.

However, this novel configuration falls outside the scope of existing codified methods. A significant research gap exists in developing a practical, simplified methodology to predict its thermal and structural behaviour in fire. This investigation aims to address this gap. Building upon the experimental and numerical work of Fourie [10] and incorporating the debonding effect between deck and concrete as recommended by Piloto et al. [11], this study seeks to develop a new simplified approach. The primary objective is to calibrate new ‘ $b_i$ ’ and ‘ $c_i$ ’ coefficients for use within an EN 1994-1-2 framework to accurately approximate temperatures in the shielded steel deck and reinforcing bars, respectively. This will provide designers with a vital tool for evaluating the fire resistance of this advanced composite slab system.

## 2. Computational Method

This study employs a two-dimensional finite element model developed in ANSYS to analyse the thermal behaviour of composite slabs under fire conditions. The methodology is structured into four key phases: (1) validation of the numerical model against experimental data from Fourie [10]; (2) insulation analysis according to prEN1994-1-2 [3] under the ISO 834 standard fire curve; (3) a parametric study of three slab geometries (VP50, VP115, VP200) with three protection types (unprotected, steel shield, mineral wool) to calibrate new thermal coefficients; and (4) a simplified load-bearing capacity analysis following [3].

### 2.1 Geometry and Components

The analysis focuses on a Voidcon® trapezoidal steel deck profile, divided into distinct thermal zones (Fig. 1): a general trapezoidal region (T) and a reentrant region (R). The geometry of these zones, defined by dimensions such as  $L_1$ ,  $L_2$ ,  $L_3$ , and  $h_2$  (Table 1), is critical for calculating view factors and subsequent temperature fields using the simplified method. The innovative steel shield protection creates an enclosed air cavity over the UPPER 2 and WEB 2 regions, shielding them from direct fire exposure.

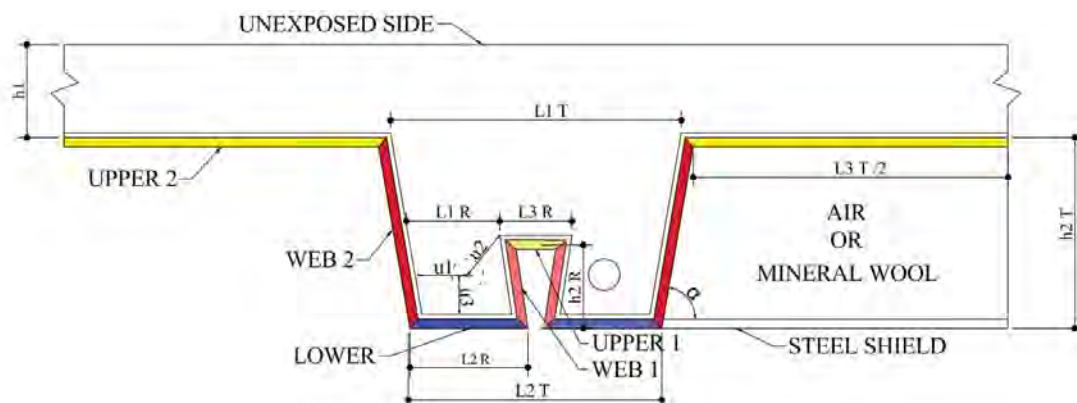


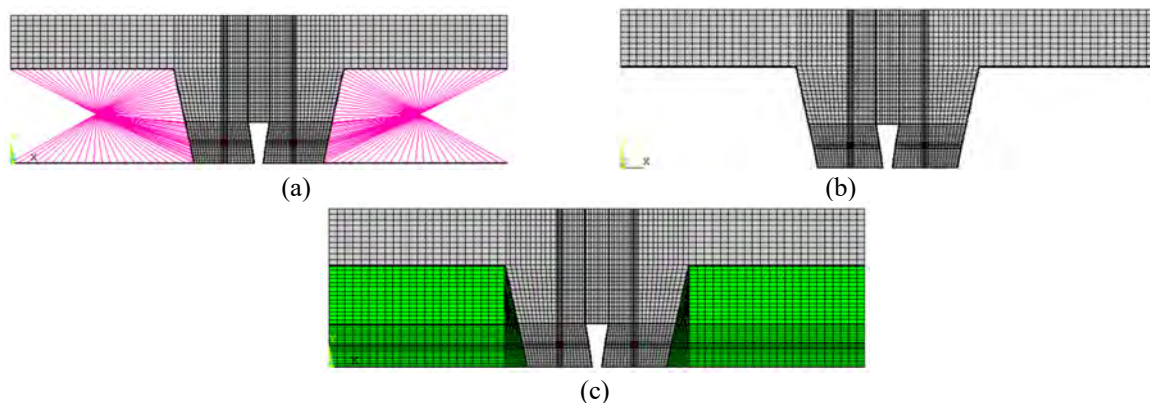
Fig. 1: Indicated dimensions and zones of the slab by Voidcon

