

# New developments on the bending resistance in composite slabs with steel deck under fire

Matheus Bez da Silveira - 41990

Dissertation presented to the  
Escola Superior de Tecnologia e Gestão of the  
Instituto politécnico de Bragança - ESTiG - IPB  
to obtain a bachelor's degree in **Civil Engineering** and  
a master's degree in **Construction Engineering**

2020-2021

# **New developments on the bending resistance in composite slabs with steel deck under fire**

**Matheus Bez da Silveira - 41990**

Dissertation presented to the  
**Escola Superior de Tecnologia e Gestão** of the  
**Instituto politécnico de Bragança - ESTiG - IPB**  
in order to obtain a bachelor's degree in **Civil Engineering** and  
a master's degree in **Construction Engineering**

Study developed under supervision of:  
**Prof. Paulo Alexandre Gonçalves Piloto**  
**Prof. Carlos Balsa**  
**Prof. Gustavo Lacerda Dias**

Master in Construction Engineering  
2020-2021

"After the Rain, the Sun Always Shines Again." Bragança 2021.

This dissertation include the critics and suggestions made by the jury.

---

Matheus Bez da Silveira - 41990

# Acknowledgments

First of all, I would like to thank my family, especially my mother Marizane Bez and my grandparents Nevio Bez e Ida Loregian Bez, for all the support that made a difference in the moments when this journey seems impossible. Your love, incentive and encouragement made it another memorable conquest in my life, so I would like you to know that this is one of the first of many fruits that we will harvest together.

I thank my supervisors Dr. Paulo Piloto, Dr. Carlos Balsa, and my co-supervisor, Dr. Gustavo Lacerda Dias, for all the contributions in my formation and professional evolution. I leave special thanks to professor Gustavo for all the effort and dedication given at the beginning of this phase. I also take this opportunity to thank all the UTFPR-PB professors who were part of my academic journey, and I take with great regard the teachings left by each one.

I thank all my friends and colleagues who somehow have been part of this long journey, both those I met in Brazil and those I met during the exchange program. Thank you!

I leave a special thanks to Ana Caroline Cadorin and Afonso Daneluz Jacobsen. Sharing a home with you was a pleasure; I thank you for being by my side in countless moments, both when I was happy and also when I needed help the most. we built an unshakable bond that I will take with me for life; I believe this union transcends friendship; it has become Family. "AP 203 Forever - Ap 203 is not just a place, it is a mood".

Alana Karolyne Dametto Dos Santos, shorty, you have no idea the difference you made in my life in so many moments. There are no words to thank you for all the support. You were the person who made the difference that allowed me to continue steadfast not only in this journey but in several other moments. In you, i found a heart that overflows love,

friendship, and affection. You are the best, thank you for everything!

César Augusto Refosco Yednak, first of all, I am happy that an academic relationship has become an "Honest (or maybe Jedi?!)" friendship. Master, I would like to thank you for all the teachings, both personal and professional, for all the support, the movies, the many hours of Dota, and the motorcycle rides. I am happy to say that you are among the few friends who have my entire confidence. Master, I would like to tell you only one thing: "May the Force be with you. I am grateful for absolutely everything, by Padawan.

I also would like to thank my Bragantina family, Fabio Tentor, Jonata Massao Ueda, Lares Araujo, and the newest member, Báraba Laje, for all the friendship, support, and bonds created during this phase full of new experiences.

# Abstract

Composite steel/concrete slabs can be considered a union of a reinforced concrete layer located above a profiled steel sheet which may or may not be reinforced by steel bars. This configuration allows lightness in the structure, whereas the negative mesh located on the top side of the slab needs to resist only against the concrete shrinkage; the profiled steel deck with the reinforcement bars is responsible for resisting the sagging moments.

The main objective of this work is to investigate the fire effect on the bending resistance of the composite slab with steel deck, comparing the behavior of Normal Weight Concrete (NWC) and Light Weight Concrete (LWC) when submitted to standard fire.

The Eurocode 1994 1-2 is responsible for providing the guidelines for structural design of composite slabs under fire conditions. This standard presents a simplified calculation model to determine the slab sagging moment. However, it neglects some important effects occurring during a fire situation, such as the air-gap effect and the influence of the concrete layer  $h_1$ .

In order to optimize the calculation model presented by Eurocode 1994 1-2, a parametric study was performed using trapezoidal and re-entrant steel decks geometries. This study comprises two trapezoidal models (Confraplus 60 and Polydeck 59s) and two re-entrant models (Multideck 50 and Bondek) with different thicknesses for  $h_1$ .

This analysis consists of a non-linear transient thermal analysis using the finite element method, performed on two different software: ANSYS and MATLAB. Based on the average temperature of each component, new coefficients and calculation proposal for annex D of Eurocode 1994-1.2 are presented, and the slabs reduction load-bearing capacity is determined.

By analyzing the results provided by this study, it was possible to conclude that Eurocode 1994-1.2 simplified calculation method produces a lower temperature field than the parametric curves and the New Calculation Proposal, thus confirming the current analytical method produces unsafe results. A comparison of the estimated temperatures between the New Proposal and the temperatures of Eurocode 1994-1.2 showed an average variation of 6% for composite slabs with trapezoidal profiles and 10% for composite slabs with re-entrant profiles, and this effect is intensified for the initial fire resistance classes, which can reach up to 40%. The variation in temperatures also leads to variations in the reduction of the resistant capacity of the slabs; when comparing the two analytical models, the variation is around 3% to 20% for most fire resistance classes and can reach up to 50% for the initial rating times of 30 min and 45 min.

**Keywords:** composite slabs, normal weight concrete, lightweight concrete, numerical model.

# Resumo

As lajes mistas em aço e concreto podem ser descritas pela união de uma camada de concreto armado localizada acima de um perfil de aço, podendo ou não ser reforçada por vergalhões de aço entre as nervuras. Esta configuração garante leveza à estrutura de modo que a malha negativa localizada no lado superior da laje resiste contra a retração do concreto, já o "deck" de aço perfilado e os vergalhões de reforço são responsáveis por resistir aos momentos de positivos da laje mista.

O principal objetivo deste trabalho é investigar o efeito do fogo na resistência à flexão das lajes mistas com plataforma de aço colaborante, comparando o comportamento do Concreto Convencional (NWC) e do Concreto de Peso Leve (LWC) quando submetidos à uma curva de incêndio padrão ISO-834.

O Eurocódigo 1994-1.2 é responsável por fornecer as diretrizes para o projeto estrutural das lajes mistas sob condições de incêndio. Esta norma apresenta um modelo simplificado de cálculo para determinar o momento positivo máximo resistente da laje. Entretanto, ela negligencia alguns efeitos importantes que ocorrem durante a fase de aquecimento, como o efeito de deslocamento ("debonding effect") entre o concreto e a plataforma de aço, e também a influência da camada de concreto  $h_1$ .

Para otimizar o modelo de cálculo apresentado pelo Eurocódigo 1994-1.2, foi realizado um estudo paramétrico utilizando diferentes geometrias de perfis de plataformas de aço, como: trapezoidais e reentrantes. Este estudo compreende dois modelos trapezoidais (Confraplast 60 e Polydeck 59s) e dois modelos reentrantes (Multideck 50 e Bondek) com diferentes espessuras de  $h_1$ .

Este estudo consiste na elaboração de análises térmicas transientes não-lineares através

do Método de Elementos Finitos (MEF) em dois softwares diferentes: ANSYS e MATLAB. Com base na temperatura média de cada componente, foram apresentados novos coeficientes e proposta de cálculo para o Anexo D do Eurocódigo 1994-1.2. Por fim, foi possível determinar a redução da capacidade resistente das lajes mistas de acordo com o tempo de exposição ao fogo, comparando os efeitos oriundos das duas abordagens analíticas: o método simplificado do Eurocódigo 1994-1.2 e a Nova Proposta de Cálculo.

Por meio da análise dos resultados obtidos através deste estudo foi possível concluir que atualmente o Eurocódigo 1994-1.2 apresenta um campo de temperaturas inferior ao das curvas paramétricas e da Nova Proposta de Cálculo, demonstrando assim que o método analítico atual produz resultados inseguros. Uma comparação acerca da estimativa de temperaturas entre a Nova Proposta e as temperaturas do Eurocódigo 1994-1.2 possibilitou demonstrar uma variação média 6% para lajes com perfis trapezoidais e 10% para lajes com perfis reentrantes, de modo que este efeito é agravado para as classes iniciais de resistência ao fogo, podendo chegar até a 40%. A variação nas temperaturas também acarreta variações na redução da capacidade resistente das lajes quando comparados os dois modelos analíticos, de forma que esta variação é na ordem de 3% a 20% para a maioria das classes de resistência ao fogo, podendo chegar até a 50% para os tempos iniciais de 30 min e 45 min.

**Palavras-chave:** lajes mistas, concreto convencional, concreto leve, modelos numérico.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	State of Art . . . . .	4
1.2	Objectives . . . . .	16
1.2.1	General objectives . . . . .	16
1.2.2	Specific objectives . . . . .	16
1.3	Dissertation Structure . . . . .	17
<b>2</b>	<b>Heat Transfer</b>	<b>19</b>
2.1	Conduction . . . . .	20
2.2	Convection . . . . .	21
2.3	Radiation . . . . .	22
<b>3</b>	<b>Thermal and Mechanical Properties of Materials</b>	<b>26</b>
3.1	Thermal Properties . . . . .	26
3.1.1	Steel . . . . .	27
3.1.2	Concrete . . . . .	30
3.1.3	Air . . . . .	35
3.2	Mechanical Properties . . . . .	38
3.2.1	Steel . . . . .	38
3.2.2	Concrete . . . . .	40
<b>4</b>	<b>Methods and Methodology</b>	<b>43</b>

4.1	Parameters for the Simulations . . . . .	44
4.2	Geometric Configuration of Steel Profiles . . . . .	45
4.3	Finite element models . . . . .	47
<b>5</b>	<b>Simplified Calculation Methods</b>	<b>49</b>
5.1	Fire Resistance Criteria . . . . .	50
5.1.1	Insulation (I) . . . . .	50
5.1.2	Integrity (E) . . . . .	51
5.1.3	Load-Bearing (R) . . . . .	51
5.2	Analytical Analysis of Insulation (I) criterion . . . . .	52
5.3	Analytical Analysis of Load-Bearing (R) criterion . . . . .	54
<b>6</b>	<b>Advanced Calculation Methods</b>	<b>61</b>
6.1	Boundary Conditions . . . . .	62
6.1.1	Standard Fire Curve ISO-834 . . . . .	62
6.1.2	Heat Transfer . . . . .	63
6.2	Finite Element Method . . . . .	64
6.2.1	MATLAB . . . . .	65
6.2.2	ANSYS . . . . .	66
<b>7</b>	<b>Results and New Proposals</b>	<b>72</b>
7.1	Temperature estimation with MATLAB . . . . .	73
7.2	Temperature estimation with ANSYS . . . . .	76
7.3	New Temperature Calculation proposal . . . . .	79
7.3.1	New coefficients proposal . . . . .	80
7.3.2	New Proposal Validation . . . . .	82
7.4	Bending resistance Reduction Factor . . . . .	85
<b>8</b>	<b>Conclusion</b>	<b>89</b>
8.1	Suggestions for Future Works . . . . .	91

A	Annex A - Data Sheet for trapezoidal geometry and NWC.	A1
B	Annex B - Data Sheet for re-entrant geometry and NWC.	B1
C	Annex C - Data Sheet for trapezoidal geometry and LWC.	C1
D	Annex D - Data Sheet for re-entrant geometry and LWC.	D1

# List of Tables

- 3.1 Relationship between the moisture content and the maximum specific heat for NWC. . . . . 30
- 3.2 Experimental results obtained by Çengel A. Y. and Ghajar J. A. for air thermal properties. . . . . 36
- 3.3 Equations for determining the steel yield strength [30]. . . . . 39
- 3.4 Reduction factors for structural steel strength at elevated temperatures [30] 40
- 3.5 Equations for determining the concrete yield strength [31]. . . . . 41
- 3.6 Normal weight concrete (NWC) and lightweight concrete (LWC) parameters of the stress-strain relationships at elevated temperatures [31]. . . . . 42
  
- 4.1 View factor ( $\phi$ ) according to each slab geometry. . . . . 47
  
- 5.1 Field of application for simplified calculation methods. . . . . 53
- 5.2 Fire resistance coefficients according to insulation criteria (I) . . . . . 53
- 5.3 Coefficients for estimating the temperature in steel deck components. . . . . 56
- 5.4 Temperature coefficients for estimating the temperature in the reinforcement bars. 57
- 5.5 Minimum effective thickness as a function of standard fire resistance. . . . . 60
  
- 7.1 New  $b_i$  coefficients proposal. . . . . 81
- 7.2 New  $c_i$  coefficients proposal. . . . . 82

# List of Figures

2.1	Geometric paramaters to determine the average view factors according to each slab profile: (a) Trapezoidal, (b) Reentrant. . . . .	24
2.2	view factors arrangement according on each slab profile: (a) Trapezoidal, (b) Reentrant. . . . .	25
3.1	Specific heat variation as a function of temperature for steel. . . . .	28
3.2	Thermal conductivity variation as a function of temperature for steel. . . .	29
3.3	Specific heat variation as a function of temperature for different moisture contents. . . . .	31
3.4	NWC density as a function of thermal variation. . . . .	32
3.5	Upper and lower limits for conventional concrete thermal conductivity as a function of temperature variation. . . . .	33
3.6	LWC density as a function of thermal variation. . . . .	34
3.7	LWC thermal conductivity as a function of temperature variation. . . . .	35
3.8	Air thermal properties as a function of temperature variation. . . . .	36
3.9	Air thermal properties as a function of temperature variation. . . . .	37
3.10	Air thermal properties as a function of temperature variation. . . . .	37
3.11	Carbon steel stress-strain relationship at elevated temperatures [30]. . . . .	39
3.12	Concrete stress-strain relationship at elevated temperatures [31]. . . . .	41
4.1	Thermal models diagram. . . . .	44
4.2	Composite Slabs Parameters. . . . .	45
4.3	Confraplus 60 geometric characteristics [mm]. . . . .	45

4.4	Polydeck 59S geometric characteristics [mm]. . . . .	46
4.5	Multideck 50 geometric characteristics [mm]. . . . .	46
4.6	Bondek geometric characteristics [mm]. . . . .	46
4.7	Geometric disposition of composite slabs: (a) Trapezoidal profile, (b) Re-entrant profile. . . . .	48
5.1	Definition of A/Lr for the ribs of composite slabs. . . . .	54
5.2	Simply supported composite slab subject to a uniformly distributed self-weight load. . . . .	55
5.3	Stress distribution on the cross section of the composite slab. . . . .	55
5.4	Parameters $u_i$ for the z-factor calculation. . . . .	58
6.1	Boundary conditions for a composite slab exposed to ISO-834 standard fire. . . . .	64
6.2	Finite element mesh in MATLAB. . . . .	66
6.3	Element SOLID70, characteristics and representation. . . . .	68
6.4	Element SHELL131, characteristics and representation. . . . .	69
6.5	Element LINK33, characteristics and representation. . . . .	70
7.1	Temperature measurement in composite slabs: (a) Trapezoidal profile (b) Re-entrant profile. . . . .	73
7.2	Composite slabs in Normal Weight Concrete: (a) Polydeck 59S Cross-section at 120 min, (b) Temperature evolution for each component obtained by simplified (S) and numerical (N) methods, considering the “air-gap” (air). . . . .	74
7.3	Composite slabs in Normal Weight Concrete: (a) Multideck 50 Cross-section at 120 min, (b) Temperature evolution for each component obtained by simplified (S) and numerical (N) methods, considering the “air-gap” (air). . . . .	74
7.4	Composite slabs in Lightweight Concrete: (a) Polydeck 59S Cross-section at 120 min, (b) Temperature evolution for each component obtained by simplified (S) and numerical (N) methods, considering the “air-gap” (air). . . . .	75

7.5	Composite slabs in Lightweight Concrete: (a) Multideck 50 Cross-section at 120 min, (b) Temperature evolution for each component obtained by simplified (S) and numerical (N) methods, considering the “air-gap” (air).	75
7.6	Temperature measurement in composite slabs: (a) Trapezoidal profile (b) Re-entrant profile.	76
7.7	Temperature evolution of composite slabs in Normal Weight Concrete: (a) Polydeck 59S, (b) Multideck 50.	77
7.8	Temperature evolution of composite slabs in Lightweight Concrete: (a) Polydeck 59S, (b) Multideck 50.	77
7.9	Comparison between thermal curves using Normal Weight Concrete using ANSYS and MATLAB software.	78
7.10	Comparison between thermal curves using Lightweight Concrete using ANSYS and MATLAB software.	78
7.11	Temperature for composite slabs with NWC. (a) Polydeck 59S, (b) Confraplus 60 (c) Multideck 50 (d) Bondek.	83
7.12	Temperature for composite slabs with LWC. (a) Polydeck 59S, (b) Confraplus 60 (c) Multideck 50 (d) Bondek.	84
7.13	Confraplus 60 bending resistance reduction factor for NWC: (a) EC 1994-1.2, (b) New Proposal.	85
7.14	Polydeck 59S bending resistance reduction factor for NWC: (a) EC 1994-1.2, (b) New Proposal.	86
7.15	Multideck 50 bending resistance reduction factor for NWC: (a) EC 1994-1.2, (b) New Proposal.	86
7.16	Bondek bending resistance reduction factor for NWC: (a) EC 1994-1.2, (b) New Proposal.	86
7.17	Confraplus 60 bending resistance reduction factor for LWC: (a) EC 1994-1.2, (b) New Proposal.	87
7.18	Polydeck 59S bending resistance reduction factor for NWL: (a) EC 1994-1.2, (b) New Proposal.	87

7.19 Multideck 50 bending resistance reduction factor for LWC: (a) EC 1994-1.2,  
    (b) New Proposal. . . . . 88

7.20 Bondek bending resistance reduction factor for LWC: (a) EC 1994-1.2, (b)  
    New Proposal. . . . . 88

# Chapter 1

## Introduction

The constructive solutions required in civil construction field are searching more and more for the union of three factors: performance, economy, and safety. The technological advance, especially in the information technology field for the structure's design and in the development of new construction materials, is evident and presents recurrent uses. However, it is necessary to ensure that they comply with the requirements established in the standards, present proven safety and durability, and promote economy in their use. By meeting these requirements, a construction solution is able to compete with traditional solutions already consolidated in the market place.

The concrete and steel composite slabs present an alternative solution that aims to safely reduce the self-weight of the structures while speeding up the slabs construction process. This constructive solution had its beginnings in North America, and became widely used from the 1960s on. However, according to Cooke G. M. E. [1], it started to be widely used in Europe only after the 1980s, since until then, it presented little data to guarantee safety and good performance in its use.

The use of composite slabs provides high performance in resistance to large loads. It can be considered a strategic solution in cases involving large spans, such as commercial or office buildings, hospitals, parking lots, etc. In these cases, the use of composite slabs aggregates economic advantages, such as a cost reduction in the function of the large-scale production and reduction in construction time due to the pre-fabrication of

the collaborating steel decks and the possibility of using the steel deck as permanent formwork.

Although composite slabs have numerous advantages, their behavior under fire conditions or when exposed to weather conditions requires special attention. Both situations are due to the steel deck's exposure. Weathering represents a probability of steel deck corrosion, thus fragilizing the material's mechanical properties because, in this type of structure, the steel has no concrete protection cover. However, as reported by Guo S. [2], this problem can be solved by applying a protective zinc coating on the exposed surface.

Regarding the fire exposure situation, this problem requires more attention since the composite slab's design considers just the steel deck and the rebars as the components to resist the bending moment of the slabs. Due to the fact that the direct exposure of steel to fire leads to a quick reduction in its mechanical properties, it is essential to specify the minimum fire resistance time in composite slabs to avoid the early collapse of the structure and ensure structural safety to the buildings. Therefore, the concrete and steel structural designs must be developed from a study concerning two data sets: the thermal properties of the materials to perform the thermal analysis and the mechanical properties of the materials to perform a structural analysis [3].

Since the structure's mechanical behavior is directly affected by the thermal performance of the slabs over the fire exposure time, once determined the structure boundary conditions, it is necessary to consider the different modes of heat transfer, such as the conduction, convection, and radiation. In such a way that the thermal energy transferred by radiation and convection requires special attention because it is through them that we can determine the fraction of energy that is absorbed by slabs components.

Nowadays, the Eurocode 1994 1-2 [4] is responsible for providing parameters for developing composite slab designs under fire situations. This standard presents a simplified calculation model that makes it possible to determine both the temperature on steel components and the slab sagging moment. However, since the last review was done more than fifteen years ago, the methodology does not consider some important factors occurring over the fire exposure, such as the air-gap effect, which consists of developing an air

layer around 0.5 mm between the collaborating steel deck and the concrete, caused by a difference in the thermal expansion coefficient of these two materials.

Another aspect that is not accounted for in the simplified model is the influence exerted by the concrete thickness  $h_1$  in determining the position of the plastic neutral axis. Since this thickness effectively contributes to the distribution of the internal heat flow of the slabs, it ends up affecting the temperatures of the steel and concrete elements. Consequently, it affects the reduction coefficients applied to calculate the maximum plastic bending resistance moment.

In order to optimize the calculation model presented by Eurocode 1994 1-2, a parametric study was performed in order to analyze the temperature distribution along composite slabs cross-sections using normal weight concrete and lightweight concrete in four different types of steel deck, which were chosen aiming to present two different geometric classes, trapezoidal and re-entrant, with different concrete thickness  $h_1$ .

After these parameters have been established, the parametric study phase began. Thermal models using the finite element method to solve non-linear transient analysis for the composite slabs were developed to determine the temperature distribution along the cross-section of the composite slab. In this phase, two different approaches already validated with experimental tests by Piloto P. et al [5–7] were performed. In this context, a two-dimensional approach was used to analyze the slabs cross-section temperatures using MATLAB software, whereas three-dimensional thermal models were developed using ANSYS software.

Therefore, with the parametric results, a new proposal for both the coefficients of Annex D from Eurocode 1994-1.2 [4] and the temperature analytical calculation method were presented. Then, a comparison between the new proposal and the current analytical method was made. This analysis highlighted the improvement provided by the new approach both in estimating temperatures and in the load-bearing, in other words, the bending resistant capacity of composite slabs under fire conditions.

## 1.1 State of Art

Thermodynamics is the physics field responsible for studying the physical phenomena of heat transfer and the conversion of different energy forms into thermal energy, and so on. This physics area was created during the Industrial Revolution. Its initial objective was to produce more efficient steam engines. Its beginning is considered due to Nicolas Léonard Sadi Carnot's work published in 1824, "Réflexions sur la Puissance Motrice du Feu et sur les Machines Propres a Développer Cette Puissance" [8]. Although much of Carnot's notes were incinerated, a small part got preserved. It contains the following postulate "In order to have continuous heat conversion into work, a system must cycle between hot and cold sources continuously. In each cycle, a certain amount of heat taken from the hot source (useful energy) is partially converted into work, the rest is rejected to the cold source (dissipated energy)", this is known as the Second Principle of Thermodynamics. For this reason, Nicolas Carnot is considered the father and founder of Thermodynamics.

Since then, thermodynamics has evolved and presents four Fundamental Laws, which represent the characteristics present in thermodynamic systems to the transfer of energy between two or more physical systems in the form of heat or work. In the particular case of civil and material engineering, there is a specific interest in the laws that govern heat transmission. That is, considering a body with a different temperature from its surroundings, the heat flow occurs to achieve thermal equilibrium, which means the zero law of thermodynamics. Also, when a thermal energy transfer between bodies occurs, in this case, the thermal propagation occurs from the warmest to the coldest body, representing the second law of thermodynamics. In this context, engineers' main tools to develop thermal analysis are thermal conductivity, which represents heat transfer capacity, being defined as the heat flow driven by a temperature gradient transmitted over perpendicular thickness to the surface area.

In civil construction, daily thermal effects such as low amplitude ambient thermal variation represent the elementary thermal analysis. In this case, a stationary state is

considered in which temperature gradients act directly with the materials thermal expansion coefficients, generating volume variations. In terms of structural volume variation of elements, this problem may be increased by the structure's staticity degree. This effect occurs mainly in the particular case of hyperstatic structure, in which the volumetric variation influences the development of internal forces that produces a stress distribution.

However, for special temperature gradient conditions, such as fire situations, thermal analysis becomes essential for structural fire safety. In these cases, transient thermal analysis may be the better option and should be chosen. After all, the heat flow and temperatures inside the structures change over time, changing the thermal and mechanical properties of the materials until the structural object reaches a critical temperature.

In 1961, the Organization of International Standards appointed a committee to develop a study of specifications for carrying fire resistance tests, originating the first design version for the standard temperature-time curve, resulting from a uniformity between the American ASTM E119 (1918) and British BS 476 (1932) curves. In 1975, a standard fire curve was presented by the publication of ISO 834 standard "Fire-Resistance Tests - Elements of Building Construction". This standard has international coverage and worked to develop national standardized fire curves in some countries, such as the case of Australia's AS 1530 (1994). Subsequently, in 1999, this standard went through a revision reformulating some test requirements and specifications of measuring instruments and instrumentation, thus introducing ISO 834-1[9].

However, the tests proposed by ISO-834 were expensive and time-consuming. For this reason, the need to develop calculation methods arose to determine the fire resistance of steel and concrete. In Europe, in 1983, the first technical standard was presented with fire resistance calculation recommendations for composite steel/concrete slabs by ECCS 1984 [10]. This standard was required to guarantee structural safety according to the fire resistance classes established by ISO 834-1 [9] without the obligation to carry out experimental tests.

In 1980, started an expansion movement in the commercialization of composite steel/-concrete deck slabs in the united kingdom. Although this practice had 20 years of application in North America, it concerned the regulating authorities in the United Kingdom and Europe, because the amount of data presented so far was insufficient to achieve the fire safety criteria established by European standards. Therefore, in 1988, Cooke et al.[1] demonstrated the fire resistance capacity of the composite slabs up to 90 min with only a reinforcement mesh in the concrete. After all, until then, for this resistance criteria, it was necessary to use reinforcement bars. These studies were grounded on tests developed by the Construction Industry Research & Information Association (CIRIA) and British Steel Corporation (BSC), performed in 1983/1985 and 1984/1986, respectively. The experiments also concluded that the reentrant geometry slabs offer better insulation and thermal shielding properties than the trapezoidal ones.

Ralph Hamerlinck realized that the structural analysis performed based on ISO 834 [9] was expensive and time-consuming and the calculation model provided by ECCS 1984 [10] was very conservative from the structural safety viewpoint. For this reason, he foresaw the development of a mathematical model that enables estimation of the fire resistance of composite concrete/steel slabs with steel deck. Therefore, in 1990, Hamerlinck published the paper "A numerical model for fire-exposed composite steel/concrete slabs" [11], in which proposed a numerical calculation model that comprises three independent numerical models. The design comprises thermal and mechanical models for the cross-section analysis and a structural analysis model for composite slabs. The model was validated by the Institute for Building Materials and Structures (TNO) experiments. Later, in 1991, Hamerlinck detailly described all the methods used on his calculation model development through the work "The behavior of fire-exposed composite steel/concrete slabs" [12].

In 1997, K. Both [13] developed a finite element model to determine the thermal and mechanical response of the Slim Flor systems exposed to fire using the DIANA software. Kees Both realized that for temperatures above 100°C, when the moisture evaporation process occurs on the concrete, there is a contact loss between the steel deck and the concrete. So a heat transfer by radiation and convection to the void layer between steel

and concrete was introduced. Supported by experimental tests previously carried out on Slim Flor systems, it was possible to validate the numerical model. A parametric study was performed and made possible the formulation of simple calculation rules for Slim Flor systems, making the thermal analysis faster and guaranteeing cost reduction to the construction system.

In 2006 Wald, et al. [14] reports several results of a research project through his paper. The subject consists of an experimental program to investigate the structural behavior of an eight-floor steel/concrete composite frame building. The project comprises seven large-scale fire tests realized at various positions of the experimental building. Most of them were performed with a natural fire test analysis to investigate the temperature development within different structural elements. A detailed explanation of each test is presented in "The Behaviour of Multi-Storey Steel Frame Buildings in Fire" [15]. The experiments were conducted by Building Research Establishment (BRE) at the Cardington Laboratoire's steel test structure build in 1993. The building had the following dimensions 21 x 45m in plan and 33m of high. The simulation of the mechanical load was performed by placing sandbags in addition to the structure's self-weight. As the structure's collapse was not reached, the tests confirmed the conservatism of Eurocode fire design. They concluded that the arrangement presented an adequate fire safety condition, that is, a standard office (building model for which the load distribution arrangement was made) has these same resistance characteristics under fire conditions. In addition to these verifications, the experimental test results were used to perform a behavior study of the connections between slabs, beams, and columns to refine the analytical and numerical calculation models.

The results obtained by the experimental fire tests developed in the Cardington laboratories recorded only a few temperature measurements points through the depth of the slab in tests 1-3. That is, there is a small amount of information on the temperatures reached in the slab. Furthermore, there is no temperature recorded in the slab in test 4. For these reasons, in 2001, Lamont S. et al. [16] performed a numerical heat transfer simulation to carry out a 2D nonlinear transient thermal analysis using the finite element

software HADAPT. Tests 1-3 were used to calibrate this model, which was then used to predict the slab temperatures in Test 4. Although the results obtained from the model have been more than satisfactory, successfully modeling the results of Tests 1-3 and effectively predicting Test 4, it should be mentioned that the model overpredicts the steel temperatures but works very well for the concrete measurements.

Gillie M. et al. in 2001 [17] developed a method of modeling composite floor slabs in fire conditions using a stress-resultant approach. Two software were used to perform the analyses. The first was SRAS, which was used to model arbitrary orthotropic slabs sections at elevated temperatures and determine their behavior. The second program, FEAI, that interfaces with the finite element package ABAQUS. It was used to build realistic structure models and determine its behavior in fire conditions. The main focus of this work was to determine the use of the SRAS to analyze the floor slab from the Cardington fire tests, presenting the slab behavior under a variety of load conditions. The research demonstrated suitable stress resistance for analyzing and modeling the behavior of concrete slabs at high temperatures. In general, the method showed satisfactory results for predicting the behavior of composite slabs.

In 2002 Gillie M. et al. [18] performed structural analysis of the third Cardington test using the results of the FEAST program. It consists of a user-defined subroutine that can be used with ABAQUS finite element software to specify the behavior of shell elements using a stress-resistance approach. The model analysis showed that in a fire situation, the structural response is governed by thermal expansion effects, and the effects of cracking and gravity loading take time to start interfering in the structure behavior. However, at extreme temperatures, a significant effect in the composite slabs is the tensile action on the reinforcement mesh, at this moment, the gravity loads directly affects the magnitude of the tensile forces in these elements. The analysis of thermal gradients through the slab's depth showed significant interference at high temperatures after the steel deck has lost most of its resistance properties. These thermal gradients produce hogging moments, giving rise to increasing deflections at the slab. By the way, these thermally induced hogging moments may be present in geometrically sagging regions. Therefore, the authors

conclude that to help composite structures perform while maintaining structural integrity during fires, it is necessary to ensure sufficient ductile reinforcement in concrete slabs.

Lamont S. et al. [19] performed finite element analyses using ABAQUS software in order to study the structural behavior of composite steel and lightweight concrete slab frame during two separate single floor compartment fires. The study of the structural behavior during a fire was modeled in a five-story tall structure. The structure was submitted initially to a short duration fire with high temperature and later to a second fire with a long duration and lower peak temperature than the first. Analyzing the results, the authors realized that the most destructive fire from the structural safety viewpoint is the short-duration fire with high intensity. In this case, large deformations arise quickly, resulting in an early failure of the structure, thus going against the sense employed in the analysis of the area under the fire curves Temperature-Time. Also it was concluded that long duration and lower intensity fire results in higher temperatures in steel and concrete as expected. However, these values are reached after a more extended period of exposure, thus ensuring that even if there are larger displacements concerning the short-duration fire, these will occur later in the structure. Therefore, as expected, the stress state of composite structures is significantly affected during the heating phase, with more significant stresses in the short fire exposure due to the high normal gradient.

Still in 2004, L. Lim et al. [20] developed a numerical model using a nonlinear finite element SAFIR software. They determined the fire behavior of two-way reinforced concrete slabs exposed to ISO-834 [9] standard fire. The model validation was performed by a comparison with experimental tests of two-way reinforced concrete slabs exposed to fire previously developed by the authors [21]. In general, the 3D analyses of two-way reinforced concrete slabs modeled with SAFIR quadrilateral elements show convergence with the experimental tests. Thus enabling the determination that in both cases, the simply supported two-way slabs have excellent fire resistance due to a double curvature deformation and the constant support at the four edges. Another factor contributing to the excellent behavior of the slabs in fire situations is the development of tensile membrane action in the initial stages of fire exposure. However, it was complicated to predict

the behavior of the composite slab with the steel deck because, for reasonable accuracy of these results, it is necessary to focus on the detailing and accuracy in modeling the debonding effect.

Since composite slabs demonstrate compliance with stringent regulations and fire resistance requirements, this kind of structure is considered one of the best examples to study the inherent fire resistance of composite structures through analytical design. This reason leads researchers to frequently use composite steel-concrete slabs in experiments and validation model development in order to ensure structural integrity during fire conditions, then, in 2006, Wang A. J. and Chung K. F. [22] conducted three standard ISO-834 [9] fire tests named CS1, CS2, and CS3 in order to assess the structural performance of simply supported composite slabs under fire using reentrant profiled steel decking. The composite slabs used in the tests were designed to attend fire resistance periods of 1, 2, and 3 hours, and design differences include concrete thicknesses and quantity of bottom rib steel reinforcement. Through the tests, the authors evaluated the fire resistance of the slabs for the load-bearing (R) criterion, determining the maximum displacements and the maximum displacement rates of the slabs.

Until recently, theoretical and experimental research investigating the effect of fire on structures has been concerned with evaluating structural behavior during the heating phase of fires. After all, internationally accepted standard fire tests use only this phase in their wordings. However, the cooling phase of structures is equally vital in ensuring structural safety under fire conditions. Fire tests in actual buildings have already shown that the structure can survive the heating phase and fail during the cooling phase. Thus in 2011, Bailey C. G. and Guo S. [23] determined the behavior of composite slabs under the heating and cooling phases, thus comprising all phases of a fire. Nine identical composite steel-concrete slabs comprising the steel mesh, normal weight concrete, and trapezoidal metal decking were tested during the experiments. Of these, seven slabs were tested under different fire conditions, including the heating and cooling phases, however, the other two were tested under ambient temperature conditions. In order to determine the structural behavior at different heating regimes, three different fire scenarios were adopted. The first

scenario consisted of heating the furnace for 40 minutes, reaching a temperature of 950 °C, followed by a cooling phase. For the second scenario, the heating took 90 minutes, reaching a temperature of 800 °C and then a cooling phase. The heating of the third scenario was precisely like the first, with changes only in the cooling phase, which was slower because the cooling fans were switched off. For fire scenarios 1 and 2, the slabs were tested under an applied static load of 72, 44, and 12 kN, representing the commonly real loads situations and enabling the investigation of different structural responses. For fire scenario 3, only one test was performed with an applied load of 44 kN. The results presented by the authors showed that the maximum vertical displacement during heating occurred in fire scenario 1 because the displacement was governed by the thermal curvature and the temperature of the steel deck. However, the highest temperature on the top surface of the slab occurred during cooling for fire scenario 2 because the time demanded by the heating phase allowed a greater time for the heat conduction through the slab. Also, in fire scenario 2, the mesh reinforcement reached the highest temperatures among all the tests. The authors determined that the slab's vertical displacement depends on both the applied load and temperature to which the slabs are exposed. In terms of residual displacement, it was determined that the cooling time directly affects the magnitude of the residual displacement.

A continuation for studies that aim to comprise the heating and cooling phases of composite slabs under fire situations was presented by Guo S. [2] in 2012. In order to validate the numerical models developed in this paper, the author used experimental fire tests applied to seven trapezoidal steel decking composite slabs tested under different fire exposure conditions. These tests were previously detailed and carried out by Guo S., and Bailey C. G. at the University of Manchester in 2011 [23]. Two nonlinear finite element models were then created using ABAQUS software, the models aimed for the simulation of thermal and mechanical behavior of composite steel/concrete slabs during heating and cooling phases. In order to simplify the thermal model, the longitudinal temperature distribution was assumed constant, enabling the production of a plane model with a steel-concrete interaction simplified to a thin layer between these materials. The simplifying

model modifications comprise a narrow strip with 180 mm width for slab simulation concerning structural analysis. The concrete, the steel sheeting, and the mesh modeling were developed using Solid elements (C3D8), shell elements (S4R), and truss elements (T3D2), respectively, and nonlinear spring elements modeled the interaction between the steel deck and concrete. The results showed that the reaction force of composite slabs suffers a significant amplitude variation during heating and cooling phases, which influences the structure load distribution. The structural analysis showed that the yield of steel deck and concrete crack could reduce the internal force induced by thermal expansion, which means that the weakening of composite slabs may benefit restrained structures at elevated temperatures. A parametric study was also performed in order to investigate the effect of concrete strength, the thickness of steel deck, and the reinforcement mesh size on the behavior of composite slabs under fire conditions. This analysis showed that the steel deck thickness carries a significant effect on composite slab behavior. The concrete strength and mesh size have a minor influence.

In the last years, an extensive range of thermal and structural models have been developed in different finite element software to predict the structural behavior of steel/concrete composite slabs under fire conditions. In these circumstances, it is worth mentioning the study developed by Jiang J. et al. [24] in 2014. The paper presents a three-dimensional finite element model of a plane reinforced concrete composite slab modeled by the shell element and beams/columns in reinforced concrete shaped by three-dimensional beam elements, both using OpenSees software. This study aimed to add an extension of the OpenSees structural analysis software framework to model steel frame composite structures under fire. The model performance was verified and validated by analytical solutions and experimental results, such as fire tests performed on simply supported composite beams and reinforced concrete slabs with membrane action investigation. In order to ensure more reliability of the results, the Cardington restrained beam tests and British Steel Corner tests were adopted. Therefore, the project carried out by the authors was the first step in the development of an open-source computational platform for structural analysis of structures under fire conditions, from dynamic fire simulation to heat transfer

analysis and mechanical analysis.

Piloto P. et al. [5] analyzed in 2018 the fire resistance of composite concrete slabs with profiled steel deck, typically reinforced by a steel mesh at the topside, including reinforcing bars between its ribs. This structural solution is commonly used in several types of buildings. However, it is necessary to verify its safety in fire situations. In general, for slabs with normal weight concrete, the fire requirements are usually specified by fire rating periods of 30, 60, 90 minutes. Usually, the design validation is performed using the ISO-834 standard fire curve [9], taking into account the criteria for stability (R), insulation (I), and integrity (E). Since experimental tests are expensive and time-consuming, fire resistance can be evaluated by numerical simulation or by simple calculation methods. For the development of this paper, the fire rating for insulation (I) criterion was evaluated using numerical and simple calculation methods. Thirty-two different trapezoidal geometry configurations were used to evaluate the effect of the concrete and steel deck thickness. The results obtained by the authors allowed the demonstration of the fire resistance (I) increase with concrete thickness for both calculation methods. However, using the numerical method, the simulation predicts a lower fire resistance (I) when compared to fundamental standards, consequently ensuring more structural safety when using this method. Therefore, a new safer design formula was proposed to define the fire resistance.

In 2019 Piloto P. et al. published two papers [6, 7] that investigate composite steel-concrete slabs' thermal behavior under standard fire test conditions. The slab's structure consists of a profiled steel sheet covered by a concrete layer. To resist the negative bending and prevent concrete cracking, a steel mesh was used on the top. In order to resist the positive bending, individual rebars were placed between its ribs. The Numerical analyses were performed using the computer software ANSYS and MATLAB. The 3D models were studied through nonlinear thermal and structural analysis using finite elements. Thus the numerical validation for the load support (R) and Insulation (I) criteria were determined. For the thermal model, an air gap between the steel deck and concrete was included to simulate the debonding effect. First, the thermal and mechanical 3D models were validated against experimental data. Then, a comparison between the Insulation (I) and

load bearing (R) results obtained through numerical models with the experimental results and the simplified calculation model of Eurocode 1994-1.2 [4] was made. This analysis showed that Eurocode 1994-1.2 overestimate the fire resistance providing unsafe results.

On the other hand, the numerical results obtained, including the perfect contact between the steel deck and the concrete, underestimate the fire resistance. So, confirming that the models developed considering the debonding effect are closer to real situations. In order to optimize the current calculation methods, a new calculation proposal to the insulation fire resistance criterion was presented.

Concerning experimental tests developed recently, it is worth mentioning the work developed by Coz-Díaz J. J. in 2020 [25]. The paper presents an experimental study to establish a performance and behavior comparison between composite slabs made in lightweight concrete (LWC) and normal weight concrete (NWC), both with trapezoidal steel decking profiles exposed to a standard time-temperature curve. In general, this comparison was developed by collecting data on temperature distribution and deflections of the composite slabs, studying the effects of fire exposure in a customized furnace designed by the authors. Thus, besides the fire resistance comparison study of different concrete types, they were concerned about presenting a new design and construction of a furnace to reproduce fire conditions established in agreement with Spanish standards.

Regarding the slab's composition, both concrete types were reinforced with polyolefin fibers. A 2mm steel bars reinforcement was placed at the slab's top to avoid shrinkage cracks in concrete. An expanded clay was adopted to produce the lightweight concrete due to its high performance and thermal insulation capability. The slabs were tested with 180 days of concrete age. The design of the new furnace for composite slabs was proved through successful tests. After all, the results demonstrated that the furnace's original design is appropriate for testing this type of structural element under fire conditions. Concerning the comparison between the different concrete types, it was noticed that the evaporation process in LWC slabs is lower than in NWC slabs due to the higher permeability of LWC and the porosity of expanded clay. Consequently, LWC heat transfer and

exposed surface temperature are lower than NWC under fire conditions. The experimental results also showed no spalling in slabs, and both integrity and insulation criteria were satisfied. However, the load criteria did not achieve the minimum value of 30 min for LWC.

The study developed by Ali T. et al. in 2020 [26] presented a finite element model to simulate a composite concrete-steel slab through ANSYS computer software. Five slabs (S-1, S-2, S-3, S-4, and S-5) with the same trapezoidal geometry characteristics were modeled, the structural components gave their difference. S-1 was modeled with Plain concrete, S-2 and S-3, both with shear connectors, with different diameters and spacing, S-4 and S-5 with steel reinforcement mesh, but with different diameters and spacing. An analytical study was carried out to investigate the structural behavior of the composite slabs for both new and existing constructions. The results allowed determining that shear connectors can increase in the maximum deflection and slab ductility. The reinforcement steel mesh also increases ductility, besides increasing the maximum ultimate load. The use of profiled deck sheet can reduce by 20% the concrete volume and, the behavior of the slabs depends mainly on the shear span.

In 2021 Bolina F, Tutikian B, Rodrigues J. P. C. [27], studied the thermal behavior of composite steel-concrete slabs in fire, aiming to make a comparison of the temperature distribution in the cross-section through several methods: experimental, numeric, and analytical. The authors carried out eight full-scale fire tests. With these experimental tests, the numerical models developed using the ABAQUS software were calibrated. These two methods were compared with the analytical method provided by Eurocode 1994-1.2 [4]. The authors noticed a convergence of the analytical method with the numerical and experimental methods only for the steel deck, but not for the concrete, the rebars (positive and negative), and the thermal insulation. Therefore, a new analytical approach was developed to determine the temperature in the rebars and new factors to evaluate the performance of the thermal insulation. Other conclusions presented by the authors were: during the experimental tests, the steel deck detachment was observed in the first 5 minutes of exposure to the ISO-834 fire curve, implying that the benefits of the composite

slab effect do not occur throughout much of the fire exposure period, the need for a review in Table D.6. of Eurocode 1994-1.2 was also mentioned. Furthermore, the location of negative rebars in the cross-section influences their temperatures.

## 1.2 Objectives

### 1.2.1 General objectives

This work initially aims to develop two-dimensional and three-dimensional finite element thermal models to study the behavior of composite slabs with collaborating steel deck under standard fire ISO-834 [9]. After that, an analytical structural analysis will be performed to determine the temporal variation of the slab's positive bending moment (sagging) due to its thermal variation.

In order to perform the thermal analyses, the software MATLAB R2019a and ANSYS Mechanical APDL 2021 R1 were used. Bearing in mind that, ensuring reliable results is one of the principal concerns of this work. It is worth mentioning that the parametric analyses were based on the finite element method, already validated by Paulo P. et al. [5–7].

### 1.2.2 Specific objectives

- Development of numerical models for thermal analysis of concrete/steel composite slabs using Normal Weight Concrete (NWC) and Lightweight Concrete (LWC).
- Determination of the temperature in all steel deck components (Upper flange, Web, Lower flange) and the rebars to the following fire resistance times: 30, 45, 60, 90, and 120 min for LWC and 45, 60, 90, and 120 min for NWC.
- Comparison of temperature results obtained through the finite element software between them and also with the simplified calculation method presented by Eurocode 1994-1.2 [4].

- Present new coefficients and a new formula for the simplified temperature calculation method presented in Annex D of EC 1994-1.2 [4]. The new coefficients are proposed for all steel deck components (Upper flange, Web, Lower Flange) and also for the reinforcing bars.
- Determination and comparison of the influence performed by different methods of temperature prediction (parametric analysis, simplified calculation method provided by EC 1994-1.2 [4] and the new calculation proposal) on the structural response of the composite slab under positive bending moment (sagging).

### 1.3 Dissertation Structure

This dissertation comprises nine chapters, plus two additional sections. The first section is dedicated for the bibliographical references and the second for annexes, containing both the technical data sheets of the composite slabs and the results of all the thermal simulations performed using ANSYS and MATLAB software.

In this first chapter, besides presenting an introduction to the subject under study, a bibliographical study was developed in order to present both a historical context of the evolution in researches associated with the determination of fire resistance in concrete/steel composite structures and in order to define essential concepts for developing this research. Besides this approach, the general and specific objectives that motivated the development of this thesis are also presented.

The second chapter presents the different ways of heat transfer in energy form, approaching and describing the laws that govern the behavior of each different form of heat transfer: conduction, convection, and radiation. The concepts and definitions around this subject are also included.

Chapter 3 presents the fire resistance criteria established by European standards through well-defined parameters in order to ensure structural safety under fire conditions.

The fourth chapter presents a brief overview of the methodology employed in developing both the simplified calculation methods and the advanced calculation methods. A

description of the materials used in the elaboration of the thermal simulations is also presented.

Chapter 5 is responsible for presenting the thermal and mechanical properties of all materials used in the composite slab design. An approach of the thermal influence on the intrinsic characteristics of the materials is required because the exposure of structural elements to a high-temperature variation affects the load bearing capacity of the element, thus compromising its structural fire safety.

The sixth chapter describes the simplified calculation methods contained in Eurocode 1994-1.2. This method consists of an analytical approach where it is possible to determine the structure's minimum fire resistance time taking into account the criteria of insulation (I) and load-bearing capacity (R).

Chapter 7 presents the advanced calculation methods. This chapter describes how the finite element model was developed using ANSYS and MATLAB software to develop a parametric analysis. This chapter also presents the boundary conditions required to solve the non-linear thermal analyses. The boundary conditions are defined in accordance to EN 1991-1.2.

Chapter 8 highlights the results obtained from the thermal simulations, which were performed with both software. This chapter also presents a new calculation proposal and new coefficients for the Annex D of Eurocode 1994-1.2. This new proposal aims to improve the temperature calculation in the steel deck components (Upper flange, Web, Lower flange) and of the rebars. The influence of the new temperatures proposal on the bending resistance moment of composite slabs is also presented.

Chapter 9 presents the conclusions about the results achieved through the parametric study, highlighting the effects of the new calculation proposal on the temperature of the components. It is also provided some suggestions for future research that will have this dissertation as a background.

# Chapter 2

## Heat Transfer

In order to ensure greater structural safety of buildings, their behavior in fire situations should be determined whenever necessary, especially in situations where the resistance capacity of structural elements depends on the contact between different types of material, such as steel and concrete, such as composite slabs with steel deck, for example. The performance of a structure concerning its load-bearing capacity depends directly on its mechanical properties. However, during fire situations, these properties are directly influenced by the temperature of the structural elements, which depends on the material's thermal properties. Therefore, it is of utmost importance to determine how the thermal variation affects the mechanical properties and also how the heat distribution occurs in the structural elements.

Bearing this concept in mind, initially, an approach to the definition of heat transfer between different systems (body) is required. By definition, heat transfer consists of determining the rates of transfer of all forms of energy that can flow from one body to another due to their temperature difference. Whereas "temperature" consists of the amount of kinetic energy present in the molecules of this body, that is, it represents the degree of molecular agitation.

According to Y. A. Çengel e A. J. Ghajar [28], the basic condition for heat transfer is the existence of a temperature difference, since the temperature difference is the driving force for heat transfer. Thus, the magnitude of the temperature gradient in a specific

direction gives the heat transfer rate along this direction. Therefore, as the temperature gradient increases, the heat transfer rates also increase. Furthermore, there are three basic mechanisms governing heat transfer: conduction, convection, and radiation.

## 2.1 Conduction

Conduction is a type of energy transfer in the form of heat. It occurs at the molecular level (between atoms or molecules) generated by a temperature gradient. The flow always occurs from the higher temperature body to the lower temperature body through contact between particles until the thermal equilibrium is reached.

According to Y. A. Çengel e A. J. Ghajar [28], conduction is the heat transfer from the most energetic particles of a substance to adjacent, less energetic particles, as a result of its interactions.

Furthermore, Forsberg, C. H. [29] also states that heat conduction occurs only upon a temperature difference between two locations in a solid or two locations in essentially non-moving liquids or gases. The author also informed that through experimental tests, it was possible to see that the heat transfer rate per unit area is proportional to the temperature gradient of the material. This observation allowed the French mathematician and physicist Joseph Fourier to introduce Fourier's law shown in equation 2.1. The Fourier's law gives the heat flux ( $\dot{h}_{cd}$ ) in  $[W/m^2]$ , which is the heat flow rate per unit area in the x-direction at the required position in a solid or fluid.

$$\dot{h}_{cd} = -\lambda \frac{d\theta}{dx} \quad (2.1)$$

were  $\lambda$  is the thermal conductivity of the material in  $[W/mK]$ , which means the the material's ability to conduct heat. The term  $\frac{d\theta}{dx}$  represents the temperature Gradient given in  $[K/m]$  in the x-direction.

A more comprehensive way to represent Furrier's law is to write it in vector form to

encompass all three Cartesian dimensions, this formulation is given in equation 2.2.

$$\vec{h}_{cd} = -\lambda \cdot \vec{\nabla}\theta \quad (2.2)$$

where  $\nabla T$  is the temperature gradient vector.

## 2.2 Convection

Heat convection is a heat transfer process between a solid surface and an adjacent gas or liquid with different temperatures, which must be in motion. It is dependent on the effects of fluid conduction and fluid motion. Thus the heat transfer rate is directly linked with the fluid velocity, implying that this phenomenon occurs due to the dynamic motion between the involved elements (the solid and the fluid). Additionally, some other factors influence the heat transfer rate, such as the fluid physical and thermal properties and the surface geometry.

According to Forsberg, C. H. [29], convection is subdivided into two classifications: forced convection and natural (or free) convection. In forced convection, a device is usually responsible for providing a movement to the fluid, so this movement presents a substantial magnitude to influence the phenomenon under analysis. This can be a fan for gases or a pump for liquids, or even a natural phenomenon such as the effect of wind on structures. Natural convection, on the other hand, is not affected by devices. The motion is smoother and caused by buoyancy effects in the fluid caused by thermal expansion.

In agreement with Y. A. Çengel e A. J. Ghajar [28], Forsberg, C. H. [29], and Hamerlicnk R. H. [11], the formulation that governs the phenomenon of heat convection was given by the English mathematician, physicist, astronomer, and theologian Sir Isaac Newton. Therefore, equation 2.3 presents Newton's law for convection.

$$\dot{h}_{net,c} = \alpha_c(\theta_s - \theta_\infty) \quad (2.3)$$

where,  $\alpha_c$  is the Convection Coefficient [ $W/m^2K$ ],  $\theta_s$  is the body surface temperature and  $\theta_\infty$  is the temperature of the gas, or the fluid.

## 2.3 Radiation

Radiation is a heat transfer process that differs from the others previously mentioned mainly by the absence of a physical medium for propagation. This process occurs in any gaseous, liquid, or solid medium with a temperature different from its surroundings. The transmission of energy by radiation results from changes in the electronic configuration of the atoms, giving rise to a release of photons. That is, electromagnetic waves arise, which promote a very speedy transmission of energy. After all, in vacuum, electromagnetic waves propagate at the speed of light.

According to Y. A. Çengel e A. J. Ghajar [28], the amount of energy emitted by radiation from the surface of a body depends on its material and the conditions and temperature of its surface, thus allowing two bodies with different geometries to emit different amounts of radiation per unit area even at the same temperature. In this context, it is necessary to define the concept of the "black body", which is a perfect emitter and absorber of radiation. It means that the black body can absorb all the radiation incident and emit radiation energy uniformly in all directions. Therefore, the black body represents an ideal surface on which radiation's greatest possible amount of energy emission is achieved. For this case, employing Stefan Boltzman's law, it is possible to determine this maximum amount of energy emitted by a black body per unit of time and per unit of the area through the equation 2.4.

$$E_b(t) = \sigma \cdot \theta^4 \quad (2.4)$$

where  $\sigma$  is the Stefan–Boltzmann constant, which is  $5.670 \cdot 10^{-8} [W/m^2 \cdot K^4]$  and  $\theta$  is the absolute temperature of the surface in [K].