**Table 1:** Dimensions of the slab by Voidcon®

	VP 50	VP115	VP 200
L1 R (mm)	30	50	85
L2 R (mm)	55	75	110
L3 R (mm)	25	25	25
L1 T (mm)	165	200	300
L2 T (mm)	115	150	230
L3 T (mm)	250	400	460
h1 (mm)	65	65	65
h2 T (mm)	50	115	200
h2 R (mm)	50	50	50
u1 (mm)	24	37	47
u2 (mm)	32	32	47
u3 (mm)	20	25	25
$\alpha$ (°)	63.40	77.73	80,07

## 2.2 Finite Element Modelling

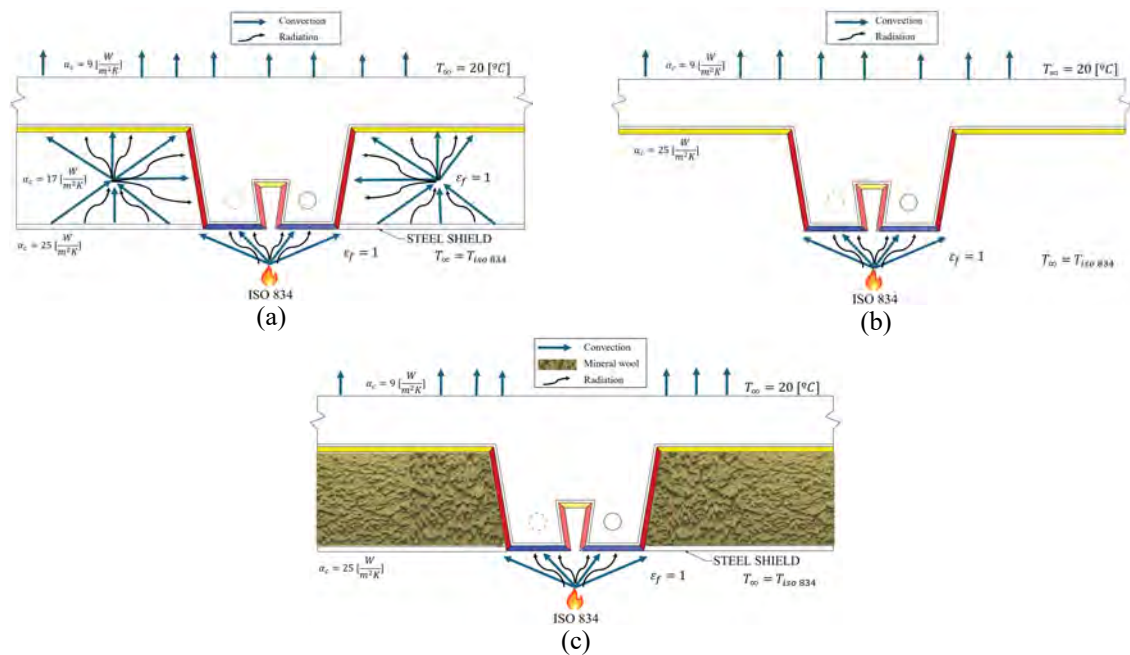
A transient, non-linear thermal analysis was conducted. The model used the PLANE55 finite element for heat conduction through solid materials (concrete, steel). Heat exchange within the steel shield's air cavity was modelled using the LINK34 finite element for convection and the LINK31 finite element for radiation, applying the Stefan-Boltzmann law. The mesh density (Fig. 2) was optimised to capture critical temperature gradients in the deck and reinforcement.