The above expression works well only for black bodies. For real surfaces, the amount of energy emitted in the form of radiation is smaller. The term that allows relating the ratio of the radiation emission capacity of a real surface to an ideal black surface is named emissivity ( $\varepsilon$ ). Therefore, emissivity is an adimensional value that for black bodies is adopted  $\varepsilon = 1$ . This value differs according to the type of material but is always smaller than 1. Consequently, it is possible to rewrite the equation 2.4 through the equation 2.5.

$$E_b(t) = \varepsilon \sigma \cdot \theta^4 \quad (2.5)$$

In the engineering field, some considerations are made, Eurocode 1993-1.2 [30] determines that for carbon steel elements,  $\varepsilon = 0.7$  should be considered, and Eurocode 1992-1.2 [31] determines the same emissivity  $\varepsilon = 0.7$  for concrete. Regarding flames, the value adopted for emissivity must be equal to 1, and considering the radiation emission is always diffuse. In other words, it presents the same intensity of heat propagation in all directions of space. In addition, Eurocode 1991-1.2 [32] presents a formulation to determine the heat flux by radiation on the structural elements surfaces exposed to the fire  $\dot{h}_{net,r}$  in  $[W/m^2]$ . The equation 2.6 represents this heat flux.

$$\dot{h}_{net,r} = \phi \varepsilon_f \varepsilon_m \sigma \left[ (\theta_r + 273)^4 - (\theta_m + 273)^4 \right] \quad (2.6)$$

where  $\phi$  is the view factor,  $\varepsilon_f$  is the emissivity of the fire,  $\varepsilon_m$  is the surface emissivity of the exposed structural element,  $\theta_r$  is the effective radiation temperature of the fire environment

given in  $[\text{°C}]$ ,  $\theta_m$  is the surface temperature of the member also in  $[\text{°C}]$ .

The view factor ( $\phi$ ) is a term of great relevance in studying the thermal behavior of structures exposed to fire situations. It is an adimensional term representing the portion of heat absorbed in the form of radiation by the surface exposed to fire, so it directly depends on the element's geometric arrangement.

The view factor presents high variability due to the high complexity involved in its determination. For this reason, the literature presents some formulations that make it easier to obtain these values for some typical cases in engineering, as is the case of composite slabs with steel deck collaborating profiles. Therefore, to determine the view factor associated with Web and Upper Flange of steel deck, the Crossed-Strings Method, proposed by Hotell H. C. in 1950 [28], was used in this study. Following this rule, Figure 2.1 shows the parameters necessary for determining the view factor in composite slabs.

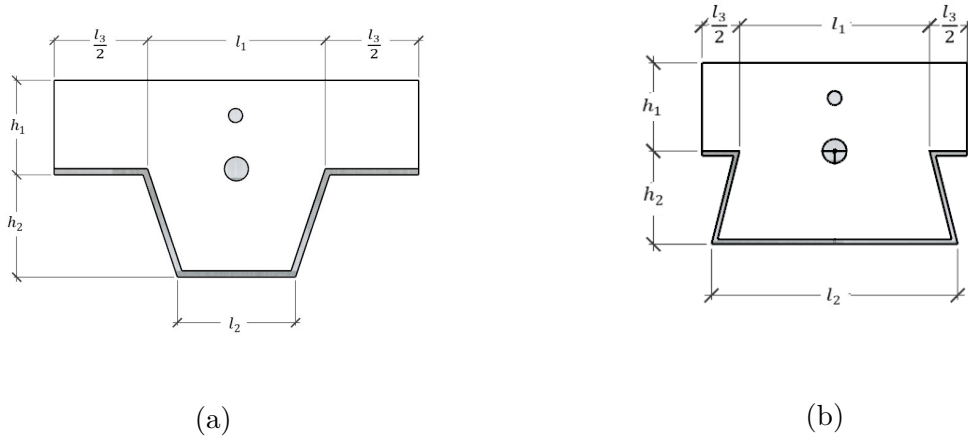


Figure 2.1: Geometric parameters to determine the average view factors according to each slab profile: (a) Trapezoidal, (b) Reentrant.

The view factor for the lower flange has a unit value. After all, there is no geometric constraint preventing the total incidence of radiation along its length. For the Upper Flange and Web, equations 2.7 and 2.8 provide the mathematical relations to determine this factor as a function of the geometric characteristics of the profiles presented in Figure 2.1.

$$\phi_{upper} = \frac{\sqrt{h_2^2 + \left(l_3 + \frac{l_1-l_2}{2}\right)^2} - \sqrt{h_2^2 + \left(\frac{l_1-l_2}{2}\right)^2}}{l_3} \quad (2.7)$$

$$\phi_{web} = \frac{\sqrt{h_2^2 + \left(\frac{l_1-l_2}{2}\right)^2} + (l_3 + l_1 - l_2) - \sqrt{h_2^2 + \left(l_3 + \frac{l_1-l_2}{2}\right)^2}}{2\sqrt{h_2^2 + \left(\frac{l_1-l_2}{2}\right)^2}} \quad (2.8)$$

The Figure 2.2 shows the arrangement of the view factors on the different profile geometries used for the composite slab's simulations.

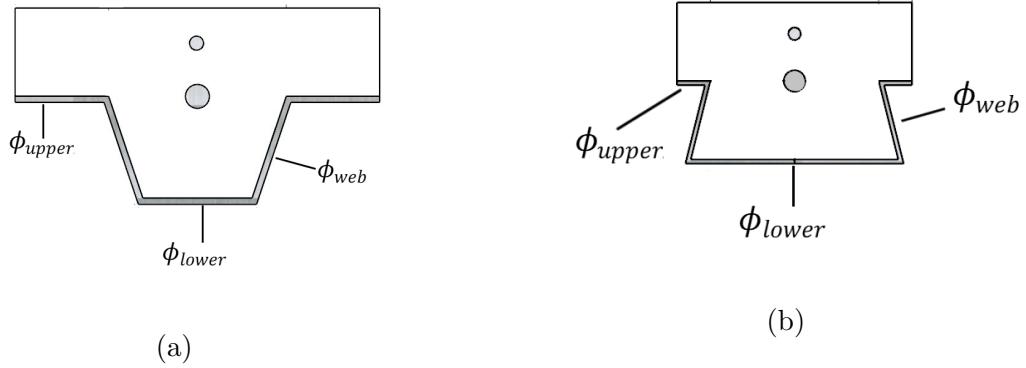


Figure 2.2: view factors arrangement according on each slab profile: (a) Trapezoidal, (b) Reentrant.

# Chapter 3

## Thermal and Mechanical Properties of Materials

The concrete and steel structures projects that aim to increase structural resistance and safety conditions in fire situations must be developed based on the study of the behavior of two important material properties: the thermal properties to perform the thermal analysis and the mechanical properties to perform the structural analysis.

The study of thermal properties results from how the thermal conductivity, specific heat, and density of materials respond to temperature increase. In order to determine the mechanical behavior, it is necessary to evaluate material characteristics such as yield stress, Young's modulus, stress-strain relationship, and expansion coefficient. [3].

### 3.1 Thermal Properties

In order to obtain results related to the steel/concrete composite slab's actual behavior, it is necessary to study the thermal behavior of parameters such as specific heat, thermal conductivity, and density as a function of the increase in temperature.

The composite slab is a heterogeneous structure, both globally and locally, in some specific elements. Thus the nonlinearity of heat transfer along the cross-section can be considered an inherent characteristic of this slab type.

The thermal properties for Normal Weight Concrete (NC) and steel are available in Eurocodes 1992-1.2, and 1993-1.2 [30, 31], respectively. For the analytical model development, the recommendations of the Eurocode 1994-1.2 [4] are followed. This standard comprises the information related to conventional concrete (NWC), steel, and Lightweight Concrete (LWC) specifications.

### 3.1.1 Steel

The thermal properties related to steel with structural and reinforcement application will be demonstrated and discussed in the sequence, which means it will comprise both the material used in the steel deck and the reinforcement bars. In general, the calculation methods developed were supported by the standards that govern the specific behavior of steel in fire situations [30] and the behavior of composite slabs [4].

The specific heat ( $C_a$ ) of steel represents the amount of heat required or expended to raise or decrease the temperature by  $1^\circ C$  per unit mass. Eurocodes 3 and 4 [4, 30] suggest the following formulation to determine the specific heat value.

$$\begin{aligned} & \text{for } 20^\circ C \leq \theta \leq 600^\circ C : \\ & C_a = 425 + 7,7 \cdot 10^{-1}\theta - 1,69 \cdot 10^{-3}(\theta)^2 + 2,22 \cdot 10^{-6}(\theta)^3, \end{aligned} \tag{3.1}$$

$$\begin{aligned} & \text{for } 600^\circ C \leq \theta \leq 735^\circ C : \\ & C_a = 666 + \frac{13002}{738 - \theta}, \end{aligned} \tag{3.2}$$

$$\begin{aligned} & \text{for } 735^\circ C \leq \theta \leq 900^\circ C : \\ & C_a = 545 + \frac{17820}{\theta - 731}, \end{aligned} \tag{3.3}$$

$$\begin{aligned} \text{for } 900^{\circ}\text{C} \leq \theta \leq 1200^{\circ}\text{C} : \\ C_a = 600, \end{aligned} \tag{3.4}$$

Figure 3.1 demonstrates the behavior of the specific heat of the steel as a function of temperature increase. It is possible to notice that for temperatures between  $0^{\circ}\text{C}$  and  $700^{\circ}\text{C}$ , the average value for the specific heat is approximately  $600 \text{ [J/kgK]}$ . Besides that, at this moment, the steel is in its Ferrite or alpha iron phase. However, when this temperature is exceeded, a phase transition process begins, consisting of a molecular rearrangement that causes a change in the material crystalline structure, which goes from a body-centered cubic structure to a face-centered cubic structure. This moment is when the phase transition occurs (Ferrite to Austenite or alpha iron to gamma iron). This process requires a considerable amount of energy [33, 34].

The temperature range in which the phase transformation occurs depends on the specific characteristics of each steel, among them the carbon content. The Austenite phase of steel needs special attention in the civil construction field because when this state is reached, the material may become more ductile and flexible depending on the cooling rate, thus compromising the resistant capacity of the structure.

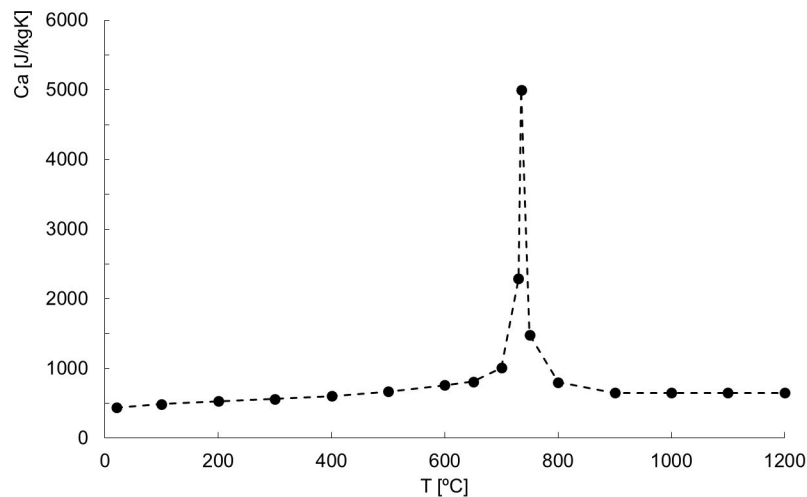


Figure 3.1: Specific heat variation as a function of temperature for steel.

According to Eurocode 4 [4], the density ( $\rho_a$ ) of both the structural steel and the reinforcing steel should be considered constant and independent of the temperature variation.

$$\rho_a = 7850, \quad \text{for } 20^\circ\text{C} \leq \theta \leq 1200^\circ\text{C} \quad (3.5)$$

where  $\rho_a$  is given in  $[\text{kg}/\text{m}^3]$  and  $\theta$  corresponds to temperature in  $[\text{C}]$ .

The thermal conductivity of steel ( $\lambda_a$ ) represents its capacity for heat transmission. There is a linear decrease as a function of temperature increase up to  $800^\circ\text{C}$  and then stabilizes at a constant value. This behavior is described by the equations 3.6 and 3.7 and is represented in Figure 3.2.

$$\lambda_a = 54 - 3,33 * 10^{-2}\theta, \quad \text{for } 20^\circ\text{C} \leq \theta \leq 800^\circ\text{C} \quad (3.6)$$

$$\lambda_a = 27,3, \quad \text{for } 800^\circ\text{C} < \theta \leq 1200^\circ\text{C} \quad (3.7)$$

where  $\lambda_a$  represents the thermal conductivity of steel in  $[\text{W}/\text{mK}]$  and  $\theta$  is the temperature in  $[\text{C}]$ .

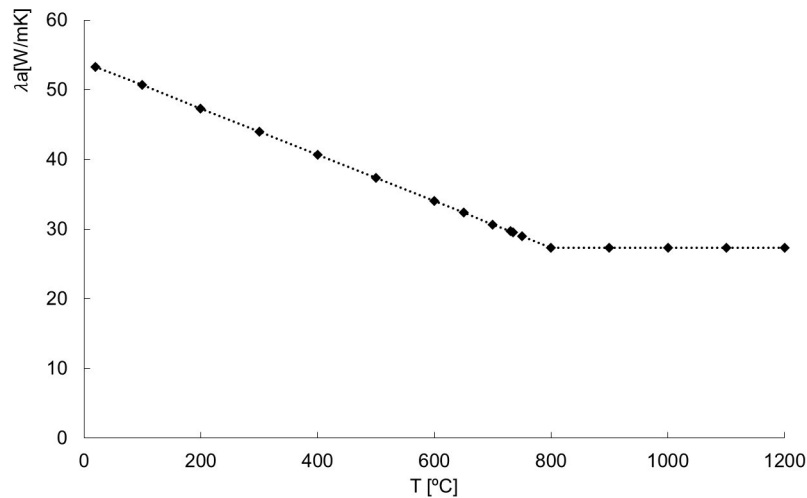


Figure 3.2: Thermal conductivity variation as a function of temperature for steel.

### 3.1.2 Concrete

This study will comprise two different concrete types, Normal Weight Concrete (NWC) and Lightweight Concrete (LWC), both with siliceous aggregates. The thermal properties of these materials were obtained according to Eurocodes 1992 part 1-2 and 1994 part 1-2 [4, 31].

#### Normal Weight Concrete (NWC)

For Normal Weight Concrete, also named conventional concrete, at moisture condition  $u=0\%$ , the specific heat  $C_p(\theta)$  is given by:

$$C_p(\theta) = 900, \quad \text{for } 20^\circ\text{C} \leq \theta \leq 100^\circ\text{C} \quad (3.8)$$

$$C_p(\theta) = 900 + (\theta - 100), \quad \text{for } 100^\circ\text{C} < \theta \leq 200^\circ\text{C} \quad (3.9)$$

$$C_p(\theta) = 900 + (\theta - 100)/2, \quad \text{for } 200^\circ\text{C} < \theta \leq 400^\circ\text{C} \quad (3.10)$$

$$C_p(\theta) = 1100, \quad \text{for } 400^\circ\text{C} < \theta \leq 1200^\circ\text{C} \quad (3.11)$$

where  $\theta$  corresponds to the concrete temperature in [ $^\circ\text{C}$ ] and  $C_p(\theta)$  refers to the specific heat in [ $\text{J}/\text{kg K}$ ].

The presented calculation method is valid for a moisture content of 0%. However, in reality, this condition is not satisfied. In order to solve this problem, Eurocode 1992-1.2 [31] provides that a peak value for the specific heat ( $C_{p.m\acute{a}x}$ ) at different moisture contents must be modeled by a constant function between 100 $^\circ\text{C}$  and 115 $^\circ\text{C}$ , decreasing linearly between 115 $^\circ\text{C}$  and 200 $^\circ\text{C}$ . The value for these constants are expressed in Table 1 3.1.

Table 3.1: Relationship between the moisture content and the maximum specific heat for NWC.

Moisture Content [%]	Cp.máx [J/kg K]
0.0	900
1.5	1470
3.0	2020

The standard suggests that for other moisture contents, a linear interpolation based

on Table 3.1 can be performed. When performing the specific heat variation as a function of temperature, the energy required to evaporate the water inside the concrete may be obtained by the area below the peak region. Figure 3.3 expresses this relationship for the moisture contents above mentioned.

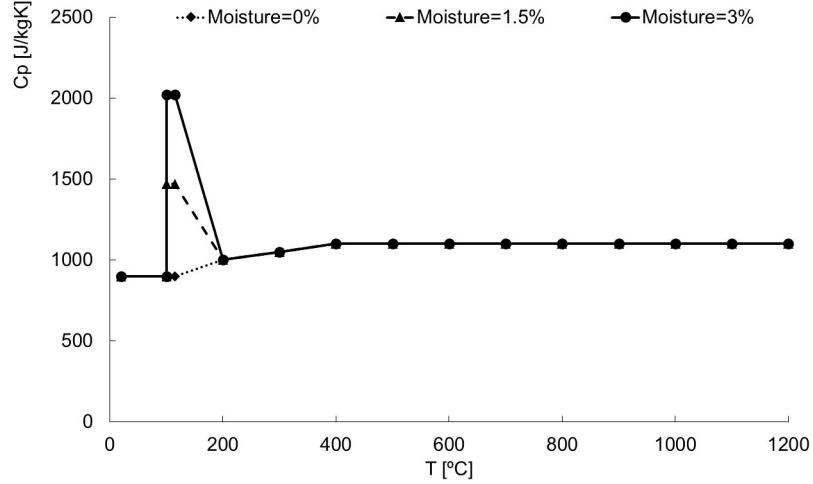


Figure 3.3: Specific heat variation as a function of temperature for different moisture contents.

Density  $\rho_{c,NWC}(\theta)$  is a property that also depends on temperature variation. After all, its value is affected by the water evaporation process that composes the concrete. The equations below demonstrate the density variation for different temperature ranges.

$$\rho_{c,NWC}(\theta) = \rho(20^{\circ}C), \quad \text{for } 20^{\circ}C \leq \theta \leq 115^{\circ}C \quad (3.12)$$

$$\rho_{c,NWC}(\theta) = \rho(20^{\circ}C) * \left(1 - \frac{0,02(\theta - 115)}{85}\right), \quad \text{for } 115^{\circ}C < \theta \leq 200^{\circ}C \quad (3.13)$$

$$\rho_{c,NWC}(\theta) = \rho(20^{\circ}C) * \left(0,98 - \frac{0,03(\theta - 200)}{200}\right), \quad \text{for } 200^{\circ}C < \theta \leq 400^{\circ}C \quad (3.14)$$

$$\rho_{c,NWC}(\theta) = \rho(20^{\circ}C) * \left(0,95 - \frac{0,07(\theta - 400)}{800}\right), \quad \text{for } 400^{\circ}C < \theta \leq 1200^{\circ}C \quad (3.15)$$

where  $\rho_{c,NWC}(\theta)$  corresponds to the conventional concrete density given in  $[\text{kg}/\text{m}^3]$ , when exposed to a temperature  $\theta$  in  $[\text{°C}]$ . On the other hand, the term  $\rho_{c,NWC}(20^{\circ}C)$  refers to the density of concrete at room temperature, so its value is  $2300 [\text{kg}/\text{m}^3]$ .

Figure 3.4 illustrates the behavior of concrete density as a function of temperature

increase.

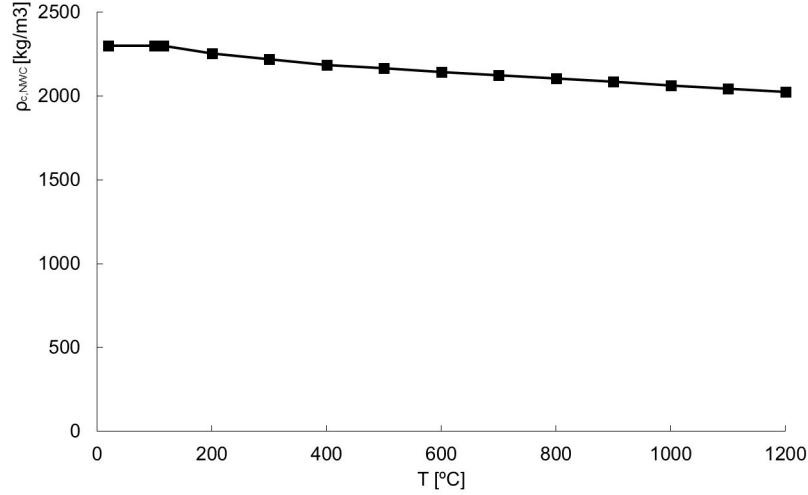


Figure 3.4: NWC density as a function of thermal variation.

For NWC thermal conductivity, any values contained between two limits defined by Eurocode 1994-1.2 [4] can be adopted. The standard presents two equations, one for the upper limit and another for the lower limit. Additionally, it suggests the use of the values contained in the upper limit for calculation purposes.

The upper limit for the thermal conductivity ( $\lambda_{c,NWC}$ ) is given by equation 3.16

$$\lambda_{c,NWC} = 2 - 0,2451 \cdot \left(\frac{\theta}{100}\right) + 0,0107 \cdot \left(\frac{\theta}{100}\right)^2, \quad for \ 20^\circ C \leq \theta \leq 1200^\circ C \quad (3.16)$$

where  $\theta$  corresponds to concrete temperature in [°C].

The lower limit for the thermal conductivity ( $\lambda_c$ ) is expressed in equation 3.17

$$\lambda_{c,NWC} = 1,36 - 0,136 \cdot \left(\frac{\theta}{100}\right) + 0,0057 \cdot \left(\frac{\theta}{100}\right)^2, \quad for \ 20^\circ C \leq \theta \leq 1200^\circ C \quad (3.17)$$

where  $\theta$  corresponds to concrete temperature in [°C].

Figure 3.5 demonstrates the upper and lower limits for the thermal conductivity of conventional concrete. For composite structures, Eurocode 1994 Part 1.2 recommends the upper limit.

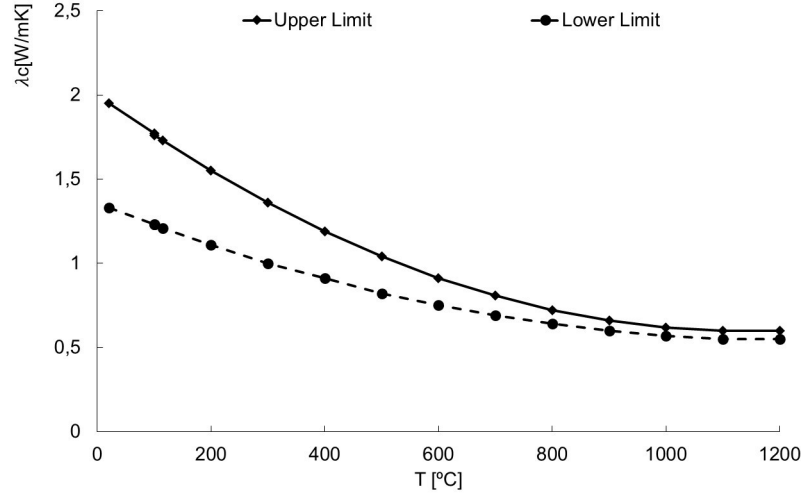


Figure 3.5: Upper and lower limits for conventional concrete thermal conductivity as a function of temperature variation.

### Lightweight Concrete (LWC)

According to Eurocode 1994-1.2 [4], for Lightweight Concrete, the specific heat  $C_c(\theta)$  may be considered constant and independent of the concrete temperature variation.

$$C_c(\theta) = 840, \quad \text{for } 20^\circ\text{C} \leq \theta \leq 1200^\circ\text{C} \quad (3.18)$$

where  $\theta$  corresponds to the concrete temperature in [°C] and  $C_c(\theta)$  refers to the specific heat in [J/kg K].

Exactly as occurs on NWC, to LWC the density is directly affected by the temperature evaporation, i.e., the LWC density depends on the moisture evaporation processes. The difference is given in the value adopted of concrete density at room temperature, instead of 2300 [kg/m<sup>3</sup>], must be taken in a range of 1600 [kg/m<sup>3</sup>] to 2000 [kg/m<sup>3</sup>], but the formulation still the same. The specific mass at room temperature for LWC ( $\rho_{c,LWC}(\theta)$ ) was considered to be 1800 [kg/m<sup>3</sup>], because it is the average value of the given range. Thus the density can be determined from the following:

$$\rho_{c,LWC}(\theta) = \rho(20^\circ C), \quad \text{for } 20^\circ C \leq \theta \leq 115^\circ C \quad (3.19)$$

$$\rho_{c,LWC}(\theta) = \rho(20^\circ C) * (1 - \frac{0,02(\theta - 115)}{85}), \quad \text{for } 115^\circ C < \theta \leq 200^\circ C \quad (3.20)$$

$$\rho_{c,LWC}(\theta) = \rho(20^\circ C) * (0,98 - \frac{0,03(\theta - 200)}{200}), \quad \text{for } 200^\circ C < \theta \leq 400^\circ C \quad (3.21)$$

$$\rho_{c,LWC}(\theta) = \rho(20^\circ C) * (0,95 - \frac{0,07(\theta - 400)}{800}), \quad \text{for } 400^\circ C < \theta \leq 1200^\circ C \quad (3.22)$$

where  $\rho_{c,LWC}(\theta)$  corresponds to the Lightweight Concrete density given in  $[\text{kg}/\text{m}^3]$ , when exposed to a temperature  $\theta$  in  $[\text{°C}]$ . On the other hand, the term  $\rho_{c,NWC}(20^\circ \text{C})$  refers to the density of concrete at room temperature, so its value is  $1800 [\text{kg}/\text{m}^3]$ .

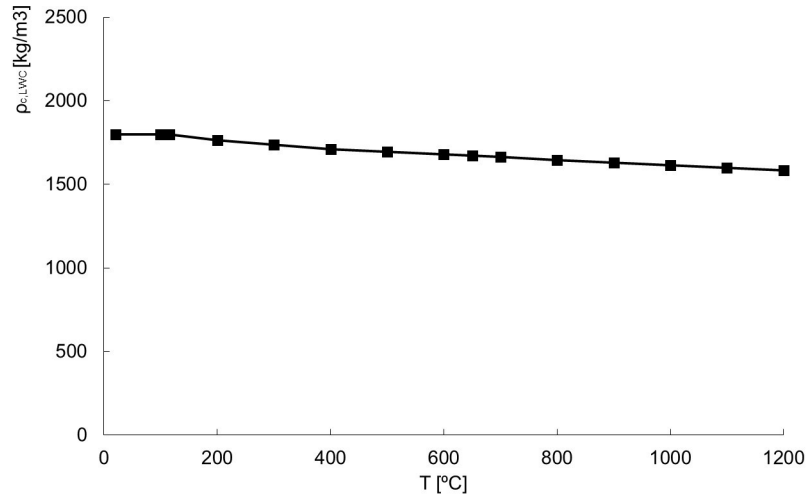


Figure 3.6: LWC density as a function of thermal variation.

For LWC, the following formulation governs the thermal conductivity ( $\lambda_{c,LWC}$ ) variation in function of temperature increase. It shows a linear decrease up to  $800^\circ\text{C}$  followed by a steady-state to a constant value.

$$\lambda_{c,LWC} = 1 - (\frac{\theta}{1600}), \quad \text{for } 20^\circ C \leq \theta \leq 800^\circ C \quad (3.23)$$

$$\lambda_{c,LWC} = 0,5, \quad \text{for } \theta > 800^\circ C \quad (3.24)$$

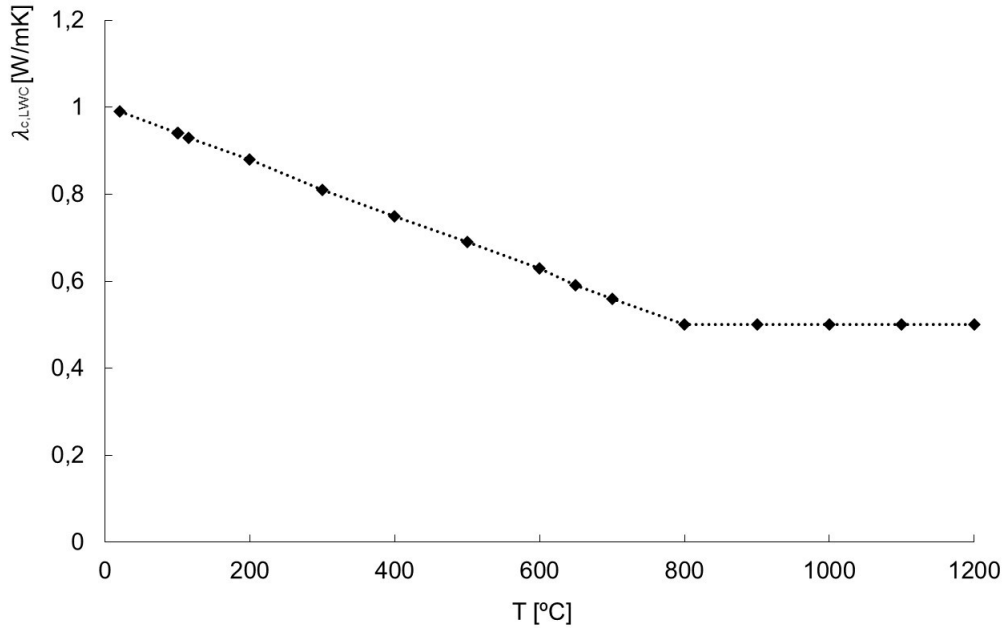


Figure 3.7: LWC thermal conductivity as a function of temperature variation.

### 3.1.3 Air

The study of the behavior of air thermal properties is necessary to determine the air-gap effect, which consists of a thin air layer that rises between the concrete and the steel sheet during the heating process. This effect occurs due to the thermal expansion difference of the two materials, which significantly affects the heat transfer in composite slabs.

Unlike steel and concrete, it was not possible to obtain the air thermal properties through technical standards. Therefore it was necessary to report to bibliography support. The book written by Çengel A. Y. and Ghajar J. A. [28], provides experimental values for the variation of specific heat, density, and thermal conductivity of air as a function of temperature increase. These values are presented in Table 3.2.

Figures 3.8, 3.9 and 3.10 shows graphically the behavior of air thermal properties varying according to temperature increase.

Table 3.2: Experimental results obtained by Çengel A. Y. and Ghajar J. A. for air thermal properties.

Temperature [°C]	Density [kg/m <sup>3</sup> ]	Specific Heat [J/kgK]	Thermal Conductivity [W/mK]
20	1.204	1007	0.02514
30	1.164	1007	0.02588
60	1.059	1007	0.02808
90	0.9718	1008	0.03024
100	0.9458	1009	0.03095
200	0.7459	1023	0.03779
300	0.6158	1044	0.04418
400	0.5243	1069	0.05015
500	0.4565	1093	0.05572
600	0.4042	1115	0.06093
700	0.3627	1135	0.06581
800	0.3289	1153	0.07037
900	0.3008	1169	0.07465
1000	0.2772	1184	0.07868
1500	0.199	1234	0.09599

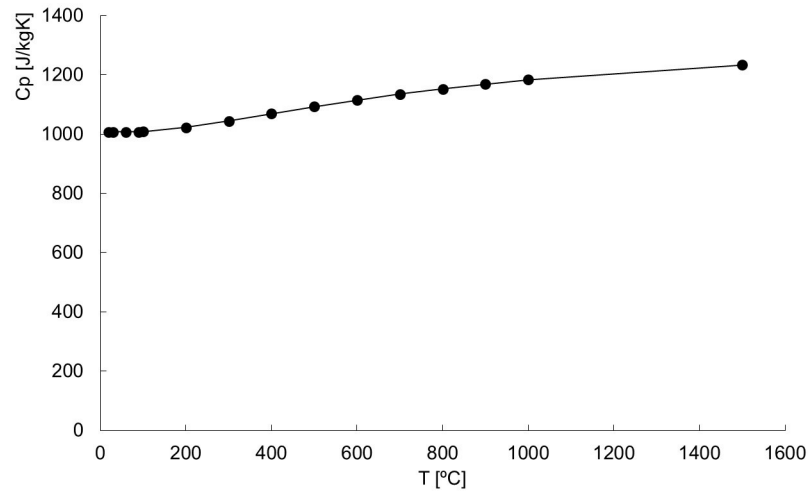


Figure 3.8: Air thermal properties as a function of temperature variation.

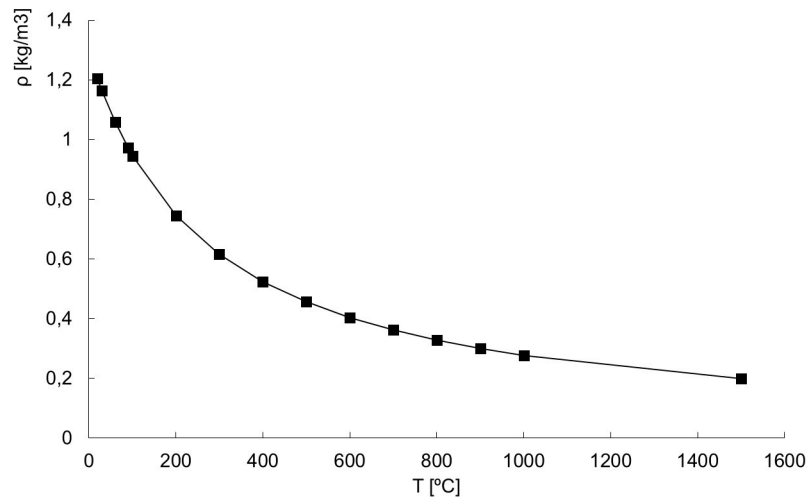


Figure 3.9: Air thermal properties as a function of temperature variation.

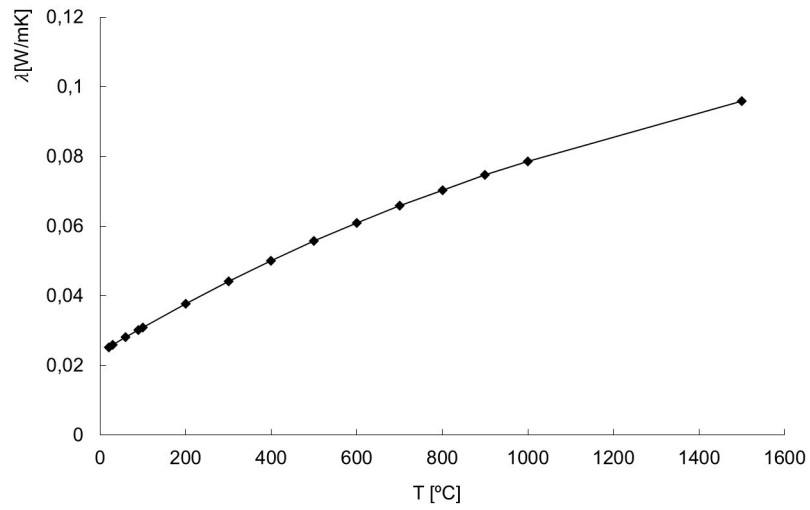


Figure 3.10: Air thermal properties as a function of temperature variation.

## 3.2 Mechanical Properties

This section is responsible for presenting and describing the mechanical properties of the materials used in the construction of composite slabs. Due to the fact that these properties are directly affected by the temperature variation to which the structural element is exposed, the concern at this point is to describe how this interference happens.

The properties of steel and concrete at room temperature (20 °C) follow the guidelines of Eurocode 1993-1.1 [35] and Eurocode 1992-1.1 [36], respectively. However, the calculation values for steel/concrete structures exposed to fire situations are presented according to Eurocode 1993-1.2 [30] and Eurocode 1992-1.2 [31].

### 3.2.1 Steel

The composite slabs investigated during this study present isostatic behavior due to the imposition of simple support conditions. Thus, in the best scenario, they will have a sagging moment corresponding to the structure dead load and live load. This condition, together with the suggestion of the Eurocode 1994-1.2 [4] to consider the steel elements as the only structural elements resistant to tension, implies that understanding the behavior of these elements under thermal variation is essential both for the preparation of numerical models with high accuracy, and to ensure the structural safety of the designed elements.

The Eurocode 1993-1.2 [30] specifies that for carbon steel and heating rates between 2 and 50 [K/min], which is the case of steel deck exposed to an ISO-834 fire curve, the strength and deformation of steel at elevated temperatures can be obtained through the stress-strain relationship. This behavior, without strain hardening effect, is shown in Figure 3.11

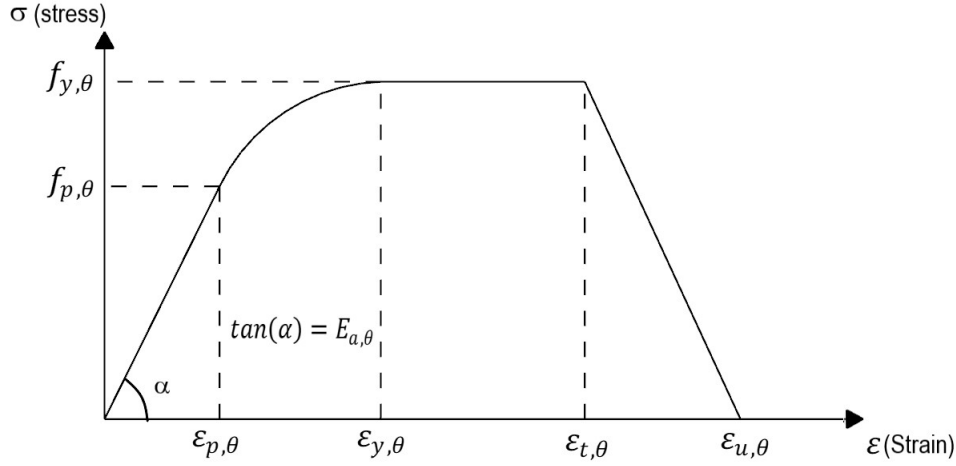


Figure 3.11: Carbon steel stress-strain relationship at elevated temperatures [30].

Were  $f_{y,\theta}$  is the effective yield strength, the  $f_{p,\theta}$  is the proportional limit stress,  $E_{a,\theta}$  is the slope of the linear elastic range. Regarding the strain we have  $\varepsilon_{p,\theta}$  as the strain at the proportional limit,  $\varepsilon_{y,\theta}$  as the yield strain,  $\varepsilon_{t,\theta}$  representing the limiting strain for yield strength, and finally  $\varepsilon_{u,\theta}$  as the ultimate strain.

Table 3.3 shows the strain limits for carbon steel and the parameters required to draw the constitutive law.

Table 3.3: Equations for determining the steel yield strength [30].

Strain range	Stress s	Tangent Modulus
$\varepsilon \leq \varepsilon_{p,\theta}$	$\varepsilon E_{a,\theta}$	$E_{a,\theta}$
$\varepsilon_{p,\theta} < \varepsilon < \varepsilon_{y,\theta}$	$f_{p,\theta} - c + \frac{b}{a} \left[ a^2 - (\varepsilon_{y,\theta} - \varepsilon)^2 \right]^{0,5}$	$\frac{b(\varepsilon_{y,\theta} - \varepsilon)}{a \left[ a^2 - (\varepsilon_{y,\theta} - \varepsilon)^2 \right]^{0,5}}$
$\varepsilon_{y,\theta} \leq \varepsilon \leq \varepsilon_{t,\theta}$	$f_{y,\theta}$	0
$\varepsilon_{t,\theta} < \varepsilon < \varepsilon_{u,\theta}$	$f_{y,\theta} \left[ 1 - \frac{\varepsilon - \varepsilon_{t,\theta}}{\varepsilon_{u,\theta} - \varepsilon_{t,\theta}} \right]$	-
$\varepsilon = \varepsilon_{u,\theta}$	0	-
Parameters	$\varepsilon_{p,\theta} = \frac{f_{p,\theta}}{E_{a,\theta}}$   $\varepsilon_{y,\theta} = 0,02$	$\varepsilon_{t,\theta} = 0,15$   $\varepsilon_{u,\theta} = 0,20$
Functions	$a^2 = (\varepsilon_{y,\theta} - \varepsilon_{p,\theta}) \left( \varepsilon_{y,\theta} - \varepsilon_{p,\theta} + \frac{c}{E_{a,\theta}} \right)$	
	$b^2 = c (\varepsilon_{y,\theta} - \varepsilon_{p,\theta}) E_{a,\theta} + c^2$	
	$c = \frac{(f_{y,\theta} - f_{p,\theta})^2}{(\varepsilon_{y,\theta} - \varepsilon_{p,\theta}) E_{a,\theta} - 2(f_{y,\theta} - f_{p,\theta})}$	

Table 3.4 presents the strength reduction factors related to the steel's stress-strain properties at elevated temperatures. The reduction coefficients for the steel deck yield stress are determined by  $k_{p0,2,\theta}$  while the reduction coefficients for the reinforcement bars are determined by  $k_{y,\theta}$ .

Table 3.4: Reduction factors for structural steel strength at elevated temperatures [30]

Steel Temperatures [°C]	Reduction factors at different temperatures relative to the value of $f_y$ at 20°C	
	$k_{p0,2,\theta}$	$k_{y,\theta}$
20	1.00	1.00
100	1.00	1.00
200	0.89	1.00
300	0.78	1.00
400	0.65	0.94
500	0.53	0.67
600	0.30	0.40
700	0.13	0.12
800	0.07	0.11
900	0.05	0.08
1000	0.03	0.05
1100	0.02	0.03
1200	0.00	0.00

### 3.2.2 Concrete

Regarding the behavior of the mechanical properties of concrete at high temperatures, it is necessary to mention at first that Eurocode 1992-1.2 [31] is the reference standard for obtaining this behavior and mentions that the methodology presented covers both types of concrete used in this study (Normal Weight Concrete (NWC) and Lightweight concrete (LWC)). The method is valid for NWC up to a strength class C90/105 and LWC up to strength class LC55/60. Therefore, this section will comprise both concrete types.

For concrete, Eurocode 1992-1.2 [31] also specifies that the stress and strain properties presented are applicable only when the heating rate is on the order of 2 to 50 [K/min].

Therefore, due to the fact that the ISO-834 [9] standard fire curve is adequate to this specification, the parameters for the stress-strain relationship of concrete at high temperatures shown here follow the regulations of Eurocode 1992-1.2.

The stress-strain relationship presented by Eurocode 1992-1.2 [31] gives the strength and deformation properties of a concrete element under compression exposed to a fire situation. This stress-strain relationship is defined by two parameters: the compressive strength ( $f_{c,\theta}$ ) and the strain ( $\varepsilon_{cu,\theta}$ ) that corresponds to this strength. Thus, Figure 3.12 presents this behavior.

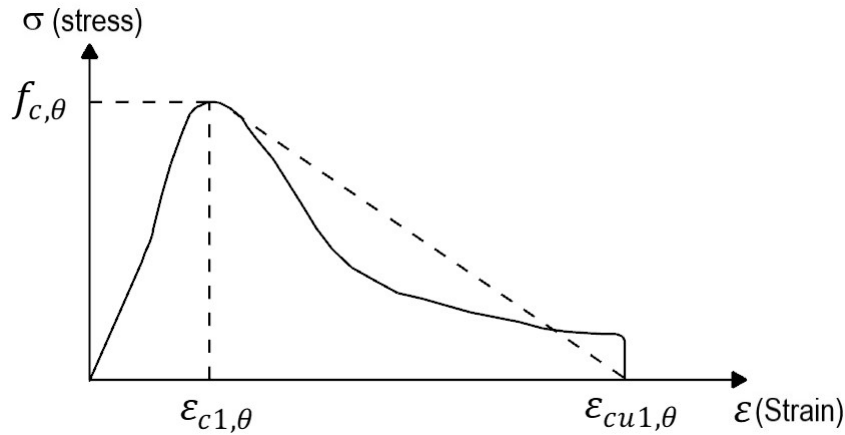


Figure 3.12: Concrete stress-strain relationship at elevated temperatures [31].

The Table 3.5 shows the strain limits for concrete, whose behavior is demonstrated in Figure 3.12.

Table 3.5: Equations for determining the concrete yield strength [31].

Range	Stress $\sigma(\theta)$
$\varepsilon \leq \varepsilon_{c1,\theta}$	$\frac{3\varepsilon f_{c,\theta}}{\varepsilon_{c1,\theta} \left[ 2 + \left[ \frac{\varepsilon}{\varepsilon_{c1,\theta}} \right]^3 \right]}$
$\varepsilon_{c1(\theta)} < \varepsilon \leq \varepsilon_{cu1,\theta}$	For numerical purposes a descending branch should be adopted. Linear or non-linear models are permitted.

The Table 3.6 presents the strength reduction factors related to the concrete stress-strain properties at elevated temperatures.

Table 3.6: Normal weight concrete (NWC) and lightweight concrete (LWC) parameters of the stress-strain relationships at elevated temperatures [31].

Concrete Temperature $\theta_c$ [ $^{\circ}C$ ]	$k_{c,\theta} = \frac{f_{c,\theta}}{f_c}$		$\varepsilon_{cu,\theta} \cdot 10^3$ <i>NWC</i>
	NWC	LWC	
20	1.00	1.00	2.50
100	1.00	1.00	4.00
200	0.95	1.00	5.5
300	0.85	1.00	7.00
400	0.75	0.88	10.00
500	0.60	0.76	15.00
600	0.45	0.64	25.00
700	0.30	0.52	25.00
800	0.15	0.40	25.00
900	0.08	0.28	25.00
1000	0.04	0.16	25.00
1100	0.01	0.04	25.00
1200	0.00	0.00	-

# Chapter 4

## Methods and Methodology

In order to present a new calculation proposal and new coefficients for the Annex D of Eurocode 1994-1.2 [4], a set of numerical simulations is required. The method requires an accurate estimation of the steel deck temperatures for each component (Upper Flange, Web, and Lower Flange) and an accurate prediction of the rebar temperature. The method also includes a comparison between the new proposal and simplified calculation method, to reduce the residuals between both methods. Based on the temperature calculation, the reduction factors are determined for each fire rating time, to find the load-bearing capacity for the sagging moment.

The advanced calculation method is based on two-dimensional and three-dimensional finite elements. Thus it comprises a parametric study using finite element software in order to obtain more realistic results. The development of the simplified calculation method is an analytical study necessary to quantify how much is the improvement of a new calculation approach based on a parametric study, and also the temperature of each composite slab component, following the design guidelines of Eurocode 1994-1.2 [4]. Then, the temperature dependent sagging moment for each type of composite slab is determined, with both approximations to verify the accuracy of the new proposal.

# 4.1 Parameters for the Simulations

The parametric studies were developed based on the results of eighty thermal simulations. Of these, forty were performed using a three-dimensional approach using the ANSYS Mechanical APDL 2021 R1 student version software. The remaining forty used a two-dimensional approach in the MATLAB R2019a program. The two-dimensional approach was chosen for MATLAB to perform an accurate simulation of the effect of the rebars on the temperature distribution along the slab cross-section, while the three-dimensional approach was chosen to verify the thermal effect of the mesh and all the spatial crossed effect.

In this study, two composite slabs with trapezoidal geometry were used, Confraplus 60 and Polydeck 59s. For this category, the following values were adopted for the  $h_1$  thickness, 50 mm, 70 mm, 90 mm, 110 mm, and 125 mm. However, for the other category, the two slabs with re-entrant geometry, Multideck 50 and Bondek are using the following  $h_1$  values: 60 mm, 70 mm, 90 mm, 110 mm, and 125 mm.

The diagram shown in Figure 4.1 represents the parameters used for each simulation totaling eighty simulations.

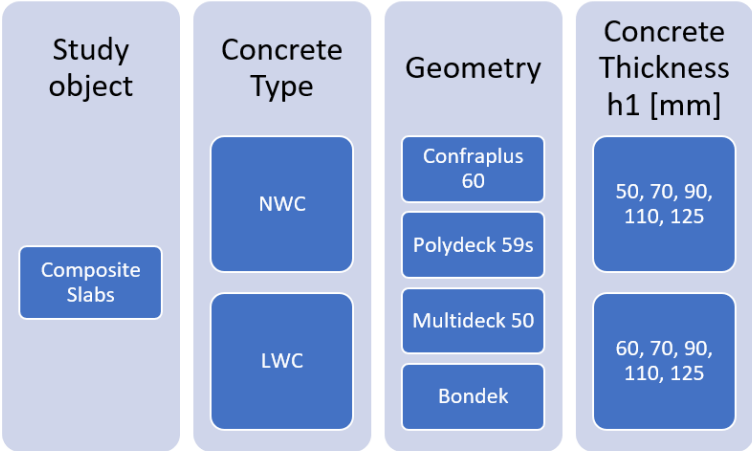


Figure 4.1: Thermal models diagram.

## 4.2 Geometric Configuration of Steel Profiles

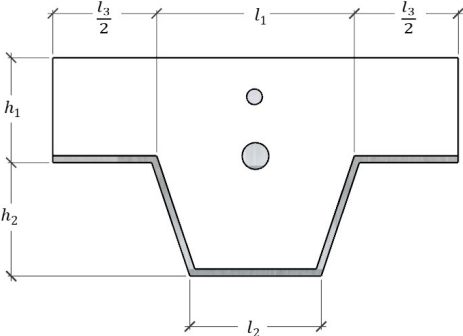


Figure 4.2: Composite Slabs Parameters.

Confraplus 60 is a trapezoidal model profile produced by ArcelorMittal. The collaborating steel deck is produced with S350 steel and the model with 1.25 mm of thickness has been selected. Its geometric characteristics are presented in the Figure 4.3.

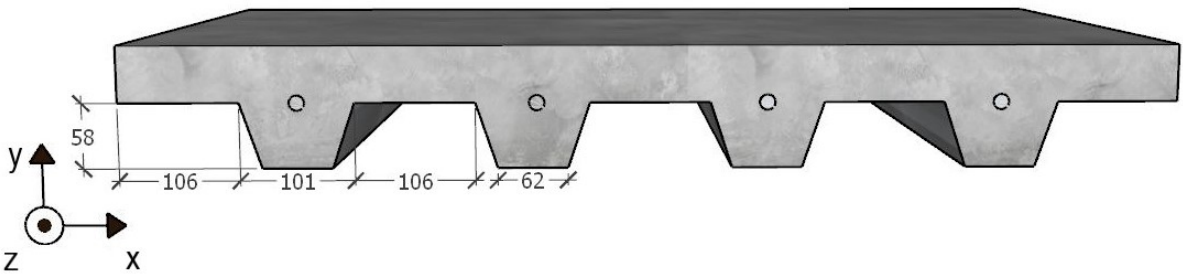


Figure 4.3: Confraplus 60 geometric characteristics [mm].

The Polydeck 59S model is the second trapezoidal profile selected. ArcelorMittal is responsible for producing this profile with a steel deck with S450 steel and 1 mm of thickness. Its geometric characteristics are presented in Figure 4.4.

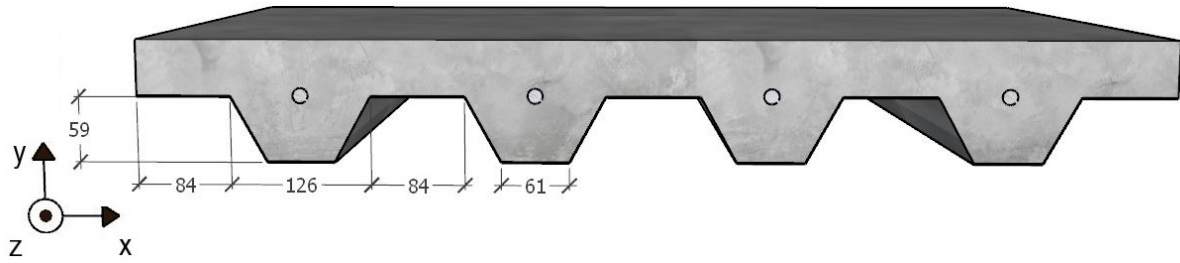


Figure 4.4: Polydeck 59S geometric characteristics [mm].

The first re-entrant model presented is the Multideck 50 produced by Kingspan Structural Products. This product has a steel profile with steel grade S450 and 1 mm of thickness. Its geometric characteristics are presented in Figure 4.5.

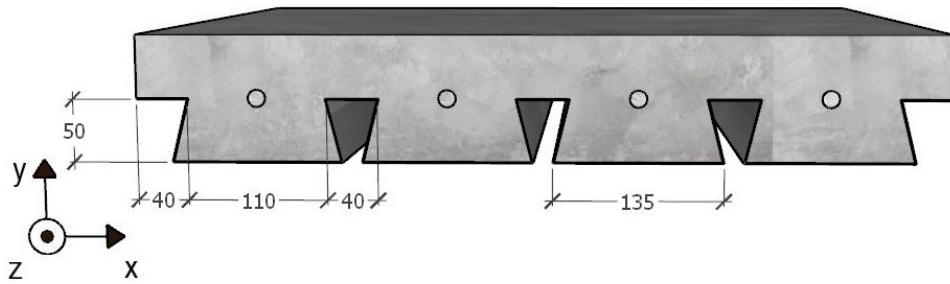


Figure 4.5: Multideck 50 geometric characteristics [mm].

The last re-entrant model is Bondek, which is developed and produced by the Lysaght company. The deck consists of a metallic profile in steel S350 and the 1 mm thickness model has been selected. Its geometric characteristics are presented in Figure 4.6.