**Fig. 2:** Mesh size for VP 115. (a) Composite slab with steel shield insulation; (b) Composite slab without insulation; (c) Composite slab with mineral wool and steel shield insulation

## 2.3 Boundary Conditions and Analysis Parameters

Thermal boundary conditions were applied in accordance with EN 1991-1-2 [12]. The fire-exposed surface was subjected to the ISO 834 time-temperature curve with a combined heat transfer coefficient of 25 W/m<sup>2</sup>K and an emissivity of 1.0. The unexposed surface assumed a constant ambient temperature (20°C) with a heat transfer coefficient of 9 W/m<sup>2</sup>K (Fig. 3). The analysis used a transient setup with a typical time step of 60 sec., with the possibility to reduce to 1 sec., using the convergence based on heat flow criteria (tolerance of 10<sup>-3</sup>, and reference value 10<sup>-6</sup> [W]).



**Fig. 3:** Thermal boundary condition. (a) Slab with steel plate insulation; (b) Slab without insulation; (c) Slab with mineral wool insulation

### 3. Simplified Calculation Method

The core objective was to calibrate new coefficients for the prEN1994-1-2 [3] simplified method to accommodate different insulation strategies. This method estimates component temperatures to determine fire resistance ( $R, I$ ).

Load-bearing capacity ( $R$ ): The average temperature in the steel deck components ( $\theta_a$ ) is calculated using Eq. (1), which is a function of the view factor ( $\Phi$ ) and the rib geometry factor ( $A/L_r$ ). The temperature in the reinforcement ( $\theta_s$ ) is calculated using Eq. (2), which depends on parameters such as the reinforcement position ( $u_3/h_2$ ) and the rib angle ( $\alpha$ ). The view factors for each zone (Table 2) were calculated using the Hottel crossed-strings method [13].

$$\theta_a = b_0 + b_1 \frac{1}{L_3} + b_2 \frac{A}{L_r} + b_3 \Phi + b_4 \Phi^2 \quad (1)$$

$$\theta_s = c_0 + c_1 \frac{u_3}{h_2} + c_2 \alpha + c_3 \frac{A}{L_r} + c_4 \alpha + c_5 \frac{1}{L_3} \quad (2)$$

Insulation ( $I$ ): The insulation time is estimated using Eq. (3), which incorporates the concrete cover ( $h_i$ ) and the view factor of the upper flange ( $\Phi_{UPPER 2}$ ).

$$t_i = a_0 + a_1 h_i + a_2 \Phi_{UPPER 2} + a_3 \frac{A}{L_r} + a_4 \frac{1}{L_3} + a_5 \frac{A}{L_r} \frac{1}{L_3} \quad (3)$$

The new empirical coefficients  $b_i$  (for steel) and  $c_i$  (for rebar) were derived from the parametric study to accurately predict temperatures within the shielded configuration, which falls outside the scope of the current standard.

**Table 2:** View factors used for the composite slabs by Voidcon® [14]

	VP 50	VP115	VP 200
$\phi_{LOWER}$	1	1	1
$\phi_{WEB 2}$	0,6974	0,48	0,48
$\phi_{UPPER 2}$	0,9301	0,78	0,7125
$\phi_{WEB 1}$	0.058	0.058	0.058
$\phi_{UPPER 1}$	0.064	0.064	0.064