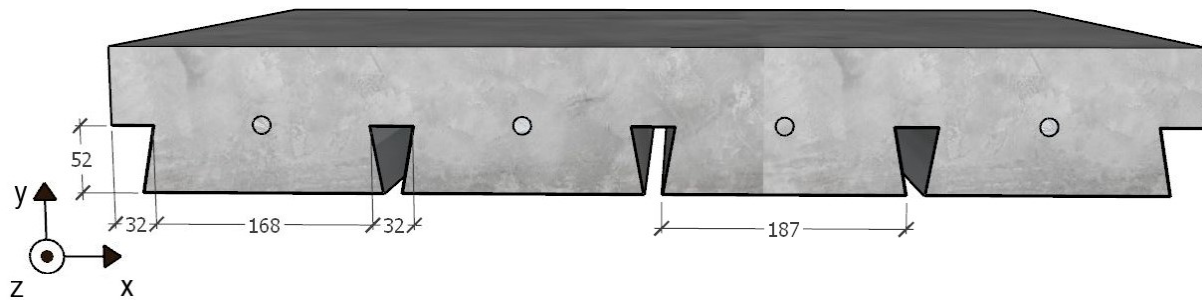


Figure 4.6: Bondek geometric characteristics [mm].

The view factor ( $\phi$ ) according to each slab is presented in Table 4.1.

Table 4.1: View factor ( $\phi$ ) according to each slab geometry.

Slab Geometry	Deck Component	View Factor ( $\phi$ )
<b>Confraplus 60</b>	Upper flange	0.73
	Web	0.56
	Lower flange	1
<b>Polydeck 59S</b>	Upper flange	0.75
	Web	0.64
	Lower flange	1
<b>Multideck 50</b>	Upper flange	0.14
	Web	0.09
	Lower flange	1
<b>Bondek</b>	Upper flange	0.12
	Web	0.09
	Lower flange	1

### 4.3 Finite element models

For both geometries, the span length along the z-axis is 750 mm in the tridimensional analysis. Additionally, in order to ensure better symmetry conditions, the width along the x-axis was fixed, being 700 mm to trapezoidal profiles and 600 mm to re-entrant profiles. Figure 4.7 shows the mesh used to the simulations carried out on Ansys. The two-dimensional simulations were carried out for both profile geometries using a representative section that comprises the width from the geometric center of one top flange to the geometric center of the subsequent top flange.

For the different types of concrete, the strength classes C25/30 for normal weight concrete and LC25/30 for lightweight concrete were adopted because they are widely used in recurrent construction sites. The moisture content of 3.0% in the concrete was assumed, being this information used for the thermal property (Specific Heat).

The following choices were adopted regarding the steel structural components inside each slab: the negative steel mesh reinforcement was developed in steel grade S500 with  $\phi = 6mm$ , and with 150mm of spacing. For reinforcement bars, S500 steel was also used,

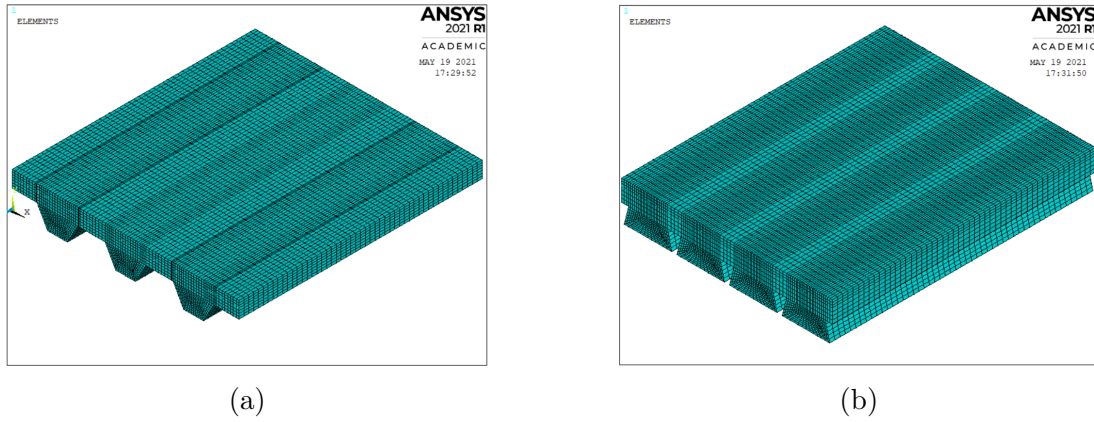


Figure 4.7: Geometric disposition of composite slabs: (a) Trapezoidal profile, (b) Re-entrant profile.

however with a diameter  $\phi = 10mm$ , the rebars were arranged at the center of each slab rib, and at the height equals to  $h_2$ .

In order to perform the thermal simulations, both the boundary conditions and a detailed description of the fire curve used are covered in chapter 7. however it is worth mentioning that all simulations were performed with the standard ISO-834 fire curve [9].

# Chapter 5

## Simplified Calculation Methods

Nowadays, the concern with fire safety is more and more present in the structural design of buildings. Usually, the structural integrity is evaluated based on ISO-834 standard fire curve tests [9]. However, this analysis is impracticable in some situations. After all, the costs are too expensive, and the tests are very time-consuming. For these reasons, it was necessary to develop new methods of calculation to supply the demand for information by the designers [37].

In Europe, the organization responsible for introducing calculation methods was the European Convention for Steel Construction (ECCS), through the technical standard "Calculation of the Fire Resistance of Composite Concrete Slabs with Profiled Steel Sheet Exposed to the Standard Fire" [10], in 1984. After that publication, several studies started to be developed to refine and develop both simplified and numerical calculation models in the field of structural fire safety, among them Hamerlink, R. et al [11] and, Both, C. [38].

Structures with steel profiled sheets are presented in Eurocode 4 part 1-2 [4] through the determination of the fire resistance according to three different criteria: insulation (I), load capacity (R), and integrity (E). The formulation for the insulation and load-bearing criteria can be obtained in Annex D. However, the integrity criterion is not affected in slabs that have the face exposed to fire lined by a steel deck.

## 5.1 Fire Resistance Criteria

In the scope of understanding the evolution of the concern with structural safety under fire conditions, its introduction was due to the publication of ECCS. Later, through contributions of different researchers as Hamerlinck R. [12], Booth K. [38], among others, the technical standard Eurocode 1994-1.2 [4] has been published, which presents the rules for determining fire resistance in structural elements.

For the correct design of the structures and in order to prevent both the collapse of the structure and the integrity of the components under fire situations, experimental tests must be performed following a heating curve, usually, the standard ISO-834 [9]. Subsequently, an safe structural behavior must be ensured regarding some criteria such as Insulation (I), Integrity (E), and Load-bearing capacity (R). The European standard EN 13501-2 [39] is responsible for the definition of these criteria and fire ratings for construction products and building elements. It also informs that the three criteria do not have to be achieved together depending on the structural element. Occasionally, two or only one can be sufficient, depending on the function of the element under study.

The ISO-834 [9] standard defines that the resistance of a structural element depends on its exposure time to a standard fire, measured in minutes, until the failure occurs under any of the criteria designated for the element.

Each country's code defines the minimum fire resistance for each building element. The EN 13501-2 [39] standard presents the most commonly used fire resistance classes, working as a standard guide helping both for the commercial design development and studies development to optimize the calculation procedures currently employed, such as the case of this thesis.

### 5.1.1 Insulation (I)

The Insulation criterion (I) basically represents the limitation of temperature increase on the unexposed side of the structural element, or in this case, the composite slab. In other words, it is the ability of the element in resisting to the action of fire on the exposed

surface and prevent the spread of heat to the unexposed surface.

According to EN 1363-1 [40] the Insulation criterion (I) is reached by achieving the shortest time between two conditions: the first refers to the average temperature ( $\bar{\theta}$ ) increase on the unexposed face, where the limit imposed is 140°C above the initial average temperature ( $\bar{\theta}_0$ ), while the second refers to the maximum temperature ( $\theta_{max}$ ) increase at any point limited by 180°C above the initial average temperature ( $\bar{\theta}_0$ ).

The equations 5.1 and 5.2 express this behavior.

$$\bar{\theta} - \bar{\theta}_0 = 140^\circ C \quad (5.1)$$

$$\theta_{max} - \bar{\theta}_0 = 180^\circ C \quad (5.2)$$

### 5.1.2 Integrity (E)

The integrity criterion (E) refers to the element's ability to resist the fire on the exposed surface, as well as to resist the penetration of hot gases and flames that could pass through holes or cracks in the slab.

According to Hamerlinck R. [12], for composite slabs is assumed that the integrity criterion is fulfilled because the steel deck works as a shielding barrier against the action of hot gases or flames. Thus, the concrete is always protected.

### 5.1.3 Load-Bearing (R)

The Load-Bearing criterion (R) refers to the ability of structural elements under in-service loading to resist excessive deformation or complete collapse under fire situations.

the maximum deflection value  $D_{limit}$  given in [mm] and the value of the deflection rate  $\left(\frac{dD}{dt}\right)_{limit}$  given in [mm/min] must be taken into account to structural elements subjected

to bending in a standard fire situation. The EN1363-1 [40] define the rules that ensure the satisfactory performance of the structure with respect to this criterion by the following equations:

$$D_{limit} = \frac{L^2}{400d} [mm] \quad (5.3)$$

$$\left(\frac{dD}{dt}\right)_{limit} = \frac{L^2}{9000d} [mm/min] \quad (5.4)$$

were  $L$  (mm) is the span of the slab, and  $d$  (mm) is the distance between the extreme fiber in the compression zone to the extreme fiber in the tension zone of the element cross-section.

The 2020 updated version of EN 1363-1 [40] presents an additional condition to this criterion, which is represented in the following requirements:

- (i) measured deflection  $\leq 1.5 \cdot D_{limit}$  or;
- (ii)  $D_{limit}$  and  $\left(\frac{dD}{dt}\right)_{limit}$  are exceeded.

## 5.2 Analytical Analysis of Insulation (I) criterion

The analysis of fire resistance through the thermal insulation criterion (I) in concrete/steel composite structures without additional protection by thermal insulators on the fire exposed surface depends on each slab's specific factors, particularly its geometry. Therefore, table 5.1 presents the geometric limits for the simplified method application.

Besides ensuring the geometric limits, Eurocode 19944-1.2 provides two formulations for evaluating the Insulation criterion (I). The first is through equation 5.5, which determines the fire resistance concerning fire insulation ( $t_i$ ), and the second is through the effective thickness of the composite slab  $h_{eff}$ . Both methods are not valid when the unexposed slab temperature reaches an average temperature increase of  $140^\circ C$  or a maximum

Table 5.1: Field of application for simplified calculation methods.

<b>Re-entrant Profiles</b>	<b>Trapezoidal Profiles</b>
$77.0 \leq l_1 \leq 135.0$ [mm]	$80.0 \leq l_1 \leq 155.0$ [mm]
$110.0 \leq l_2 \leq 150.0$ [mm]	$32.0 \leq l_2 \leq 132.0$ [mm]
$38.5 \leq l_3 \leq 97.5$ [mm]	$40.0 \leq l_3 \leq 115.0$ [mm]
$50.0 \leq h_1 \leq 130.0$ [mm]	$50.0 \leq h_1 \leq 125.0$ [mm]
$30.0 \leq h_2 \leq 60.0$ [mm]	$50.0 \leq h_2 \leq 100.0$ [mm]

temperature of  $180^\circ C$  above the initial average temperature.

$$t_i = a_0 + a_1 \cdot h_1 + a_2 \cdot \phi + a_3 \cdot \frac{A}{L_r} + a_4 \cdot \frac{1}{l_3} + a_5 \cdot \frac{A}{L_r} \cdot \frac{1}{l_3} \quad (5.5)$$

where  $t_i$  is the fire resistance by thermal insulation criteria [min],  $\phi$  is the top flange view factor,  $l_3$  is the top flange width given in [mm] and, finally,  $\frac{A}{L_r}$  corresponds to the ratio between the concrete volume and exposed area per meter of rib length of the steel deck, it is given in [mm], and its calculation is performed through the equation 5.6. And finally, the coefficients  $a_i$  depend on the type of concrete which will be used in the structure, and are shown in Table 5.2.

$$\frac{A}{L_r} = \frac{h_2 \cdot \left(\frac{l_1+l_2}{2}\right)}{l_2 + 2 \cdot \sqrt{h_2^2 + \left(\frac{l_1-l_2}{2}\right)^2}} \quad (5.6)$$

Table 5.2: Fire resistance coefficients according to insulation criteria (I)

<b>Concrete Type</b>	$a_0$ [min]	$a_1$ [min/mm]	$a_2$ [min]	$a_3$ [min/mm]	$a_4$ [mm.min]	$a_5$ [min]
NWC	-28.80	1.55	-12.60	0.33	-735.00	-48.00
LWC	-79.20	2.18	-244	0.56	-542.00	-52.30

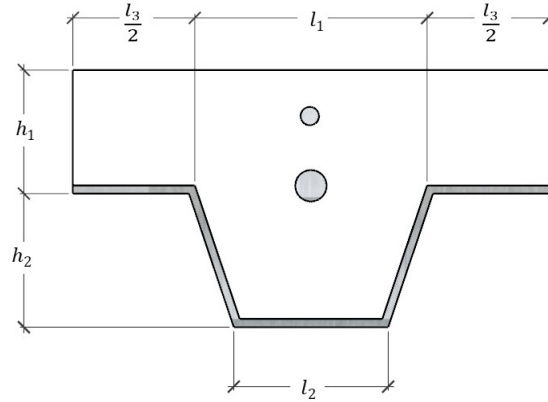


Figure 5.1: Definition of  $A/Lr$  for the ribs of composite slabs.

### 5.3 Analytical Analysis of Load-Bearing (R) criterion

The simplified calculation for the Load-Bearing criterion (R) presented in Eurocode EC 1994 1.2 [4] can be applied to simply support composite slabs when exposed to an ISO-834 standard fire [9]. The structural restrains for the composite slabs analyzed in this study are shown in Figure 5.2.

The standard evaluates the maximum positive plastic bending moment of the slab. For this purpose, the standard classifies the calculation coefficients into two large groups according to the type of concrete and their respective fire resistance classes. For conventional concrete, the classes R-60, R-90, and R-120 are considered, while for lightweight concrete, the fire resistance classes are R-30, R-60, R-90, and R-120.

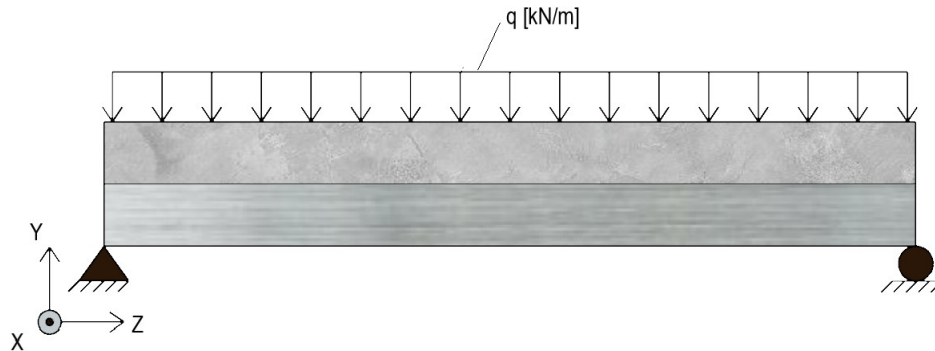


Figure 5.2: Simply supported composite slab subject to a uniformly distributed self-weight load.

The fact that the resistant moment of the slab is calculated through a plastic analysis implies that the element which contributes to the negative portion of the moment (the compressed part of the slab) is only the concrete situated above the neutral line ( $X_{pl}$ ). The steel elements effectively act in the positive component of the moment, in other words, the tensile component, so the effective elements are only those which are below the ( $X_{pl}$ ). That is, it comprises the Upper Flange, Lower Flange, Web, and the reinforcing bars. The stress distribution on the cross section of composite slabs are shown in Figure 5.3.

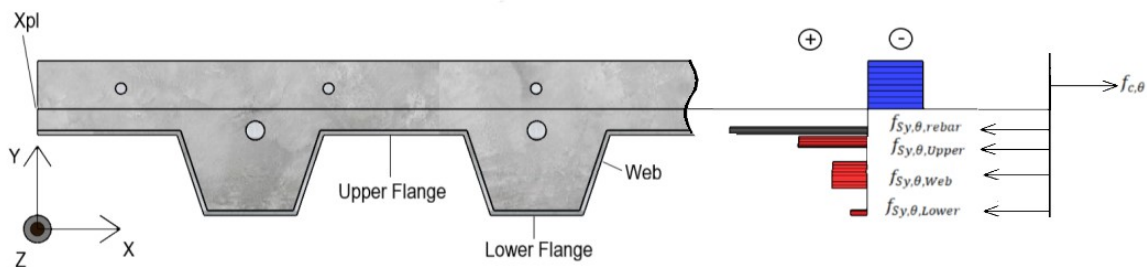


Figure 5.3: Stress distribution on the cross section of the composite slab.

Initially, the temperature  $\theta_a$  in each of the steel deck components (Upper flange, Web and, Lower Flange) should be determined by the following equation.

$$\theta_a = b_0 + b_1 \cdot \frac{1}{l_3} + b_2 \cdot \frac{A}{L_r} + b_3 \cdot \phi + b_4 \cdot \phi^2 \quad (5.7)$$

where  $\theta_a$  is the temperature given in  $^{\circ}C$ , the parameter  $\phi$  is adimensional and corresponds to the view factor of the steel deck component under analysis. Finally, the terms  $b_i$  refers to the standard coefficients for temperature determination, which depends on the type of concrete used in the structure and changes according to the standard fire resistance that must be achieved. The parameters  $b_i$  are presented in Table 5.3. For values not presented in the Table 5.3, linear interpolation can be performed.

Table 5.3: Coefficients for estimating the temperature in steel deck components.

Concrete	Standard Fire Resistance [min]	Components of Steel Deck	$b_0$ [ $^{\circ}C$ ]	$b_1$ [ $^{\circ}C$ * mm]	$b_2$ [ $^{\circ}C$ * mm]	$b_3$ [ $^{\circ}C$ ]	$b_4$ [ $^{\circ}C$ ]
NWC	R-60	Lower Flange	951	-1197	-2.32	86.4	-150.7
		Web	661	-833	-2.96	537.7	-351.9
		Upper Flange	340	-3269	-2.62	1148.4	-679.8
	R-90	Lower Flange	1018	-839	-1.55	65.1	-108.1
		Web	816	-959	-2.21	464.9	-340.2
		Upper Flanger	618	-2786	-1.79	767.9	-472
	R-120	Lower Flange	1063	-679	-1.13	46.7	-82.8
		Web	925	-949	-1.82	344.2	-267.4
		Upper Flange	770	-2460	-1.67	592.6	-379
LWC	R-30	Lower Flange	800	-1326	-2.65	114.5	-181.2
		Web	483	-286	-2.26	439.6	-244
		Upper Flange	331	-2284	-1.54	488.8	-131.7
	R-60	Lower Flange	955	-622	-1.32	47.7	-81.1
		Web	761	-558	-1.67	426.5	-303
		Upper Flange	607	-2261	-1.02	664.5	-410
	R-90	Lower Flange	1019	-478	-0.91	32.7	-60.8
		Web	906	-654	-1.36	287.8	-230.3
		Upper Flange	789	-1847	-0.99	469.5	-313
	R-120	Lower Flange	1062	-399	-0.65	19.8	-43.7
		Web	989	-629	-1.07	186.1	-152.6
		Upper Flange	903	-1561	-0.92	305.2	-197.2

The rebar temperature calculation process differs from the other steel components, so it presents different formulation and coefficients, which also are provided by Eurocode 1994-1.2 [4] through the equation 5.8.

$$\theta_s = c_0 + c_1 \cdot \frac{u_3}{h_2} + c_2 \cdot z + c_3 \cdot \frac{A}{L_r} + b_4 \cdot \alpha + b_5 \cdot \frac{1}{l_3} \quad (5.8)$$

where  $\theta_s$  is the temperature in the rebar, given in  $^{\circ}C$ , the component  $u_3$  represents the distance from the rib centroid to the Lower Flange given in [mm], the  $z$ -factor represents the position of the rebar concerning the slab rib, it is given in [ $mm^{-0.5}$ ], and the term  $\alpha$  corresponds to the angle formed between the steel sheet web and the horizontal direction in [degrees( $^{\circ}$ )].

The coefficients  $c_i$ , as well as  $b_i$ , depend on the concrete type and vary according to the standard fire resistance. They are used to determine the temperature at the reinforcing bars. These parameters are presented in Table 5.4 and linear interpolation for intermediate values is also allowed.

Table 5.4: Temperature coefficients for estimating the temperature in the reinforcement bars.

Concrete Type	Standard Fire Resistance [min]	$c_0$ [ $^{\circ}C$ ]	$c_1$ [ $^{\circ}C$ ]	$c_2$ [ $^{\circ}C * mm^{0.5}$ ]	$c_3$ [ $^{\circ}C * mm$ ]	$c_4$ [ $^{\circ}C/^{\circ}$ ]	$c_5$ [ $^{\circ}C * mm$ ]
NWC	R-60	1191	-250	-240	-5.01	1.04	-925
	R-90	1342	-256	-235	-5.30	-1.39	-1267
	R-120	1387	-238	-227	-4.79	1.68	-1326
LWC	R-30	809	-135	-243	-0.70	-0.48	-315
	R-60	1336	-242	-292	-6.11	1.63	-900
	R-90	1381	-240	-269	-5.46	2.24	-918
	R-120	1397	-230	-253	-4.44	2.47	-906

To determine the parameters for the reinforcement bars position in relation to the rib of the slab, Eurocode 1994-1.2 [4] presents a system which is represented in Figure 5.4, where  $u_1$  and  $u_2$  represent the shortest distance between the reinforcement bar and the two webs of the rib, the  $u_3$  component corresponds to the distance between the reinforcement and the Lower Flange. Whereas the  $z$ -factor is determined in terms of  $u_1, u_2$  and  $u_3$  through the equation 5.9.

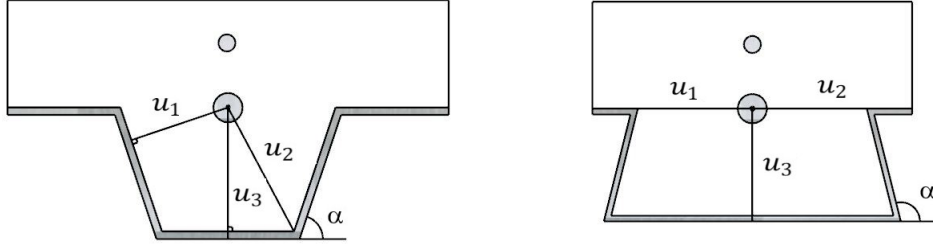


Figure 5.4: Parameters  $u_i$  for the z-factor calculation.

$$\frac{1}{z} = \frac{1}{\sqrt{\frac{1}{u_1}}} + \frac{1}{\sqrt{\frac{1}{u_2}}} + \frac{1}{\sqrt{\frac{1}{u_3}}} \quad (5.9)$$

After determining the temperatures in the elements responsible for resisting the tensile forces, that is, the steel deck and rebars, Eurocode 1994-1.2 provide the equation 5.10 to determine the neutral axis position ( $X_{pl}$ ) in the cross-section of the composite slab.

$$\sum_{i=1}^n A_i k_{y,\theta,i} \left( \frac{f_{y,i}}{\gamma_{M,f,i,a}} \right) + \alpha_{slab} \sum_{j=1}^m A_j k_{c,\theta,j} \left( \frac{f_{c,j}}{\gamma_{M,f,i,c}} \right) = 0 \quad (5.10)$$

were  $f_{y,i}$  is the nominal yield strength  $f_y$  for the element steel area  $A_i$ . This value should be taken as positive if it is in the compressed region (above the plastic neutral axis) and negative otherwise. The term  $f_{c,j}$  refers to the design strength for the elemental concrete area  $A_j$  at 20°C under compression, and  $\alpha_{slab}$  is the reduction coefficient regarding the rectangular tension block hypothesis for concrete elements. At last, the terms  $k_{y,\theta,i}$  and  $k_{c,\theta,j}$  refer to the reduction factors for stress-strain relationships of structural steel and concrete respectively, at elevated temperatures, in particular the term  $k_{y,\theta,i}$  is related with the temperatures  $\theta_s$  and  $\theta_a$ .

According to Eurocode 1994-1.2 [4], the reduction factors for steel ( $k_{y,\theta,i}$ ) are presented in Table 3.4. However, for the concrete, the same standard suggests adopting  $k_{c,\theta,j}=1$ .

Therefore, after obtaining the plastic neutral axis position values ( $X_{pl}$ ), it becomes

possible to calculate the design sagging moment resistance ( $M_{fi,t,Rd}$ ) for composite slabs according to equation 5.11.

$$M_{fi,t,Rd} = \sum_{i=1}^n A_i z_i k_{y,\theta,i} \left( \frac{f_{y,i}}{\gamma_{M,fi,a}} \right) + \alpha_{slab} \sum_{j=1}^m A_j z_j k_{c,\theta,j} \left( \frac{f_{c,j}}{\gamma_{M,fi,c}} \right) \quad (5.11)$$

Where  $z_i$  and  $z_j$  represent the distance from the neutral axis to the respective gravity centers of the areas  $A_i$  and  $A_j$ .

The bending resistance reduction factor ( $\frac{M_{fi,t,Rd}}{M_{Rd}}$ ) represents the ratio between the sagging moment for each fire resistance class ( $M_{fi,t,Rd}$ ), and slab's sagging moment at room temperature ( $M_{Rd}$ ). Therefore, it represents the bending resistance reduction in function of the temperature increase for each time corresponding to the fire rating.

The term  $M_{Rd}$  represents the maximum resistant capacity of the composite slab, which also was calculated through the equations 5.10 and 5.11. However, it is calculated at 20°C, and for this reason, the coefficients  $k_{y,\theta,i}$  and  $k_{c,\theta,j}$  are equal to one.

An alternative formulation comprises a less accurate method but with a good approximation by calculating the effective thickness  $h_{eff}$  for the composite slab using equations 5.12 and 5.13. However, if  $l_3 > 2l_1$ , the value of  $h_1$  should be adopted for  $h_{eff}$ .

$$h_{eff} = h_1 + 0,5 \cdot h_2 \left( \frac{l_1 + l_2}{l_1 + l_3} \right), \quad \text{for } \frac{h_2}{h_1} \leq 1,5 \text{ and } h_1 > 40 \text{ mm} \quad (5.12)$$

$$h_{eff} = h_1 \left[ 1 + 0,75 \cdot h_2 \left( \frac{l_1 + l_2}{l_1 + l_3} \right) \right], \quad \text{for } \frac{h_2}{h_1} > 1,5 \text{ and } h_1 > 40 \text{ mm} \quad (5.13)$$

Table 5.5 presents the relationship between the ISO-834 [9] standard fire resistance concerning the thermal insulation criterion (I) and the minimum effective thickness of the composite slab  $h_{eff}$ .

Table 5.5: Minimum effective thickness as a function of standard fire resistance.

<b>Standard Fire Resistance [min]</b>	<b>Minimum Effective Thickness - <math>h_{eff}</math> [mm]</b>
R 30	$60 - h_3$
R 60	$80 - h_3$
R 90	$100 - h_3$
R 120	$120 - h_3$
R 180	$150 - h_3$
R 240	$175 - h_3$

Where  $h_3$  corresponds to the concrete layer thickness that might be above the slab in some cases.

# Chapter 6

## Advanced Calculation Methods

The advanced calculation method is the definition given by Eurocodes to the numerical analyses, mainly carried out on finite element software. This type of analysis aims to determine the structural response to fire, including isolated structural elements or complete structures, allowing when necessary, to assess the interaction between parts of the structure directly exposed to fire and those that are not.

Advanced calculation models enable a more realistic analysis of structures exposed to fire when compared to simplified calculation methods. Based on the fundamental physical behavior of structures, advanced methods use iterative processes in the numerical analysis of nonlinear problems to provide a safe approximation of structural behavior under fire exposure. However, since this work aims to analyze the thermal behavior of the structures over time to determine the temperature distributions and suggest new calculation proposals, only the thermal analysis will be taken into account.

For the correct use of the advanced methods, Eurocode 1994-1.2 [4] demands that the analysis of structures exposed to fire must be divided into two models: the thermal model for determining the development and distribution of temperatures along with the structural element, and the mechanical model for evaluating the mechanical behavior of the structure during a fire situation. Furthermore, Eurocode 1991-1.2 [32] informs that the gas properties, mass exchange, and energy exchange must be taken into account for the thermal analyses.

## 6.1 Boundary Conditions

The boundary conditions are used in numerical analyses to make it possible to solve the differential equations intrinsic to the model, thus controlling the reactions generated by the application of loads of different natures such as mechanical or thermal. Since the mechanical behavior is directly affected by the slab's thermal performance over the time to fire exposure, bearing in mind the structure boundary conditions, it is necessary to master the different natures of heat transfer that act on the slab's, that is, the conduction, convection, and radiation.

In thermal analysis, finite element meshes are generally used to elaborate solids in which conduction is the predominant heat transfer method. Therefore, it is also necessary to represent radiation and convection. These other methods are represented by imposing boundary conditions in the structure, which are characterized by a heat flow across surface areas. The boundary conditions presented in this paper follow the guidelines of Eurocode 1991-1.2 [4]

### 6.1.1 Standard Fire Curve ISO-834

In general, the time evolution of temperature in numerical methods can be represented both by natural fire curves or by the standard ISO-834 fire curve [9]. Therefore, to perform the thermal analysis according to the fire resistance criteria established by EN 13501-2 [39] and simulate the slab's heating, the ISO-834 fire curve was adopted because it presents coverage in several international standards, besides presenting easy implementation in software.

The equation 6.1 provides the guideline to obtain bulk temperature following the standard fire ISO-834.

$$\theta = 345 \cdot \log_{10}(8 \cdot t + 1) + 20 \tag{6.1}$$

Where  $\theta$  is the temperature in [ $^{\circ}C$ ], and  $t$  is the time in seconds.

### 6.1.2 Heat Transfer

As mentioned in the introduction section regarding the boundary conditions, a heat flux by radiation and convection through the slab's surfaces were considered. In general, the fire exposure in composite slabs is modeled using convection and radiation on the exposed surface (bottom surfaces) and natural convection on the unexposed surface (top surfaces). Therefore, the following will present the parameters provided by Eurocode 1991-1.2 to formulate the boundary conditions.

First, an initial temperature condition concerning the ambient temperature of  $20^{\circ}C$  was applied to all the slab nodes. Concerning the convection phenomenon, a convection coefficient  $\alpha_c = 9 [W/m^2K]$  was employed together with a bulk temperature of  $20^{\circ}C$  on the unexposed surface. For the exposed surface, a convection coefficient  $\alpha_c = 25 [W/m^2K]$  was adopted but now considering the bulk temperature following the standard fire ISO 834.

Considering the radiation, an important material property that must be taken into account is the emissivity ( $\epsilon$ ), through which it is possible to determine the rate of heat absorption and emission of the materials. Based on EN 1994-1-2 [4], for concrete and steel must consider the value of 0.70. For the fire compartment, the emissivity of the flames should be considered equal to 1.00. In composite slabs with trapezoidal and re-entrant geometry, the View Factor ( $\phi$ ) is a geometric factor responsible for directly influencing the amount of radiation received by the steel deck exposed surface. For this reason, " $\phi$ " is an essential component that must be associated with steel emissivity.

Concerning radiative emissivity, Hamerlinck [11] presented an important characteristic that must be highlighted. In composite slabs, the structural element in contact with the fire, the steel deck, has its surface covered by a thin galvanized coating, giving low emissivities for low temperatures. Nevertheless, at temperatures around  $400^{\circ}C$  and  $500^{\circ}C$ , the zinc coating melts, and the surface blackens, thus increasing emissivity. It is worth

mentioning that with high heating rates, the surface blackens at a higher temperature. After all, the speed of temperature increase determines the speed of blackening.

The Figure 6.1 presents the Boundary conditions for the composite slabs.

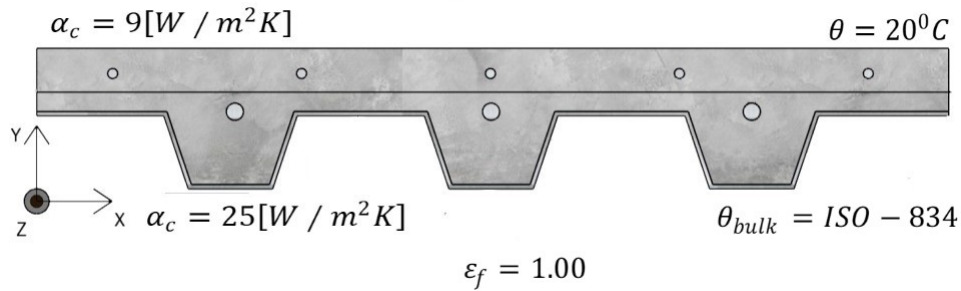


Figure 6.1: Boundary conditions for a composite slab exposed to ISO-834 standard fire.

## 6.2 Finite Element Method

The finite element method (FEM) comprises a numerical analysis method based on the subdivision of the domain of the structure into smaller sections designated finite elements. This method aims to obtain a more realistic solution for engineering problems by approximating the solutions for problems governed by partial differential equations. It was initially developed to evaluate stresses in structural systems. However, it has been used in various problems, such as Heat Transfer and Fluid Mechanics.

In this work, the numerical analyses were carried out only for thermal simulations of composite slabs. Two different software programs that utilize finite elements and have global coverage were used for the simulations, MATLAB and ANSYS. In MATLAB, two-dimensional geometric and mathematical models were developed, allowing the analysis of the temperature development in the slabs' cross-section comprising all the necessary elements: the steel deck, the rebars, the air layer (air-gap) responsible for the debonding effect, and the concrete.

Three-dimensional analyses were performed using ANSYS software. Finite shell elements (SHELL131) were used to simulate the steel deck and the air-gap, responsible

for the debonding effect, while the concrete was modeled using solid elements, such as SOLID70. Finally, the reinforcement bars and the steel mesh (responsible for preventing cracking of the concrete at the top of the slab) were modeled using LINK33 finite elements.

### 6.2.1 MATLAB

To develop a two-dimensional nonlinear transient thermal analysis the software MATLAB (MATrix LABoratory) was selected because it is a simple-to-use software with worldwide dissemination.

After creating a thermal model using the "createpde" function for thermal model analysis, it was necessary to determine the cross-section geometry. Four faces were required for each slab, each one referring to its respective material, one for concrete, one for the rebar, one for the steel deck, and one for the air layer. After that, the finite element mesh was created, which is responsible for solving the partial differential equations involving the problems of heat transfer.

In order to generate the finite element mesh, finite elements with triangular geometry were adopted. These elements have three nodes and one degree of freedom related to temperature, thus permitting linear interpolations and a complete Gauss integration.

To optimize the model concerning the accuracy of results and processing time a convergence test was performed to define the size of the mesh elements. In these circumstances,  $10^{-4}$  was adopted as a satisfactory proportional error for the nodal temperature calculations. In other words, the size of mesh elements was adjusted until the discrepancy in nodal temperature calculations has the maximum value of  $10^{-4}$  in the worst case. The finite element mesh is presented in Figure 6.2.

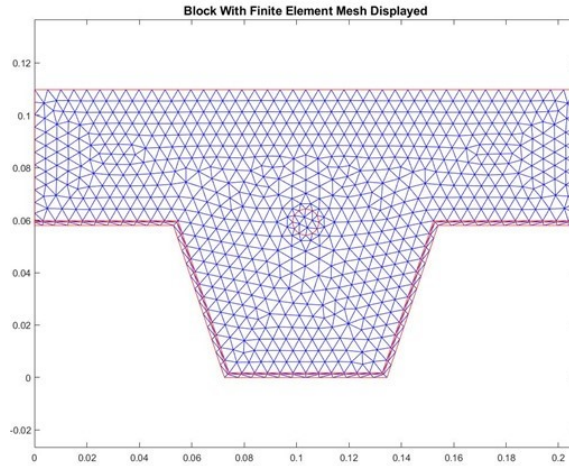


Figure 6.2: Finite element mesh in MATLAB.

The finite element mesh is composed by either two or three different sub-domains. One model considers the perfect contact between steel and concrete, which means two materials, concrete and steel, and the other considers the debonding effect during the heating phase, thus considering the steel deck, the air-gap, and the concrete. The modeling of several faces during the geometric model development represents the sub-domains in the thermal model. For instance, the thermal models considering the air-gap effect have four faces, which means each slab component (concrete, rebar, steel deck, and air-gap) has its respective face. It is worth mentioning that the faces carry the geometric representation of the associated component; thus, the circumference in the center of the mesh is due to the rebar diameter representation.

Regarding the geometry disposition of the finite element mesh on the models, the maximum mesh edge length varies according to each steel deck profile. However, in general, the limitation is given by two sequential upper flange centroids comprising one rib.

### 6.2.2 ANSYS

Ansyes Inc. is a company responsible for developing and marketing simulation software that makes it possible to determine the behavior associated with several products used in

different areas of engineering. The company is based in Canonsburg, Pennsylvania, USA, founded by John Swanson in 1970.

For the thermal models developed in this study, the Mechanical APDL 2021 R1 product of Ansys Student 2021 R1 was used. Three finite elements available in the Ansys library (SOLID70, LINK31, SHELL131) were used. Therefore, the elements were chosen to meet the geometric conditions of each component of the composite slabs, enabling nonlinear transient thermal analysis.

The SOLID70 finite element was used to model the concrete because its three-dimensional configuration supports constructing structures behavior such as wide walls and slabs. For the steel decks and the debonding effect, the two-dimensional element SHELL131 was adopted. This is a shell element generally used in the analysis of thin structures, presenting good results when analyzing the response to bending and deformation. Finally, to represent the rebars and the negative steel mesh, the one-dimensional LINK33 elements were used.

## **SOLID70**

SOLID70 is a 3-D element with eight nodes with a single degree of freedom associated with the temperature at each node. The element has a 3-D thermal conduction capability, and it can be applied to a 3-D steady-state or, as in the case of this study, to transient thermal analysis.

The geometry, node locations, and the coordinate system for this element are shown in Figure 6.3a. This element is defined not only by the eight nodes but also by the orthotropic properties of the material used, which must correspond to the element coordinate directions presented in Figure 6.3a.

The 8-node solid brick element, SOLID70, has a full Gauss integration with 2x2x2 integration points, which means there are 2 Gaussian integration points along each direction. The linear interpolating function used to solve the temperature is described in Equation 6.2.

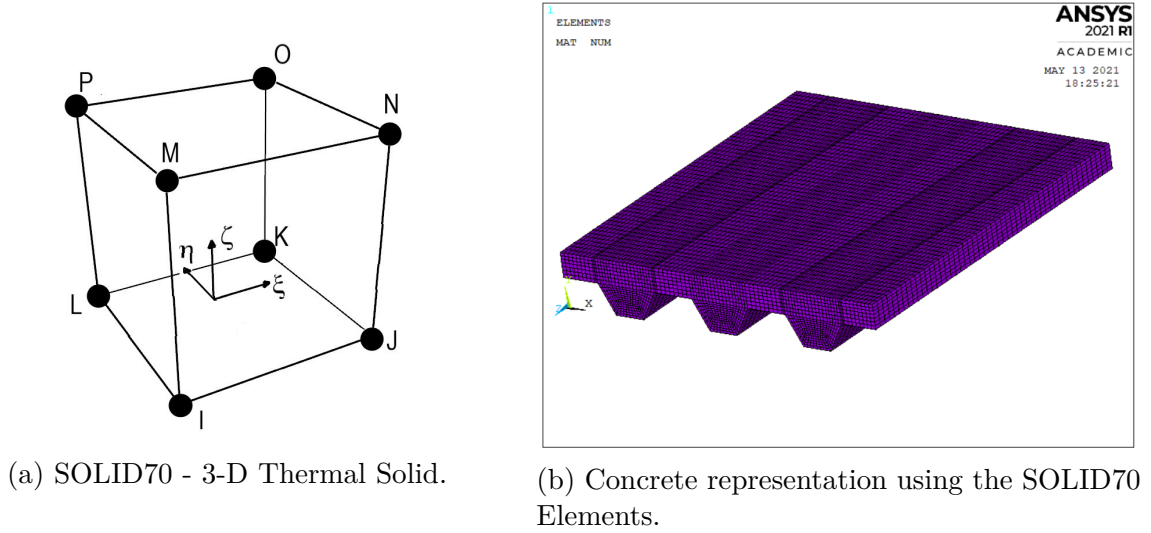


Figure 6.3: Element SOLID70, characteristics and representation.

$$\begin{aligned}
 \theta = & \frac{1}{8}(\theta_I(1 - \xi)(1 - \eta)(1 - \zeta) + \theta_J(1 + \xi)(1 - \eta)(1 - \zeta) \\
 & + \theta_K(1 + \xi)(1 + \eta)(1 - \zeta) + \theta_L(1 - \xi)(1 + \eta)(1 - \zeta) + \theta_M(1 - \xi)(1 - \eta)(1 + \zeta) \\
 & + \theta_N(1 + \xi)(1 - \eta)(1 + \zeta) + \theta_O(1 + \xi)(1 + \eta)(1 + \zeta) + \theta_P(1 - \xi)(1 + \eta)(1 + \zeta))
 \end{aligned}
 \tag{6.2}$$

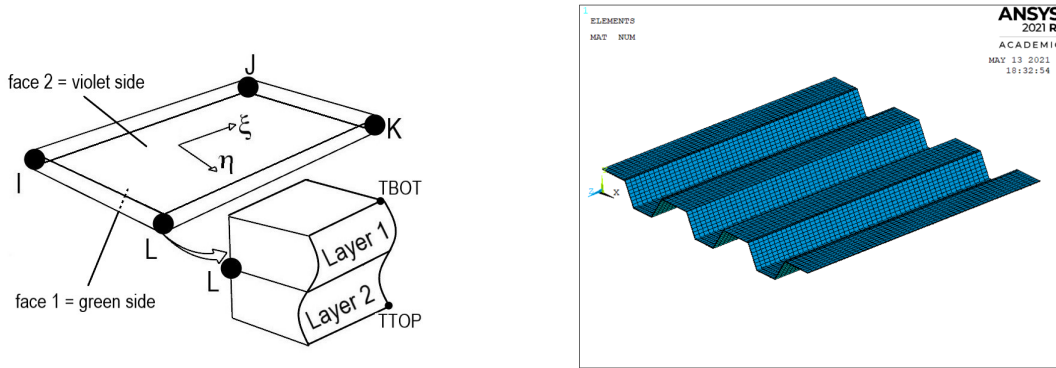
## SHELL131

SHELL131 is a 3-D layered shell element, which has four nodes with up to 32 degrees of freedom regarding the temperature at each node. This conducting shell element can apply to a 3-D, steady-state, or transient thermal analysis.

The element has a thermal conduction capability along its plane as well as through its thickness. It also generates temperatures that can be moved to the corresponding structural finite element (SHELL181) enabling the thermal bending. This method has not been used in this thesis.

The location of the nodes, the geometry characteristics, and coordinates systems are shown in Figure 6.4a. SHELL131 is an element defined by four nodes, a material angle

and properties for each layer, and one thickness per layer. Due to this ability to generate more than one layer with distinct material properties, it was possible to elaborate models using only one element subdivided into two layers to simulate the steel deck and the debonding effect.



(a) SHELL131 - 4-Node Layered Thermal Shell. (b) Steel deck representation using the SHELL131 Elements.

Figure 6.4: Element SHELL131, characteristics and representation.

The SHELL131 element enables quadratic or linear temperature variation through each layer. Quadratic is most often used for transient analysis or for strongly temperature-dependent materials, and linear is commonly used in steady states with weakly temperature-dependent materials. Because the steel deck has a low thickness and high conductivity, there is a low interference in the temperature field distribution. Thus it is possible to consider the temperature along with the steel deck thickness constant, as demonstrated by L. M. S. Prates [41]. Therefore, for this study, a linear temperature variation evaluated perpendicular to the plane of the steel deck surface will be considered.

For this element, the calculation of the temperature distribution is performed both along the surface and along with the thickness. Equation 6.3 and equation 6.4 present the layer shape functions for calculating the temperature in the plane and in the thickness, respectively. The SHELL131 element has a full Gauss integration with  $2 \times 2$  integration points in the plane and 2 integration point in thickness.

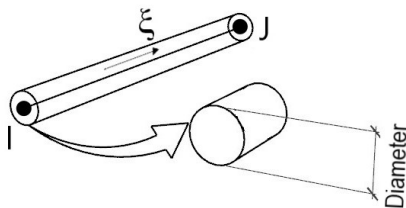
$$\theta = \frac{1}{4}(\theta_I(1-\xi)(1-\eta) + \theta_J(1+\xi)(1-\eta) + \theta_K(1+\xi)(1+\eta) + \theta_L(1-\xi)(1+\eta)) \quad (6.3)$$

$$\theta = \frac{1}{2}(\theta_I(1-\xi) + \theta_J(1+\xi)) \quad (6.4)$$

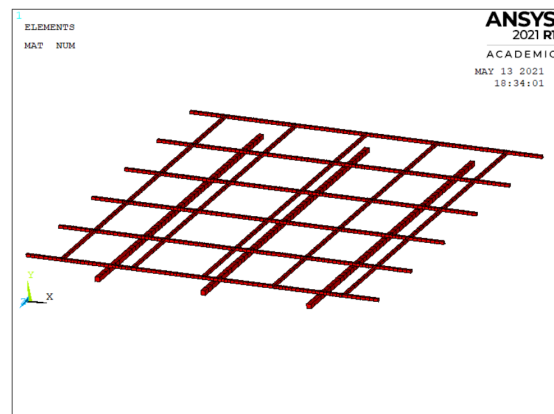
### LINK33

LINK33 is a unidimensional finite element with a single degree of freedom associated with the temperature at each node. The element can conduct heat between its nodes, therefore working as a conducting bar that can apply to a steady-state or transient thermal analysis.

The geometry, node positions, and the coordinate system for this conducting bar are shown in Figure 6.5a. This element is defined by the cross-sectional area, the material properties and, two nodes. It is assumed that the heat flows only in the longitudinal direction of the element. Thus, the conductivity must be considered in the same direction.



(a) LINK33 - 3-D Conduction Bar.



(b) Rebars and negative mesh representation using the LINK33 Elements.

Figure 6.5: Element LINK33, characteristics and representation.

The possibility of defining the cross-section size is a quality of this type of element

that allows modeling different rebars (both positive and negative) in their respective thicknesses.

To determine the temperature of this element, exact integration is used, and the shape function are described by equation 6.5.

$$\theta = \frac{1}{2}(\theta_I(1 - \xi) + \theta_J(1 + \xi)) \quad (6.5)$$

### Convergence Criterion

The convergence criterion adopted for the simulations developed using ANSYS software was based on the "heat flow (W)" with a reference value  $REF = 10^{-6}$  and a tolerance  $TOL = 10^{-3}$ .

For the same simulation time, the solution converges when in two sequential iterations, the relative error associated with the heat flow that generates temperatures in two neighbor nodes (i and j) is less than or equal to the reference value multiplied by the tolerance value, as shown in equation 6.6. Otherwise, a new iteration is performed with a new heat flow through the adjusted temperatures. This process occurs until the condition of minimum relative error associated with the heat flux is satisfied.

$$W_{i+1} - W_i = 10^{-6} \cdot 10^{-3} = 10^{-9} \quad (6.6)$$

# Chapter 7

## Results and New Proposals

This section is intended to present the results obtained through the parametric study developed to estimate the thermal behavior of composite slabs during a fire situation. It focused mainly on the thermal evolution of the steel deck components (Upper flange, Web, and Lower flange) and the rebars.

Initially, the results of the two-dimensional thermal analysis performed in MATLAB are presented, which was later tested against the results of the three-dimensional analysis obtained through ANSYS software. For both cases, each component's thermal analysis results come from the average of the nodal temperatures along the component length. It should be mentioned that only some of the parametric results are presented in this section. However, all the specifications of each analysis are presented in detail in the annexes. Thus, Annex A refers to the trapezoidal geometry and NWC slabs, Annex B refers to the re-entrant geometry and NWC slabs, Annex C refers to the trapezoidal geometry and LWC slabs, and Annex D refers to the re-entrant geometry and LWC slabs.

After proving the similarity between the results obtained through the two software, a new calculation proposal was developed to estimate the temperatures in the steel deck components and the rebars. In order to preserve some characteristics of the Eurocode 1994-1.2 [4], the new calculation proposal was based on the existing proposal, promoting a reformulation of the current coefficients ( $b_i$  and  $c_i$ ) of Annex D, and inserting new coefficients that enable a better approximation to the temperature as a function of the

profile geometry.

Based on the new calculation proposal, the temperatures in each component were calculated, thus allowing estimating the new reduction coefficients for the steel ( $k_{p0,2,\theta}$  and  $k_{y,\theta}$ ). Subsequently, an analytical study of the composite concrete/steel slabs structural response was developed aiming to highlight the influence on the bending resistance moment of the slabs, i.e., demonstrating the effect of the new proposal on the Load-Bearing criterion (R).

## 7.1 Temperature estimation with MATLAB

The thermal analysis on the slab's cross-section using MATLAB has been developed to highlight the thermal evolution of the steel components in two model scenarios. The first one was developed considering an air layer between the steel and the concrete (debonding effect) and second without this effect.

The results for the temperature of each component are presented for the MATLAB numerical results (N), while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively. Figure 7.1 schematically represents where the thermal evolution over time was analyzed.

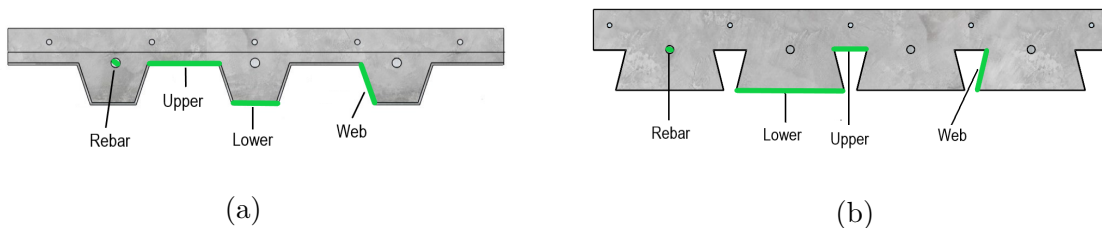


Figure 7.1: Temperature measurement in composite slabs: (a) Trapezoidal profile (b) Re-entrant profile.

Figure 7.2 show the thermal behavior of the trapezoidal Polydeck 59S slab with 90 mm NWC thickness, and Figure 7.3 presents the thermal behavior of the re-entrant Multideck

50 slab with 90 mm NWC thickness.

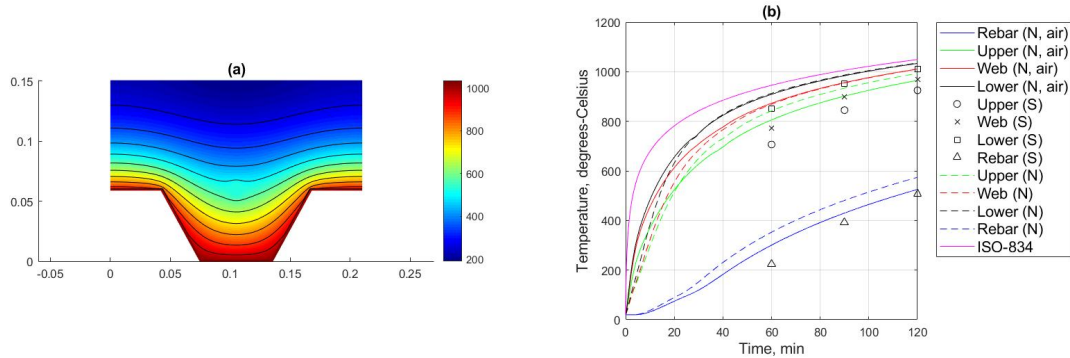


Figure 7.2: Composite slabs in Normal Weight Concrete: (a) Polydeck 59S Cross-section at 120 min, (b) Temperature evolution for each component obtained by simplified (S) and numerical (N) methods, considering the “air-gap” (air).

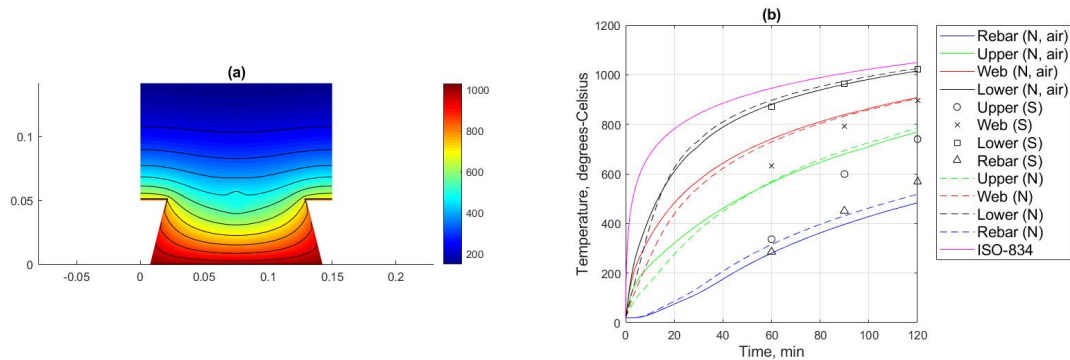


Figure 7.3: Composite slabs in Normal Weight Concrete: (a) Multideck 50 Cross-section at 120 min, (b) Temperature evolution for each component obtained by simplified (S) and numerical (N) methods, considering the “air-gap” (air).

Through the thermal curves presented in Figures 7.2 and 7.3, it is possible to observe some composite slab heating process characteristics. First, between the temperatures of 600°C and 800°C, there is a slight decrease in the steel profiles’ heating speed because, in this temperature range, the steel goes through a phase transition. This phenomenon was previously detailed in the Thermomechanical Properties Section. Another critical characteristic refers to the debonding effect, which has little influence on the steel deck temperature. However, it is very highlighted in the rebar temperature. The debonding effect highlights the influence of the thermal conductivity property. This property is

considerably higher in steel than in air and leads to an evident difference in temperature that reaches the concrete and later the rebar.