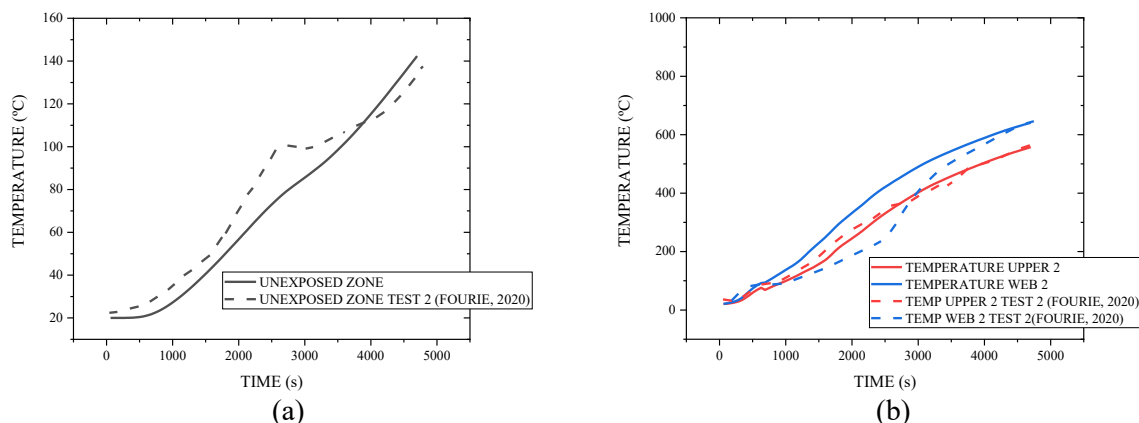
## 4. Materials

The thermal properties for structural steel (deck and rebars) were defined according to FprEN1993-1-2 [15]. Normal-weight concrete properties were assigned according to prEN1994-1-2 [3]. The model included temperature-dependent properties for air [13] and mineral wool (density 70 kg/m<sup>3</sup>) based on manufacturer data [16] and [17]. To simulate debonding between the concrete and steel deck, an air gap of 0.5 mm was included into the model at the interface, as recommended by Piloto et al. [11].

## 5. Results and Discussion

### 5.1 Model Validation

The numerical model was validated against the experimental data from Fourie [10]. Fig. 4 (a) shows the temperature on the unexposed slab surface, demonstrating excellent agreement between the ANSYS simulation and experimental results. Fig. 1b compares temperatures in the critical UPPER 2 and WEB 2 zones of the steel deck. A divergence is observed in the WEB 2 zone, attributable to the debonding effect (formation of an air gap) between the concrete and steel deck, under fire conditions [10, 11]. The Root Mean Square (RMS) error between numerical and experimental results was calculated for key zones (Table 3), confirming the model's accuracy, with all values well within the acceptable 100 °C tolerance specified by EN1363-1 [18].



**Fig. 4:** Comparison of the experimental results by Fourie [10] with ANSYS model by this study. (a) Unexposed zone; (b) steel sheet zones

**Table 3:** Root mean square error (°C) between experimental and numerical results

REGION ZONE	RMS (°C)
WEB 2	82.1
UPPER 2	18.1
UNEXPOSED	10.4

## 5.2 Insulation Performance (Criterion I)

The fire resistance time for the insulation criterion (I) was evaluated for all slab configurations (VP50, VP115, VP200) and insulation types (Table 4). The steel shield provided a significant and consistent improvement, increasing the failure time by approximately 25% against the maximum temperature criterion ( $T_0+180^{\circ}\text{C}$ ) across all slab depths. Mineral wool insulation performed exceptionally well, particularly in deeper decks. For the VP115 and VP200 profiles, the mineral wool insulation prevented the insulation failure criteria from being reached within the 240-minute benchmark for fire rating classification [19].

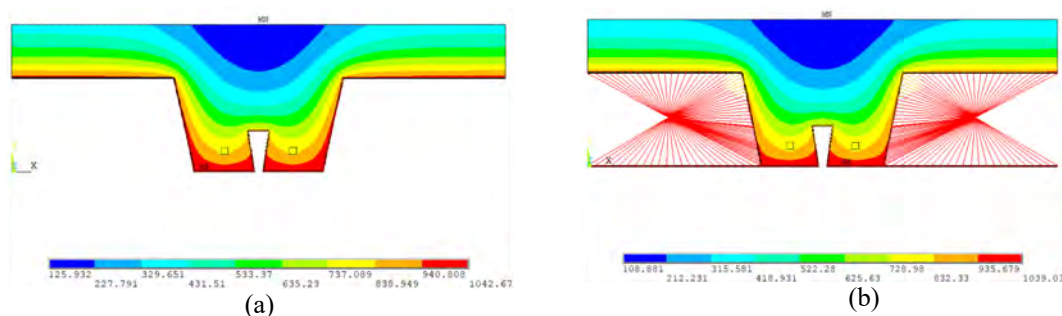
**Table 4:** Time limit for the (I) criteria

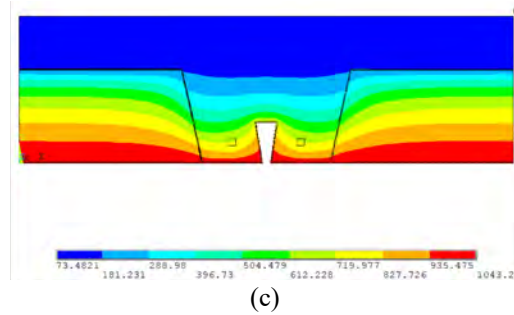
Type of slabs	Insulation type	$T_0+180$ (min)	$T_0+140$ (min)
VP 50	without insulation	61.4	66.4
	steel shield	78.6	77.6
	mineral wool	109.2	113.2
VP 115	without insulation	61.1	83.1
	steel shield	80.0	97.0
	mineral wool	333.0 <sup>a</sup>	276.3 <sup>a</sup>
VP 200	without insulation	62.8	102.8
	steel shield	81.1	107.1
	mineral wool	449.2 <sup>a</sup>	501.8 <sup>a</sup>

a) Exceeded the fire rating of 240 minutes for criterion (I) according to standard EN 13501-2 [19].

## 5.3 Thermal Behaviour and Parametric Study

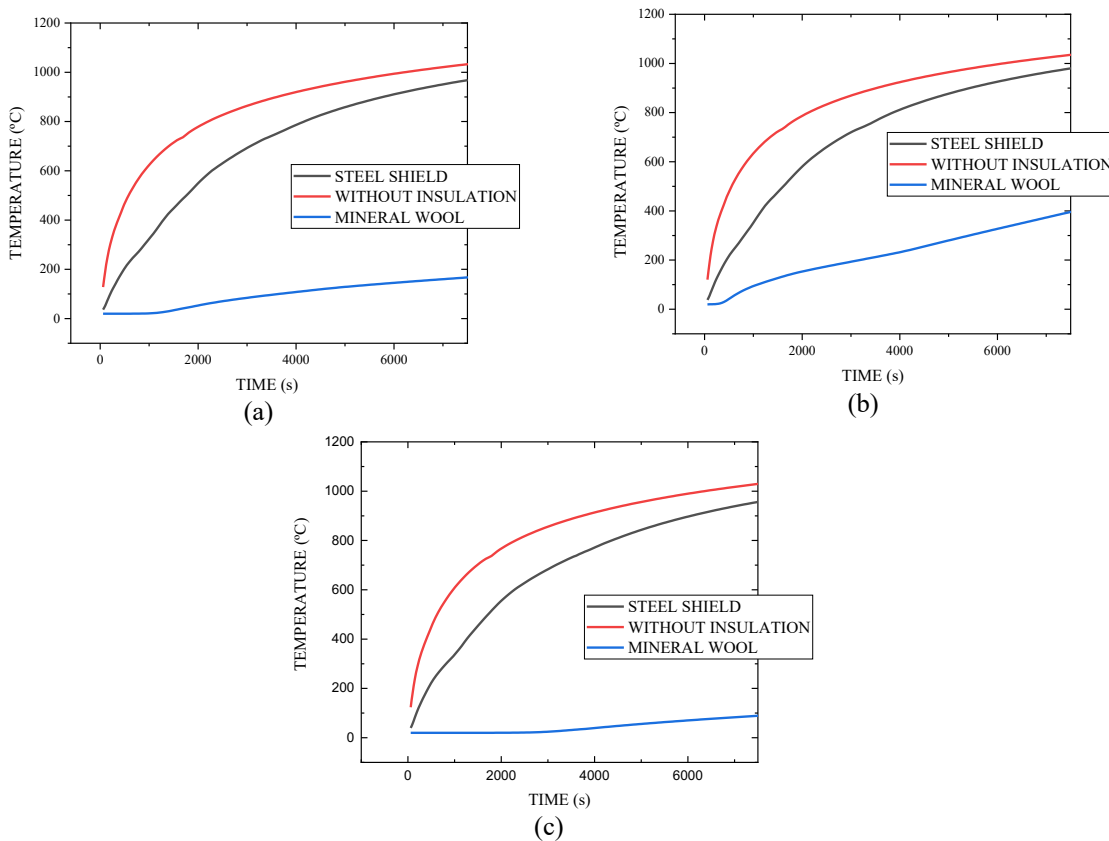
The temperature distribution for the VP115 slab at 120 minutes (7200 s) is shown in Fig. 5. The steel shield effectively creates a cooler cavity, reducing heat flow into the concrete above it. Mineral wool provides superior insulation, maintaining near-ambient temperatures in the upper deck zones.





**Fig. 5:** Temperature field over the composite slabs under parametric of iso 834 curves for the same  $h_1=65\text{mm}$  for a time equal to 7200 seconds: (a) VP115 without insulation; (b) VP115 with steel shield; (c) VP115 with mineral wool

A detailed analysis of the UPPER 2 zone temperature history (Fig. 6) reveals the substantial benefit of both insulation types. Mineral wool's performance is dominant, limiting the temperature rise to under  $200^\circ\text{C}$  for the entire duration. The steel shield also provides a major reduction in temperature compared to the unprotected case.