Next, the thermal evolution in slabs composed with Lightweight Concrete will be demonstrated. Figure 7.4 show the thermal behavior of the trapezoidal Polydeck 59S slab with 90 mm LWC thickness, and Figure 7.5 presents the thermal behavior of the re-entrant Multideck 50 slab with 90 mm LWC thickness.

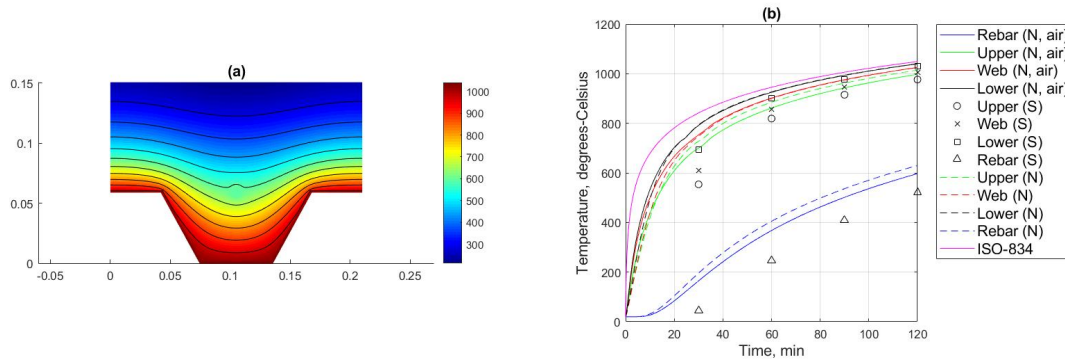


Figure 7.4: Composite slabs in Lightweight Concrete: (a) Polydeck 59S Cross-section at 120 min, (b) Temperature evolution for each component obtained by simplified (S) and numerical (N) methods, considering the “air-gap” (air).

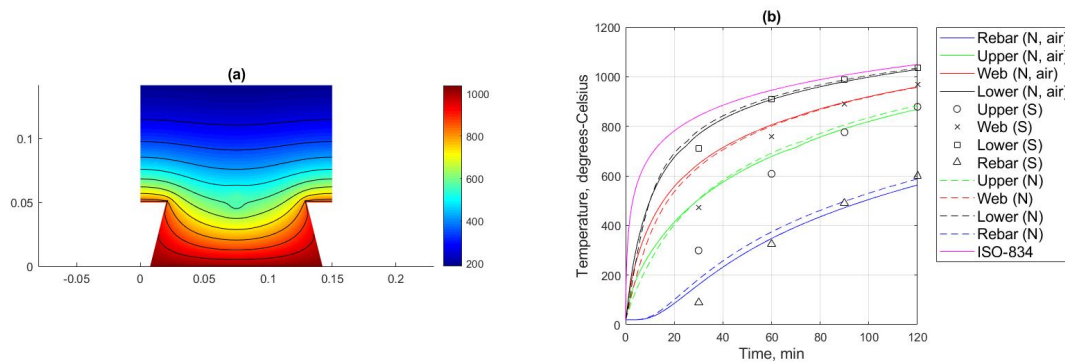


Figure 7.5: Composite slabs in Lightweight Concrete: (a) Multideck 50 Cross-section at 120 min, (b) Temperature evolution for each component obtained by simplified (S) and numerical (N) methods, considering the “air-gap” (air).

For both types of concretes used, one can see the difference between the parametric results and the simplified calculation method of Eurocode 1994-1.2 [4]. In this case, it is evident that the results obtained through nonlinear transient thermal analyzes have a higher temperature at all components and also during all the analysis duration. Then, it is possible to verify that the current Eurocode produces unsafe results from a structural viewpoint since the thermal results directly influence the mechanical response of the slabs.

## 7.2 Temperature estimation with ANSYS

In order to compare the two-dimensional results obtained using MATLAB software, three-dimensional nonlinear transient thermal analysis was developed using ANSYS software. This test came in order to verify whether different finite element modeling approaches produce, or not, similar results for composite slabs subjected to the same heat conditions.

Figure 7.6 schematically represents where the thermal evolution over time was analyzed.

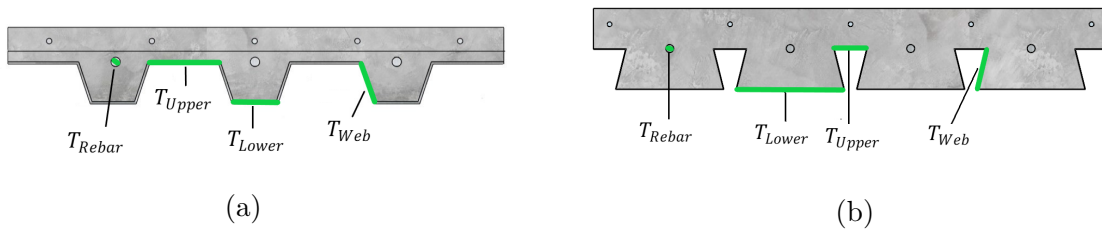


Figure 7.6: Temperature measurement in composite slabs: (a) Trapezoidal profile (b) Re-entrant profile.

Figure 7.7 shows the thermal curves obtained using the results provided by the ANSYS software using an air-gap of 0.5 mm. Figure 7.7a represents the thermal behavior of the Polydeck 59S slab with 90 mm NWC thickness, and Figure 7.7b presents the thermal behavior of the Multideck 50 re-entrant slab with 90 mm NWC thickness.

The results were also obtained for Lightweight Concrete (LWC). Figure 7.8 shows the thermal curves obtained using the results provided by the ANSYS software. Figure 7.8a

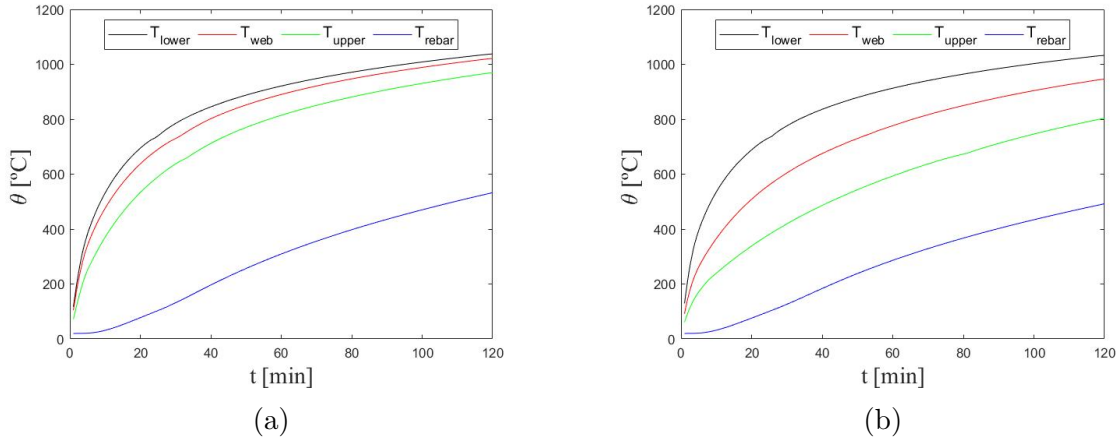


Figure 7.7: Temperature evolution of composite slabs in Normal Weight Concrete: (a) Polydeck 59S, (b) Multideck 50.

represents the thermal behavior of the Polydeck 59S slab with 90 mm LWC thickness, and Figure 7.8b presents the thermal behavior of the Multideck 50 re-entrant slab with 90 mm LWC thickness.

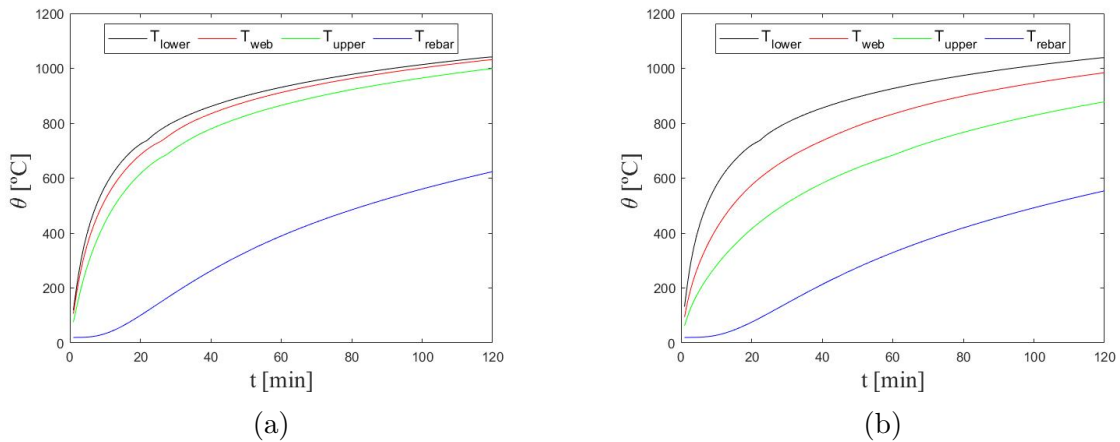


Figure 7.8: Temperature evolution of composite slabs in Lightweight Concrete: (a) Polydeck 59S, (b) Multideck 50.

The technical considerations concerning the contents presented in the graphics presented in Figures 7.7 and 7.8 follow the same approach presented in the subsection of this chapter concerning the results obtained using the MATLAB software for the results considering an air-gap of 0.5 mm.

Therefore, a comparison was made between the thermal curves obtained through both software. Figure 7.9 presents this comparison for the Polydeck 59S composite slab with 90mm thickness in NWC, while Figure 7.10 presents the same approach in LWC.

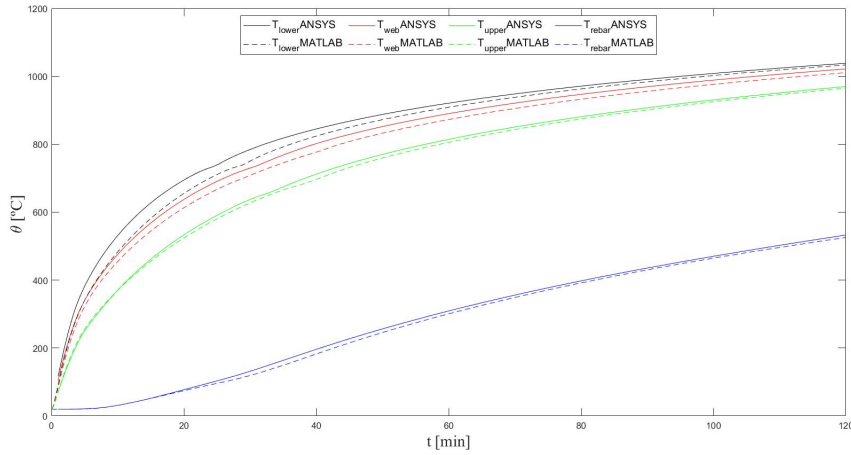


Figure 7.9: Comparison between thermal curves using Normal Weight Concrete using ANSYS and MATLAB software.

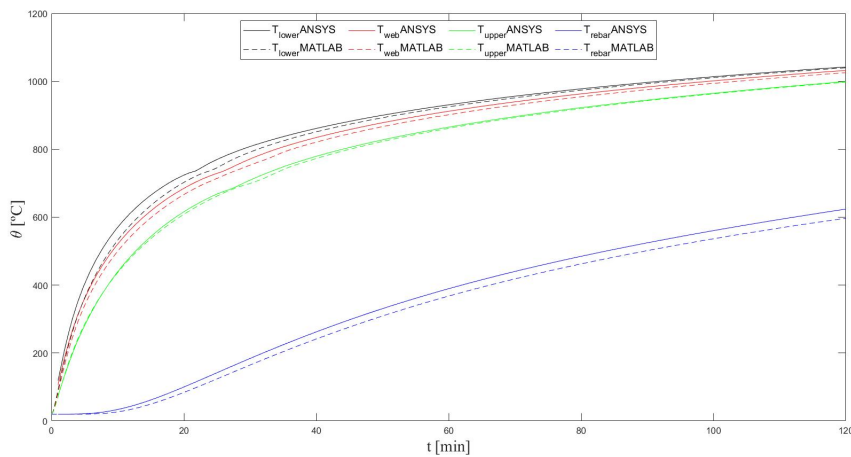


Figure 7.10: Comparison between thermal curves using Lightweight Concrete using ANSYS and MATLAB software.

As shown in Figures 7.9 and 7.10, the temperature curves obtained using ANSYS are in good agreement to those obtained through MATLAB. It is noteworthy only the fact that the ANSYS curves present a slightly higher temperature evolution than that obtained using MATLAB. This effect is due to the difference between two-dimensional and three-dimensional models, different types of the finite elements, and convergence methods.

At the same time, in Ansys, link elements were used to model the rebars, shell elements were used to model the steel deck and air-gap effect, and solid elements to model the concrete. In addition, the shell element chosen has only a node which connects two layers, the steel deck and the air-gap. However, the difference in temperatures is quite small, on average  $10^{\circ}C$  to  $15^{\circ}C$ , reaching a maximum of  $35^{\circ}C$ , and thus has no influence in obtaining the reduction coefficients for steel.

### 7.3 New Temperature Calculation proposal

Based on the temperatures obtained through parametric analysis, it was possible to determine a new calculation proposal to estimate the temperature in the steel deck components ( $\theta_a$ ) and the rebars ( $\theta_s$ ), for the specific time defined by fire rating. In addition to the reformulation and correction of the coefficients, new coefficients are also introduced, allowing the analytical calculation of temperatures for slabs requesting a fire-resistance time of 45 min.

In order to preserve the equation structure proposed in Eurocode 1994-1.2 [4], the current structure was maintained. However, the  $b_i$  and  $c_i$  coefficients were reformulated. An additional coefficient has been added to the equation to optimize the temperatures according to each composite slab profile, i.e., trapezoidal (trap.) and re-entrant (Reen.). Therefore, the expressions 7.1 and 7.2 represent the new calculation proposal for temperatures.

$$\theta_a = (b_0 + b_1 \cdot \frac{1}{l_3} + b_2 \cdot \frac{A}{L_r} + b_3 \cdot \phi + b_4 \cdot \phi^2) \cdot b_5 \quad (7.1)$$

$$\theta_s = (c_0 + c_1 \cdot \frac{u_3}{h_2} + c_2 \cdot z + c_3 \cdot \frac{A}{L_r} + b_4 \cdot \alpha + b_5 \cdot \frac{1}{l_3}) \cdot c_6 \quad (7.2)$$

### 7.3.1 New coefficients proposal

By introducing new coefficients in the equations presented here, it is expected that it will be possible to reproduce the results of the parametric analyses in an analytical way to promote better reliability to composite slab projects from the point of view of structural safety.

In order to obtain the best fit for the new coefficients, the Ordinary Least Squares Method was employed between the temperatures obtained through the calculation proposal presented by Eurocode 1994-1.2 [4] and the result obtained through the thermal analyses. This method was used for all the four types of profiles analyzed, as well as for all the thicknesses studied. The average of the coefficients obtained through the several thicknesses and between slabs with the same geometric shape made it possible to normalize in one coefficient ( $b_i$  or  $c_i$ ) for each fire resistance time the most accurate approximation that makes it possible to estimate the temperatures analytically. Table 7.1 presents the new coefficients to determine the temperature of steel deck components (Upper Flange, Web, Lower Flange), and Table 7.2 presents the new coefficients to determine the temperature of the rebars.

Table 7.1: New  $b_i$  coefficients proposal.

Concrete	Fire Resistance [min]	Steel Deck	$b_0$	$b_1$	$b_2$	$b_3$	$b_4$	$b_5$ Reen.	$b_5$ Trap.
NWC	45min	Upper flange	741.681	-1662.508	-2.983	95.626	-185.548	0.805	1.196
		Web	635.365	-722.240	-3.292	689.524	-344.986	1.116	0.938
		Lower flange	65.719	-1003.212	-0.842	3413.949	-819.347	1.847	0.404
	60min	Upper flange	784.199	-1203.728	-2.348	86.101	-151.088	0.827	1.174
		Web	755.223	-829.652	-2.906	558.943	-346.533	1.040	0.979
	90min	Upper flange	857.473	-841.761	-1.561	64.953	-108.279	0.860	1.140
		Web	867.775	-957.472	-2.199	471.327	-338.061	1.010	0.995
		Lower flange	832.185	-2674.885	-1.739	842.270	-459.529	1.187	0.873
	120min	Upper flange	919.406	-680.486	-1.135	46.638	-82.886	0.886	1.114
		Web	954.715	-948.415	-1.817	346.186	-266.592	0.995	1.006
		Lower flange	949.386	-2414.930	-1.646	619.924	-373.440	1.116	0.913
	LWC	30min	Upper flange	707.052	-1333.093	-2.679	114.271	-181.238	0.846
Web			617.936	-285.157	-2.183	489.380	-233.828	1.072	0.952
Lower flange			602.463	-2041.618	-1.401	673.167	-124.325	1.297	0.815
45min		Upper flange	778.304	-977.333	-1.999	80.970	-131.232	0.869	1.131
		Web	729.593	-420.919	-1.935	451.609	-269.052	1.037	0.979
		Lower flange	712.807	-2130.545	-1.228	668.287	-261.018	1.216	0.865
60min		Upper flange	824.177	-623.389	-1.327	47.611	-81.232	0.882	1.118
		Web	807.934	-557.537	-1.664	433.574	-300.574	1.016	0.988
		Lower flange	785.929	-2206.045	-1.007	724.299	-397.923	1.159	0.879
90min		Upper flange	906.500	-478.614	-0.913	32.668	-60.857	0.911	1.089
		Web	926.942	-653.858	-1.359	289.299	-229.586	0.995	1.005
		Lower flange	925.111	-1831.257	-0.984	485.781	-308.685	1.084	0.930
120min		Upper flange	964.213	-399.340	-0.651	19.790	-43.724	0.929	1.071
		Web	997.217	-628.997	-1.070	186.448	-152.413	0.990	1.010
		Lower flange	1010.532	-1554.441	-0.917	309.836	-195.989	1.052	0.954

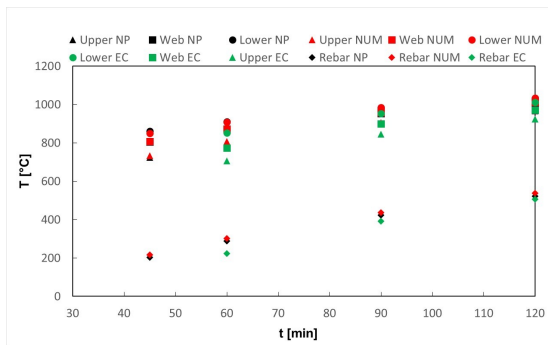
Table 7.2: New  $c_i$  coefficients proposal.

Concrete	Fire Resistance [min]	$c_0$	$c_1$	$c_2$	$c_3$	$c_4$	$c_5$	$c_6$ Reen.	$c_6$ Trap.
NWC	45min	1119.424	-238.565	-225.829	-4.848	0.753	-799.074	0.967	1.074
	60min	1222.465	-248.614	-236.672	-4.994	1.042	-924.710	0.924	1.085
	90min	1340.456	-256.056	-235.114	-5.301	1.390	-1267.220	0.914	1.085
	120min	1366.326	-238.609	-228.442	-4.797	1.677	-1326.630	0.911	1.085
LWC	30min	869.303	-133.293	-228.595	-0.699	0.481	-314.874	0.941	1.088
	45min	1136.412	-186.526	-257.236	-3.387	1.059	-607.138	0.929	1.080
	60min	1389.993	-240.148	-284.908	-6.077	1.635	-899.743	0.924	1.088
	90min	1408.635	-239.078	-265.938	-5.447	2.244	-917.988	0.911	1.090
	120min	1410.768	-229.550	-251.558	-4.436	2.471	-906.106	0.916	1.083

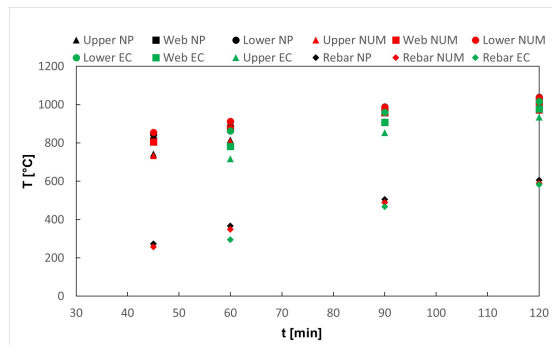
### 7.3.2 New Proposal Validation

In order to verify the differences between the Eurocode 1994-1.2 [4] temperature calculation method (EC), the numeric results (NUM), and the new calculation proposal (NP), comparison graphs were developed. Figure 7.11 establish this comparison for each steel deck component (Upper flange, Web, Lower flange) and the rebars for Normal Weight Concrete. While Figure 7.12 establishes this comparison for composite slabs in LWC.

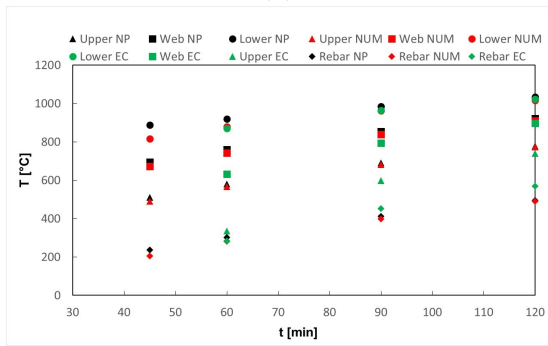
Through the graphs presented in Figures 7.11 and 7.12, it is evident that the new proposal is quite close to the temperature values obtained through parametric studies, demonstrating that, in fact, there is an improvement in the accuracy of the results. For both types of concrete, the new proposal contributes significantly to the first stages of fire resistance time, the range in which the Eurocode shows more discrepancy with numerical results. For the specific case of Lightweight Concrete, it is also noted that there is a significant improvement in the temperature values for the rebars. Therefore, it is possible to say that the greatest differences in temperature values occur for the fire rating 30 min, which can reach 40% as in the re-entrant slabs. The variations are smaller for the other fire rating classes, being on average 6% for the trapezoidal slabs and 10% for the re-entrant slabs.



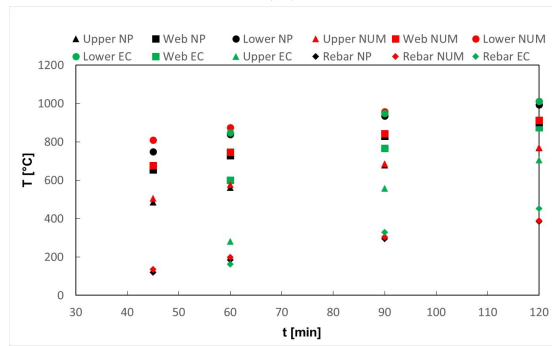
(a)



(b)

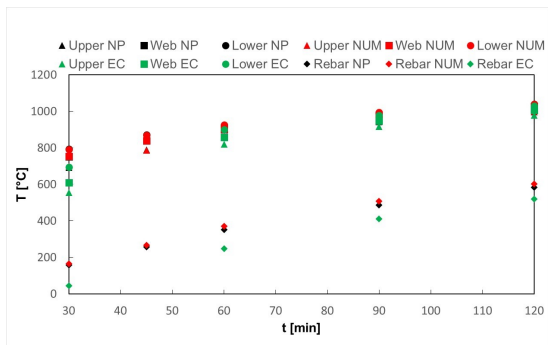


(c)

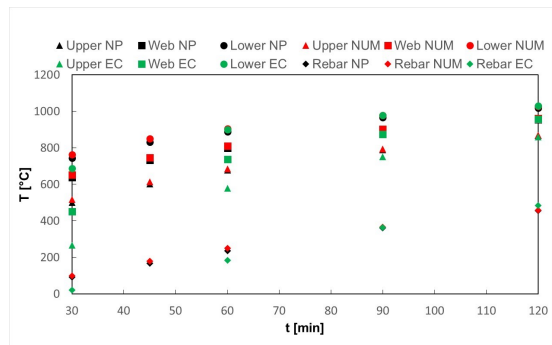


(d)

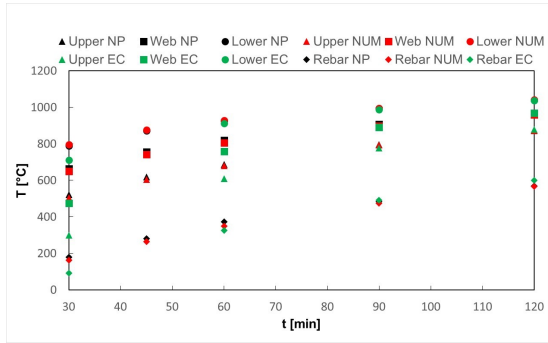
Figure 7.11: Temperature for composite slabs with NWC. (a) Polydeck 59S, (b) Confraplus 60 (c) Multideck 50 (d) Bondek.



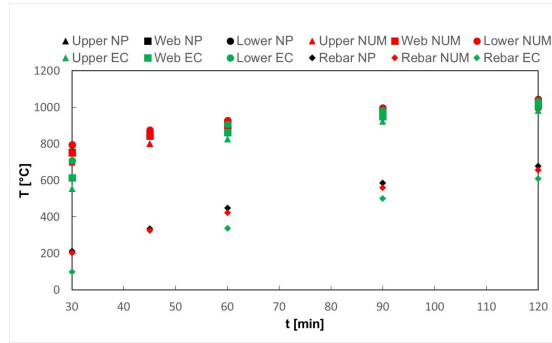
(a)



(b)



(c)



(d)

Figure 7.12: Temperature for composite slabs with LWC. (a) Polydeck 59S, (b) Confraplus 60 (c) Multideck 50 (d) Bondek.

# 7.4 Bending resistance Reduction Factor

The bending resistance reduction factor ( $\frac{M_{fi,t,Rd}}{M_{RD}}$ ) represents the ratio between the sagging moment for each fire resistance class ( $M_{fi,t,Rd}$ ), and slab’s sagging moment at room temperature ( $M_{RD}$ ). Therefore, it is an approach that allows determining the rate of reduction on the slabs resistant capacity as a function of exposure time to fire. Thus, it is possible to evaluate the behavior of composite slabs regarding the Load-Bearing criterion (R).

Several comparisons between the bending resistance reduction factor encompassing both concrete types and the different thicknesses of each slab were developed in order to prove the improvement provided by the new calculation proposal.

The Figures 7.13, 7.14, 7.15 and 7.16, shows the comparison of Bending Resistance Reduction Factor between the Eurocode 1994-1.2 [4] results, and the new calculation proposal results, for all thickness of composite slabs with Normal Weight Concrete.

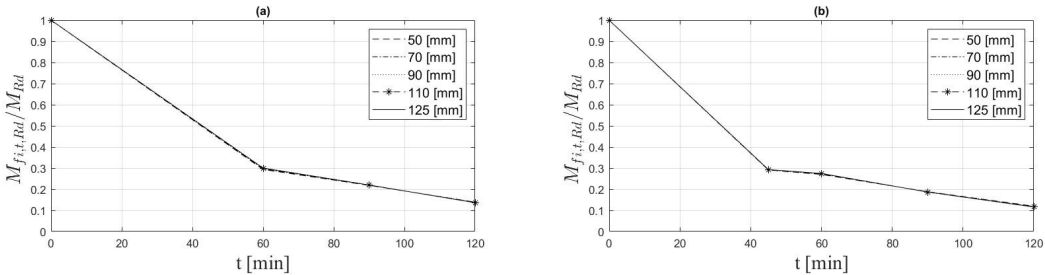


Figure 7.13: Confraplus 60 bending resistance reduction factor for NWC: (a) EC 1994-1.2, (b) New Proposal.

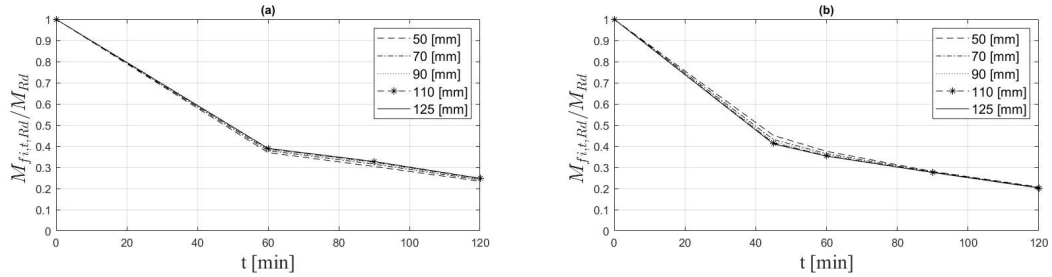


Figure 7.14: Polydeck 59S bending resistance reduction factor for NWC: (a) EC 1994-1.2, (b) New Proposal.

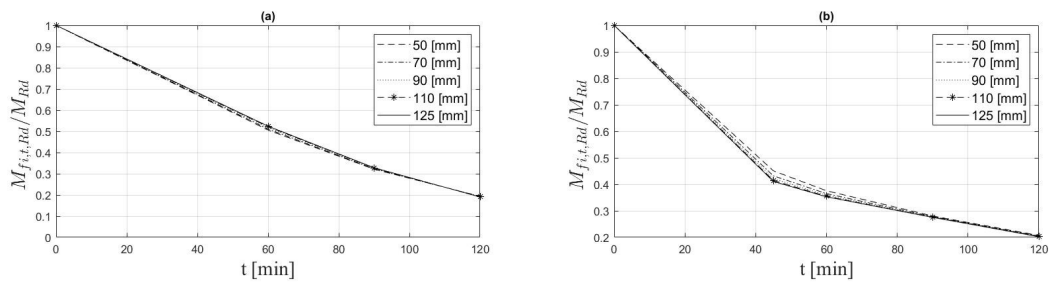


Figure 7.15: Multideck 50 bending resistance reduction factor for NWC: (a) EC 1994-1.2, (b) New Proposal.

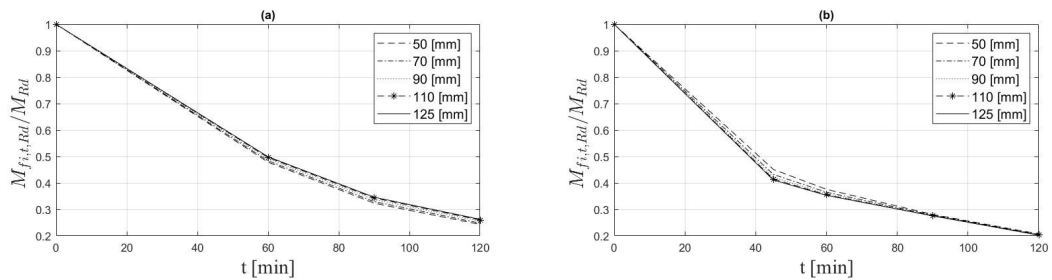


Figure 7.16: Bondek bending resistance reduction factor for NWC: (a) EC 1994-1.2, (b) New Proposal.

The Figures 7.17, 7.18, 7.19 and 7.20, shows the comparison of Bending Resistance Reduction Factor between the Eurocode 1994-1.2 [4] results, and the new calculation proposal results, for all thickness of composite slabs with Lightweight Concrete.

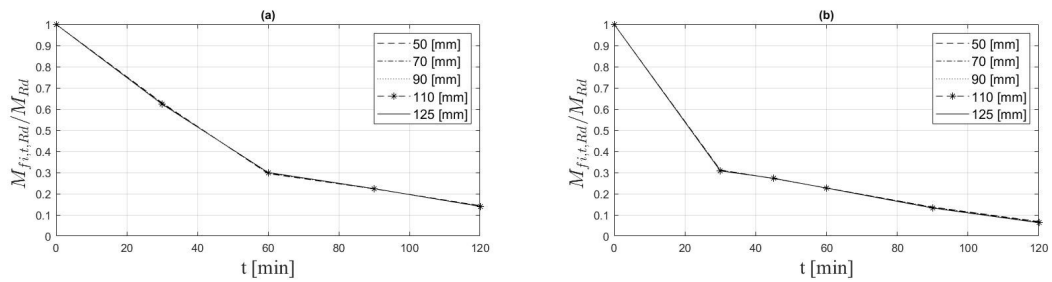


Figure 7.17: Confraplus 60 bending resistance reduction factor for LWC: (a) EC 1994-1.2, (b) New Proposal.

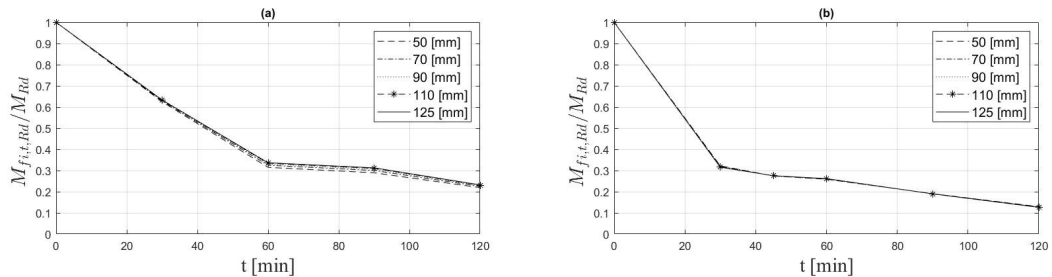


Figure 7.18: Polydeck 59S bending resistance reduction factor for NWL: (a) EC 1994-1.2, (b) New Proposal.

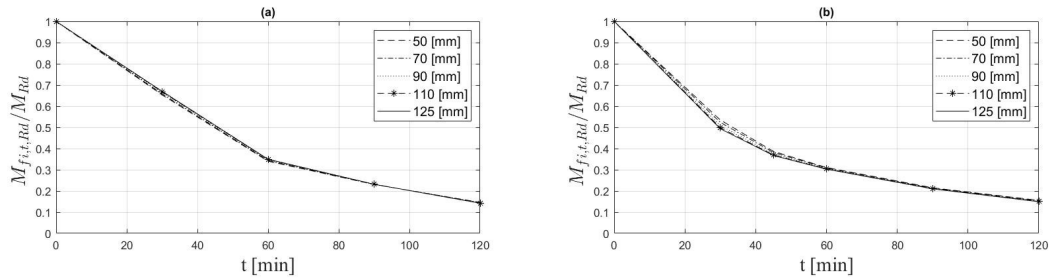


Figure 7.19: Multideck 50 bending resistance reduction factor for LWC: (a) EC 1994-1.2, (b) New Proposal.

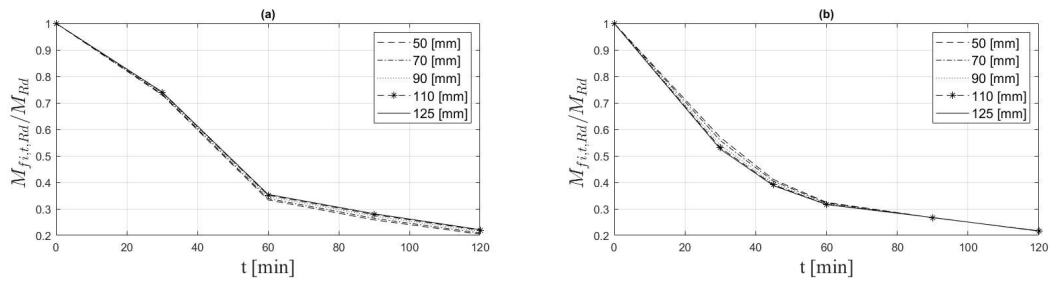


Figure 7.20: Bondek bending resistance reduction factor for LWC: (a) EC 1994-1.2, (b) New Proposal.

Therefore, through the graphs presented, it is possible to conclude that there is a significant reduction in the bending resistance moment of composite slabs when comparing the results of the new calculation proposal based on parametric analysis with the simplified method presented by Eurocode 1994-1.2 [4]. In all cases, without exceptions, the reduction is higher when the new calculation proposal is used. Through a quantitative approach, it is possible to state that the reduction is in the order of 3% to 20% for most of the fire resistance times. However, for the initial times of 30 min and 45 min, the effect is more stringent, reaching 50% in Lightweight Concrete for trapezoidal profiles.

# Chapter 8

## Conclusion

The main objective of this study was to present a new calculation proposal, aiming the reformulation of the analytical method presented in Annex D of Eurocode 1994-1.2 [4], through a new formulation and new coefficients. In order to estimate the temperatures of the steel deck components and also the rebars temperature, besides introducing the parameters that allow the calculation of the temperatures for a 45 min of fire resistance time in an analytical approach.

The new proposal is based on a parametric study, using the finite element method developed in a bi-dimensional approach using MATLAB software. It was possible to investigate both the temperature distribution along the cross-section of the composite slabs using perfect contact and the influence of using a 0.5 mm air layer between steel and concrete to represent the debonding effect, which mainly influences the temperature of the rebars. After all, a layer of low thermal conductivity between the steel and the concrete affects the thermal energy that initially reaches the concrete and subsequently reaches the region of the rebars. Then was also presented a difference in the temperature calculation of the rebars and the steel deck components, obtained using the simplified calculation method of the Eurocode 1994-1.2 and using a non-linear transient thermal analysis. Due to that fact, it was highlighted a constant difference in temperature values throughout the analysis time in such a way that the parametric study shows higher temperatures. It was also observed that the amplitude in the temperature difference between the parametric

results and the analytical results of the Eurocode simplified calculation method is more significant for first fire rating classes.

In order to validate the results from the thermal analyses in MATLAB, several three-dimensional transient non-linear thermal analyses were developed using the ANSYS software. Therefore, comparing the results, it was possible to validate the temperature results since the ANSYS results show only a slight increase in temperature, being on average between  $10^{\circ}C$  and  $15^{\circ}C$  and reaching the extreme of  $35^{\circ}C$ . The differences presented between the numerical models developed are attributed to a few factors: difference in the geometry of the finite elements used, the difference in the types of finite elements used, the difference in the convergence parameters.

Regarding the validation of the numerical model through experimental tests, it should be mentioned that the thermal models used have already been validated against experimental tests by several works developed by Piloto P. et al. [5–7]. Therefore, the purpose of this project is not to validate the numerical model but to use an already validated numerical model for the development of a study that allows the development of safer analytical calculation methods in order to ensure structural safety in fire situations and contribute to adding improvements to the Eurocode formulations.

New calculation proposals were then presented for an analytical approach in determining temperatures in each steel deck component (Upper flange, Web, and Lower flange) and rebars. In addition to the new formulation, a revision was made to the old coefficients  $b_i$  and  $c_i$ . The introduction of new coefficients to the equations allowing the improvement of temperature estimation regarding the nature of the geometry of the steel deck profiles was also made.

The new proposal was then compared with the results provided by Eurocode 1994-1.2 [4] simplified calculation method. The difference is quite expressive; the variations are on average of 6% for the trapezoidal slabs and 10% for the re-entrant slabs. However, for the first times of fire resistance, this situation is more significant. For example, in the 30 min resistance time, it can reach 40% in re-entrant slabs temperature measurement.

The performance of the new calculation proposal was also evaluated concerning the

load-bearing criterion (R). The maximum bending moment in each resistance time ( $M_{fi,tRd}$ ) was calculated for all slabs geometry, different h1 thickness and concrete types. This value was then divided by the maximum resistant moment of the slab at room temperature ( $M_{RD}$ ), thus allowing the calculation of the load bearing capacity reduction rate of the slabs along the time of exposure to an ISO-834 standard fire curve. The results prove the existence of a reduction in the order of 3% to 20% for most of the fire resistance times. However, this effect is increased for the initial times of 30 min and 45 min, reaching 50% in Lightweight Concrete for trapezoidal profiles.

## 8.1 Suggestions for Future Works

This study only analyzed the behavior of composite slabs exposed to the standard ISO-834 fire curve, so it is necessary to study the effects generated by different temperature curves, especially concerning natural fire curves.

Another suggestion is to improve the MATLAB code in order to develop a three-dimensional model with an adequate representation of the rebars and the thermal influence produced by the presence of these components on the composite slabs, which is currently only possible in a two-dimensional approach.

Considering the support conditions of composite slabs, It would be interesting to perform studies with different support conditions besides the simple support to determine not only the sagging moments but also the hogging moments.

Another alternative approach refers to a revision in the thermal properties of LWC since the current Eurocode neglects some important effects, such as the energy demand for the evaporation of the water present in the concrete.

# Bibliography

1. Cooke, G. M. E., LKawson, R. M. & Newman, G. M. *Fire Resistance of Composite Deck Slabs*. 1988.
2. Guo, S. Experimental and numerical study on restrained composite slab during heating and cooling. *Journal of Constructional Steel Research* **69**, 95–105. ISSN: 0143-974X (2012).
3. Guoqiang, L. & Peijun, W. Properties of Steel at Elevated Temperatures. *Advanced Topics in Science and Technology in China* **2013**, 37–65. ISSN: 19956827 (2013).
4. CEN. *Eurocode 4 - Design of composite steel and concrete structures - Part 1-2: General rules - Structural fire design* Brussels, 2005.
5. Piloto, P., Prates, L., Balsa, C. & Rigobello, R. Numerical simulation of the fire resistance of composite slabs with steel deck. *International Journal of Engineering and Technology(UAE)* **7**, 83–86 (Apr. 2018).
6. Piloto, P., Prates, L., Balsa, C. & Rigobello, R. Fire Resistance of Composite Slabs with Steel Deck: From Experiments to Numerical Simulation. *Portuguese Association for Experimental Mechanics* **31**, 85–94. ISSN: 1646-7078 (2019).
7. Piloto, P. *et al.* THREE-DIMENSIONAL NUMERICAL MODELLING OF FIRE EXPOSED COMPOSITE SLABS WITH STEEL DECK. *MATTER: International Journal of Science and Technology* **5**, 48–67 (Aug. 2019).
8. Carnot, S. *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance* (Chez Bachelier, Libraire, 1824).

9. For Standardization, I. O. *ISO 834-1: Fire Resistance Tests - Elements of Building Construction - Part 1: General Requirements*. Standard (International Organization for Standardization, Switzerland, Nov. 1999).
10. European Convention for Constructional Steelwork. Technical Committee 3, F. S. o. S. S. *Calculation of the Fire Resistance of Composite Concrete Slabs with Profiled Steel Sheet Exposed to the Standard Fire Calculation of the Fire Resistance of Composite Concrete Slabs with Profiled Steel Sheet Exposed to the Standard Fire N<sup>o</sup> 32-37* (European Convention for Constructional Steelwork, 1984).
11. Hamerlinck, R. & Stark, J. W. B. A Numerical Model for Fire-exposed Composite Steel / concrete Slabs (1990).
12. Hamerlinck, R. *The Behaviour of Fire-Exposed Composite Steel/Concrete Slabs* 1991.
13. Both, C., Fellingner, J. H. & Twilt, L. Shallow floor construction with deep composite deck: From fire tests to simple calculation rules. *Heron* **42**, 145–158. ISSN: 00467316 (1997).
14. Wald, F. *et al.* Experimental behaviour of a steel structure under natural fire. *Fire Safety Journal* **41**, 509–522. ISSN: 03797112 (2006).
15. Steel, B. *The Behaviour of Multi-storey Steel Framed Buildings in Fire* ISBN: 9780900206504 (British Steel, 1999).
16. Lamont, S., Usmani, A. & Drysdale, D. Heat transfer analysis of the composite slab in the Cardington frame fire tests. *Fire Safety Journal* **36**. Response of Composite Steel Framed Structures to Fire, 815–839. ISSN: 0379-7112 (2001).
17. Gillie, M., Usmani, A., Rotter, M. & O' Connor, M. Modelling of heated composite floor slabs with reference to the Cardington experiments. *Fire Safety Journal* **36**. Response of Composite Steel Framed Structures to Fire, 745–767. ISSN: 0379-7112 (2001).

18. Gillie, M., Usmani, A. & Rotter, J. A structural analysis of the Cardington British Steel Corner Test. *Journal of Constructional Steel Research* **58**, 427–442. ISSN: 0143-974X (2002).
19. Lamont, S., Usmani, A. & Gillie, M. Behaviour of a small composite steel frame structure in a “long-cool” and a “short-hot” fire. *Fire Safety Journal* **39**, 327–357. ISSN: 0379-7112 (2004).
20. Lim, L., Buchanan, A., Moss, P. & Franssen, J.-M. Numerical modelling of two-way reinforced concrete slabs in fire. *Engineering Structures* **26**, 1081–1091. ISSN: 0141-0296 (2004).
21. Lim, L. & Lim, L. Experimental fire tests of two-way concrete slabs (1992).
22. Wang, A. Fire resistance design of composite slabs in building structures: from research to practice. *Structural engineer* (2006).
23. Guo, S. & Bailey, C. Experimental behaviour of composite slabs during the heating and cooling fire stages. *Engineering Structures* **33**, 563–571. ISSN: 0141-0296 (2011).
24. Jiang, J., Usmani, A. & Li, G.-Q. Modelling of Steel-Concrete Composite Structures in Fire Using OpenSees. *Advances in Structural Engineering* **17**, 249–264. eprint: <https://doi.org/10.1260/1369-4332.17.2.249> (2014).
25. del Coz-Díaz, J. J., Martínez-Martínez, J. E., Alonso-Martínez, M. & Álvarez Rabanal, F. P. Comparative study of LightWeight and Normal Concrete composite slabs behaviour under fire conditions. *Engineering Structures* **207**, 110196. ISSN: 0141-0296 (2020).
26. Ali, T., Yehia, S. & El-Didamouny, M. Analytical study on concrete slabs with decking profiled steel sheet. *International Journal of Advanced Research in Engineering and Technology* **11**, 939–950. ISSN: 0976-6499 (2020).
27. Bolina, F., Tutikian, B. & Rodrigues, J. P. C. Thermal analysis of steel decking concrete slabs in case of fire. *Fire Safety Journal* **121**, 103295. ISSN: 0379-7112 (2021).

28. Cengel, Y. & Ghajar, A. *Heat and Mass Transfer, Fundamentals & Application, Fifth Edition in SI Units* 496. ISBN: 9780471457282 (2015).
29. Forsberg, C. *Heat Transfer Principles and Applications* ISBN: 9780128022962 (Elsevier Science & Technology, 2020).
30. CEN. *Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design* Brussels, 2004.
31. CEN. *Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design* Brussels, 2004.
32. CEN. *Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire* Brussels, 2002.
33. Prado, T. C., Moura, S., Sassine, A. & Vega, O. Caracterização do carbono em amostras de aço.
34. Choi, I. R., Chung, K. S. & Lee, H. Thermal and mechanical properties of structural steel SN400 at elevated temperatures. *International Journal of Steel Structures* **17**, 999–1007. ISSN: 20936311 (2017).
35. CEN. *Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings* Brussels, 2005.
36. CEN. *Eurocode 2: Design of concrete structures - Part 1-1 : General rules and rules for buildings* Brussels, 2004.
37. Concrete, F. *Fire design of concrete structures in accordance with CEB FIP model code 90* ISBN: 9782883940130 (CEB, 1991).
38. Both, C. *The fire resistance of composite steel-concrete slabs* 1998.
39. CEN. *EN 13501-2 : Fire classification of construction products and building elements. Classification using data from fire resistance tests, excluding ventilation services*. Brussels, 2010.
40. CEN. *EN 1363-1:2020 - Fire resistance tests - Part 1: General requirements* Brussels, 2020.

41. Prates, L. M. S. Simulação Numérica do Comportamento ao Fogo de Estruturas Mistas (Lajes). *MSc thesis, Instituto Politécnico de Bragança*, 524 (2018).

# Appendix A

## Annex A - Data Sheet for trapezoidal geometry and NWC.

Data Sheet for composite slabs with trapezoidal geometry and Normal Weight Concrete.

**Data Sheet**

**Model 1 - Polydeck 59S -  $h_1 : 50mm$**

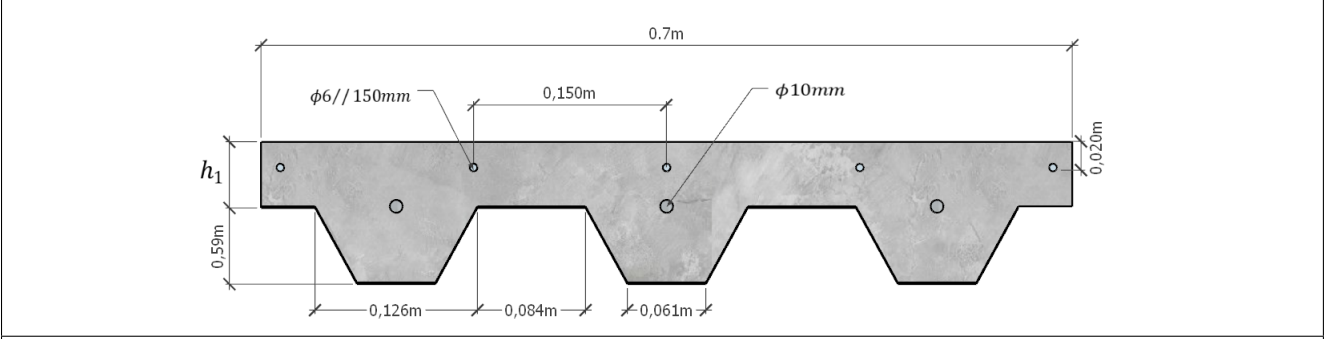
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

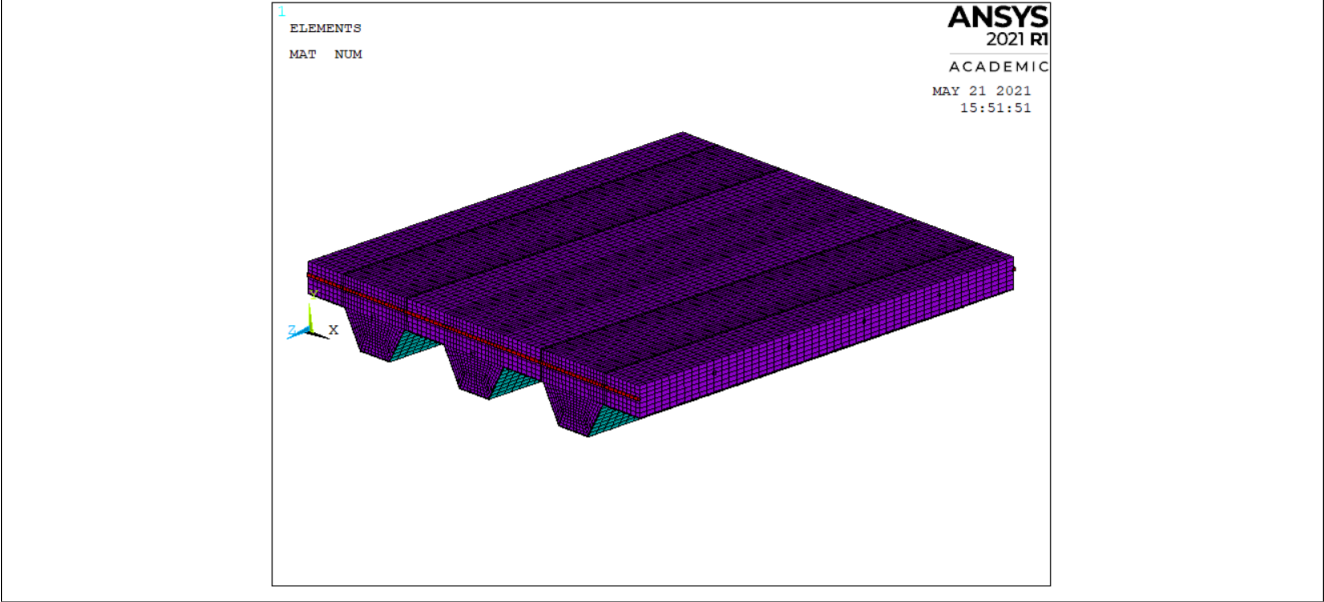
**Detailing**

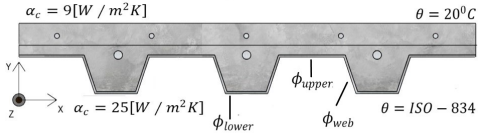
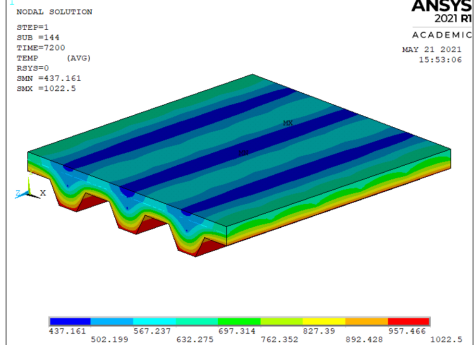
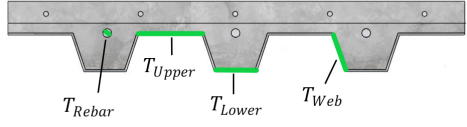
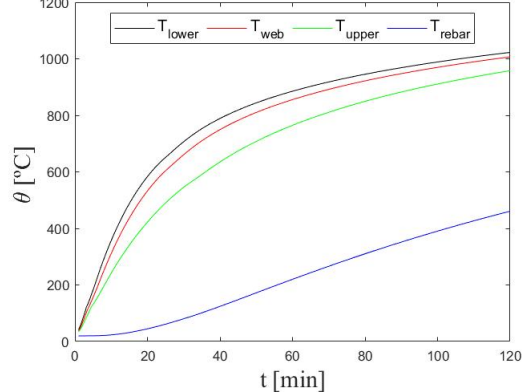
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

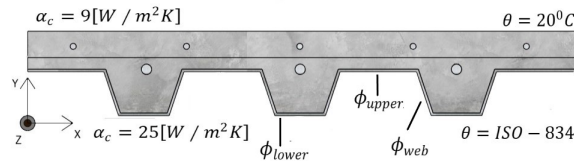


Model 1 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s Time Step Size: 60 s	Tolerance Value: $1 \cdot 10^{-3}$	
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s Máximum Time Step: 60 s	Min. Reference Value: $1 \cdot 10^{-6}$	
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 1 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

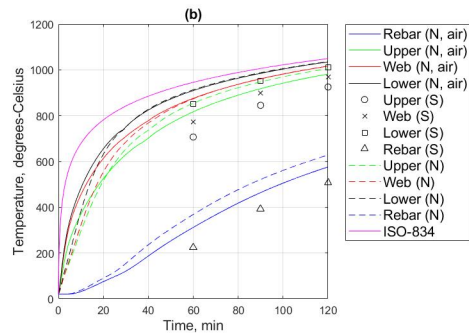
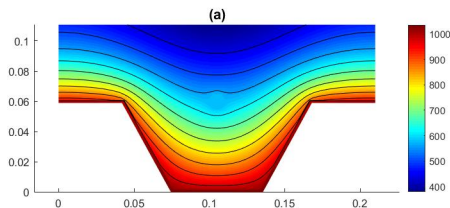
**Boundary Conditions**



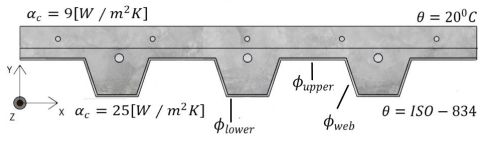
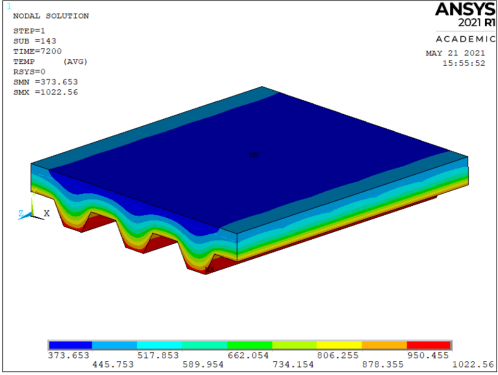
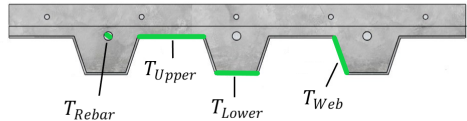
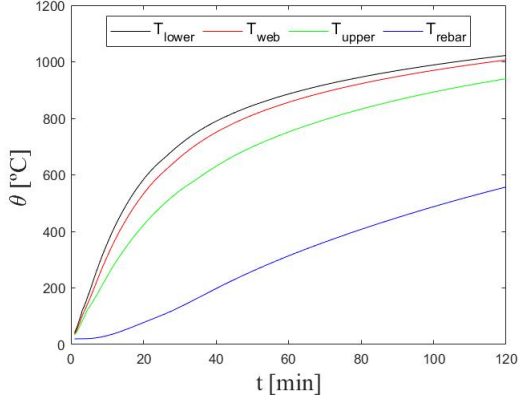
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



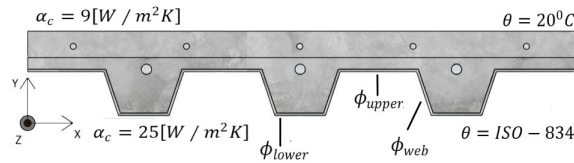
Data Sheet											
Model 2 - Polydeck 59S - $h_1 : 70mm$											
Basic Data (1/3)											
Parametric Study	Author: Silveira, M. B.		year:2021								
Detailing											
Steel Deck	Concrete	Steel Bars									
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500								
Cross-Section											
<p>The diagram shows a cross-section of a trapezoidal steel deck with a total width of 0.7m and a height of <math>h_1</math>. The top surface is flat with a thickness of 0.020m. The bottom surface features a series of trapezoidal indentations. Reinforcement includes <math>\phi 6 // 150mm</math> bars in the top flange and <math>\phi 10mm</math> bars in the bottom flange. Dimensions for the indentations are: 0.126m for the first, 0.084m for the second, and 0.061m for the third. A vertical dimension of 0.59m is shown for the depth of the first indentation. A horizontal dimension of 0.150m is shown between the first and second reinforcement bars.</p>											
Tridimensional Finite Element Model											
<p>The image displays a 3D finite element model of the steel deck structure. The model is rendered in purple and shows a grid of elements. A coordinate system with X, Y, and Z axes is visible in the bottom left corner. The ANSYS 2021 R1 ACADEMIC logo and date (MAY 21 2021 15:54:47) are in the top right corner. A table with the following content is located in the top left corner of the image area:</p> <table border="1"> <thead> <tr> <th colspan="2">1</th> </tr> <tr> <th>ELEMENTS</th> <th></th> </tr> <tr> <th>MAT</th> <th>NUM</th> </tr> </thead> <tbody> <tr> <td></td> <td></td> </tr> </tbody> </table>				1		ELEMENTS		MAT	NUM		
1											
ELEMENTS											
MAT	NUM										

Model 2 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 2 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

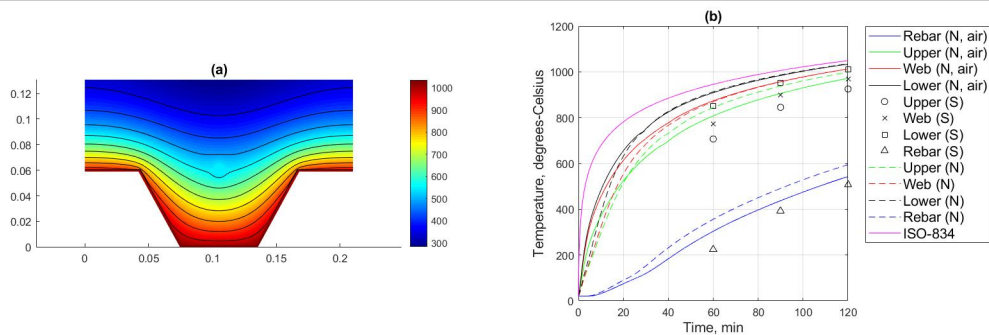
**Boundary Conditions**



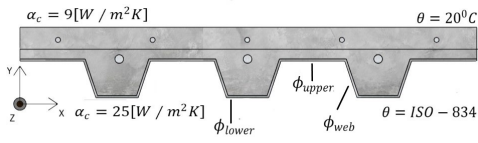
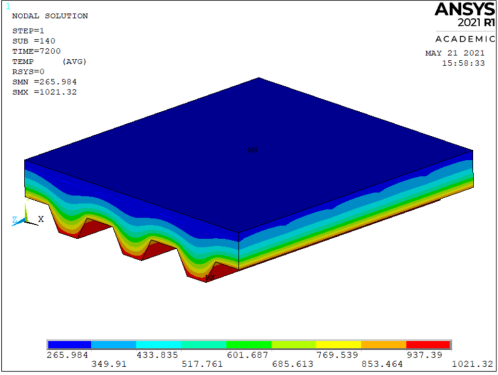
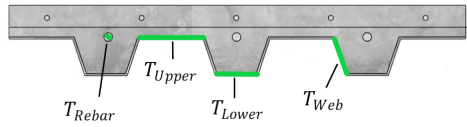
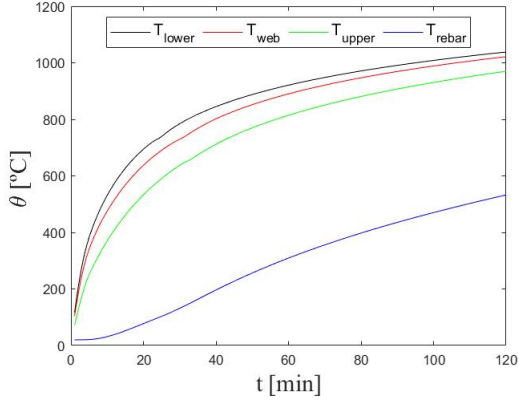
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



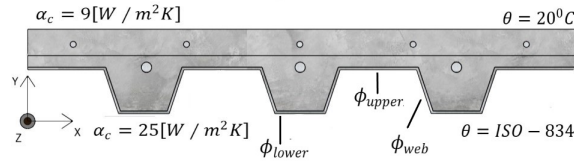
Data Sheet			
Model 3 - Polydeck 59S - $h_1 : 90mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			

Model 3 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 3 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

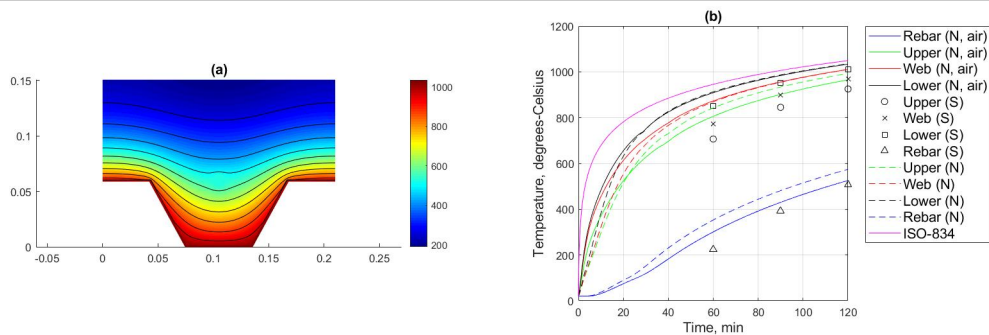
**Boundary Conditions**



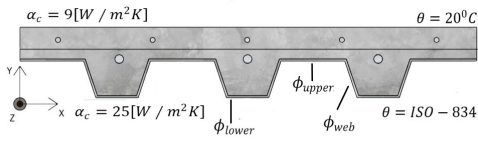
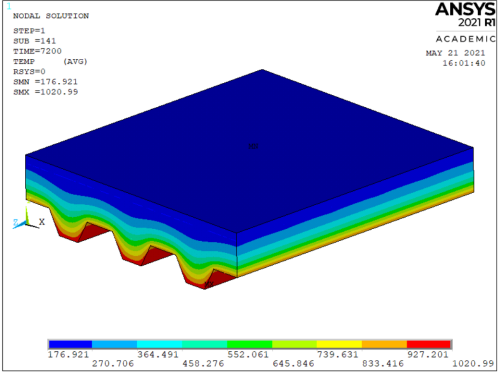
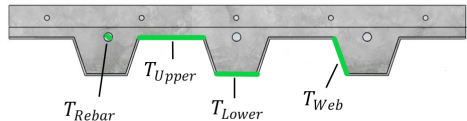
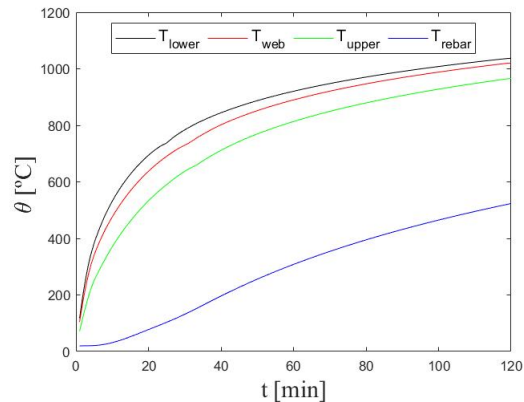
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



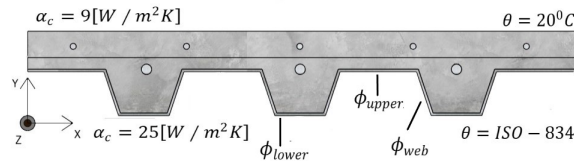
Data Sheet			
Model 4 - Polydeck 59S - $h_1 : 110mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.	year:2021	
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			

Model 4 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 4 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

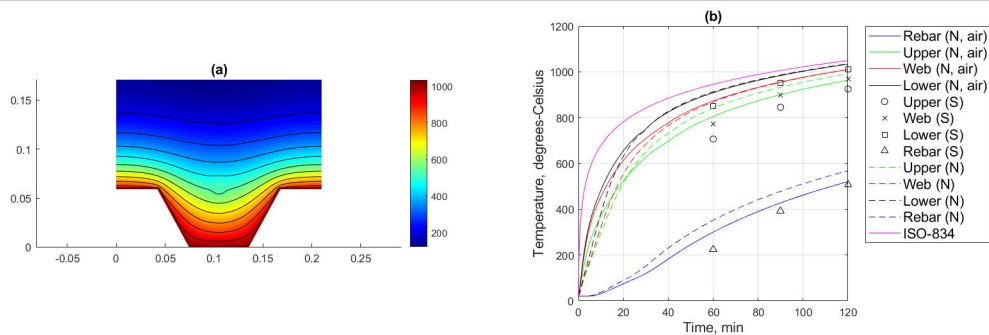
**Boundary Conditions**



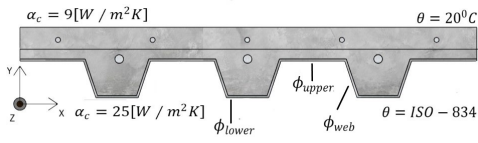
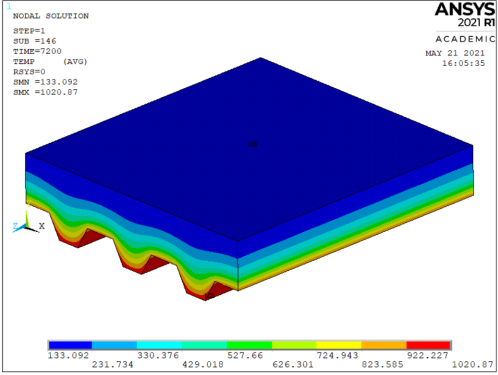
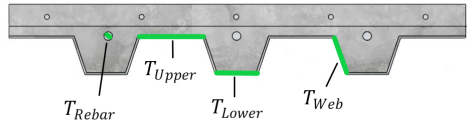
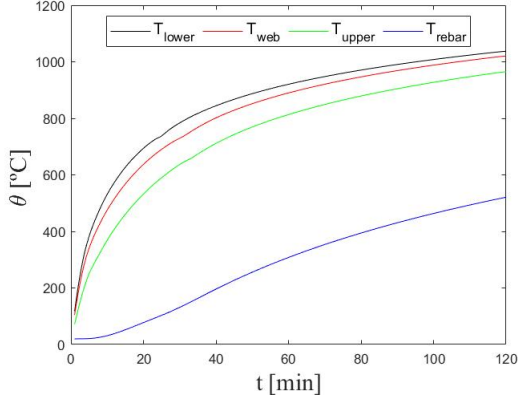
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



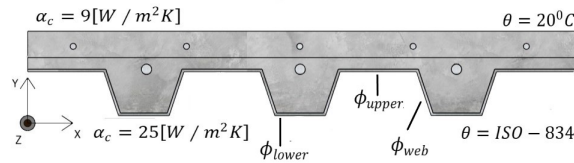
Data Sheet			
Model 5 - Polydeck 59S - $h_1 : 125mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.	year:2021	
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			

Model 5 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 5 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

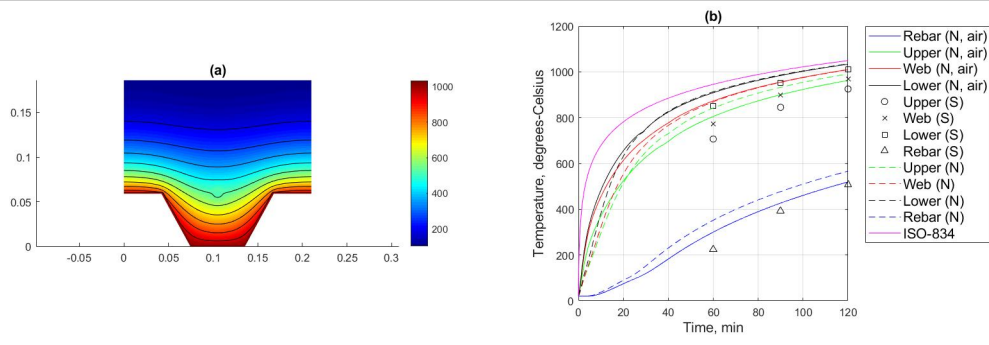
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 6 - Confraplus 60 -  $h_1 : 50mm$**

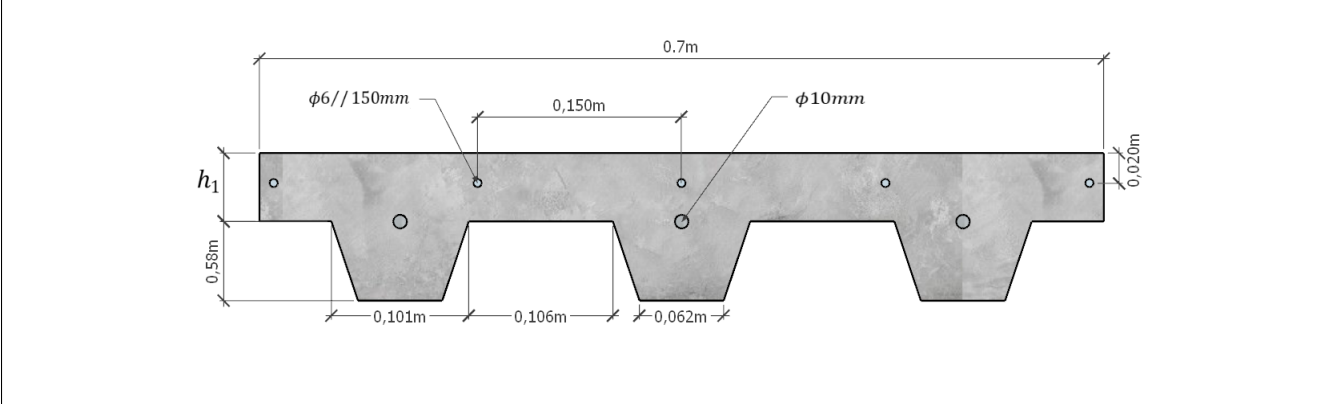
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

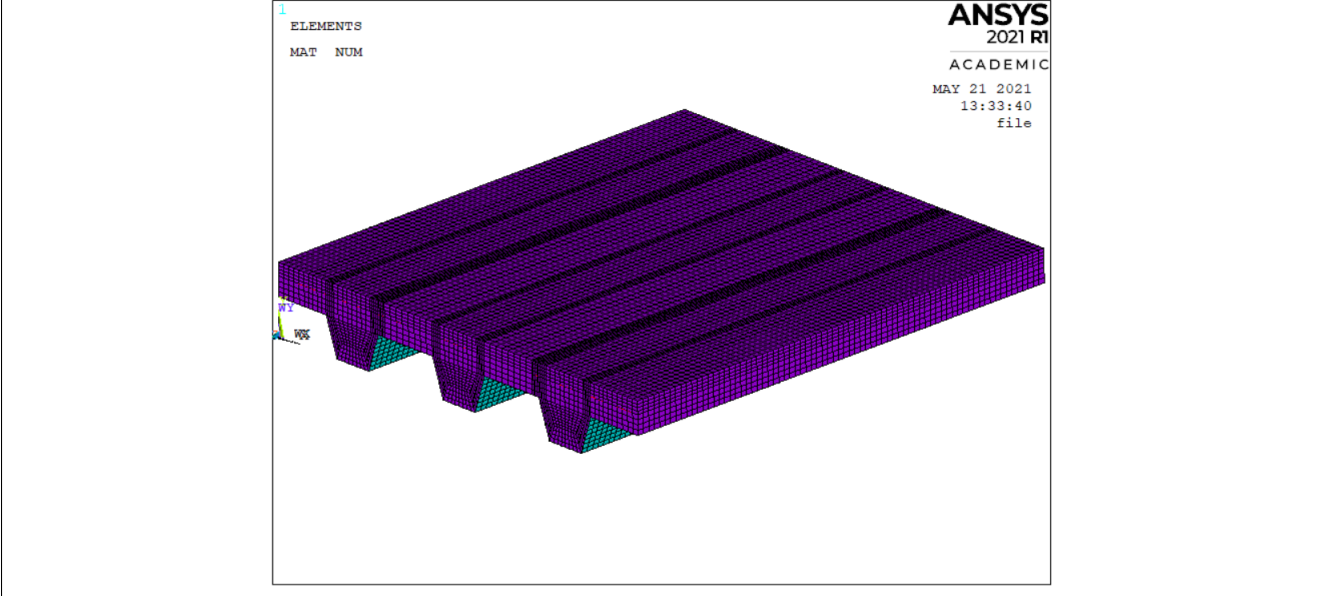
**Detailing**

Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

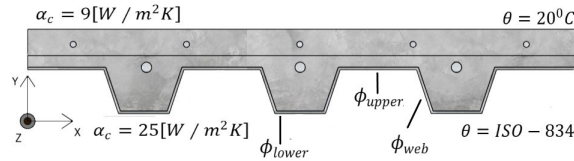


Model 6 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s Time Step Size: 60 s	Tolerance Value: $1 \cdot 10^{-3}$	
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s Máximum Time Step: 60 s	Min. Reference Value: $1 \cdot 10^{-6}$	
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
Additional Data		Temperature Graph	

**Model 6 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

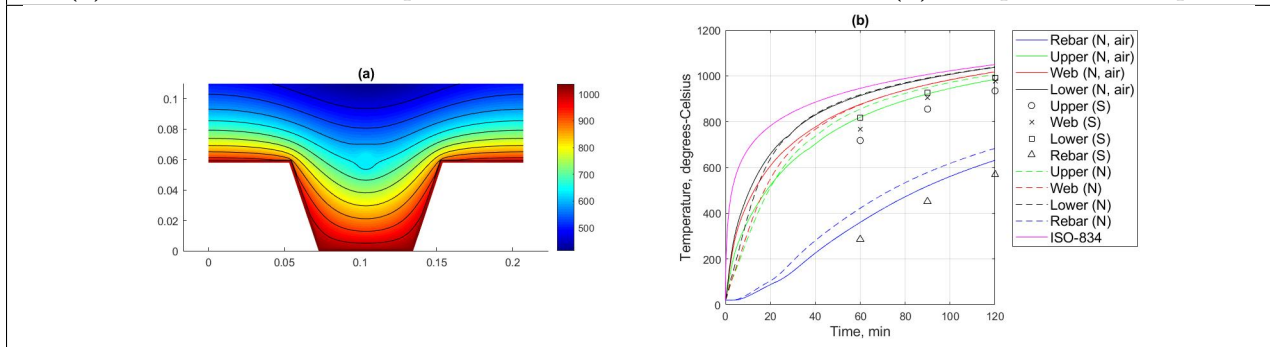
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 7 - Confraplus 60 -  $h_1 : 70mm$**

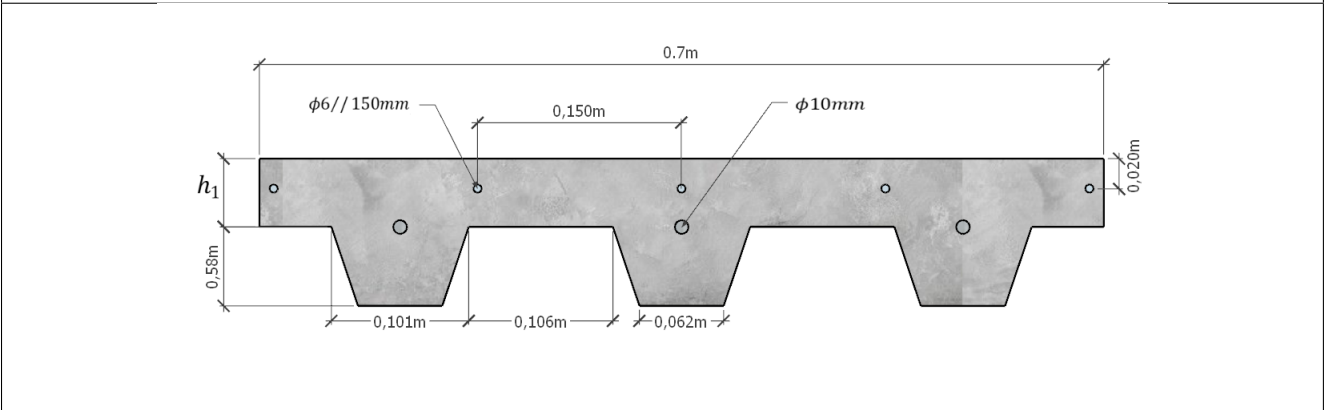
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

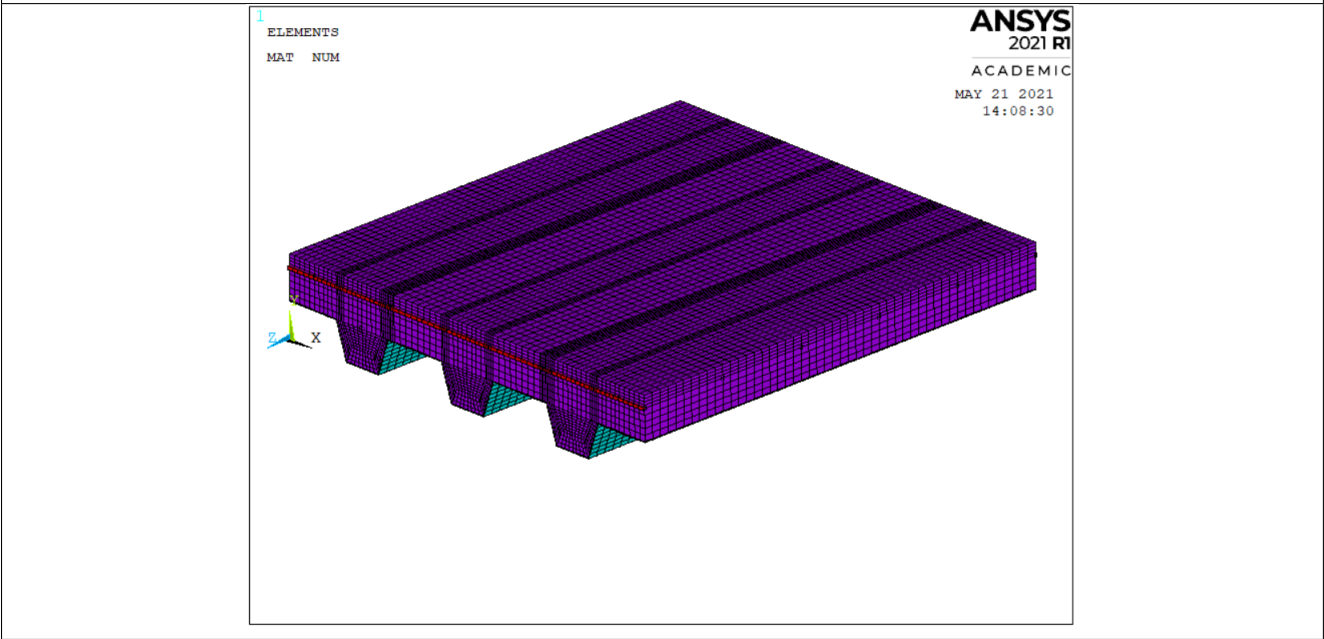
**Detailing**

Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal	Density: Normal Weight	<b>Reinforcement Bars</b>	<b>Steel mesh</b>
Thickness: 1.25mm	Class: C25/30	Description: $\phi 6 // 150$	Description: $3\phi 10$
Grade: S350	Moisture: 3.0%	Grade: S500	Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

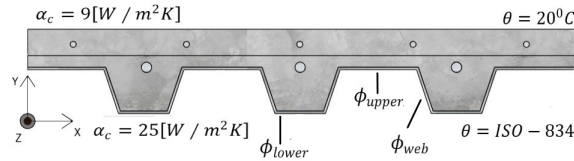


Model 7 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
Additional Data		Temperature Graph	

**Model 7 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

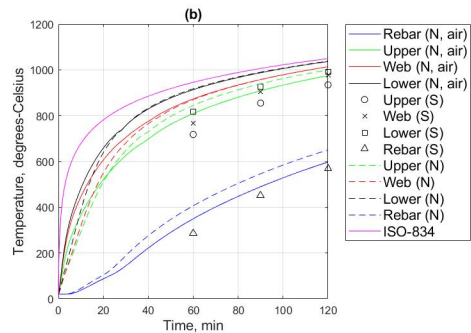
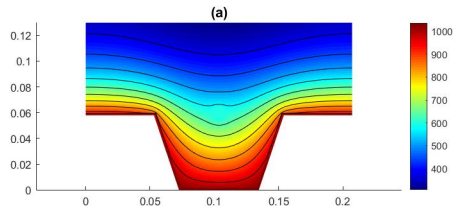
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 8 - Confraplus 60 -  $h_1 : 90mm$**

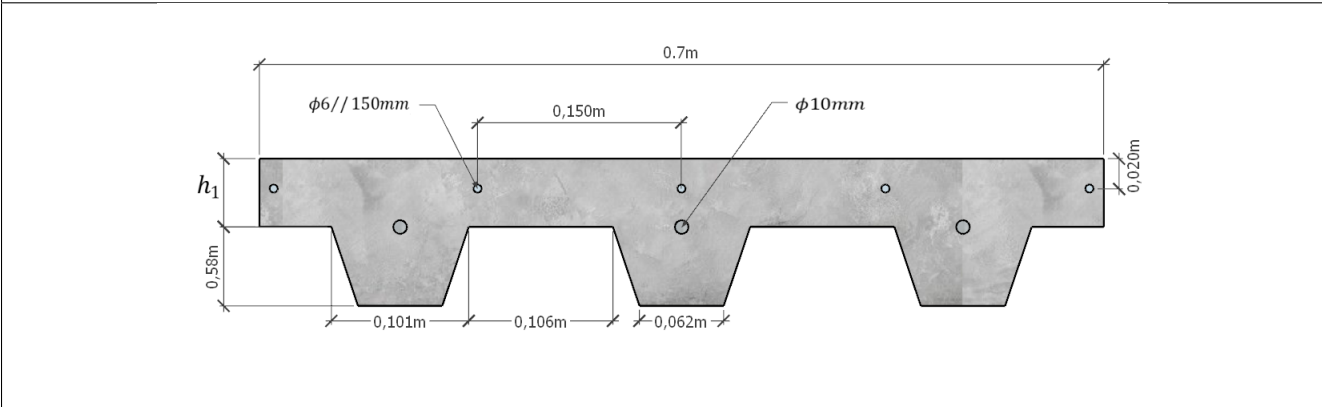
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

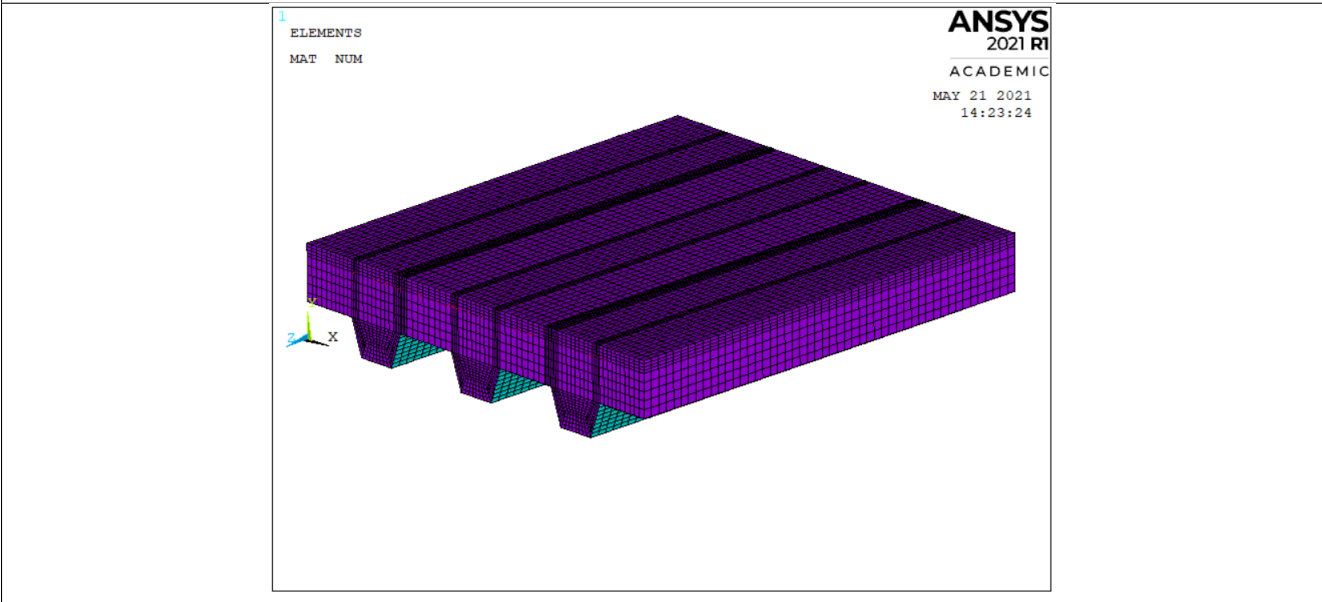
**Detailing**

Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**



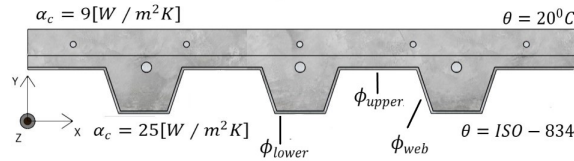
**Model 8 - Thermal Analysis with ANSYS - (2/3)**

ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s Time Step Size: 60 s	Tolerance Value: $1 \cdot 10^{-3}$	
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s Máximum Time Step: 60 s	Min. Reference Value: $1 \cdot 10^{-6}$	
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
Additional Data		Temperature Graph	

**Model 8 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
<b>Emissivity (<math>\varepsilon</math>)</b>	<b>Temperature Curve</b>	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

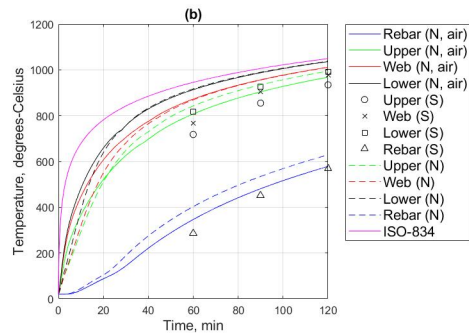
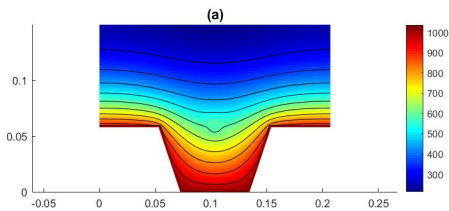
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 9 - Confraplus 60 -  $h_1 : 110mm$**

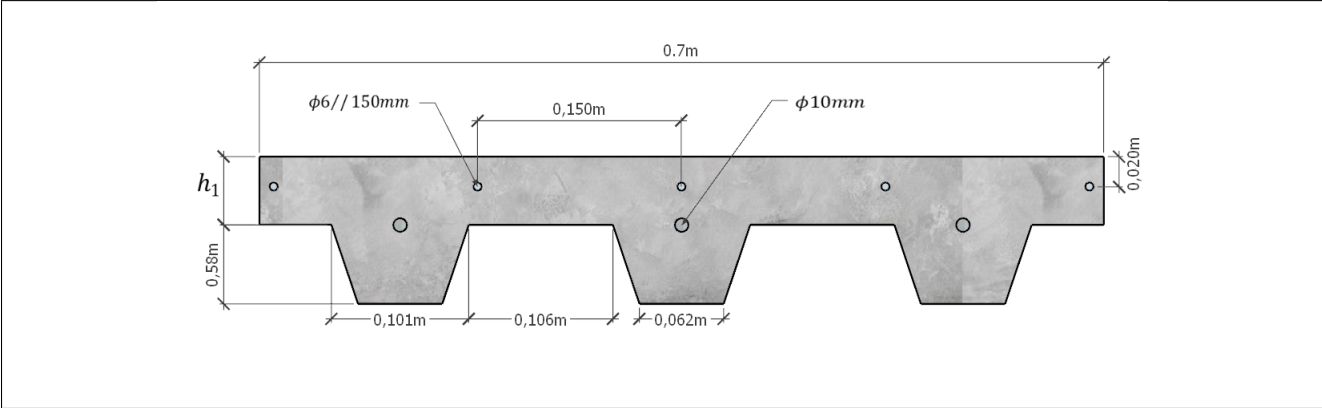
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

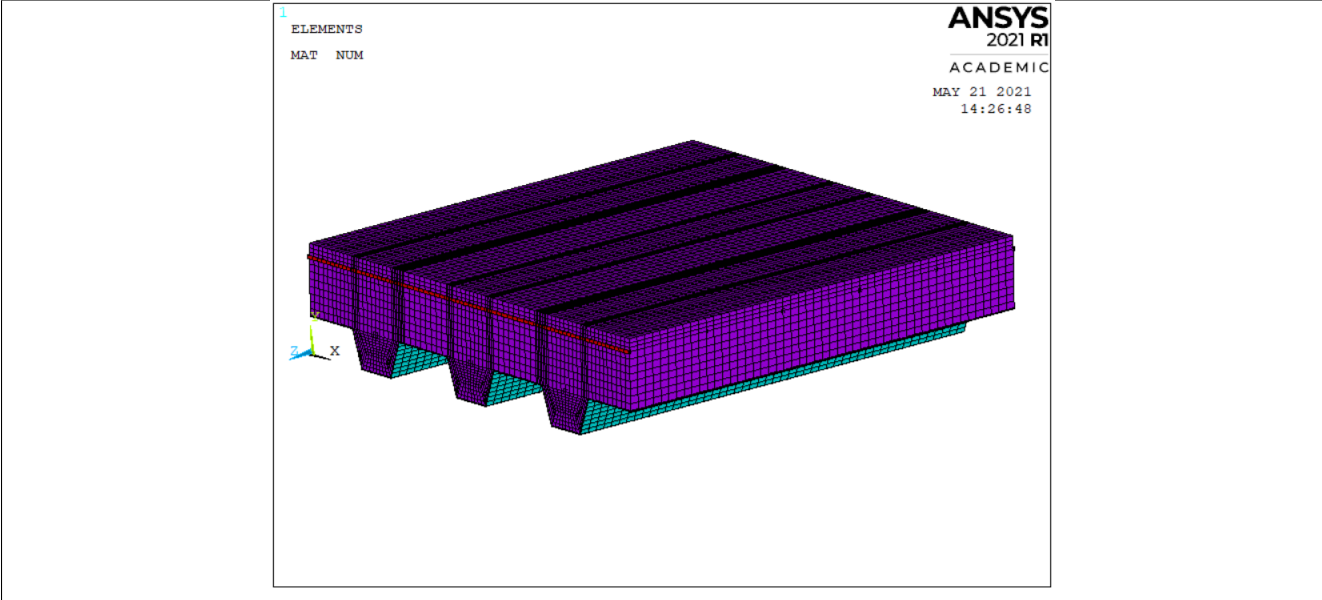
**Detailing**

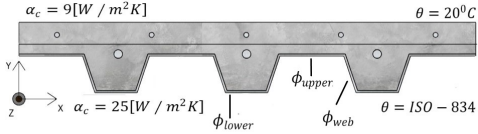
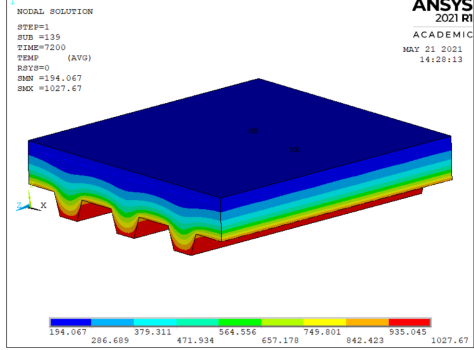
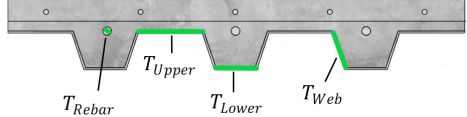
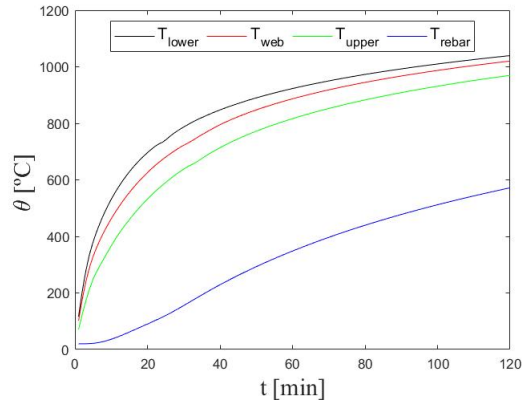
Steel Deck	Concrete	Reinforcement Bars	Steel mesh
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Description: $\phi 6 // 150$ Grade: S500	Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

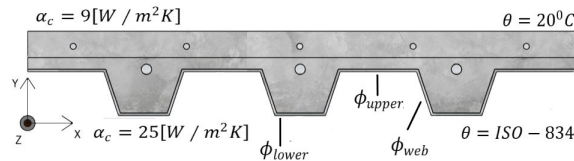


Model 9 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s Time Step Size: 60 s	Tolerance Value: $1 \cdot 10^{-3}$	
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s Máximum Time Step: 60 s	Min. Reference Value: $1 \cdot 10^{-6}$	
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 9 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

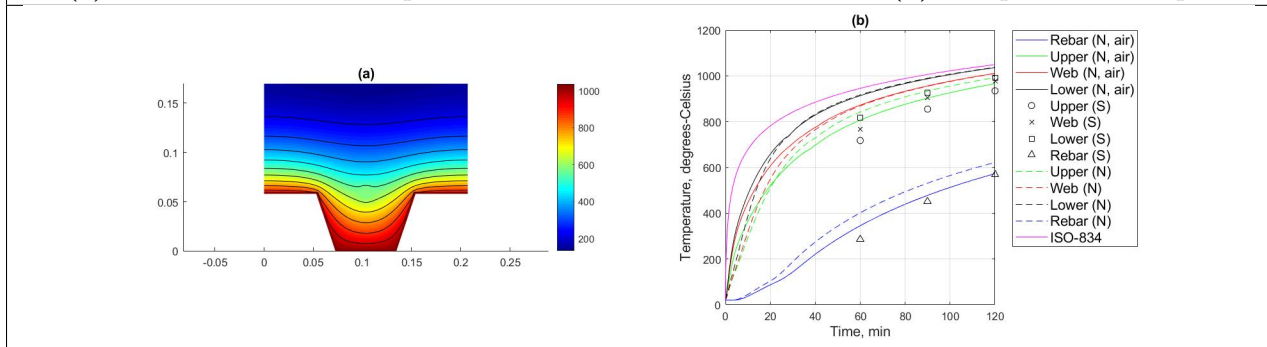
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 10 - Confraplus 60 -  $h_1 : 125mm$**

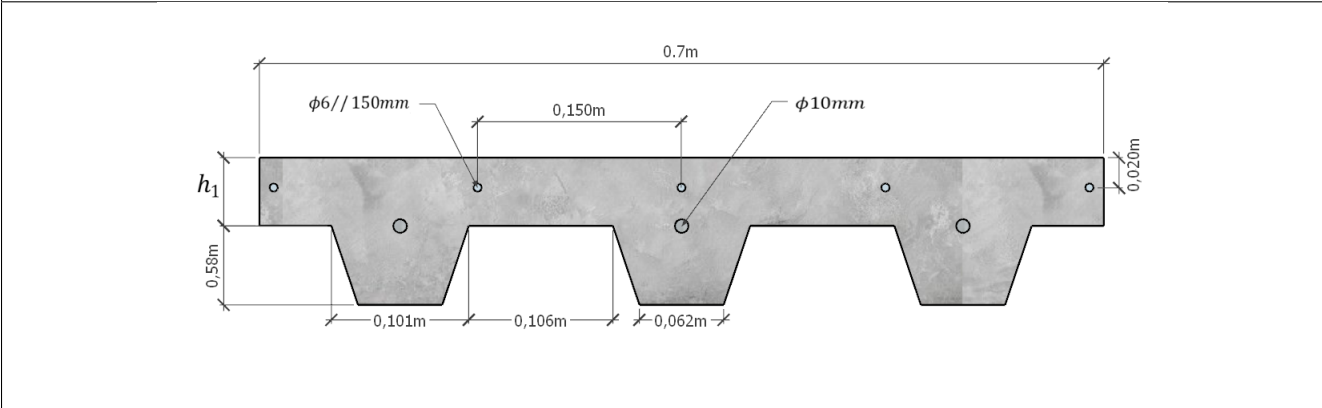
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

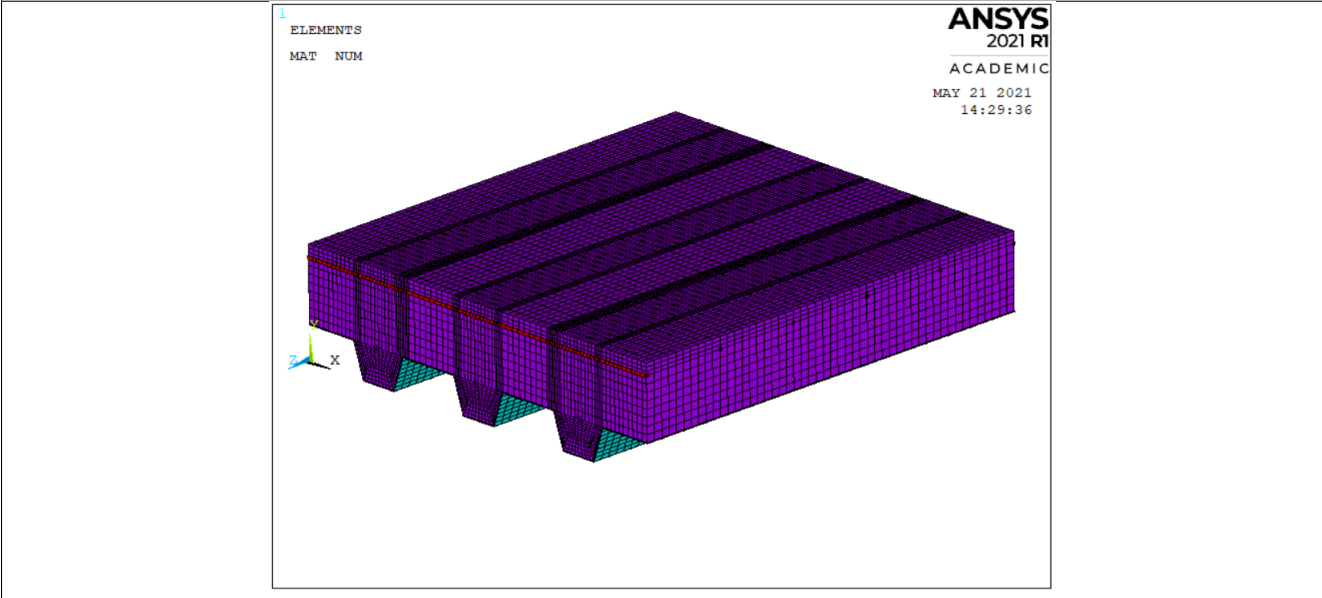
**Detailing**

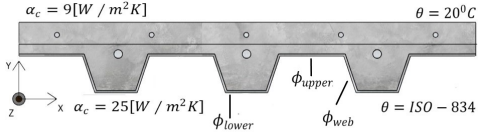
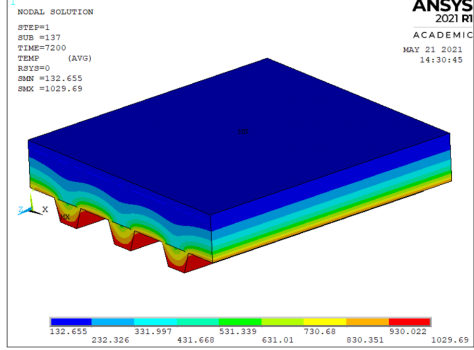
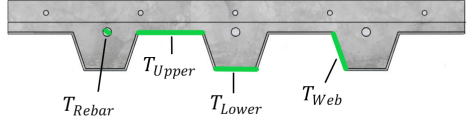
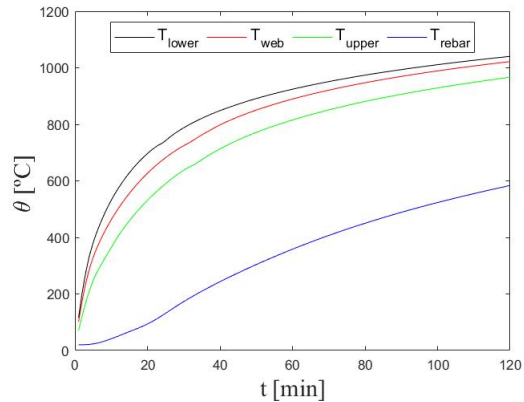
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

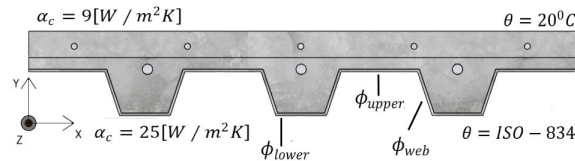


Model 10 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s Time Step Size: 60 s	Tolerance Value: $1 \cdot 10^{-3}$	
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s Máximum Time Step: 60 s	Min. Reference Value: $1 \cdot 10^{-6}$	
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 10 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

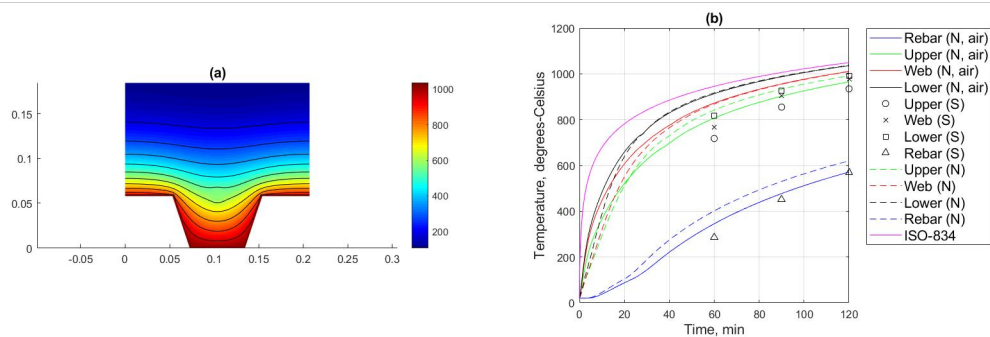
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



# Appendix B

## Annex B - Data Sheet for re-entrant geometry and NWC.

Data Sheet for composite slabs with re-entrant geometry and Normal Weight Concrete.