**Fig. 6:** Comparison of temperature history in the upper 2 zones for the composite slabs under parametric of iso 834 curve for the same  $h_1=65\text{mm}$  for a time from 0 to 7200 seconds: (a) VP115; (b)VP50; (c) VP200

Table 5 presents a quantitative comparison for the VP115 slab, highlighting the dramatic temperature reduction offered by mineral wool in the protected web and upper zones (e.g., 89% reduction in Upper 2 at 60 minutes). The steel shield also provided a significant reduction (12-17%). As expected, the temperature in the directly exposed Lower flange was largely unaffected by either insulation type.

**Table 5:** Comparison of the temperature between insulation strategies for VP115

Time (min)	Region	Without insulation (°C)	Steel shield (°C)	Difference % (a)	Mineral wool (°C)	Difference % (b)
60	LOWER	923.2	920.6	0.27	917.8	0.65
	WEB 2	888.8	778.9	12.36	391.3	44.00
	UPPER 2	906.3	751.0	17.13	99.3	89.07
90	LOWER	994.4	990.6	0.40	987.6	0.70
	WEB 2	966.9	897.5	7.14	491.2	49.14
	UPPER 2	979.3	881.1	10.01	135.9	86.21
120	LOWER	1039.7	1038.1	0.09	1035.1	0.384
	WEB 2	1018.7	969.7	4.81	567.2	44.20
	UPPER 2	1025.9	958.1	6.60	163.2	84.07

(a) Difference between without insulation and steel shield  
(b) Difference between without insulation and mineral wool

#### 5.4 New Calibrated Coefficients for Simplified Method

Table 6 presents the proposed  $b_i$  coefficients to determine the temperature in steel deck components using the Steel Shield, maintaining their use in Eq. (1). It is noted that in the lower region, the “ $b_2$ ” parameters are low, since in this insulation proposal, the lower region is not protected, making the geometric parameters less relevant. This is due to the exposure in this region being practically the same.

**Table 6:** New coefficient “ $b_i$ ” proposal to determine the temperature in steel deck under fire curve iso 834 for a steel shield insulation

TIME (min)	STEEL DECK REGION	$b_0$ (°C)	$b_1$ (°C.mm)	$b_2$ (°C.mm)	$b_3$ (°C)	$b_4$ (°C)
60	UPPER 2	655.63	-734.815	-0.32	193.9096	-52.90
	WEB 2	898.73	-18071.9	-1.57	276.0602	-210.84
	LOWER	953.79	-868.995	-0.13	17.31293	-40.132
90	UPPER 2	770.62	-17598.3	-1.14	511.3276	-186.22
	WEB 2	892.69	-12026.7	-1.09	491.0991	-404.97
	LOWER	1047.78	-473.694	-0.09	7.664627	-57.90
120	UPPER 2	897.64	-16998.5	-1.20	443.8899	-178.63
	WEB 2	973.99	-5684.49	-0.61	228.0133	-188.25
	LOWER	980.55	-170.244	-0.05	75.57389	-14.705

Table 7 presents the proposed “ $b_i$ ” coefficients for determining the temperature in steel deck components using the mineral wool, maintaining their use in Eq. (1).

**Table 7:** New coefficients "b<sub>i</sub>" proposal to determine the temperature in steel deck under fire curve iso 834 for a mineral wool insulation

TIME (min)	STEEL DECK REGION	b <sub>0</sub> (°C)	b <sub>1</sub> (°C.mm)	b <sub>2</sub> (°C.mm)	b <sub>3</sub> (°C)	b <sub>4</sub> (°C)
60	UPPER 2	0	-80115.3	-5.54224	1182.233	-0.00016
	WEB 2	546.542	-5772.11	-4.82394	291.80	-0.00262
	LOWER	953.796	-868.995	-0.13103	17.31	-40.1328
90	UPPER 2	0	-131140	-8.22638	1844.938	-0.00041
	WEB 2	474.912	-0.3311	-4.53379	718.85	-378.888
	LOWER	1047.79	-473.694	-0.09809	7.66	-57.907
120	UPPER 2	0	-189471	-11.2556	2582.478	0
	WEB 2	802.465	-13254.1	-5.70221	325.1772	-0.00084
	LOWER	980.556	-170.244	-0.05367	75.57389	-14.7057

For the regions UPPER 1 and WEB 1, which are areas without any insulation, the calculations can be performed using the coefficients presented in the new approach proposed by Carlos Balsa et al. [20].