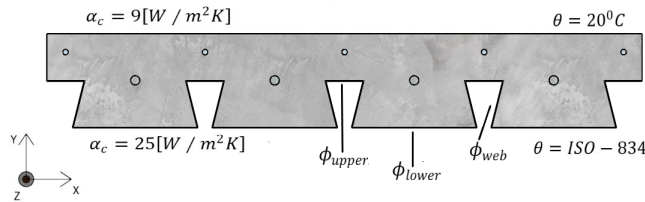
Data Sheet			
Model 11 - Multideck 50 - $h_1 : 60mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
<p>The diagram shows a cross-section of a multideck slab with a total width of 0.6m and a total height of <math>h_1</math>. The slab has a top thickness of 0.020m and a bottom thickness of 0.050m. The reinforcement consists of <math>\phi 6 // 150mm</math> bars in the top deck and <math>3\phi 10</math> bars in the bottom deck. The spacing between the reinforcement bars is 0.150m. The bottom deck has a width of 0.135m. The top deck has a width of 0.040m. The bottom deck has a width of 0.110m. The top deck has a width of 0.040m.</p>			
Tridimensional Finite Element Model			
<p>The image shows a 3D finite element model of the multideck slab. The model is composed of a grid of elements, with the top deck and bottom deck represented by different colors (purple and cyan). The model is shown from a perspective view, highlighting the re-entrant geometry and the reinforcement layout. The ANSYS 2021 R1 ACADEMIC logo and date (MAY 21 2021 16:07:03) are visible in the top right corner.</p>			

Model 11 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
Additional Data		Temperature Graph	

**Model 11 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

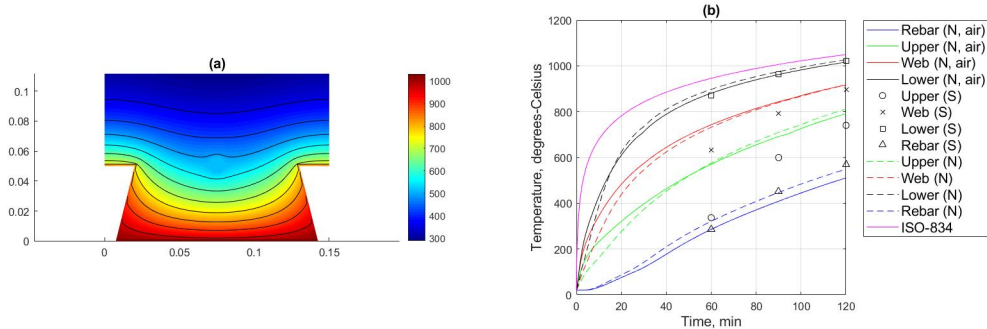
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 12 - Multideck 50 -  $h_1 : 70mm$**

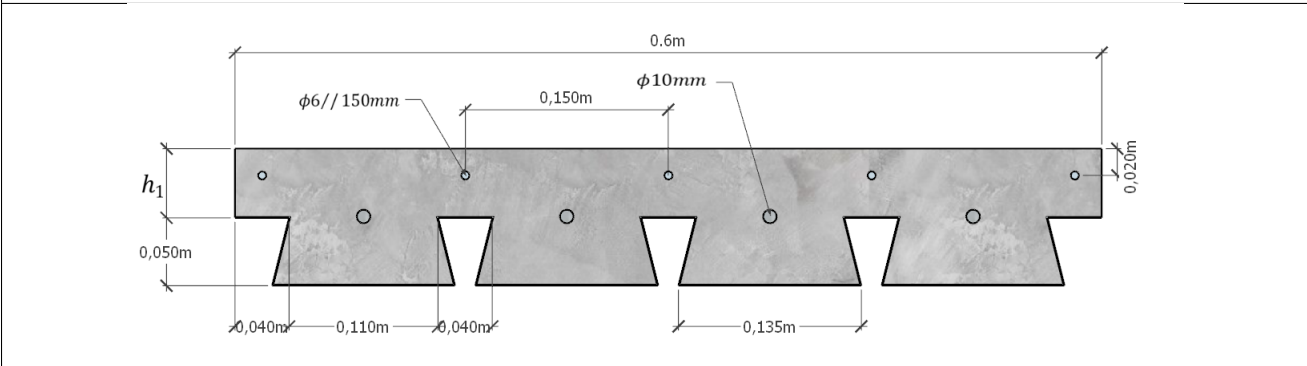
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

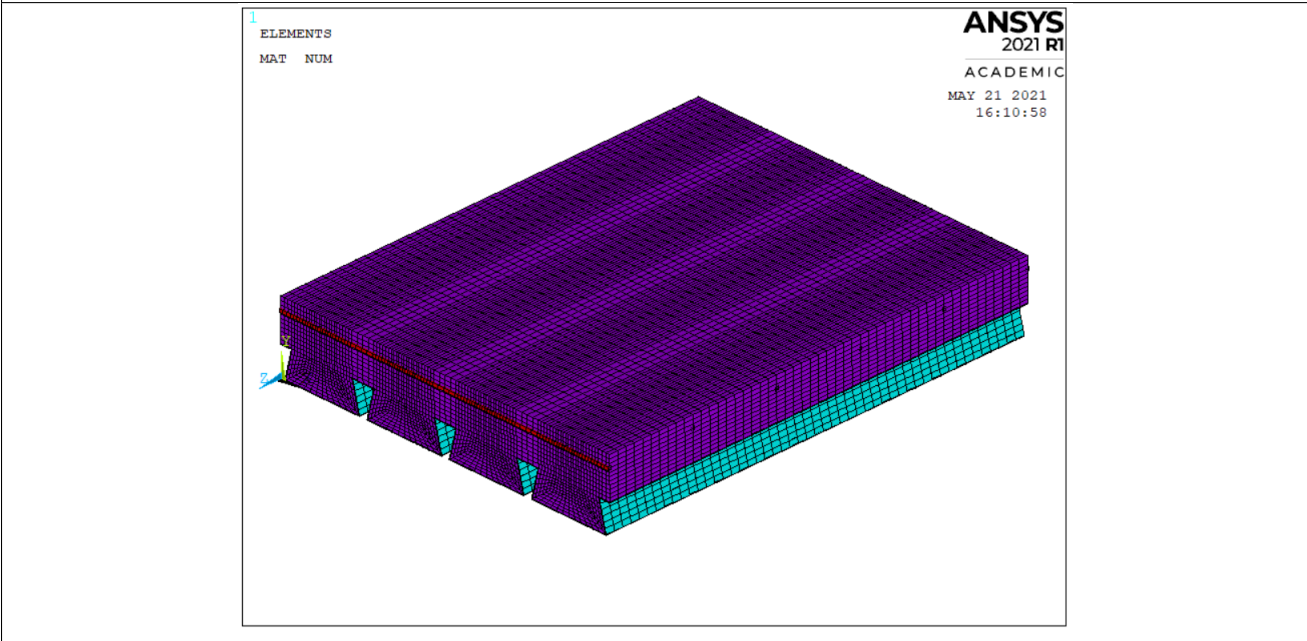
**Detailing**

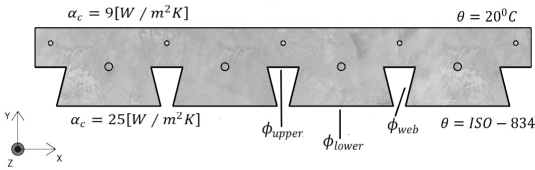
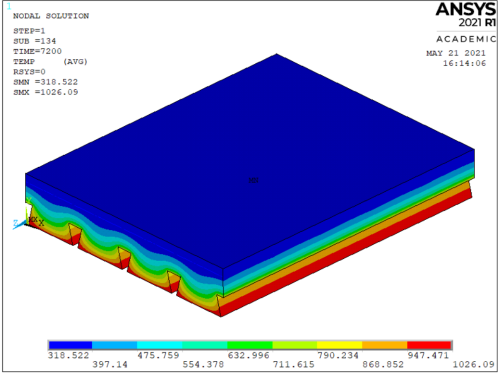
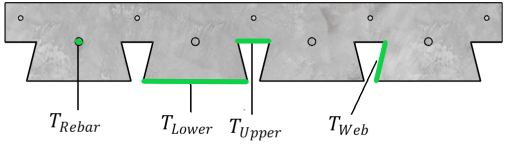
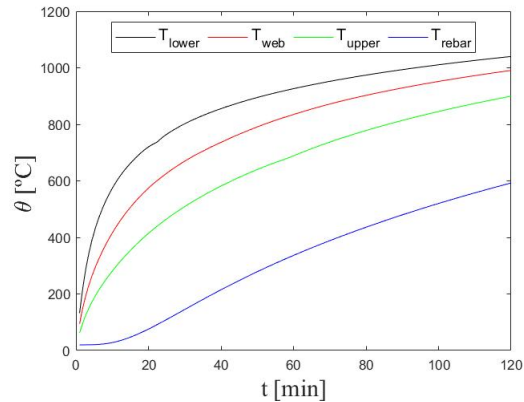
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

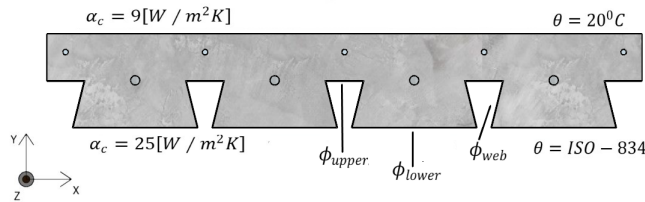


Model 12 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 12 - Thermal Analysis with MATLAB - (3/3)**

<b>MATLAB Element</b>	<b>Convection Coef. (<math>\alpha_c</math>)</b>	<b>View Factor (<math>\phi</math>)</b>
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
<b>Emissivity (<math>\varepsilon</math>)</b>	<b>Temperature Curve</b>	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

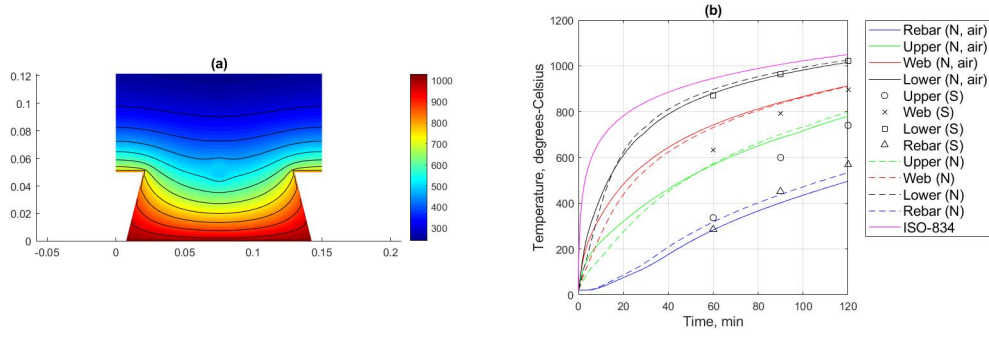
**Boundary Conditions**



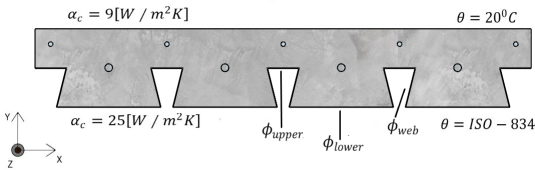
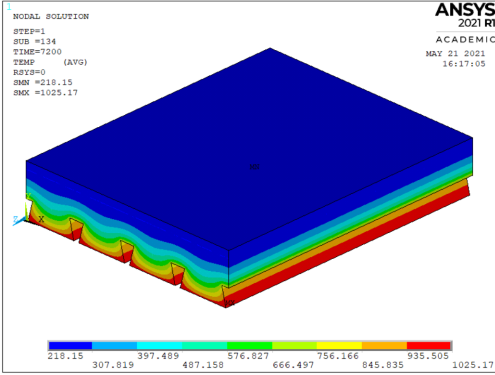
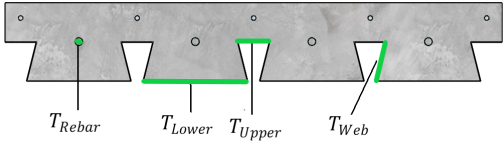
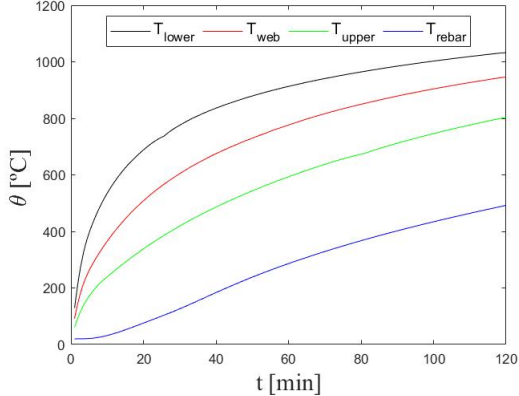
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



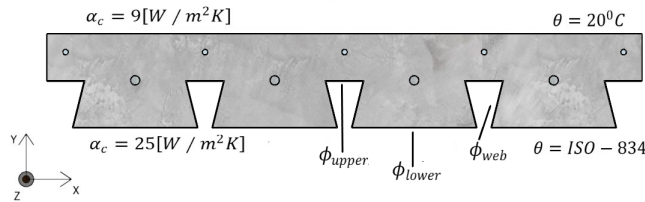
Data Sheet			
Model 13 - Multideck 50 - $h_1 : 90mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
<p>The diagram shows a cross-section of a multideck slab with a total width of 0.6m and a total height of <math>h_1</math>. The slab has a top flange thickness of 0.020m and a bottom flange thickness of 0.050m. The top flange contains reinforcement bars with a diameter of <math>\phi 6 // 150mm</math> and a spacing of 0.150m. The bottom flange contains reinforcement bars with a diameter of <math>\phi 10mm</math>. The bottom flange has a width of 0.135m. The top flange has a width of 0.040m. The bottom flange has a width of 0.110m. The bottom flange has a width of 0.040m. The bottom flange has a width of 0.135m.</p>			
Tridimensional Finite Element Model			
<p>The image shows a 3D finite element model of the multideck slab. The model is composed of a dense mesh of elements, colored in purple and cyan. The model is shown in a perspective view, highlighting the top and bottom flanges and the internal structure. The ANSYS logo and version information (ANSYS 2021 R1 ACADEMIC, MAY 21 2021, 16:16:13) are visible in the top right corner. The text 'ELEMENTS MAT NUM' is visible in the top left corner.</p>			

Model 13 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Maximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 13 - Thermal Analysis with MATLAB - (3/3)**

<b>MATLAB Element</b>	<b>Convection Coef. (<math>\alpha_c</math>)</b>	<b>View Factor (<math>\phi</math>)</b>
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
<b>Emissivity (<math>\varepsilon</math>)</b>	<b>Temperature Curve</b>	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

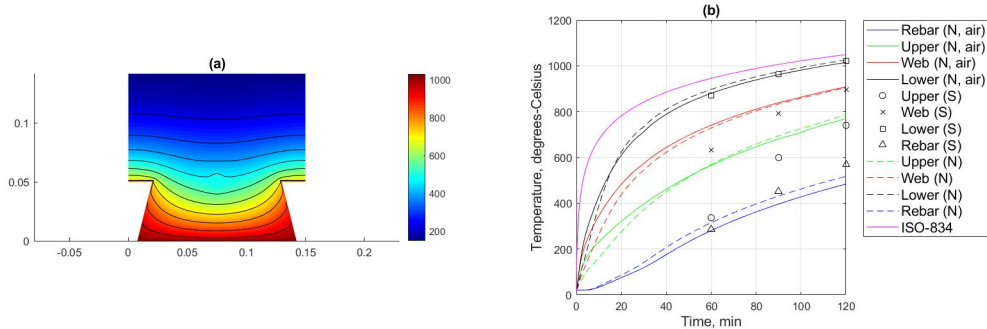
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 14 - Multideck 50 -  $h_1 : 110mm$**

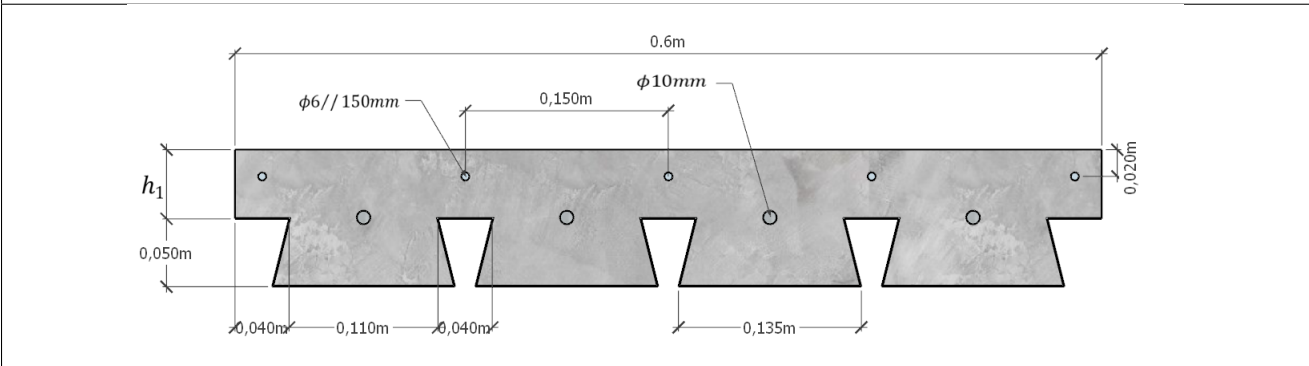
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

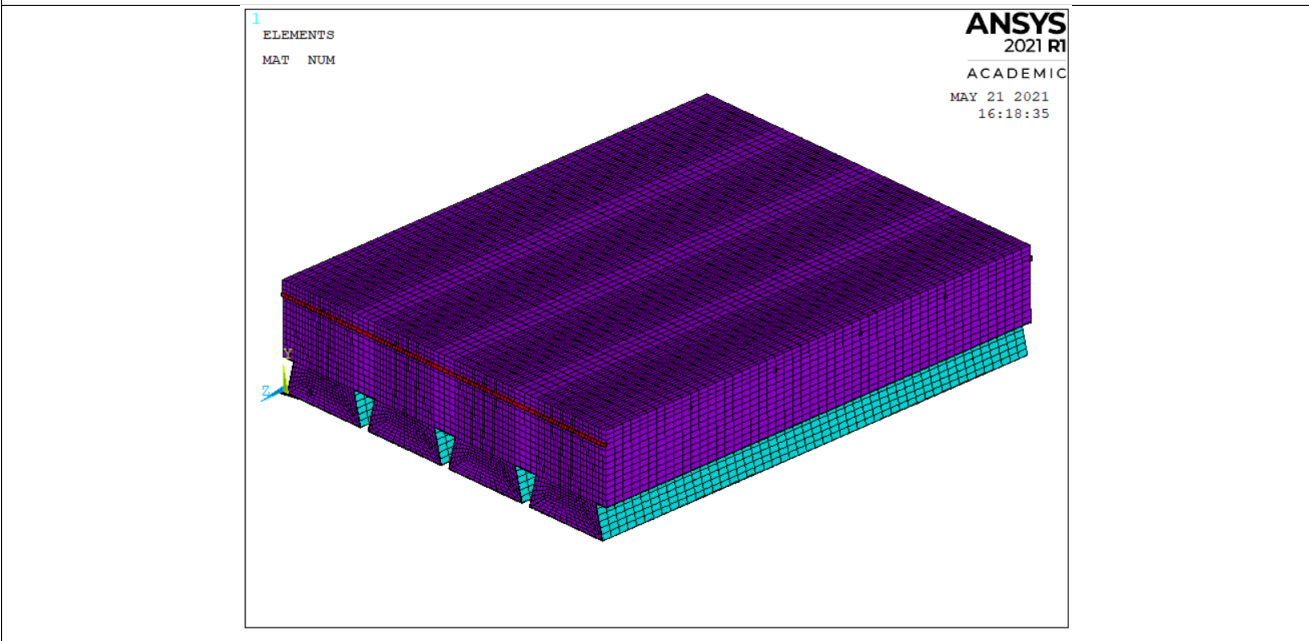
**Detailing**

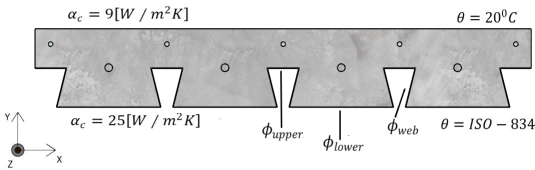
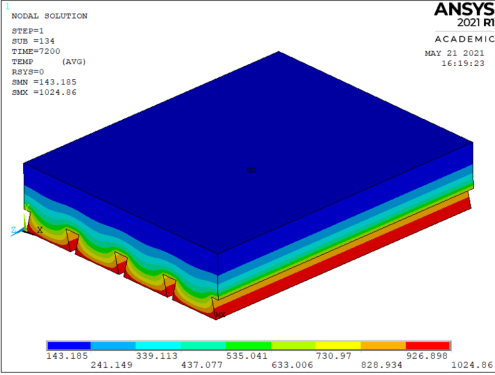
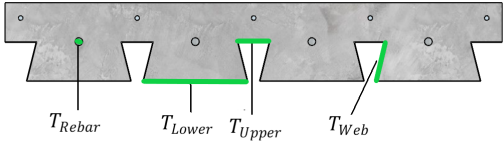
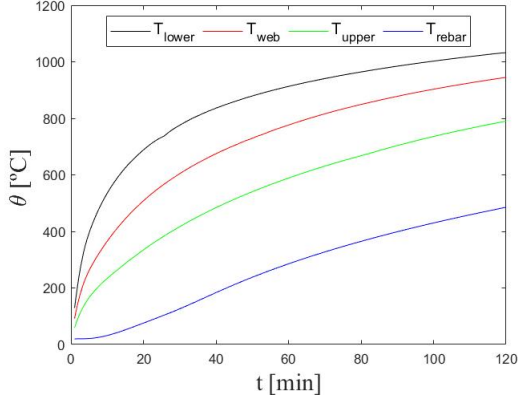
Steel Deck	Concrete	Reinforcement Bars	Steel Bars
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

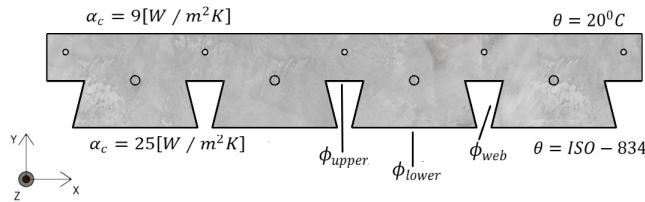


Model 14 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 14 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

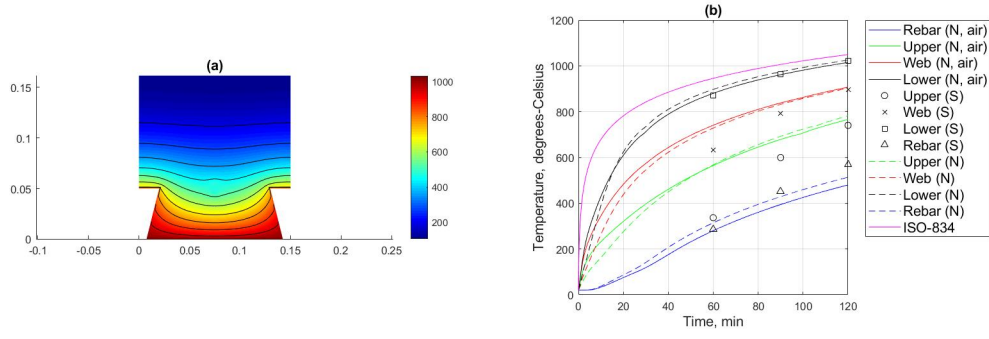
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

Model 15 - Multideck 50 -  $h_1 : 125mm$

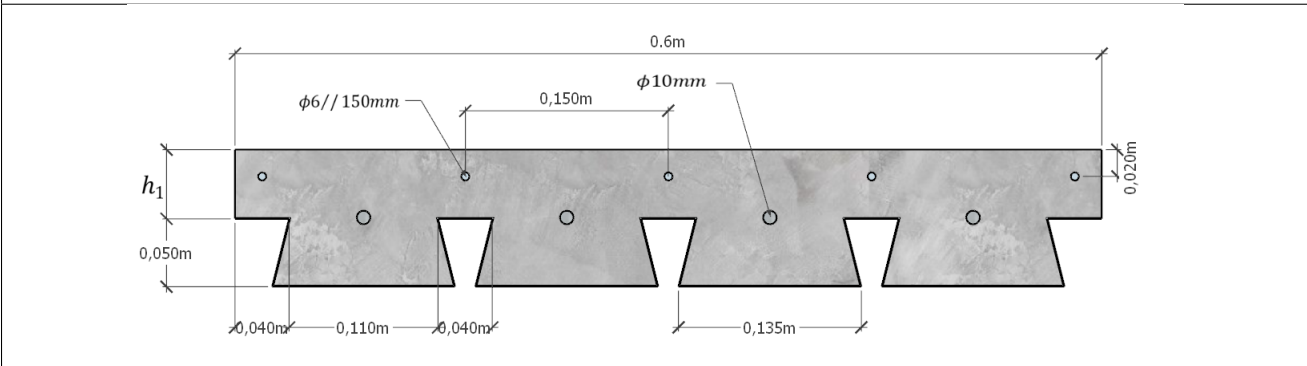
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

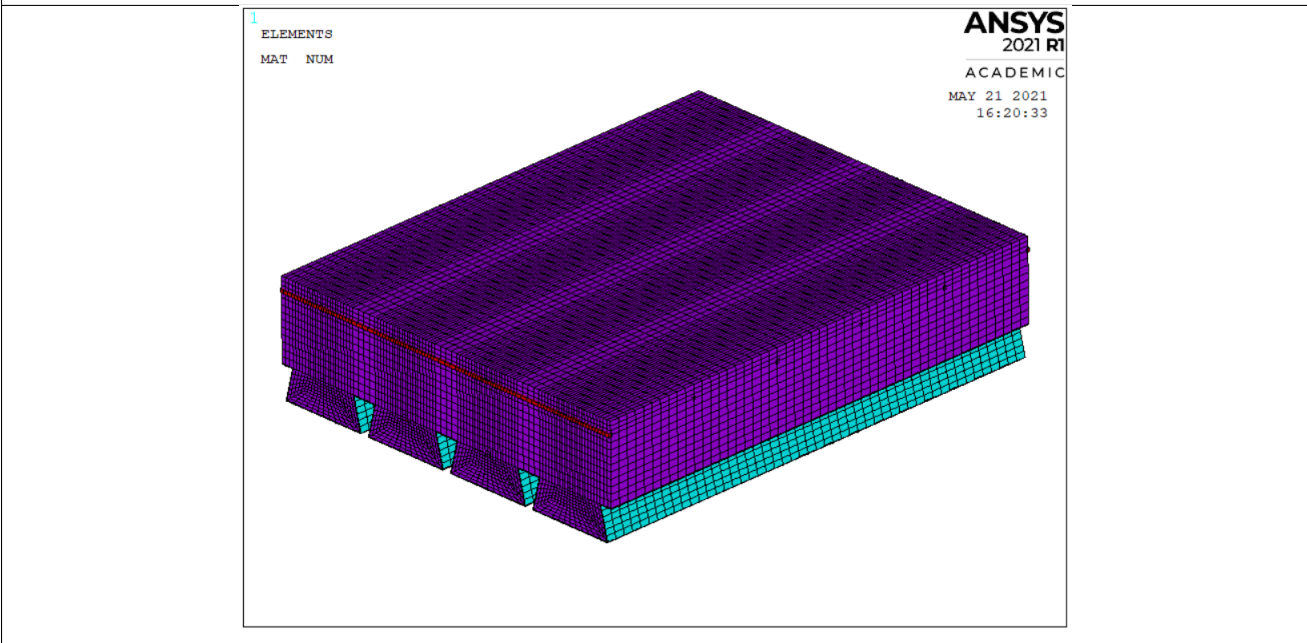
**Detailing**

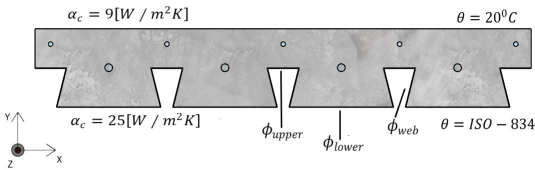
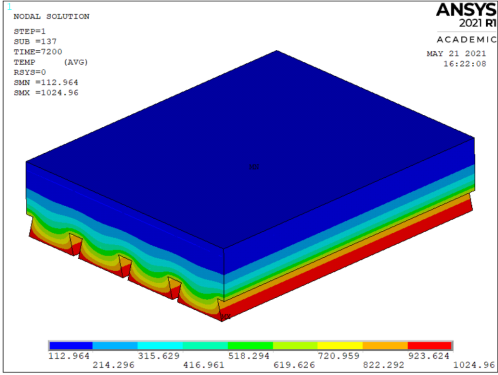
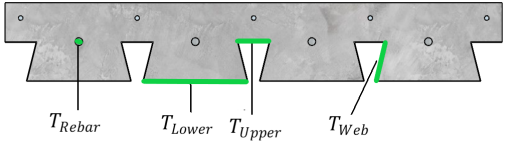
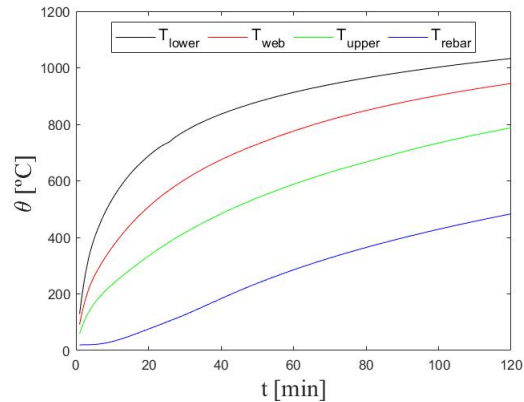
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

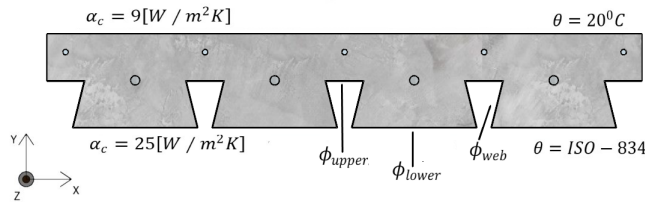


Model 15 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 15 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

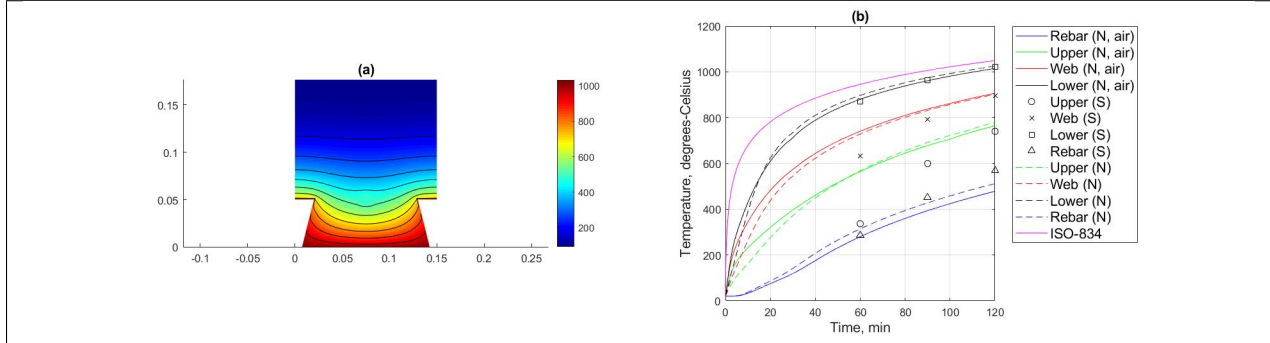
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 16 - Bondek -  $h_1 : 60mm$**

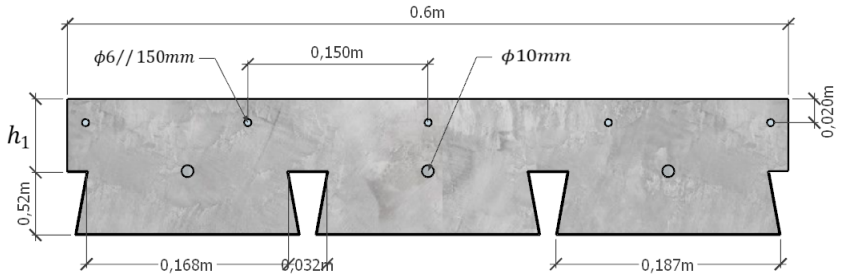
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

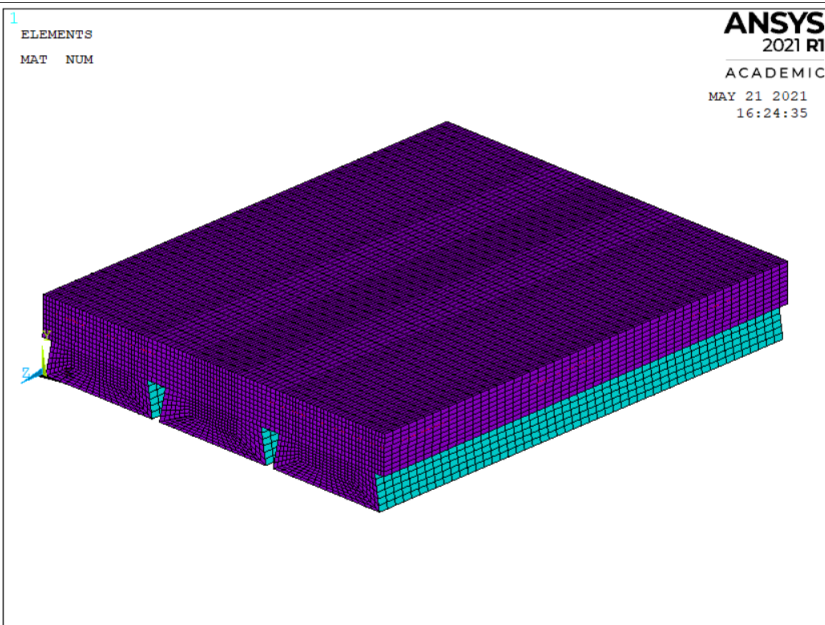
**Detailing**

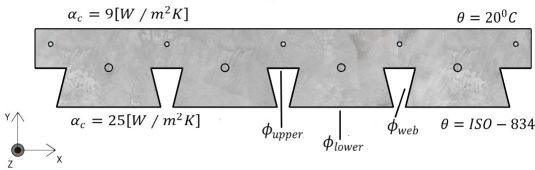
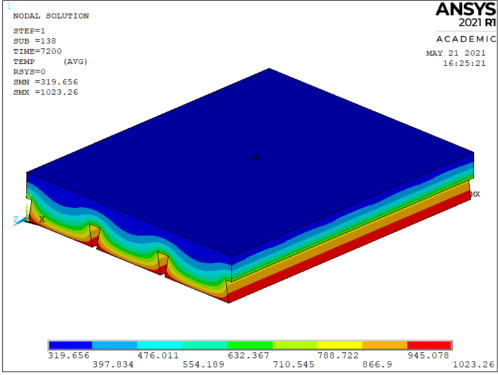
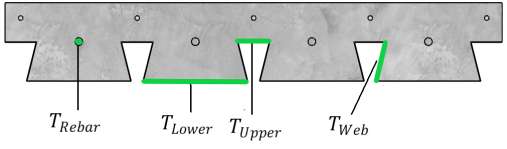
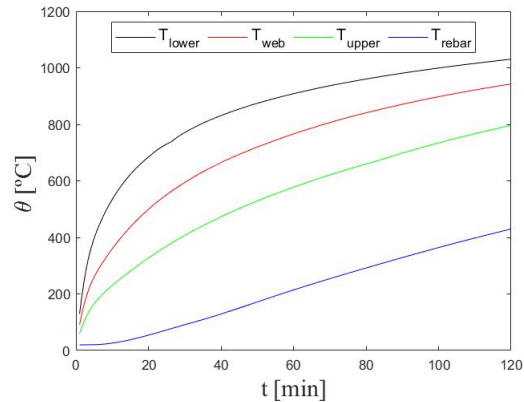
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

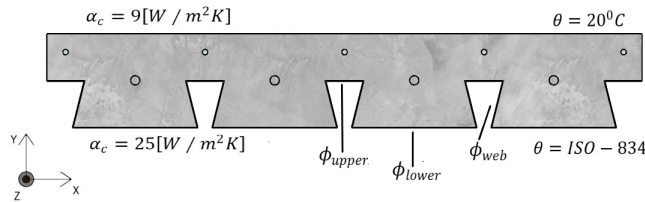


Model 16 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 16 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

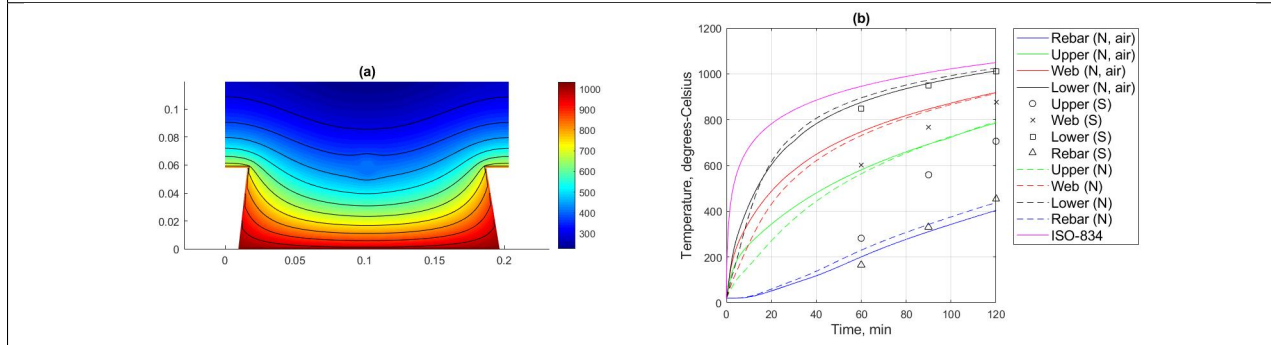
**Boundary Conditions**



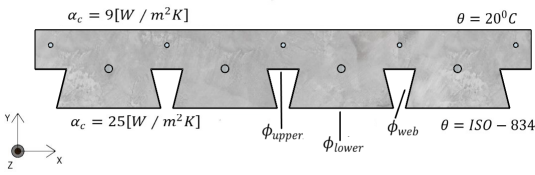
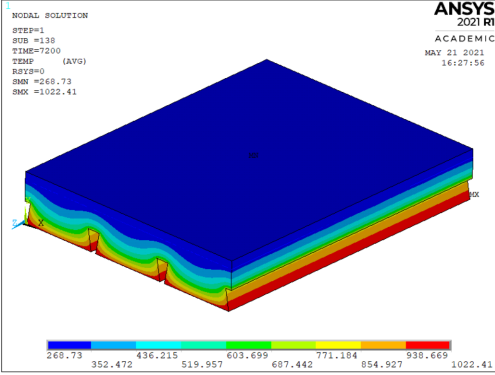
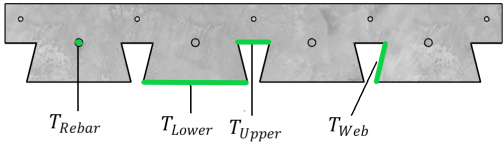
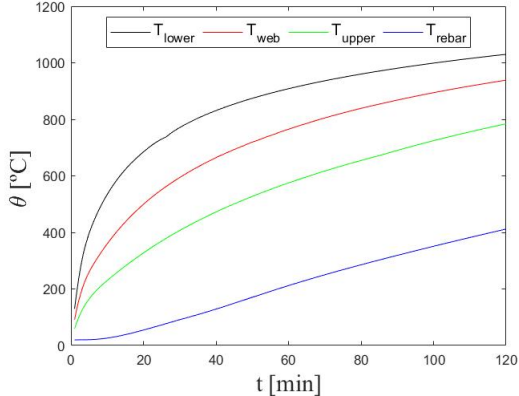
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



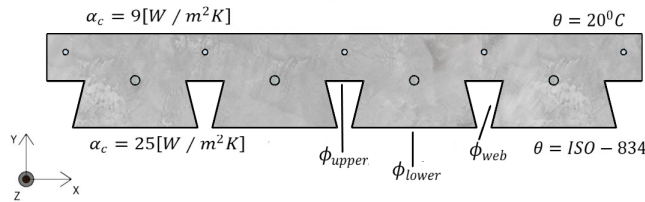
Data Sheet			
Model 17 - Bondek - $h_1 : 70mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			
<div style="display: flex; justify-content: space-between;"> <div style="border: 1px solid black; padding: 5px;"> <p>ELEMENTS MAT NUM</p> </div> <div style="text-align: right;"> <p><b>ANSYS</b> 2021 R1 ACADEMIC MAY 21 2021 16:27:10</p> </div> </div>			

Model 17 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s Time Step Size: 60 s	Tolerance Value: $1 \cdot 10^{-3}$	
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s Maximum Time Step: 60 s	Min. Reference Value: $1 \cdot 10^{-6}$	
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 17 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

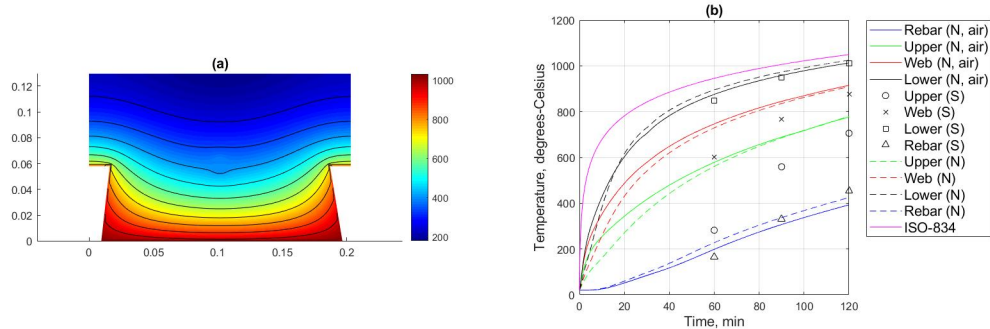
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 18 - Bondek -  $h_1 : 90mm$**

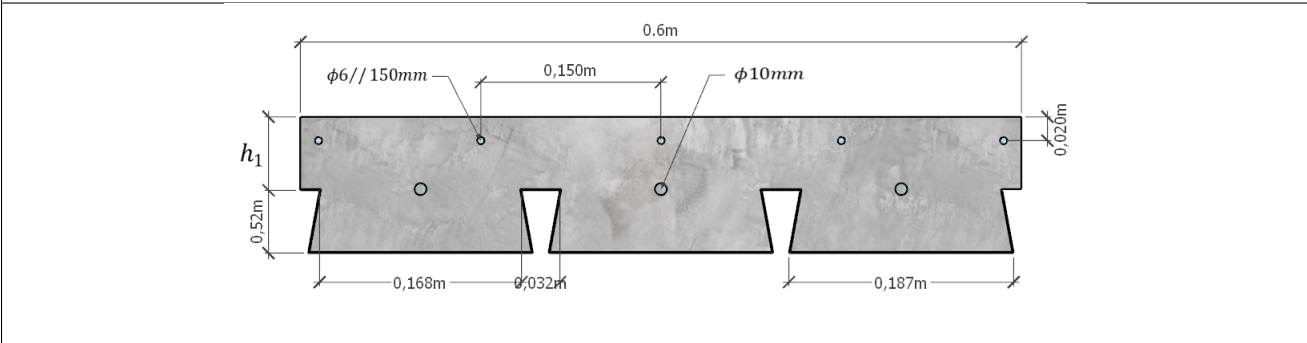
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

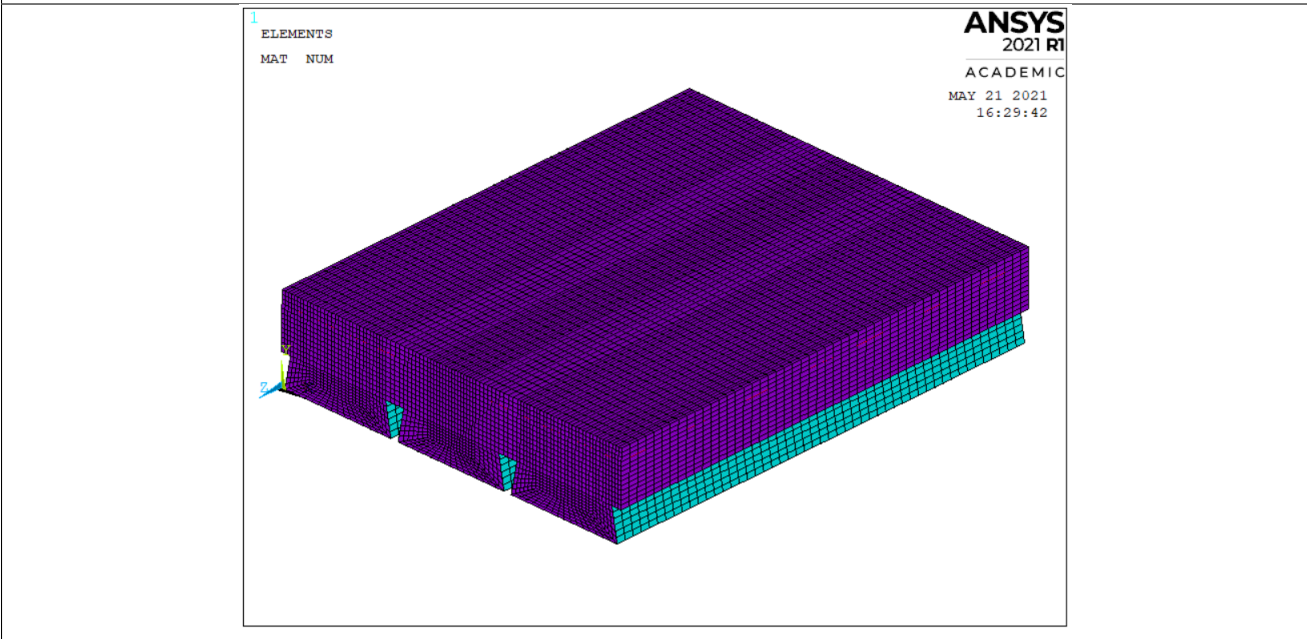
**Detailing**

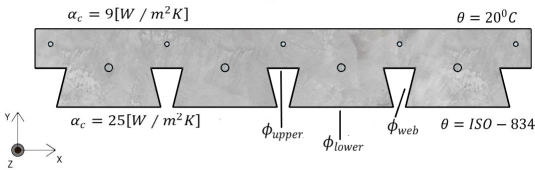
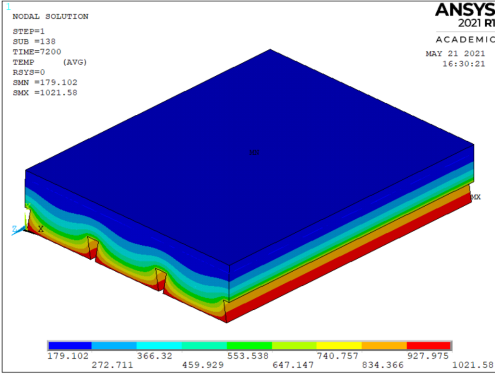
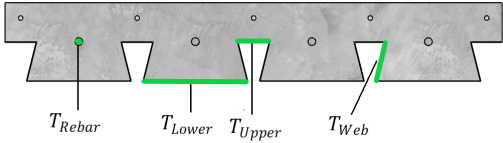
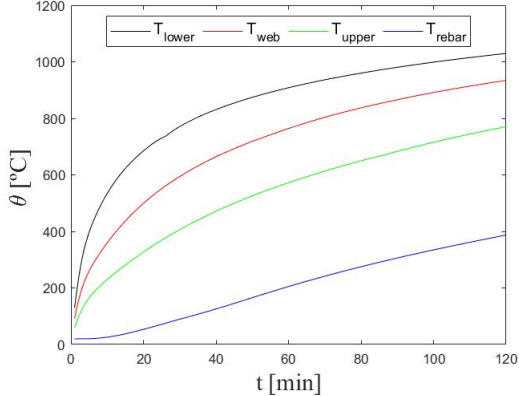
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

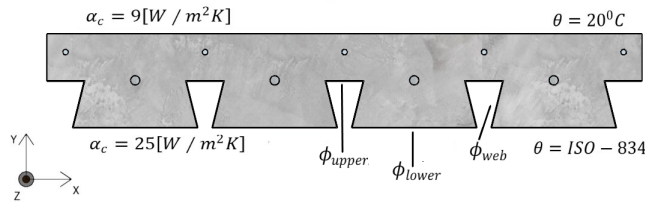


Model 18 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Maximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 18 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

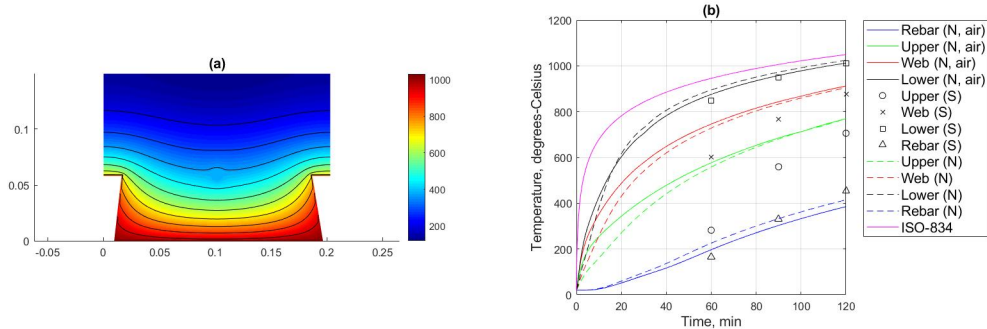
**Boundary Conditions**



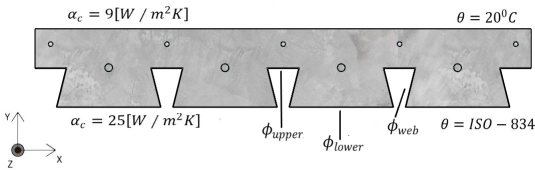
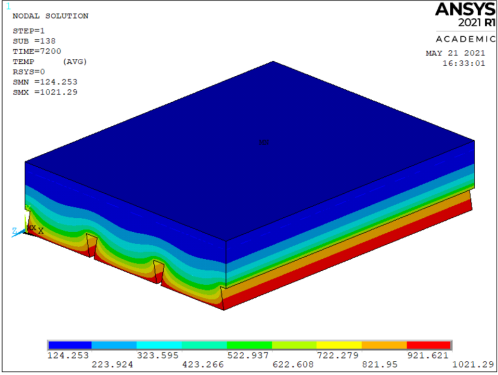
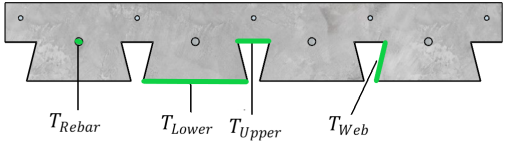
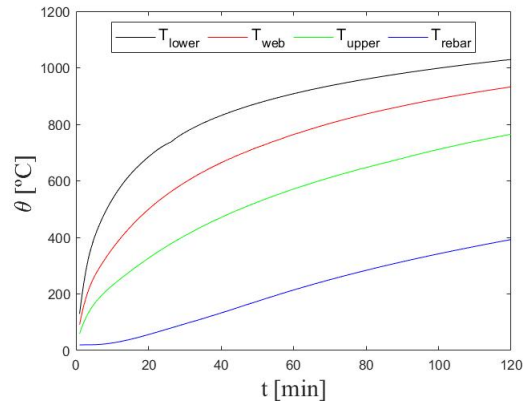
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



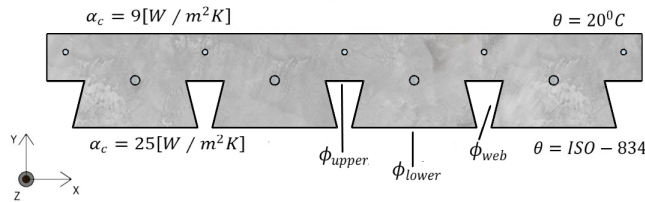
Data Sheet			
Model 19 - Bondek - $h_1 : 110mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			

Model 19 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 19 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

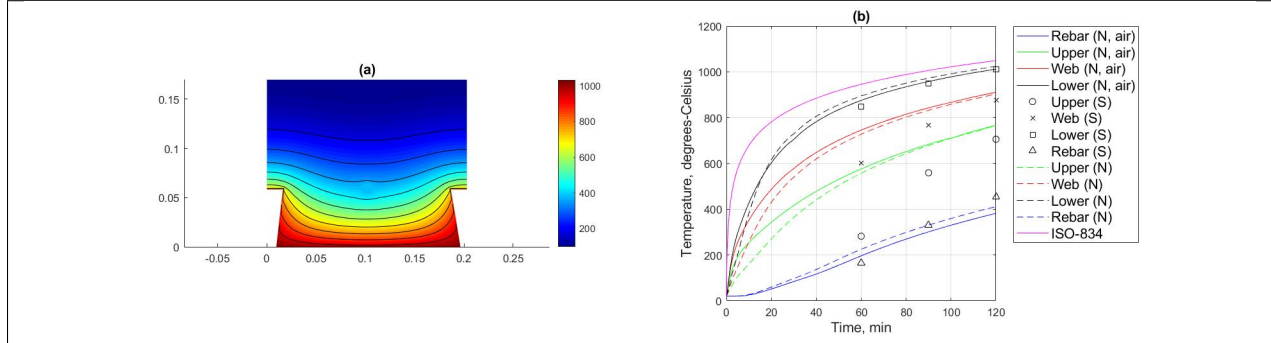
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



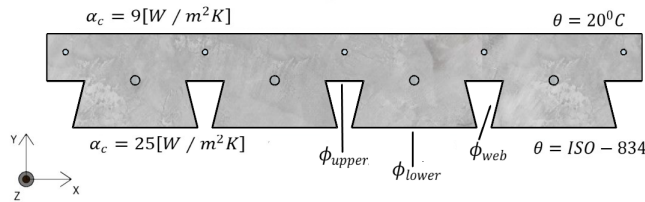
Data Sheet			
Model 20 - Bondek - $h_1 : 125mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: C25/30 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			
<div style="display: flex; justify-content: space-between;"> <div style="font-family: monospace;"> <p>1</p> <p>ELEMENTS</p> <p>MAT NUM</p> </div> <div style="text-align: right;"> <p><b>ANSYS</b></p> <p>2021 R1</p> <p>ACADEMIC</p> <p>MAY 21 2021</p> <p>16:35:21</p> </div> </div>			

Model 20 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
Additional Data		Temperature Graph	

**Model 20 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

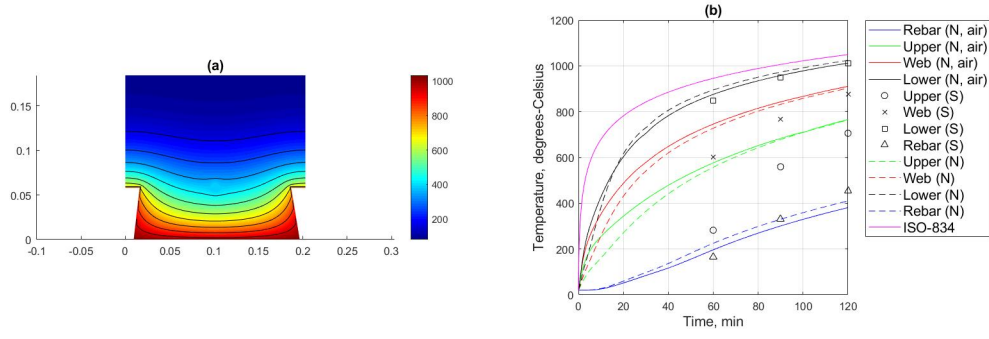
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



# Appendix C

## Annex C - Data Sheet for trapezoidal geometry and LWC.

Data Sheet for composite slabs with trapezoidal geometry and Lightweight Concrete.

**Data Sheet**

**Model 21 - Polydeck 59S -  $h_1 : 50mm$**

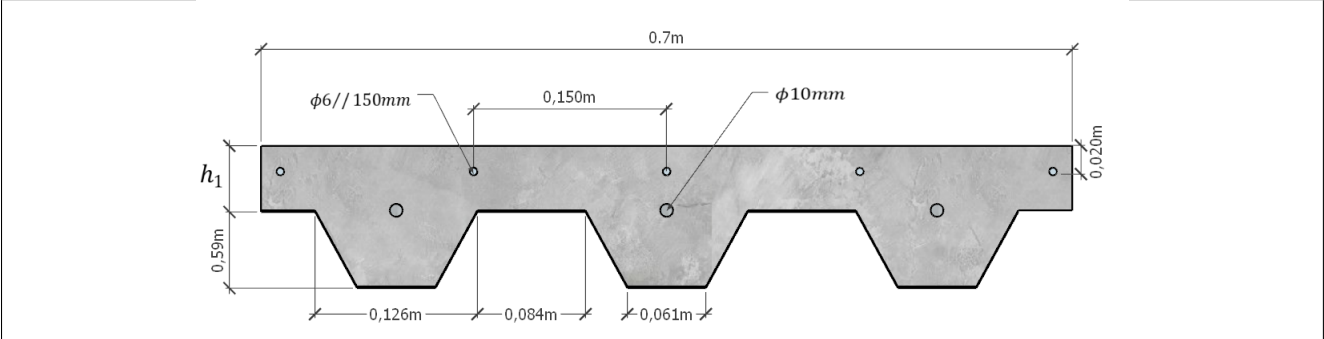
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

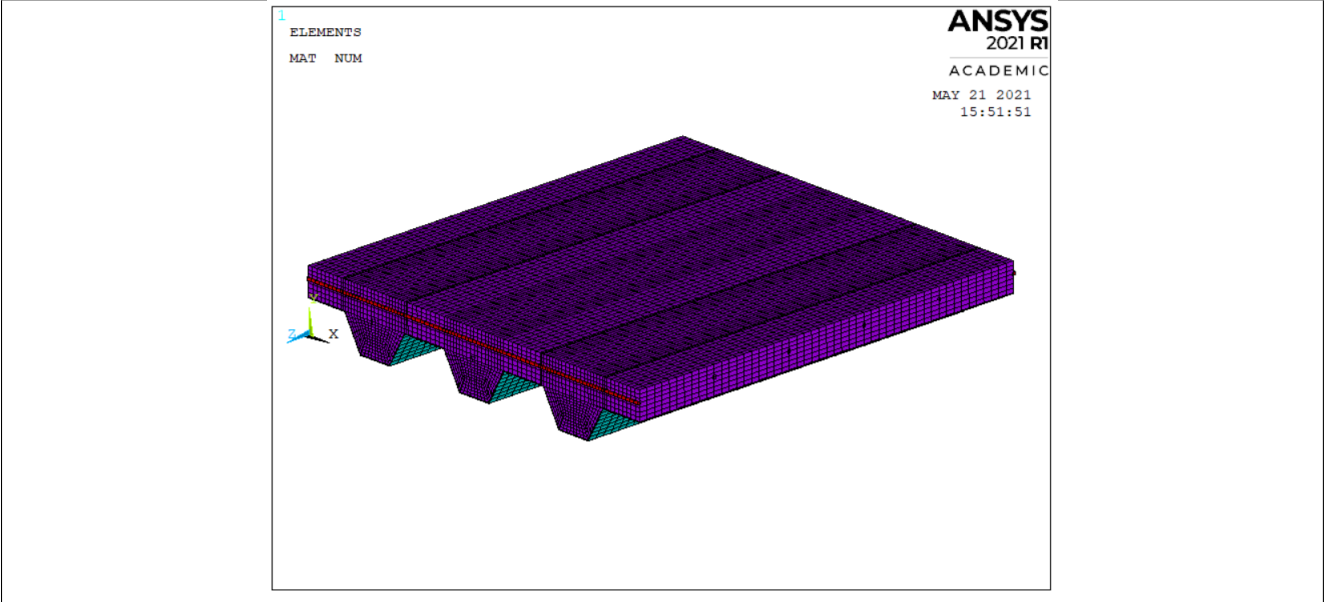
**Detailing**

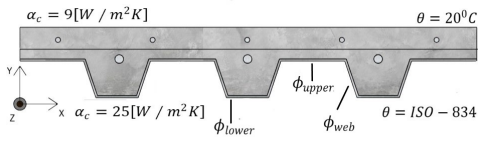
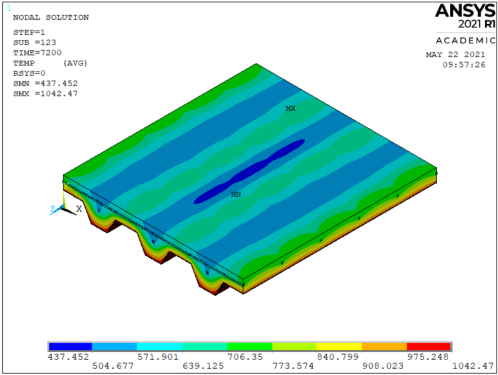
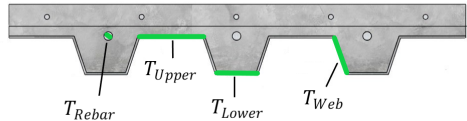
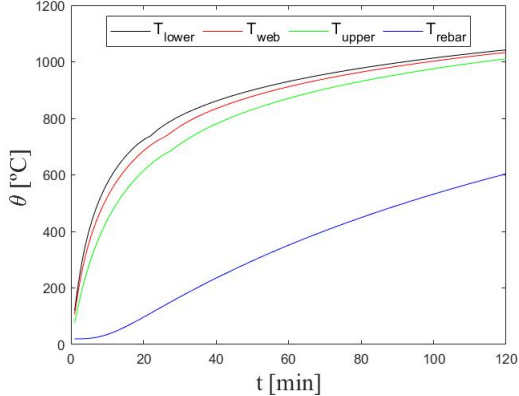
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

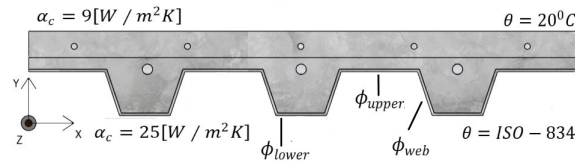


Model 21 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Maximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 21 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )		
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Temperature Curve	
	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

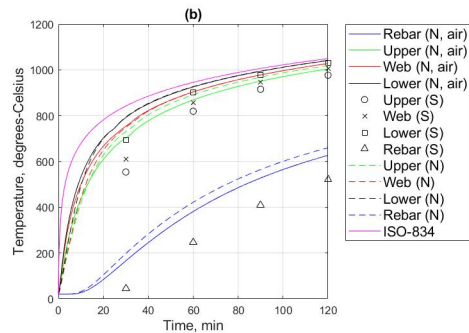
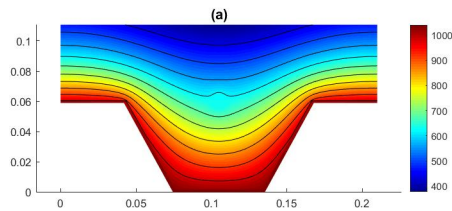
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 22 - Polydeck 59S -  $h_1 : 70mm$**

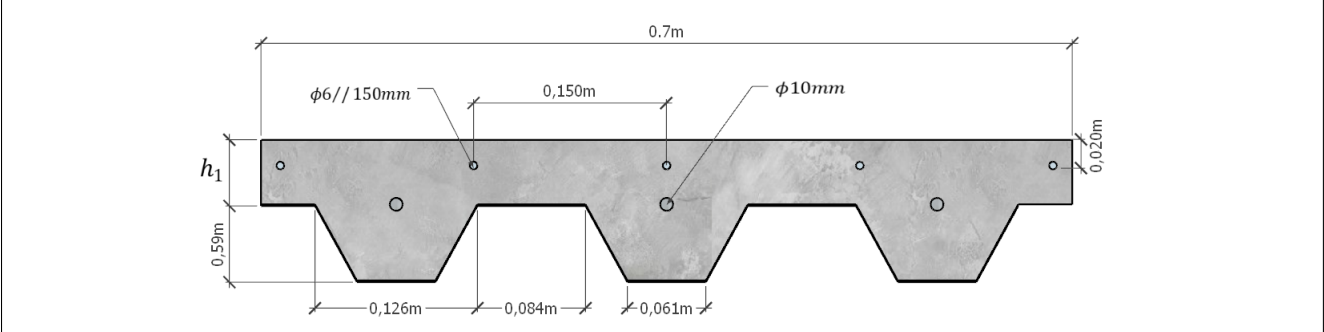
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

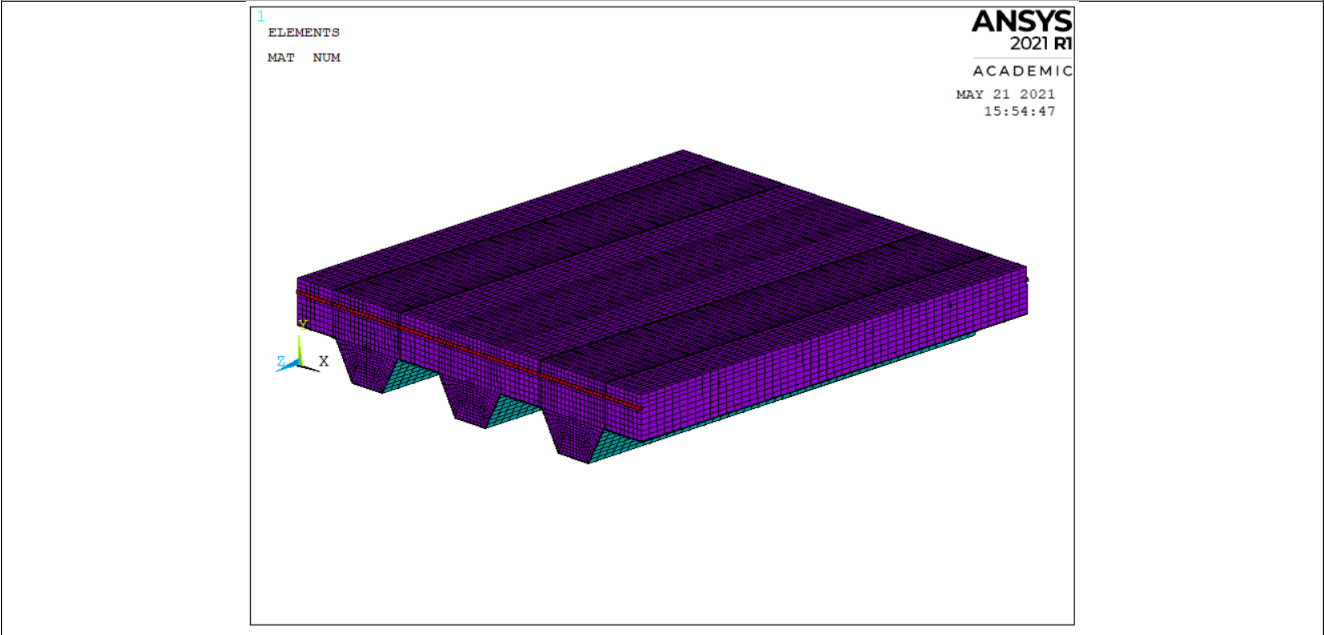
**Detailing**

<b>Steel Deck</b>	<b>Concrete</b>	<b>Steel Bars</b>	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

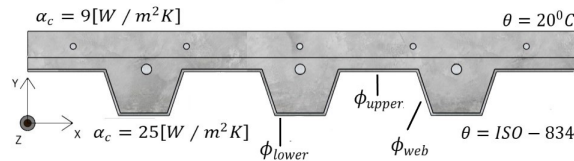


Model 22 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
Additional Data		Temperature Graph	

**Model 22 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
<b>Emissivity (<math>\varepsilon</math>)</b>	<b>Temperature Curve</b>	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

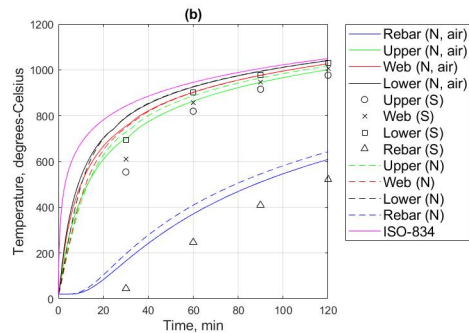
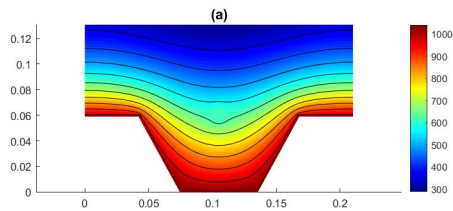
**Boundary Conditions**



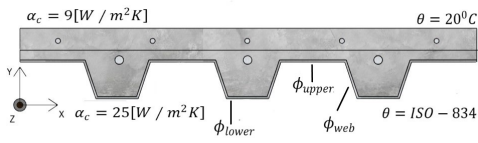
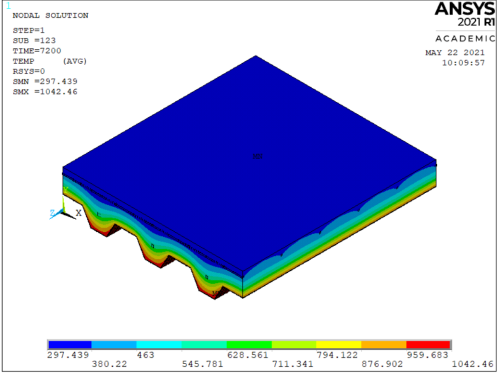
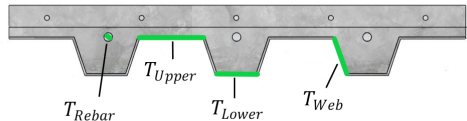
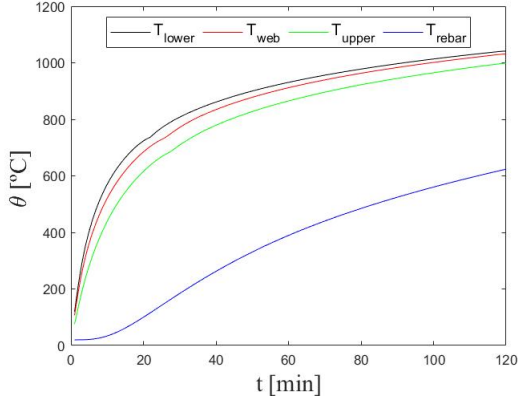
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



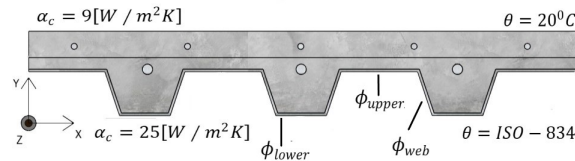
Data Sheet			
Model 23 - Polydeck 59S - $h_1 : 90mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.	year:2021	
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			
<div style="display: flex; justify-content: space-between; align-items: flex-start;"> <div style="border: 1px solid black; padding: 5px;"> <p>1</p> <p>ELEMENTS</p> <p>MAT NUM</p> </div> <div style="text-align: right;"> <p><b>ANSYS</b></p> <p>2021 R1</p> <p>ACADEMIC</p> <p>MAY 21 2021</p> <p>15:57:01</p> </div> </div>			

Model 23 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 23 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

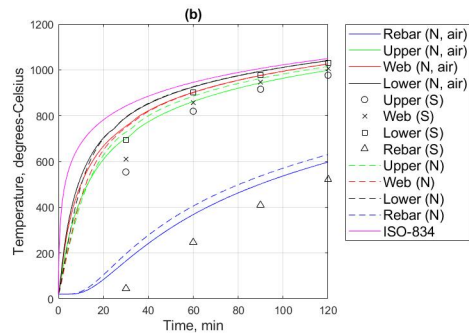
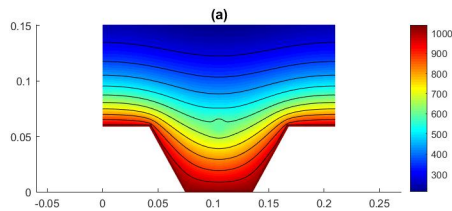
**Boundary Conditions**



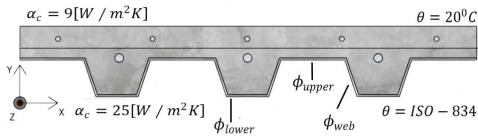
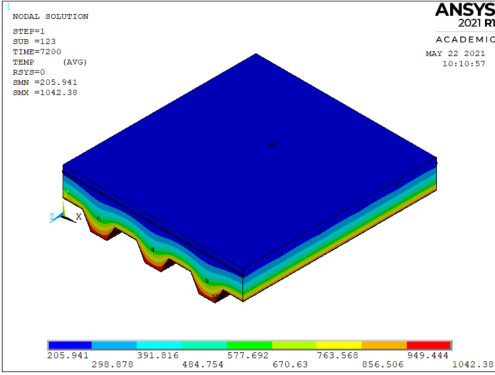
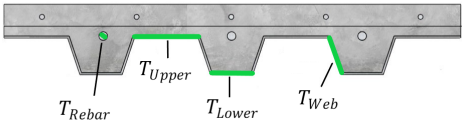
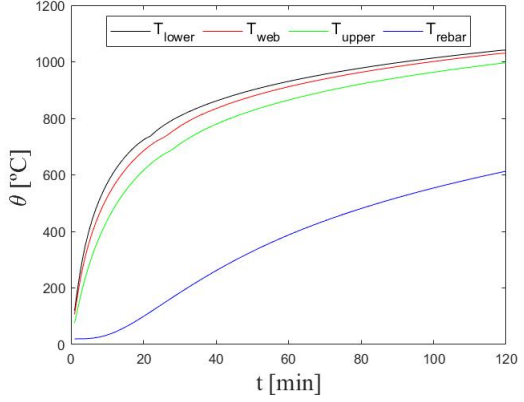
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



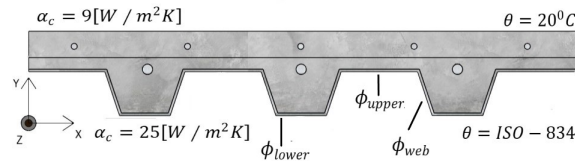
Data Sheet			
Model 24 - Polydeck 59S - $h_1 : 110mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
<p>The diagram shows a cross-section of a trapezoidal steel deck with a total width of 0.7m and a height of <math>h_1</math>. The top surface is flat with a thickness of 0.020m. The bottom surface features a series of trapezoidal indentations. The width of the top flange is 0.59m. The reinforcement details include <math>\phi 6 // 150mm</math> bars in the top flange and <math>\phi 10mm</math> bars in the bottom chord. The dimensions of the indentations are: 0.126m for the first indentation, 0.084m for the second, and 0.061m for the third. A spacing of 0.150m is indicated between the reinforcement bars.</p>			
Tridimensional Finite Element Model			
<p>The image displays a 3D finite element model of the steel deck structure. The model is rendered in purple and shows the trapezoidal indentations. A coordinate system with X, Y, and Z axes is visible in the bottom left corner. The ANSYS 2021 R1 logo and version information are shown in the top right corner.</p>			

Model 24 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s Time Step Size: 60 s	Tolerance Value: $1 \cdot 10^{-3}$	
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s Maximum Time Step: 60 s	Min. Reference Value: $1 \cdot 10^{-6}$	
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 24 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

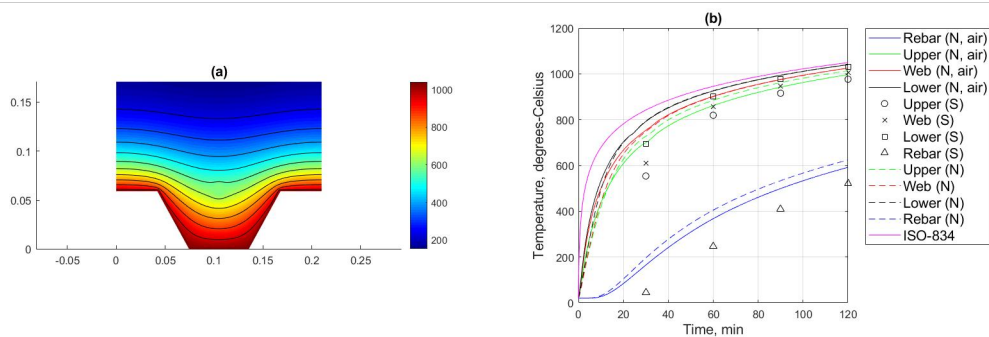
**Boundary Conditions**



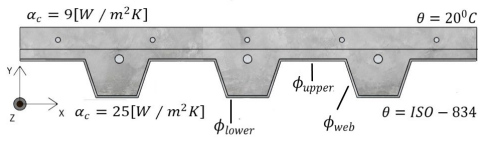
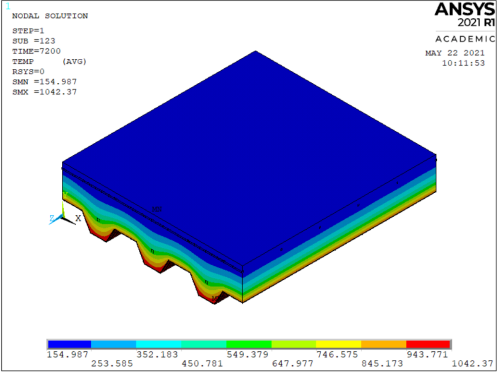
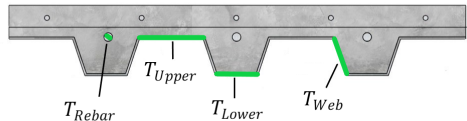
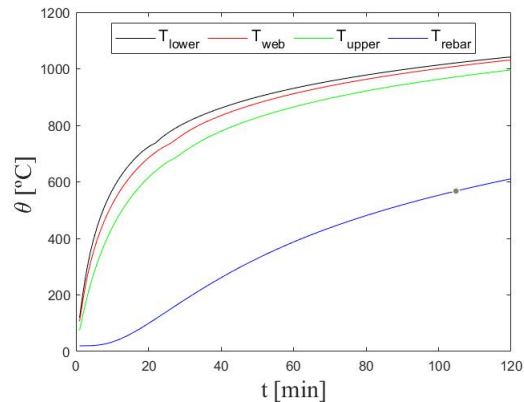
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



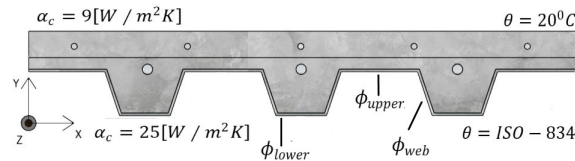
Data Sheet			
Model 25 - Polydeck 59S - $h_1 : 125mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
<p>The diagram shows a cross-section of a trapezoidal steel deck with a total width of 0.7m and a height of <math>h_1</math>. The top flange has a thickness of 0.020m. Reinforcement includes <math>\phi 6 // 150mm</math> bars in the top flange and <math>\phi 10mm</math> bars in the web. The web has a height of 0.59m. The bottom flange has a height of 0.061m. The spacing between the bottom flanges is 0.126m, and the spacing between the top flanges is 0.150m. The bottom flange has a width of 0.084m.</p>			
Tridimensional Finite Element Model			
<p>The image shows a 3D finite element model of the steel deck structure. The model is composed of a mesh of elements, with the top flange and web shown in purple and the bottom flange in green. The model is displayed in a 3D perspective view with a coordinate system (X, Y, Z) shown in the bottom left corner. The ANSYS 2021 R1 ACADEMIC logo and date (MAY 21 2021 16:03:34) are visible in the top right corner.</p>			

Model 25 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s Time Step Size: 60 s	Tolerance Value: $1 \cdot 10^{-3}$	
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s Maximum Time Step: 60 s	Min. Reference Value: $1 \cdot 10^{-6}$	
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 25 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.75 Web: 0.64 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

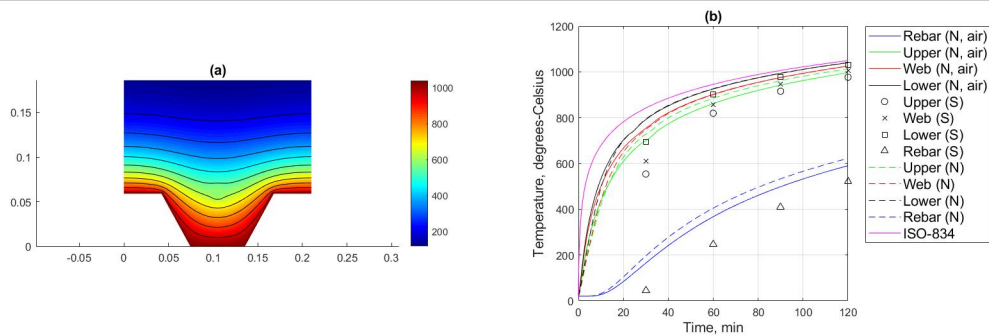
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 26 - Confraplus 60 -  $h_1 : 50mm$**

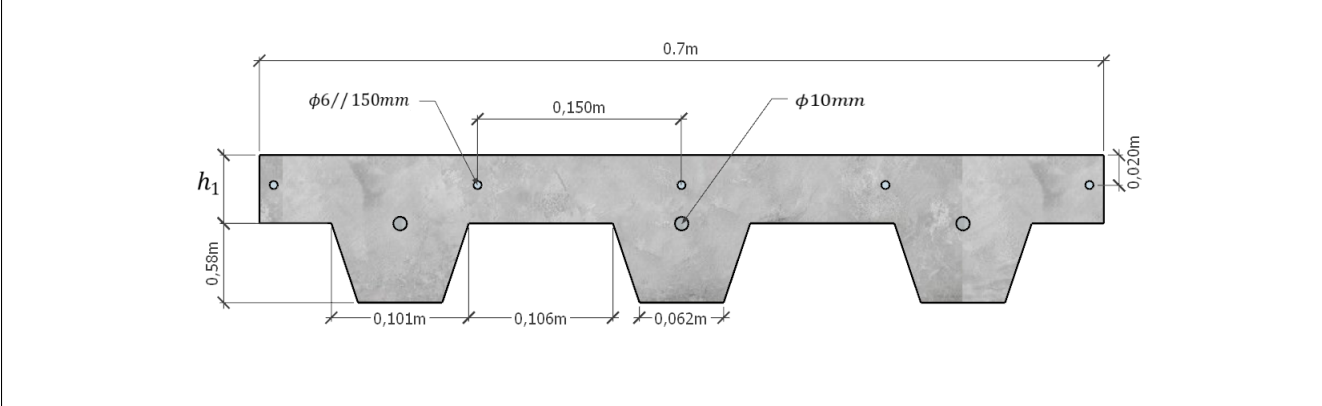
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

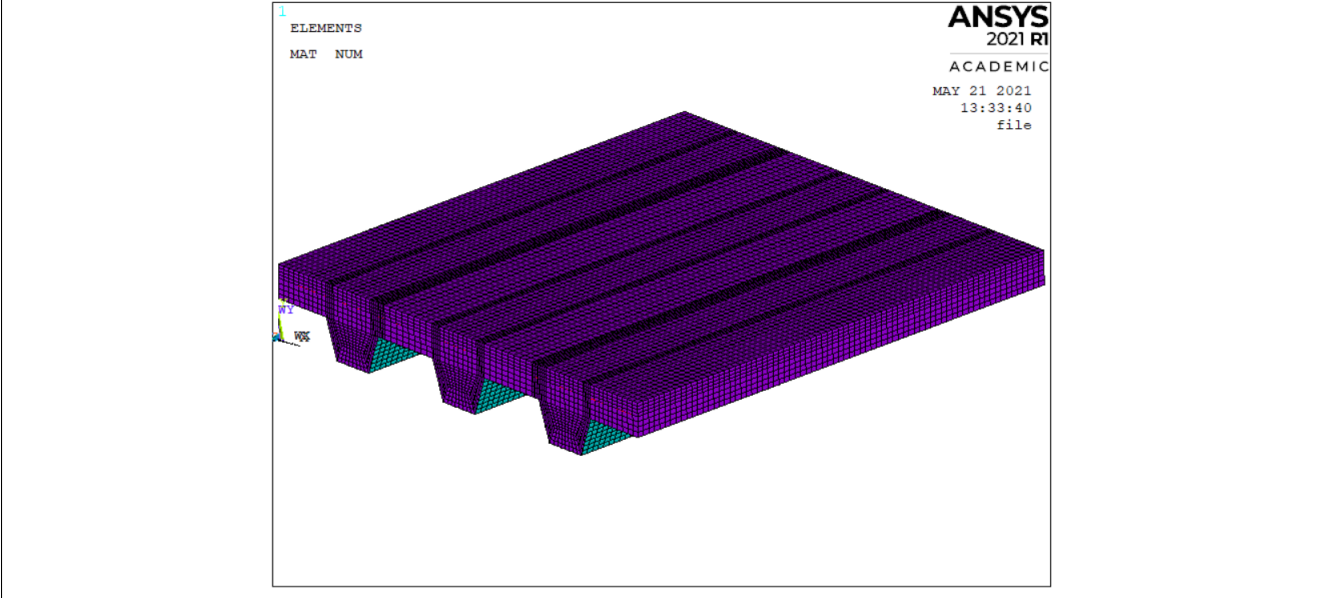
**Detailing**

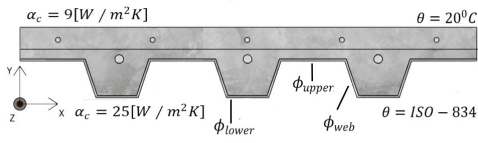
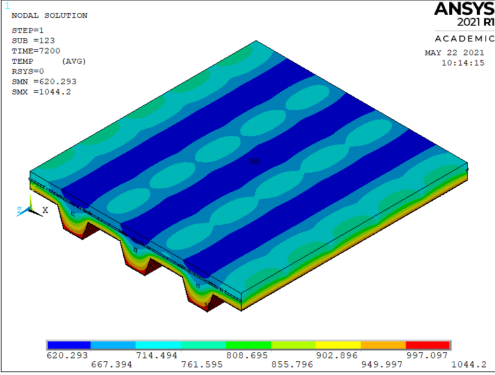
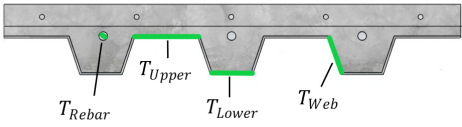
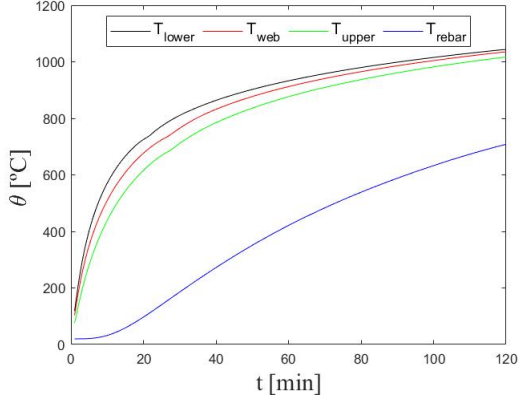
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

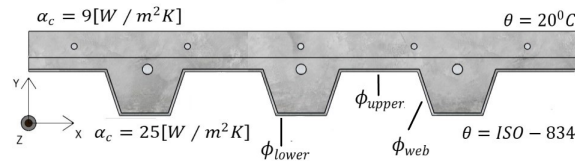


Model 26 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 26 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

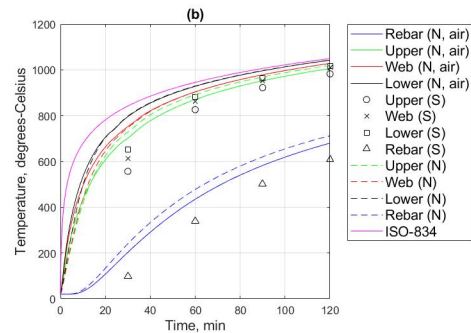
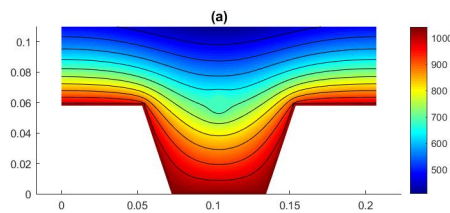
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 27 - Confraplus 60 -  $h_1 : 70mm$**

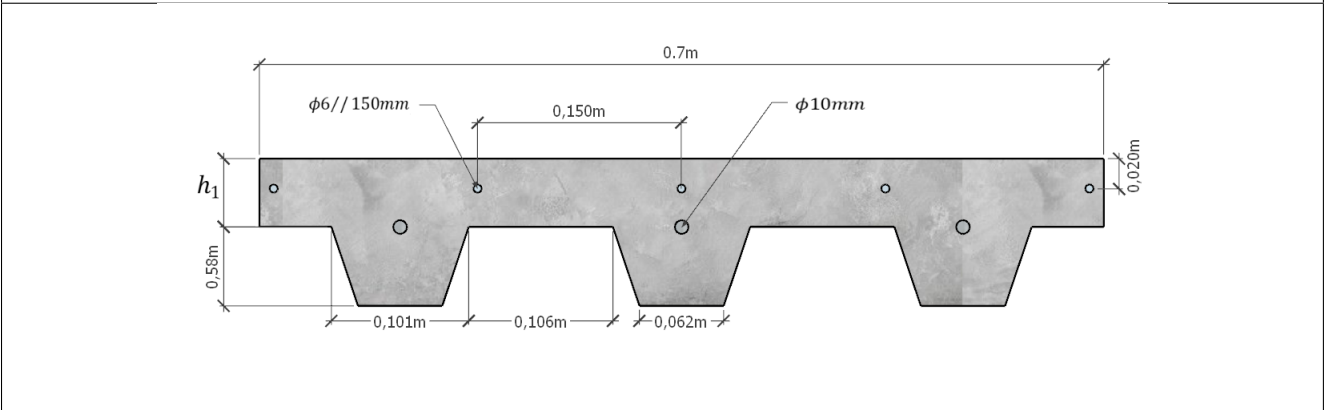
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

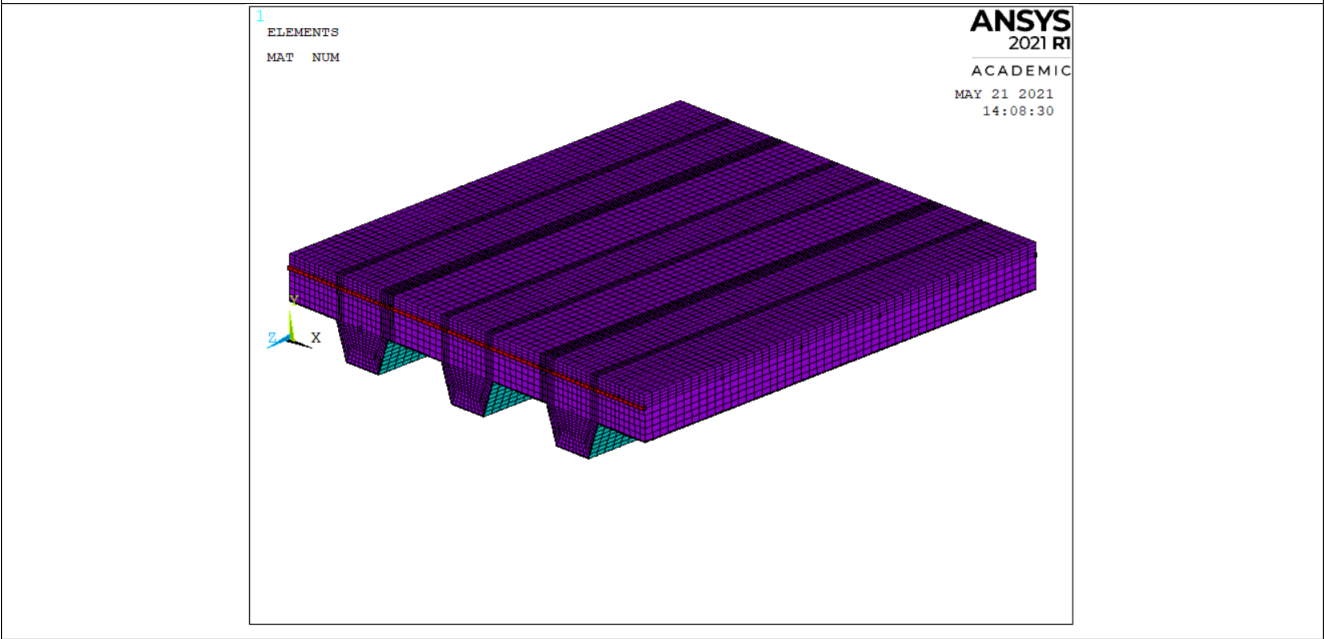
**Detailing**

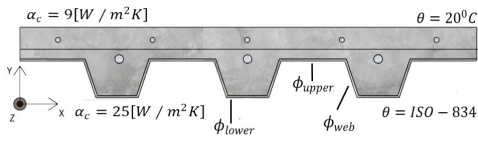
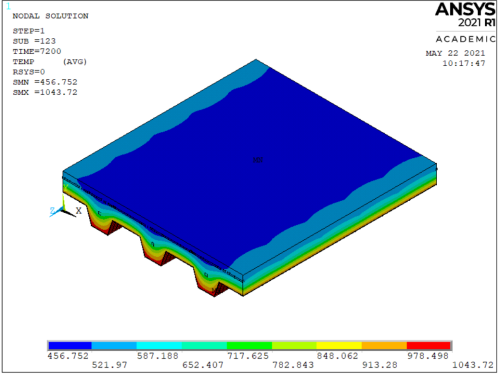
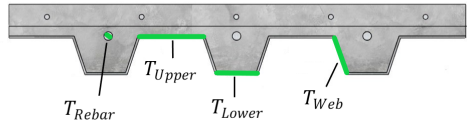
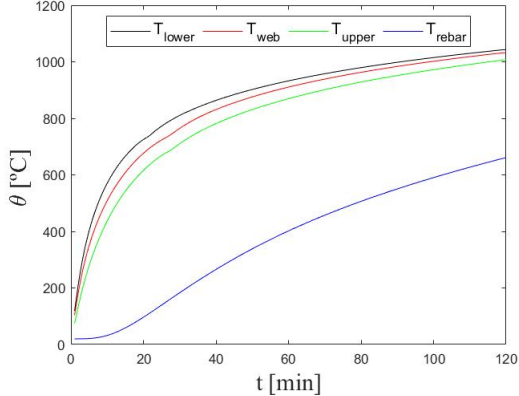
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal	Density: Normal Weight	<b>Reinforcement Bars</b>	<b>Steel mesh</b>
Thickness: 1.25mm	Class: LC25/28	Description: $\phi 6 // 150$	Description: $3\phi 10$
Grade: S350	Moisture: 3.0%	Grade: S500	Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

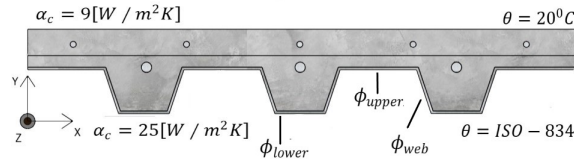


Model 27 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 7 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

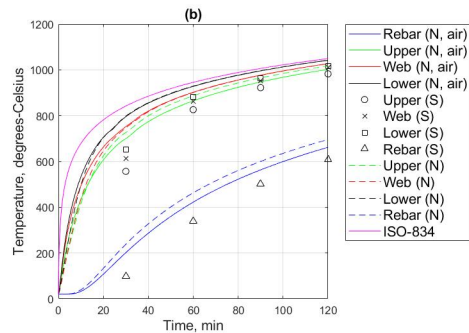
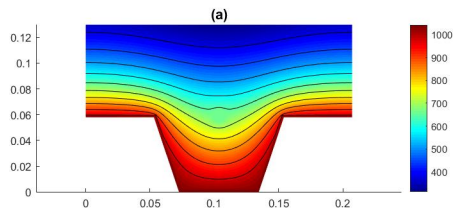
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 28 - Confraplus 60 -  $h_1 : 90mm$**

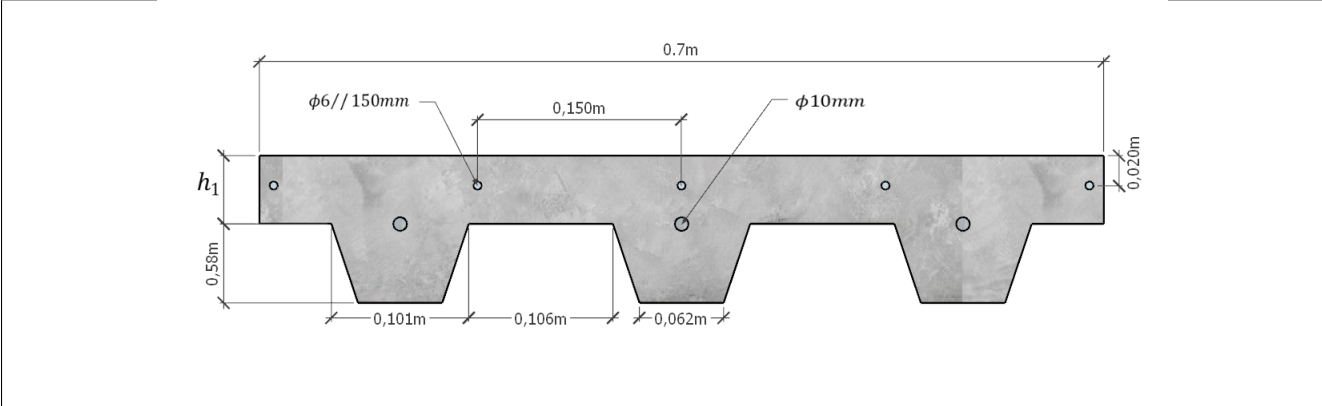
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

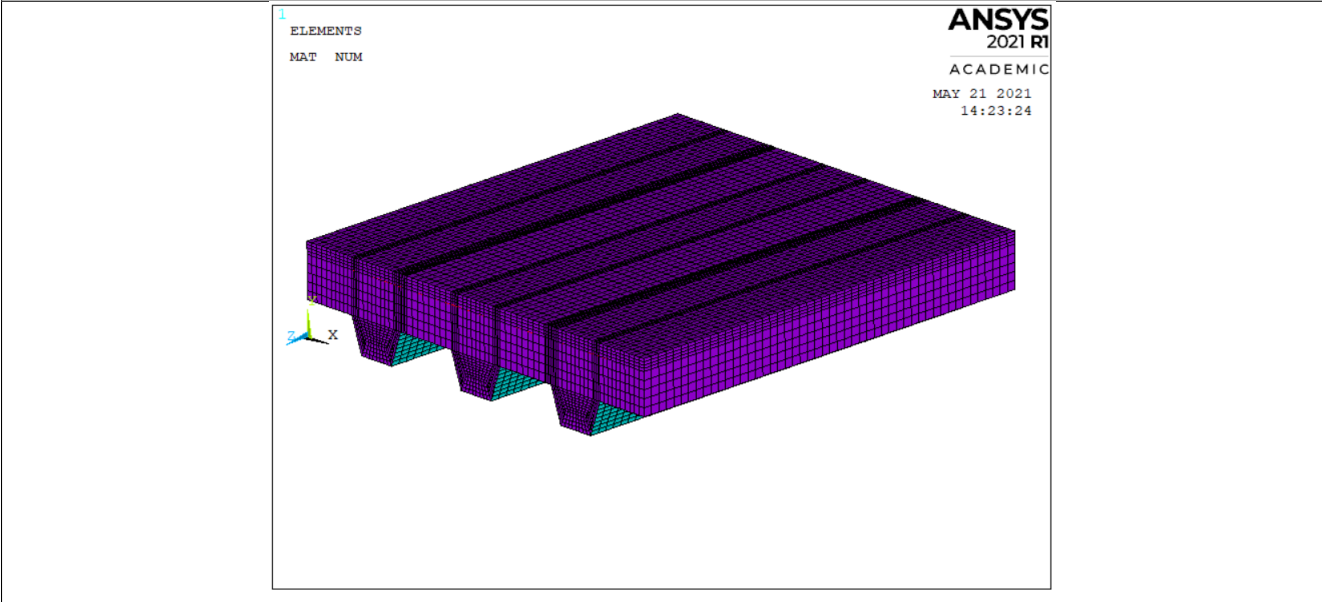
**Detailing**

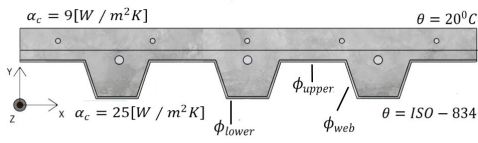
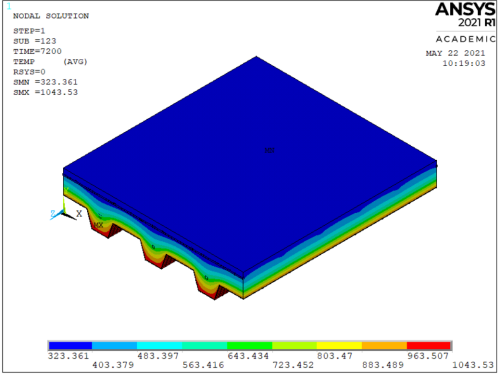
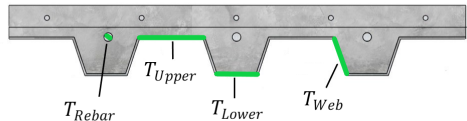
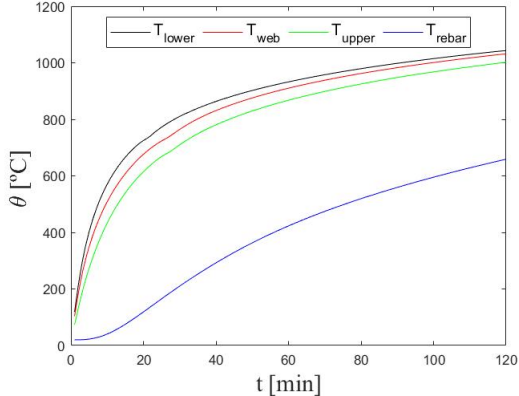
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

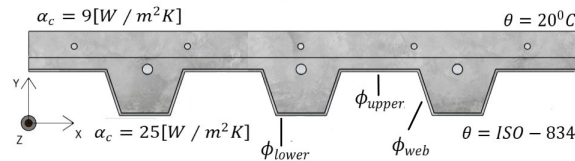


Model 28 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s Time Step Size: 60 s	Tolerance Value: $1 \cdot 10^{-3}$	
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s Maximum Time Step: 60 s	Min. Reference Value: $1 \cdot 10^{-6}$	
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 28 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )		
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Temperature Curve	
	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

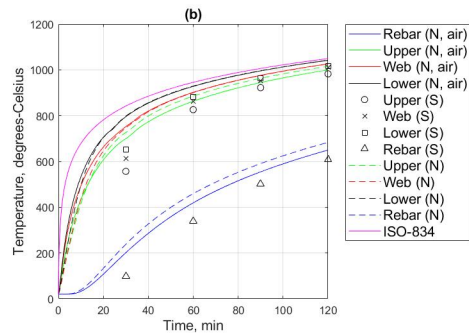
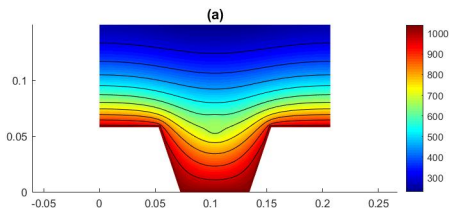
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 29 - Confraplus 60 -  $h_1 : 110mm$**

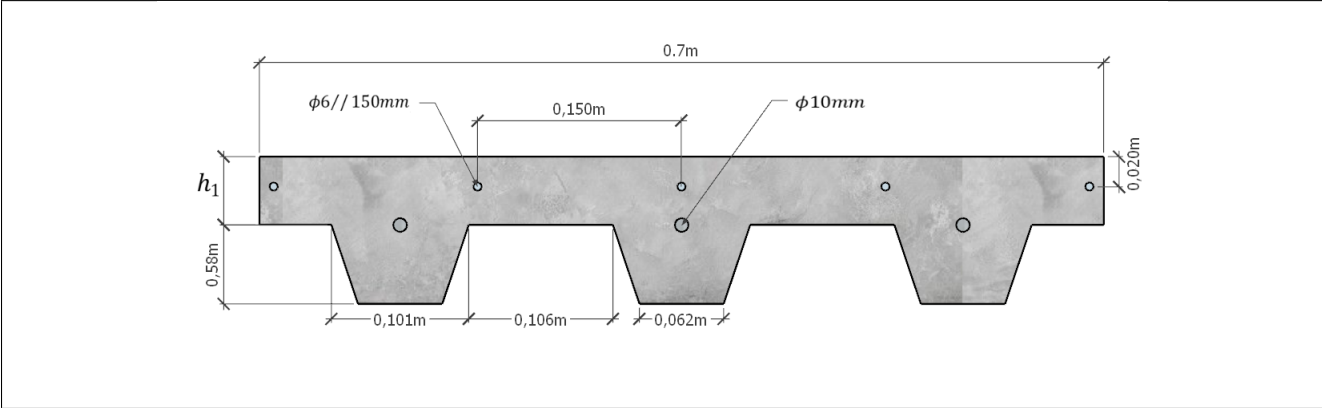
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

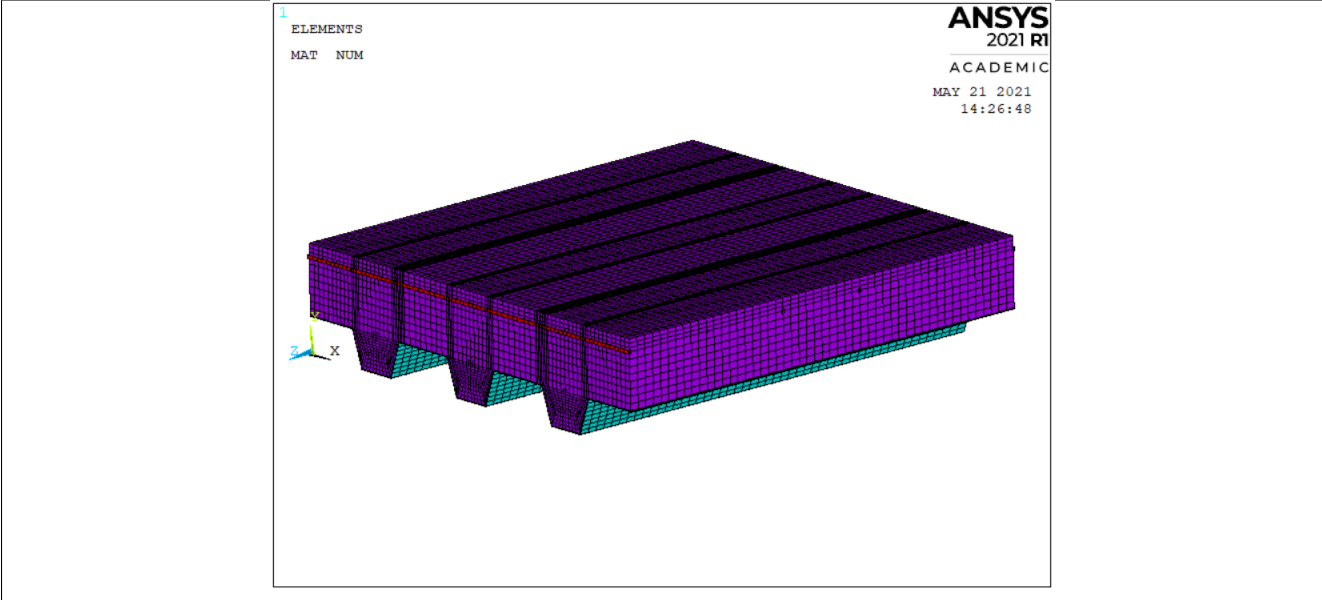
**Detailing**

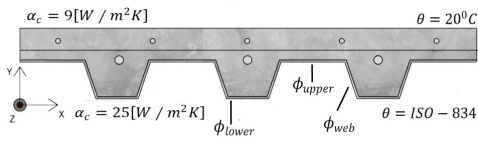
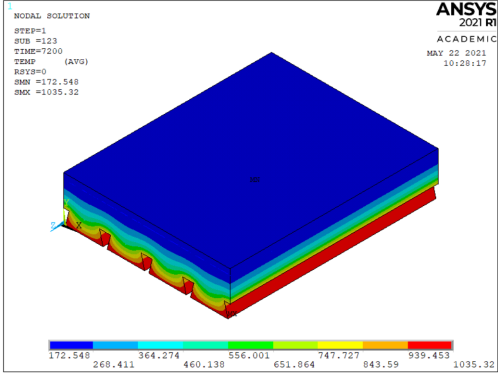
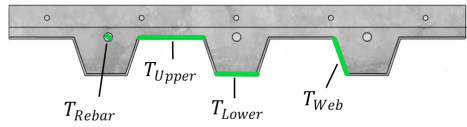
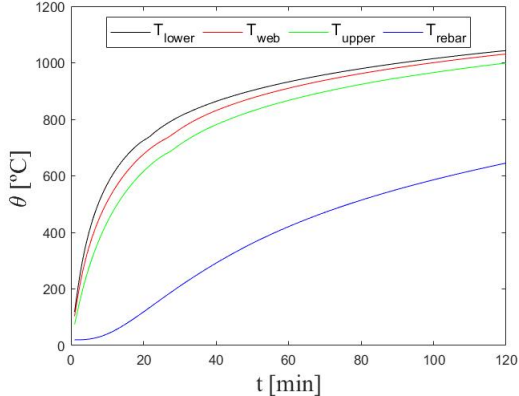
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

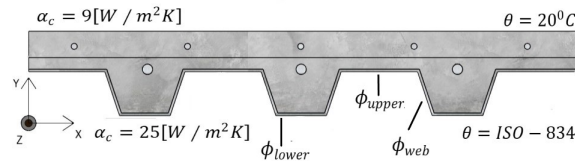


Model 29 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 29 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

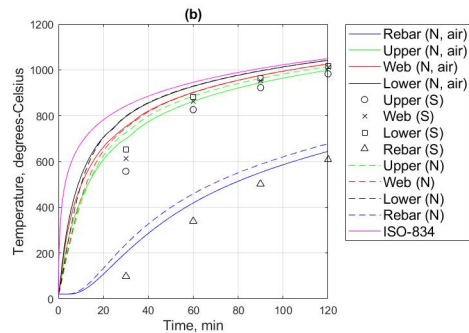
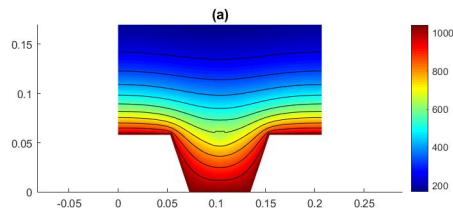
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 30 - Confraplus 60 -  $h_1 : 125mm$**

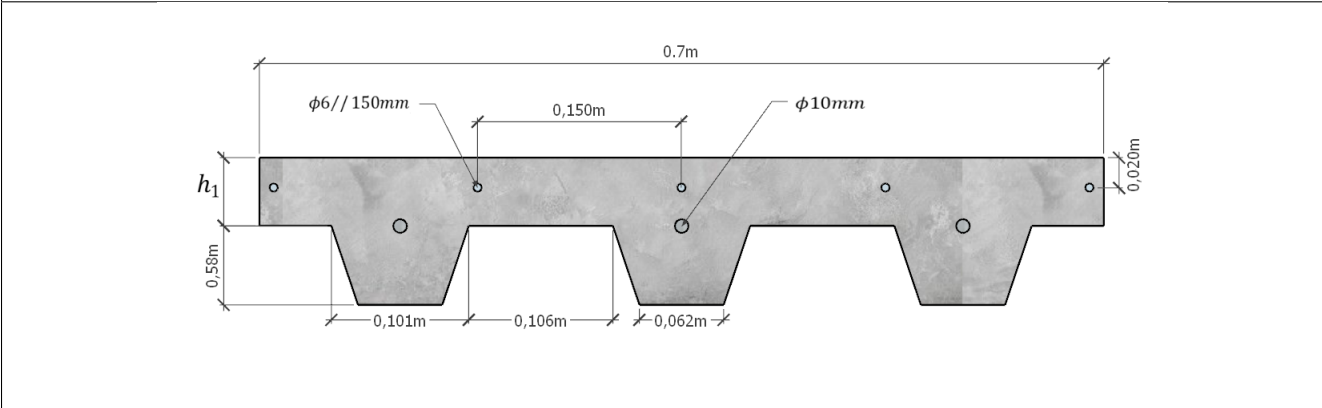
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

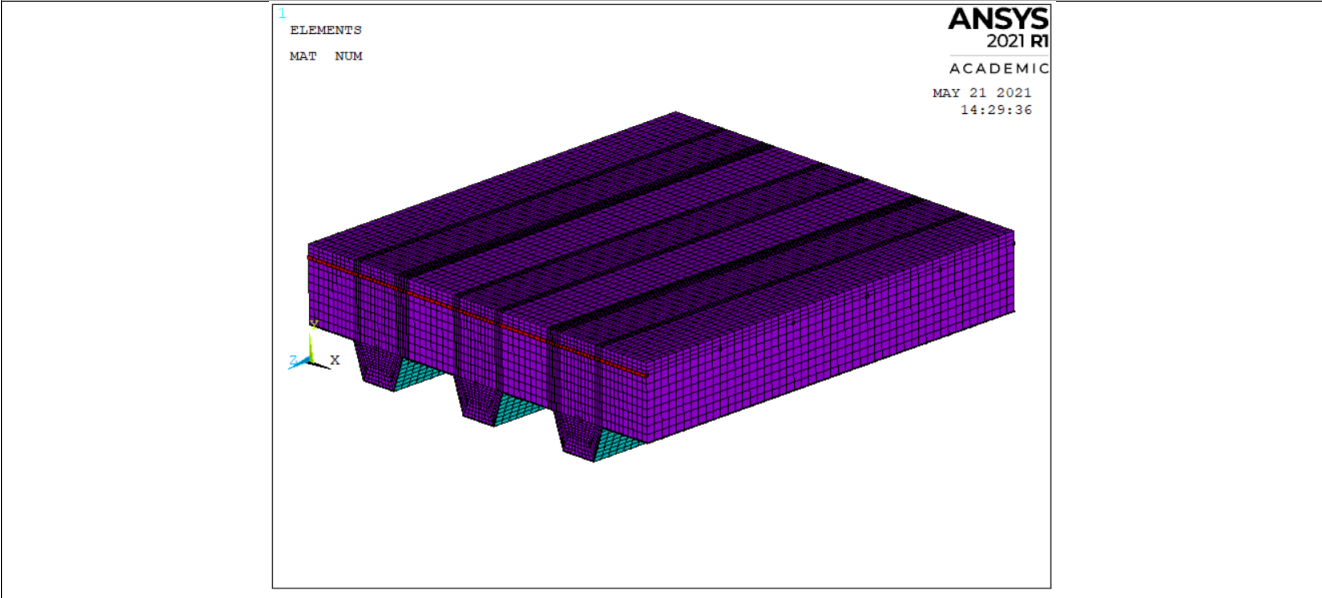
**Detailing**

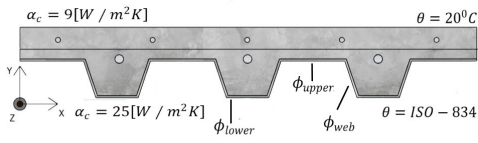
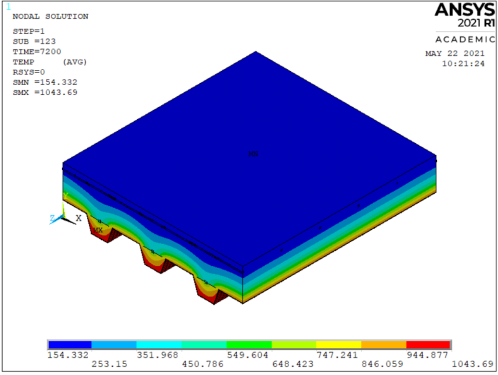
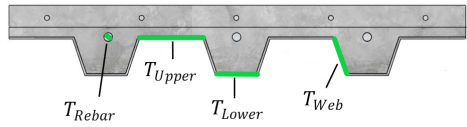
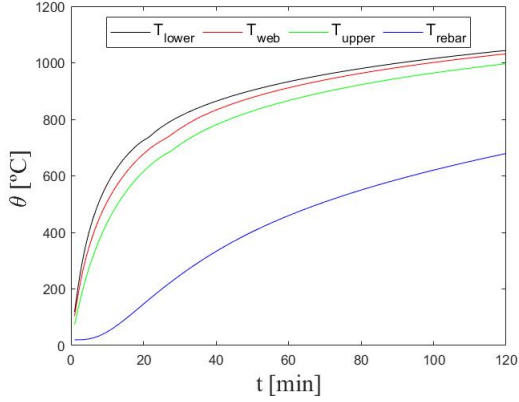
Steel Deck	Concrete	Steel Bars	
Geometry: Trapezoidal Thickness: 1.25mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

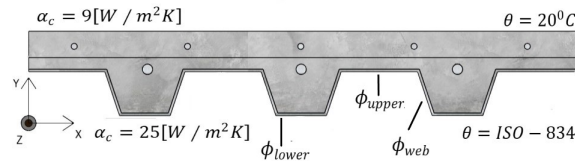


Model 30 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 30 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.73 Web: 0.56 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

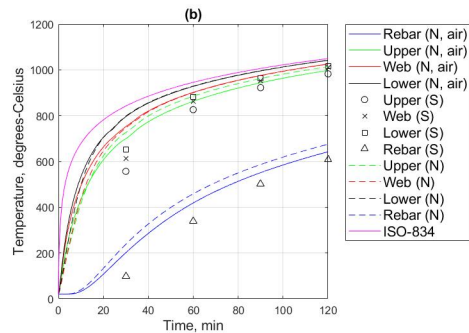
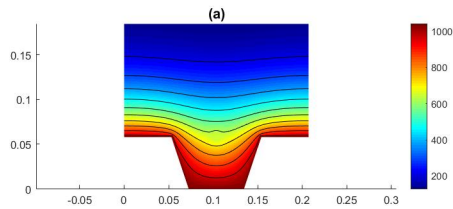
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



# Appendix D

## Annex D - Data Sheet for re-entrant geometry and LWC.

Data Sheet for composite slabs with re-entrant geometry and Lightweight Concrete.