Tables 8 and 9 present new coefficients to determine the average temperatures of the rebars with Steel Shield and Mineral Wool insulation, respectively, maintaining their use in Eq. (2).

**Table 8:** New coefficients "c<sub>i</sub>" proposal to determine the temperature in steel deck under fire curve iso 834 for a steel shield insulation

TIME (min)	c <sub>0</sub> (°C)	c <sub>1</sub> (°C)	c <sub>2</sub> (°C.mm <sup>0.5</sup> )	c <sub>3</sub> (°C.mm)	c <sub>4</sub> (°C/°)	c <sub>5</sub> (°C.mm)
60	947.1	-201.6	-268.1	-3.25	4.17	-4585.2
90	1027.5	-198.8	-176.1	-3.98	3.63	-14491.4
120	1153.7	-271.6	-158.3	-3.92	2.94	-12363.0

**Table 9:** New coefficients "c<sub>i</sub>" proposal to determine the temperature in steel deck under fire curve iso 834 for a mineral wool insulation

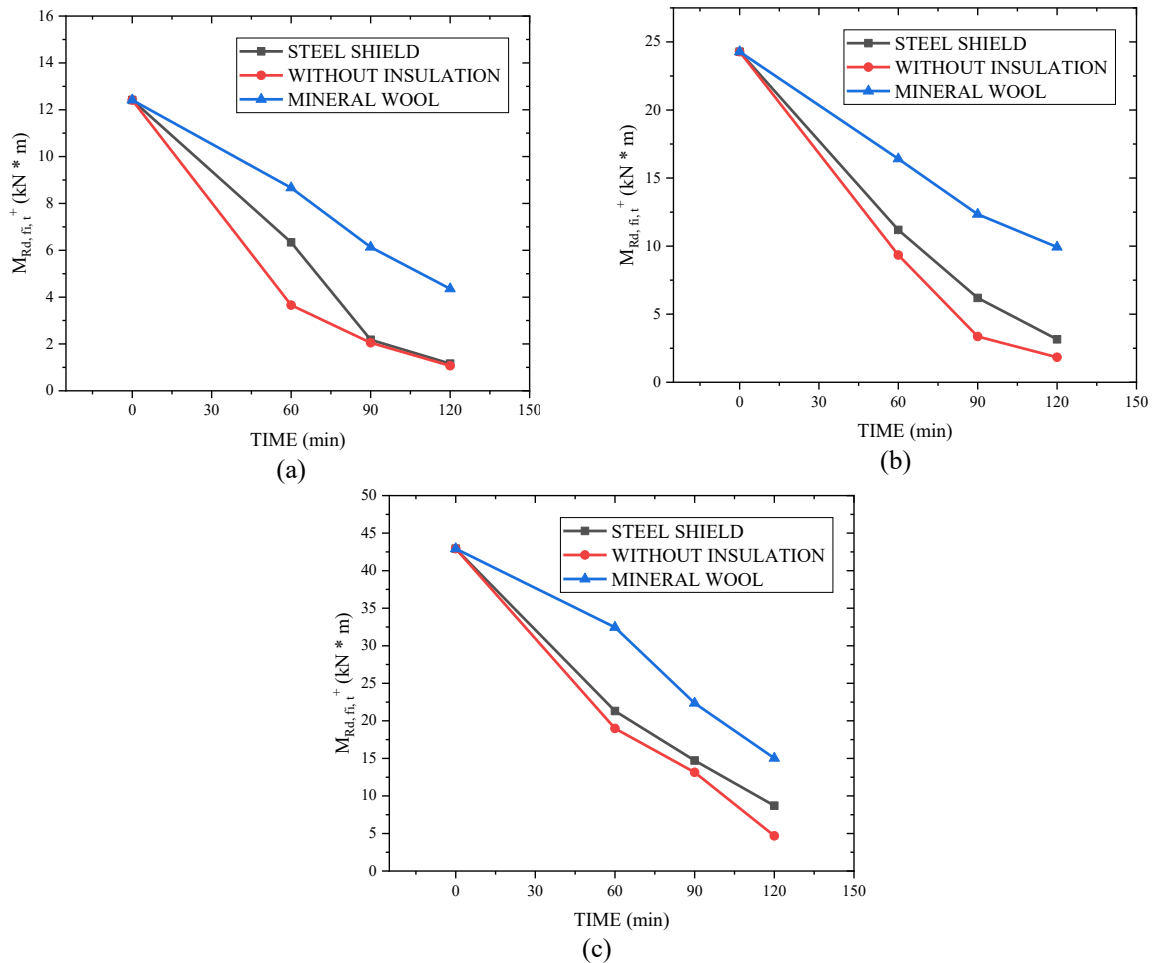
TIME (min)	c <sub>0</sub> (°C)	c <sub>1</sub> (°C)	c <sub>2</sub> (°C.mm <sup>0.5</sup> )	c <sub>3</sub> (°C.mm)	c <sub>4</sub> (°C/°)	c <sub>5</sub> (°C.mm)
60	930.078	-292.355	-117.716	-3.74446	0.936562	-7273.17
90	963.447	-143.803	-177.807	-1.52391	1.434412	-10.1888
120	1007.2	-253.709	-198.434	-3.50322	4.105537	-8.06392

### 5.5 Load-Bearing Capacity (Criterion R)

The mechanical impact of the reduced temperatures was assessed by calculating the evolution of the bending moment capacity ( $M_{Rd,fi,t^+}$ ) over time using the methodology from prEN1994-1-2 [3] (Eqs. 4-5). The results for the VP115 slab are shown in Figure 7. The enhanced thermal protection directly translates to improved structural performance. The slab with a steel shield maintains its load-bearing capacity for a longer duration than the unprotected slab. The slab with mineral wool insulation exhibits the most superior performance, retaining a significant portion of its capacity throughout the entire fire exposure, thus offering the highest potential for achieving extended fire resistance ratings.

$$\sum_{i=1}^m A_i k_{y,i} \left( \frac{f_{y,i}}{\gamma_{M,y}} \right) + \alpha_{slab} \sum_{j=1}^n A_j k_{c,j} \left( \frac{f_{c,j}}{\gamma_{M,c}} \right) = 0 \quad (4)$$

$$M_{Rd,fi,t} = \sum_{i=1}^m A_i z_i k_{y,i} \left( \frac{f_{y,i}}{\gamma_{M,y}} \right) + \alpha_{slab} \sum_{j=1}^n A_j z_j k_{c,j} \left( \frac{f_{c,j}}{\gamma_{M,c}} \right) \quad (5)$$



**Fig. 7:** Evolution of the loss of load-bearing capacity of the slab ( $M_{Rd,fi,t}$ ) over time under the ISO 834 fire curve for three conditions: without insulation, with a steel shield, and with mineral wool insulation. (a) VP50; (b) VP115; (c) VP200

## 6. Conclusion

This study developed and validated a numerical methodology to assess the fire performance of composite slabs with steel decking, specifically evaluating a novel steel shield insulation system. The key conclusions are as follows:

1. The finite element model, incorporating a 0.5 mm air gap to simulate debonding, was successfully validated against experimental data. It demonstrated high accuracy, particularly for the unexposed surface (RMS error of 10.4 °C), providing a reliable tool for parametric analysis.
2. Both insulation systems significantly enhanced fire performance. The steel shield provided a consistent ~25% improvement in insulation failure time across all slab profiles. Mineral wool offered superior protection, preventing insulation failure within 240 minutes for the deeper VP115 and VP200 slabs and reducing temperatures in critical deck zones by up to 89%.
3. The core output of this work is the calibration of new empirical coefficients ( $a_i$ ,  $b_i$ ,  $c_i$ ) for use with the prEN1994-1-2 simplified method. These coefficients enable designers to accurately predict temperatures in steel deck components and rebars for slabs employing either steel shield or mineral wool insulation, bridging a critical gap in current design codes.

4. The enhanced thermal protection directly translated to improved structural integrity. The load-bearing capacity was maintained for a significantly longer duration in insulated slabs, with mineral wool offering the most substantial gain in fire resistance. This research provides practising engineers with a validated, code-compliant methodology for designing efficient and fire-safe composite slabs using innovative insulation techniques, facilitating their adoption in modern steel structures. Future work should focus on further experimental validation and extending the analysis to include structural connections and natural fire scenarios.

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