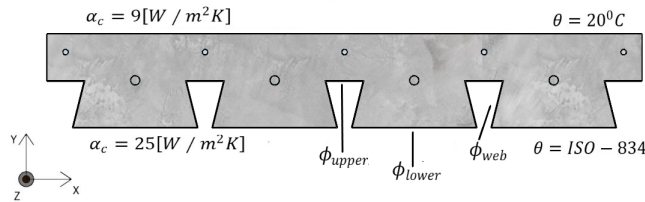
Data Sheet			
Model 31 - Multideck 50 - $h_1 : 60mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
<p>The diagram shows a cross-section of a multideck slab with a total width of 0.6m and a total height of <math>h_1</math>. The slab has a top thickness of 0.020m and a bottom thickness of 0.050m. The reinforcement consists of <math>\phi 6 // 150mm</math> bars in the top deck and <math>\phi 10mm</math> bars in the bottom deck. The spacing between the top bars is 0.150m, and the spacing between the bottom bars is 0.135m. The bottom deck has a width of 0.110m, with 0.040m overhangs on each side. The top deck has a width of 0.040m on each side.</p>			
Tridimensional Finite Element Model			
<p>The 3D finite element model shows the multideck slab with a mesh of elements. The top surface is purple, and the bottom surface is cyan. The model is shown from an isometric perspective.</p> <p>ELEMENTS MAT NUM</p> <p><b>ANSYS</b> 2021 R1 ACADEMIC MAY 21 2021 16:07:03</p>			

Model 31 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
Additional Data		Temperature Graph	

**Model 31 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

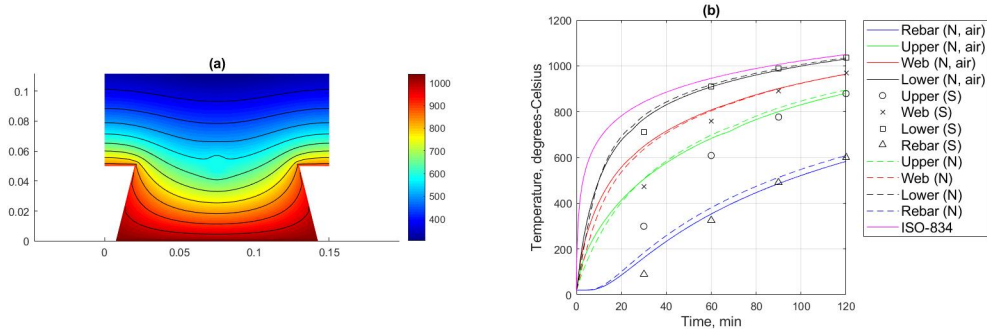
**Boundary Conditions**



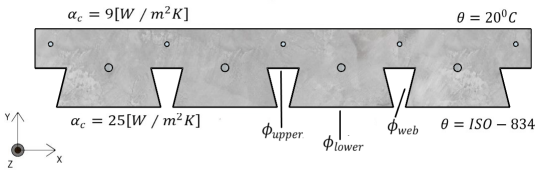
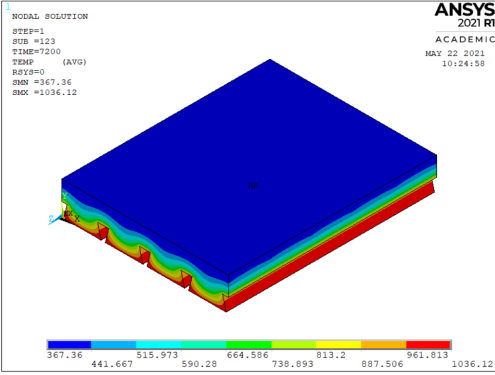
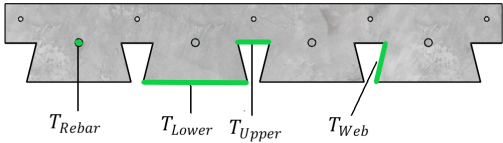
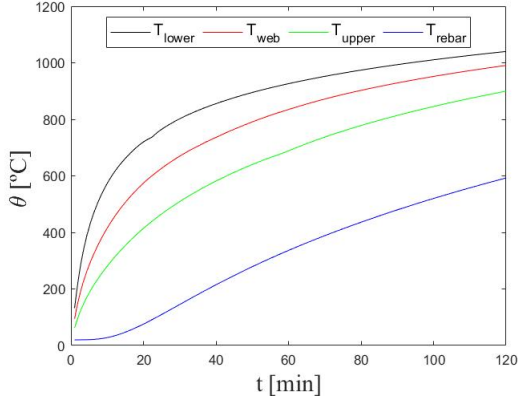
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



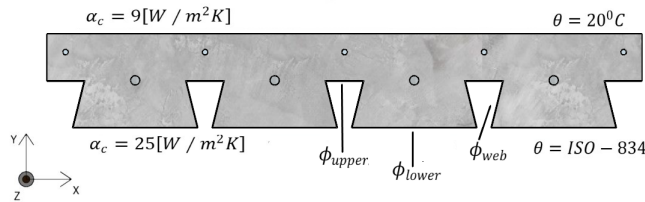
Data Sheet			
Model 32 - Multideck 50 - $h_1 : 70mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
<p>The diagram shows a cross-section of a multideck slab with a total width of 0.6m and a total height of <math>h_1</math>. The slab has a top flange thickness of 0.020m and a bottom flange thickness of 0.050m. The top flange contains reinforcement bars with a diameter of <math>\phi 6 // 150mm</math> and a spacing of 0.150m. The bottom flange contains reinforcement bars with a diameter of <math>\phi 10mm</math> and a spacing of 0.135m. The bottom flange has a width of 0.040m and a depth of 0.110m. The total height of the slab is <math>h_1</math>.</p>			
Tridimensional Finite Element Model			
<p>The image shows a 3D finite element model of the multideck slab. The model is composed of a grid of elements, with the top surface colored purple and the bottom surface colored cyan. The model is shown in a perspective view, highlighting the re-entrant geometry of the bottom flange. The ANSYS 2021 R1 ACADEMIC logo and date (MAY 21 2021 16:10:58) are visible in the top right corner.</p>			

Model 32 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 32 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

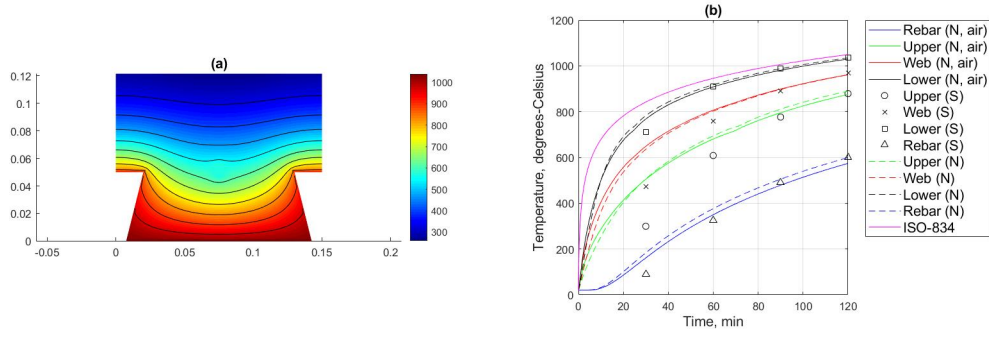
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 33 - Multideck 50 -  $h_1 : 90mm$**

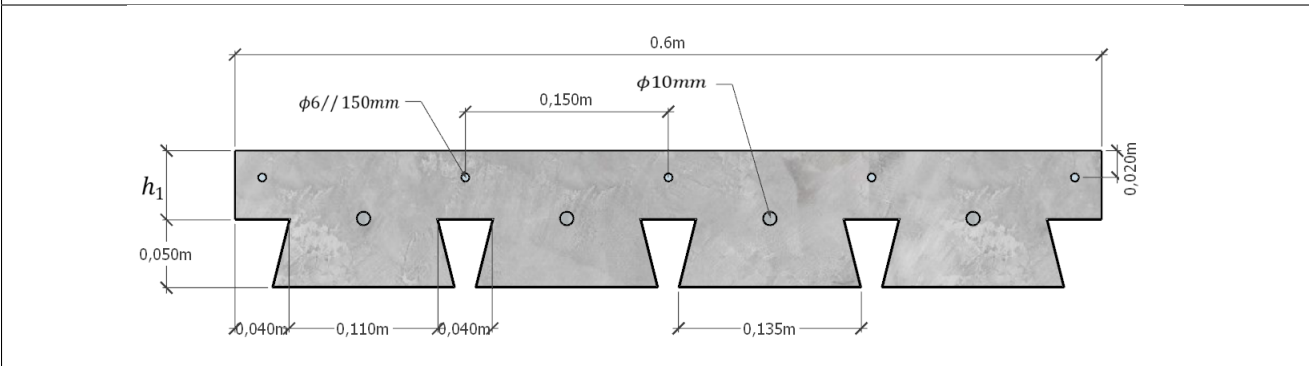
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

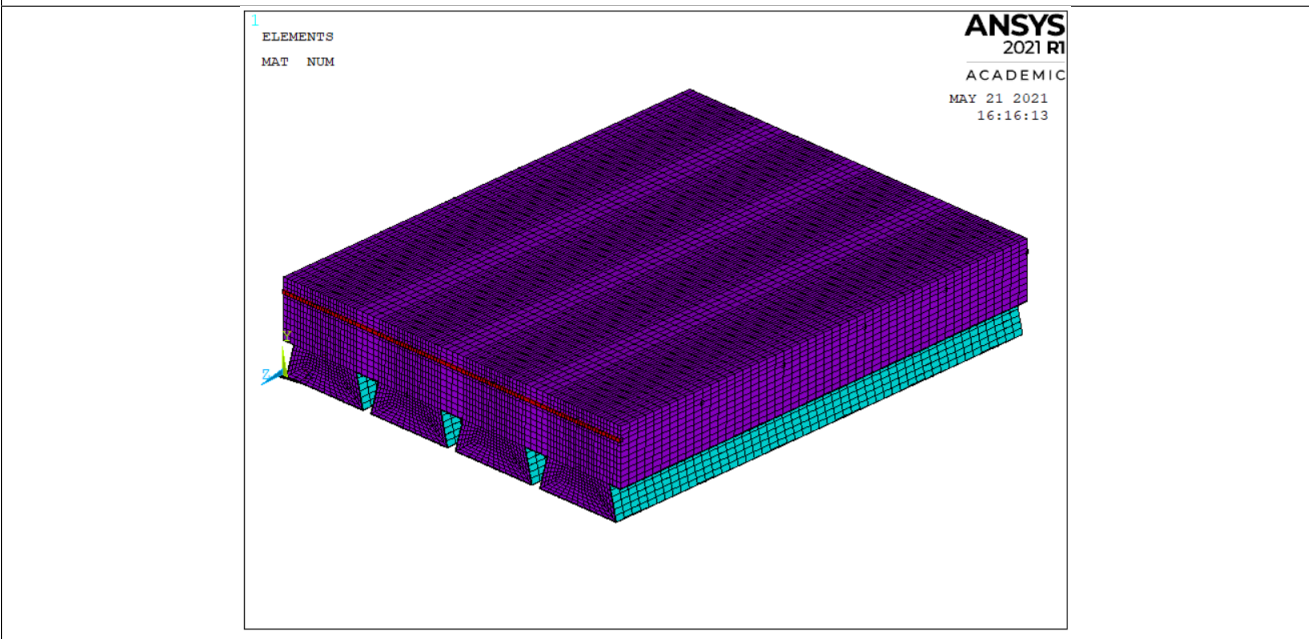
**Detailing**

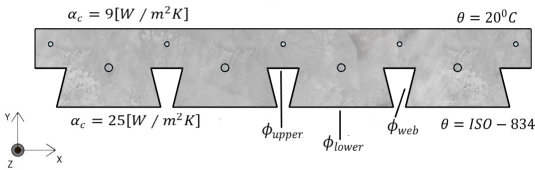
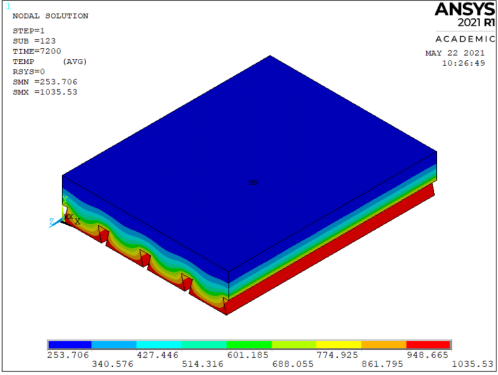
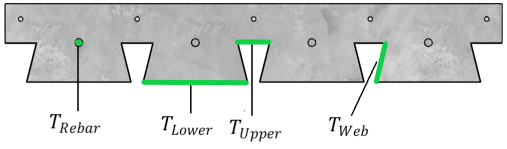
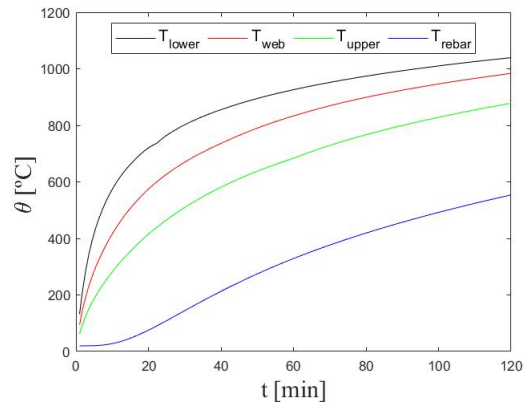
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

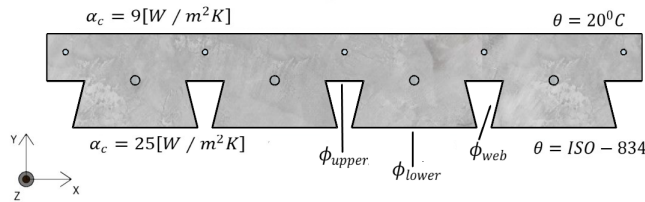


Model 33 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 33 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

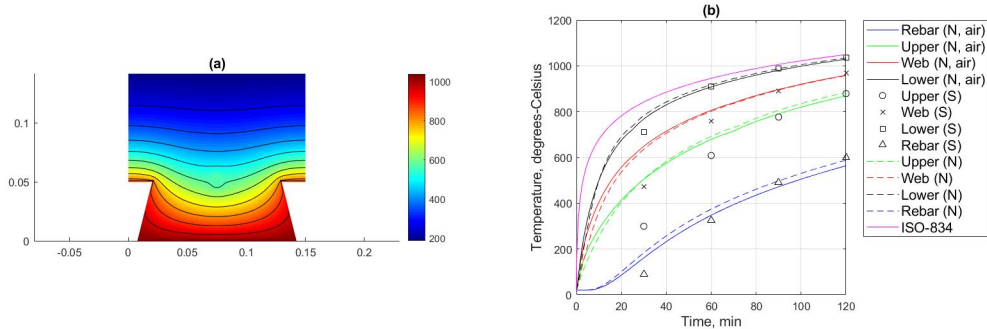
**Boundary Conditions**



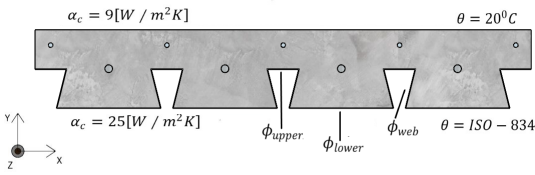
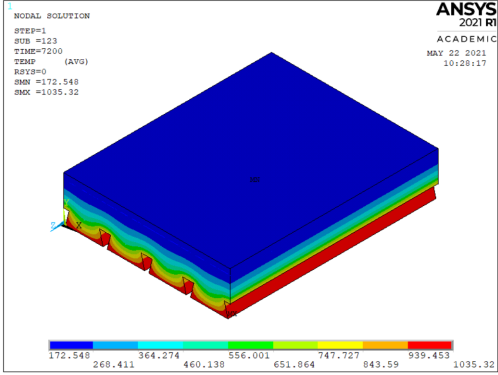
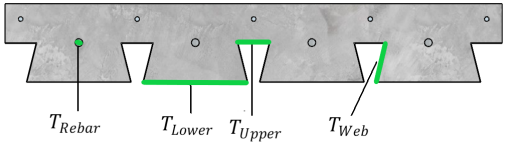
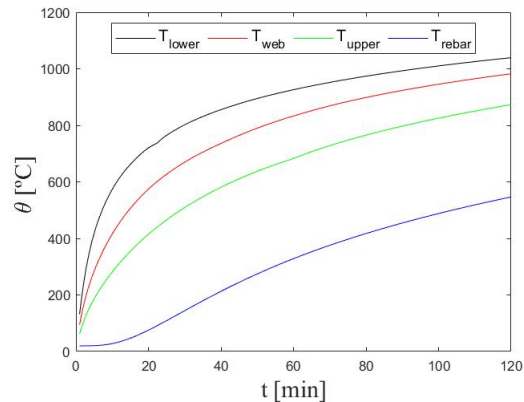
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



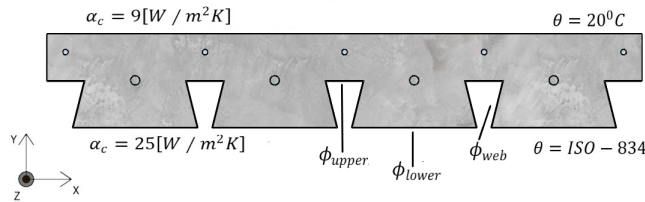
Data Sheet			
Model 34 - Multideck 50 - $h_1 : 110mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
<p>The diagram shows a cross-section of a multideck slab with a total width of 0.6m and a height of <math>h_1</math>. The slab has a top flange thickness of 0.020m and a bottom flange thickness of 0.050m. The top flange contains reinforcement bars with a diameter of <math>\phi 6 // 150mm</math> spaced at 0.150m. The bottom flange contains reinforcement bars with a diameter of <math>\phi 10mm</math> spaced at 0.135m. The bottom flange has a width of 0.040m on each side of the central opening. The total length of the slab is 0.6m.</p>			
Tridimensional Finite Element Model			
<p>The image shows a 3D finite element model of the multideck slab. The model is composed of a grid of elements, with the top surface colored purple and the bottom surface colored cyan. The model is shown in a perspective view, highlighting the re-entrant geometry of the bottom flange. The ANSYS 2021 R1 ACADEMIC logo and date (MAY 21 2021 16:18:35) are visible in the top right corner.</p>			

Model 34 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 34 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

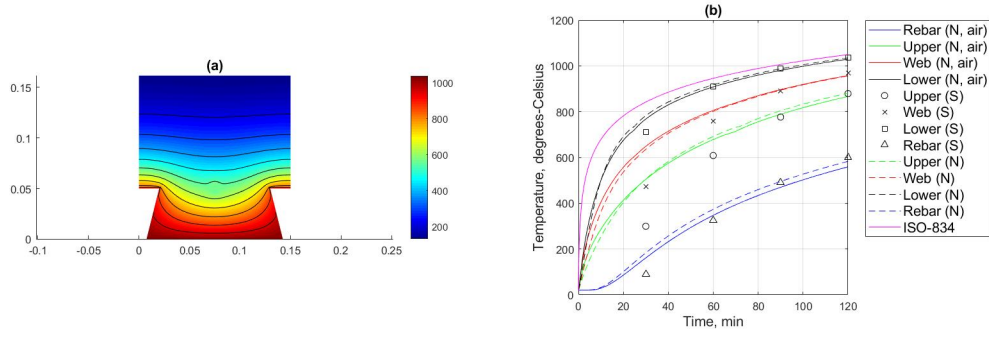
**Boundary Conditions**



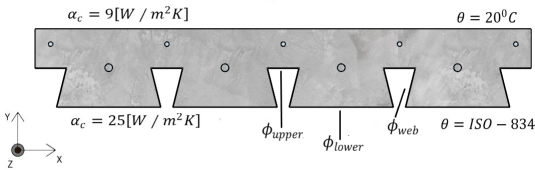
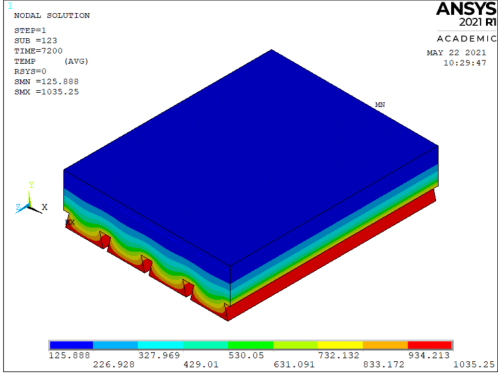
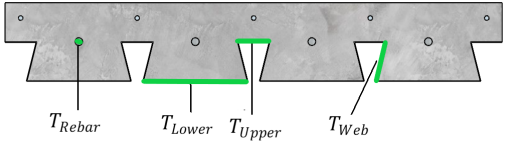
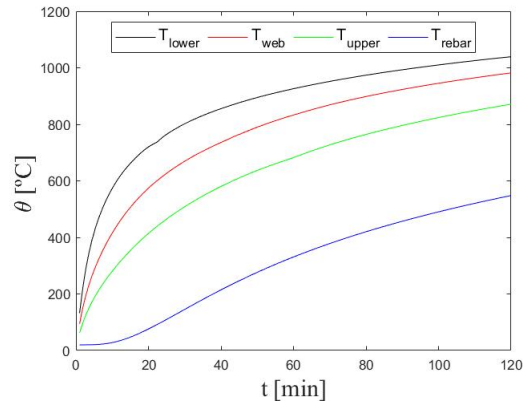
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



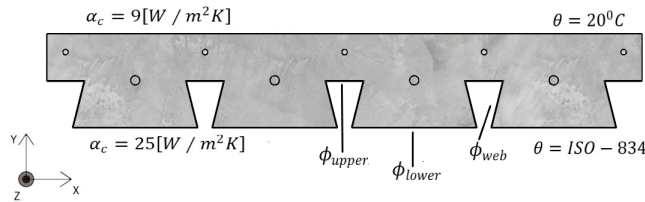
Data Sheet			
Model 35 - Multideck 50 - $h_1 : 125mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
<p>The diagram shows a cross-section of a multideck slab with a total width of 0.6m and a total height of <math>h_1</math>. The slab has a top flange thickness of 0.020m and a bottom flange thickness of 0.050m. The bottom flange features three trapezoidal cutouts. Reinforcement includes <math>\phi 6 // 150mm</math> bars in the top flange and <math>\phi 10mm</math> bars in the bottom flange. Dimensions for the cutouts and bar spacing are provided: 0.040m, 0.110m, 0.040m, and 0.135m.</p>			
Tridimensional Finite Element Model			
<p>The image displays a 3D finite element model of the multideck slab. The model is rendered in purple and cyan, showing the mesh structure. The top surface is a flat grid, while the bottom surface shows the trapezoidal cutouts. The model is presented in a perspective view.</p> <p><b>ANSYS 2021 R1</b> ACADEMIC MAY 21 2021 16:20:33</p>			

Model 35 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 35 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.14 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

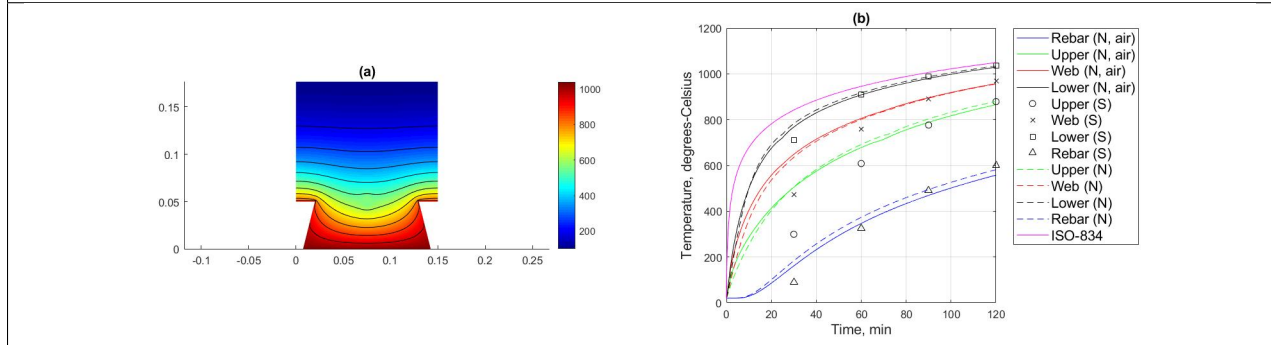
**Boundary Conditions**



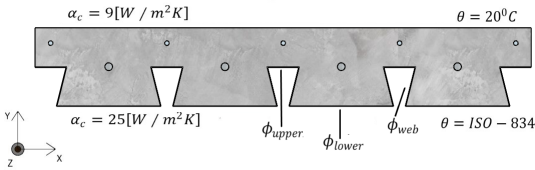
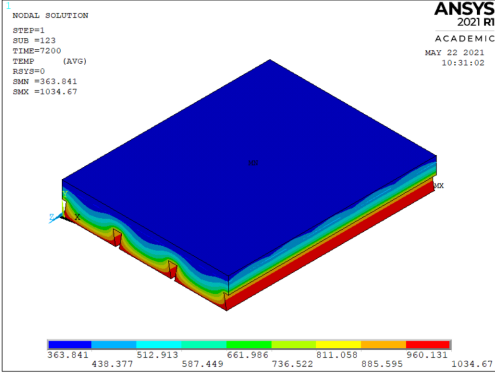
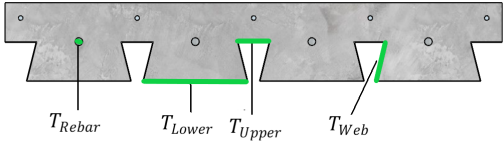
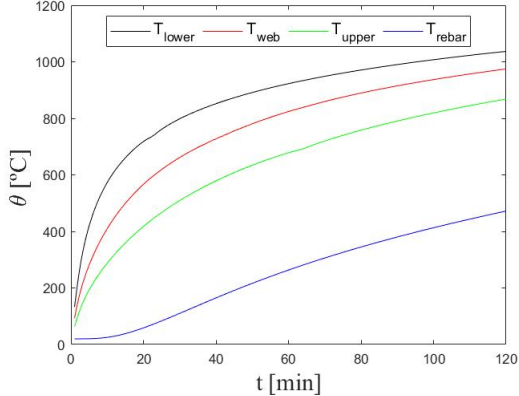
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



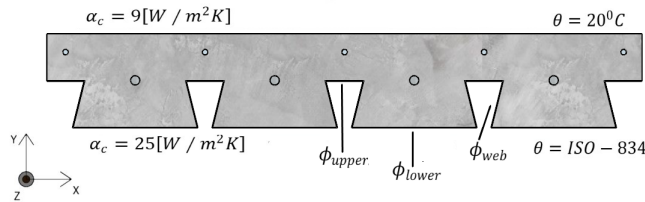
Data Sheet			
Model 36 - Bondek - $h_1 : 60mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			

Model 36 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 16 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 W/m^2K$ Unexposed Surface: $9 W/m^2K$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ C$	

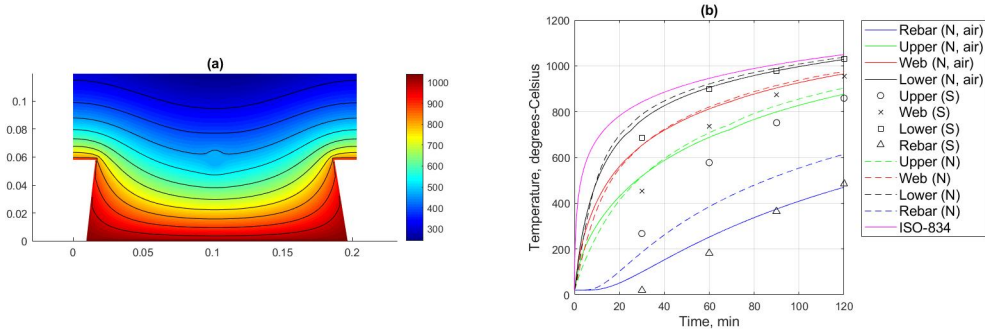
**Boundary Conditions**



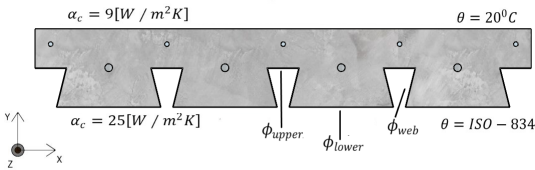
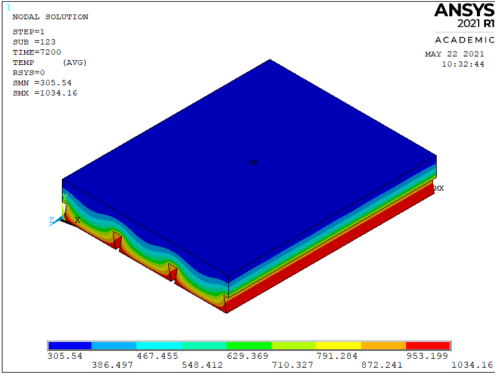
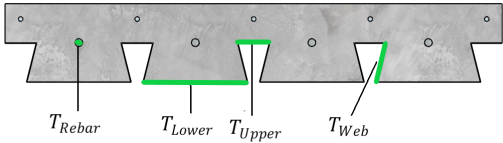
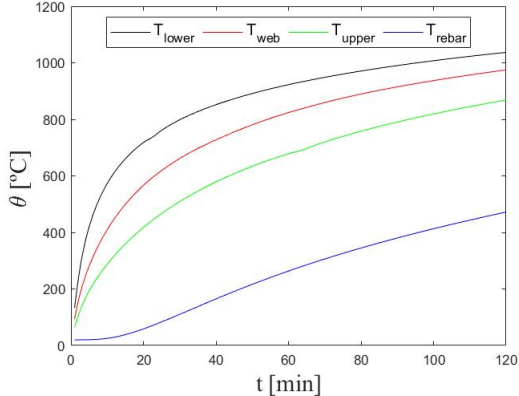
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



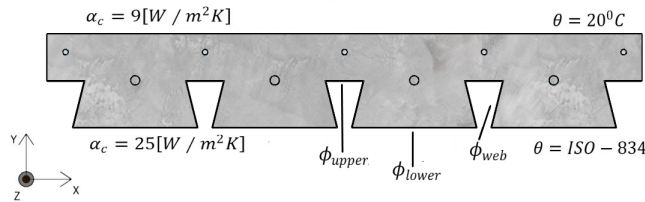
Data Sheet			
Model 37 - Bondek - $h_1 : 70mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			
<div style="display: flex; justify-content: space-between;"> <div style="font-family: monospace;"> <p>ELEMENTS MAT NUM</p> </div> <div style="text-align: right;"> <p><b>ANSYS</b> 2021 R1 ACADEMIC MAY 21 2021 16:27:10</p> </div> </div>			

Model 37 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 17 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

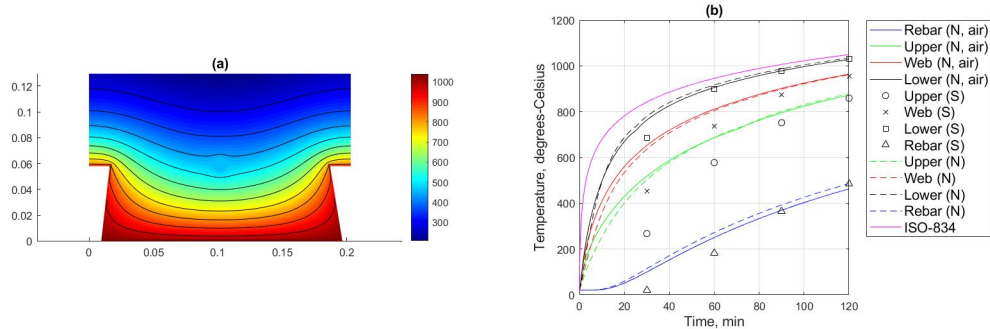
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



**Data Sheet**

**Model 38 - Bondek -  $h_1 : 90mm$**

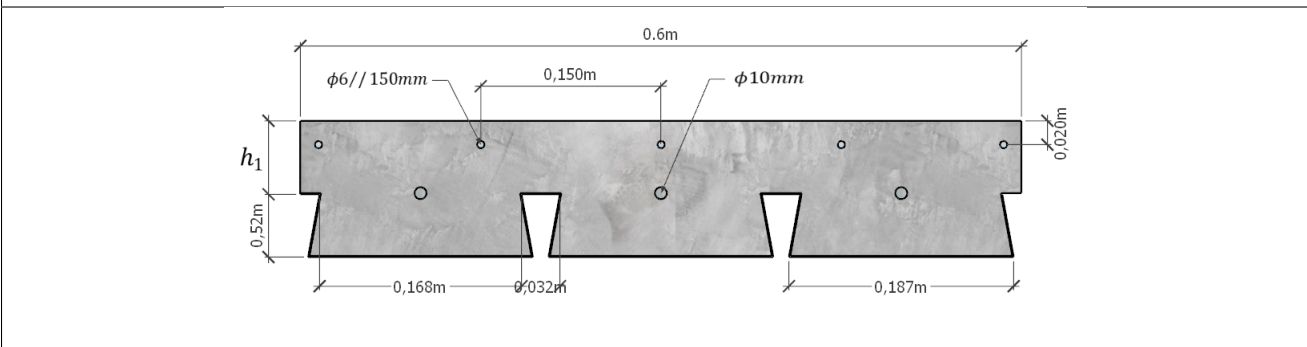
**Basic Data (1/3)**

<b>Parametric Study</b>	<b>Author: Silveira, M. B.</b>	<b>year:2021</b>
-------------------------	--------------------------------	------------------

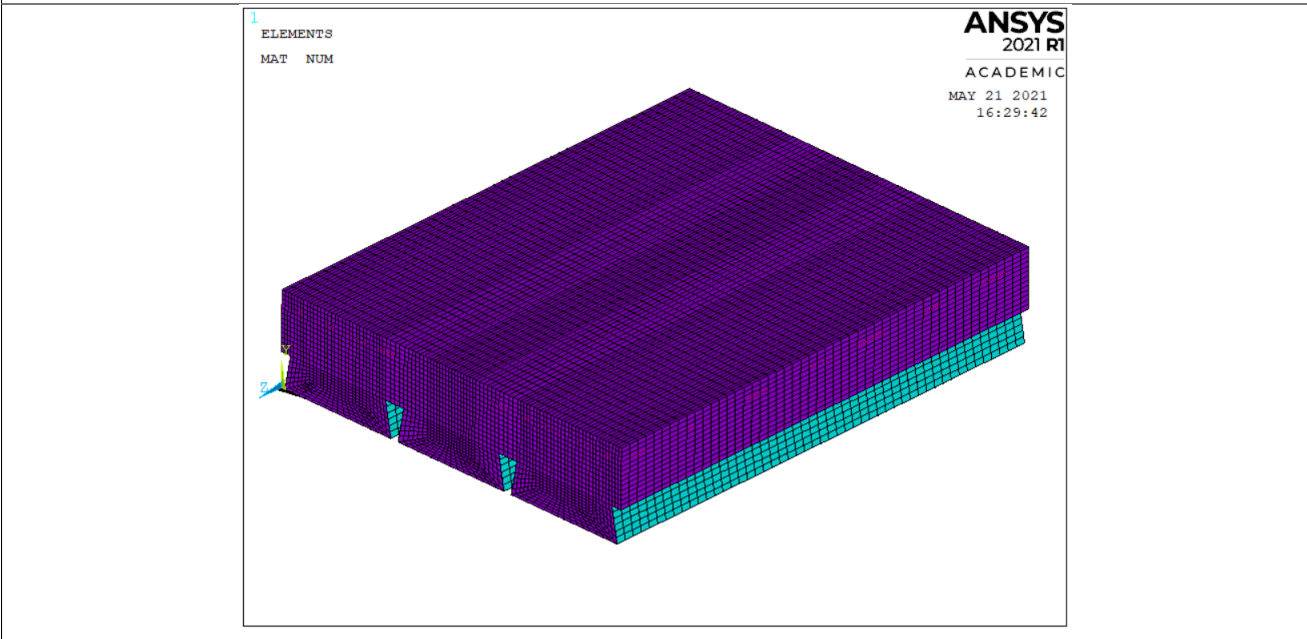
**Detailing**

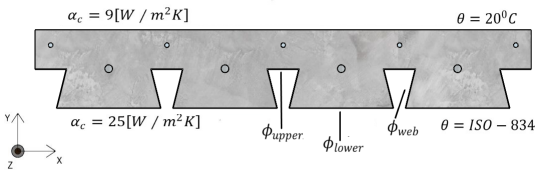
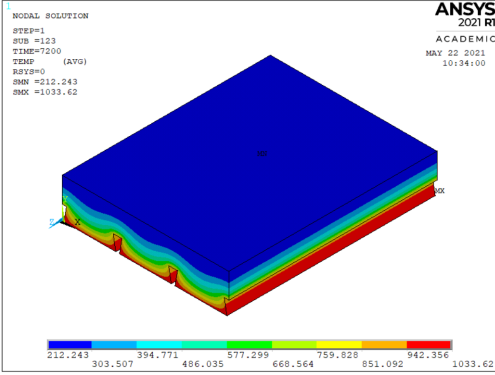
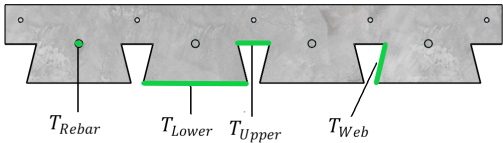
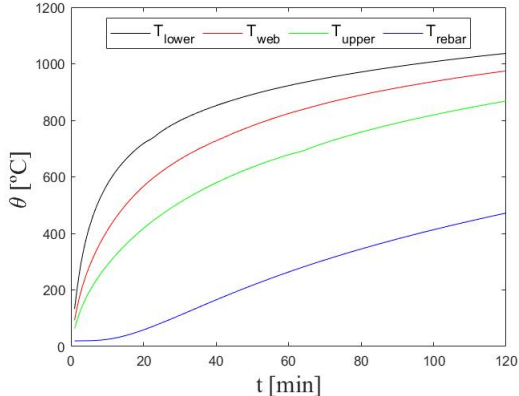
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	<b>Reinforcement Bars</b> Description: $\phi 6 // 150$ Grade: S500	<b>Steel mesh</b> Description: $3\phi 10$ Grade: S500

**Cross-Section**



**Tridimensional Finite Element Model**

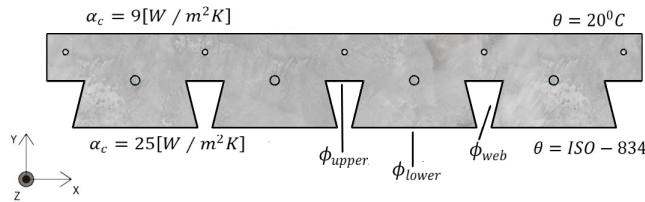


Model 38 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 38 - Thermal Analysis with MATLAB - (3/3)**

<b>MATLAB Element</b>	<b>Convection Coef. (<math>\alpha_c</math>)</b>	<b>View Factor (<math>\phi</math>)</b>
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
<b>Emissivity (<math>\varepsilon</math>)</b>	<b>Temperature Curve</b>	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

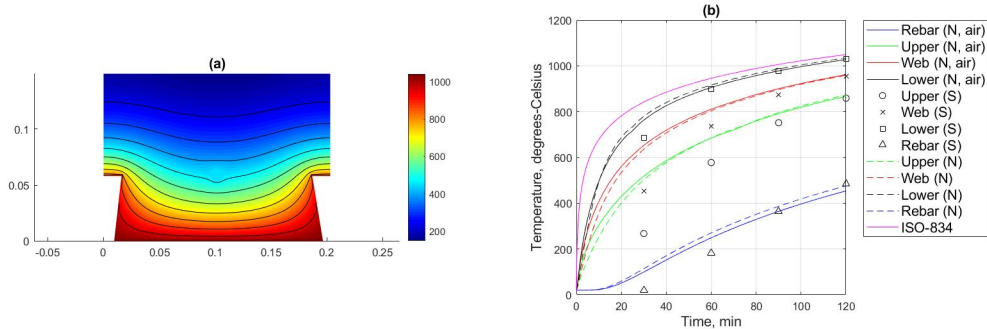
**Boundary Conditions**



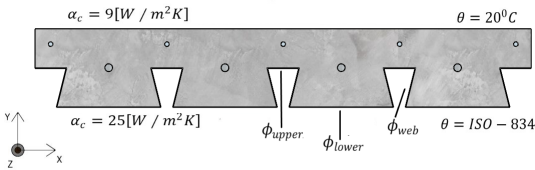
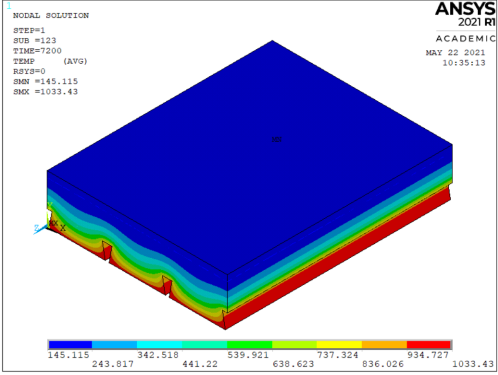
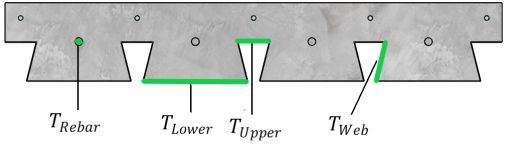
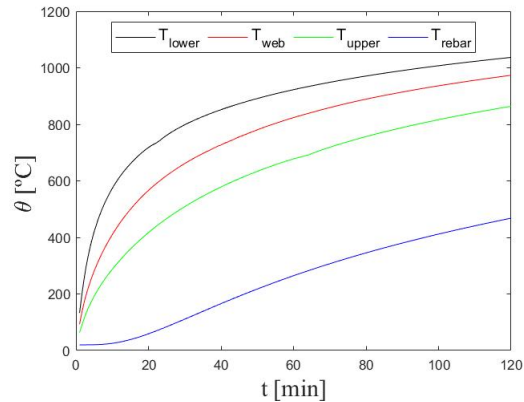
**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



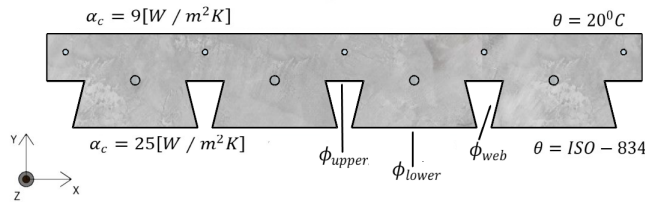
Data Sheet			
Model 39 - Bondek - $h_1 : 110mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
Tridimensional Finite Element Model			
<div style="display: flex; justify-content: space-between;"> <div style="font-family: monospace;"> <p>ELEMENTS MAT NUM</p> </div> <div style="text-align: right;"> <p><b>ANSYS</b> 2021 R1 ACADEMIC MAY 21 2021 16:31:43</p> </div> </div>			

Model 39 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
			
Additional Data		Temperature Graph	
			

**Model 39 - Thermal Analysis with MATLAB - (3/3)**

MATLAB Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
Emissivity ( $\varepsilon$ )	Temperature Curve	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

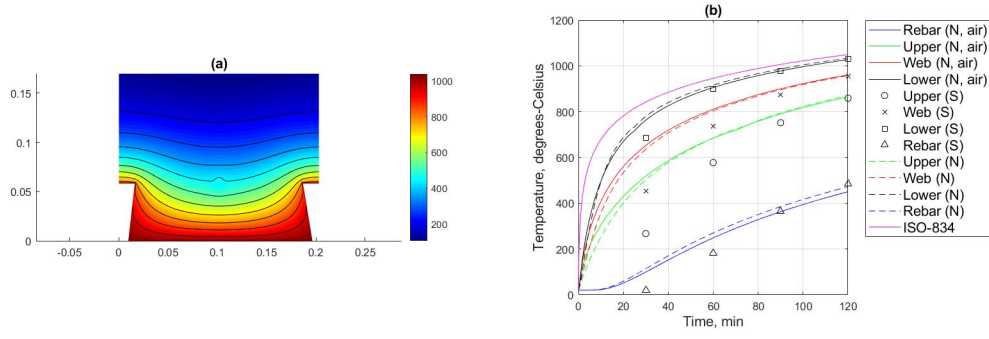
**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**



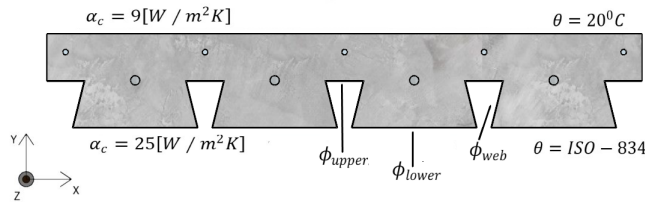
Data Sheet			
Model 40 - Bondek - $h_1 : 125mm$			
Basic Data (1/3)			
Parametric Study	Author: Silveira, M. B.		year:2021
Detailing			
Steel Deck	Concrete	Steel Bars	
Geometry: Re-entrant Thickness: 1.00mm Grade: S350	Density: Normal Weight Class: LC25/28 Moisture: 3.0%	Reinforcement Bars Description: $\phi 6 // 150$ Grade: S500	Steel mesh Description: $3\phi 10$ Grade: S500
Cross-Section			
<p>The diagram shows a cross-section of a Bondek slab with a total width of 0.6m and a height of <math>h_1</math>. The slab has a top thickness of 0.020m and a bottom thickness of 0.52m. Reinforcement includes <math>\phi 6 // 150mm</math> bars in the top and <math>\phi 10mm</math> bars in the bottom. The bottom reinforcement is spaced at 0.150m. The slab has two trapezoidal indentations with a width of 0.032m. The distance from the left edge to the first indentation is 0.168m, and the distance between the two indentations is 0.187m.</p>			
Tridimensional Finite Element Model			
<p>The image shows a 3D finite element model of the Bondek slab. The model is a rectangular block with a mesh of purple and cyan elements. The slab has two trapezoidal indentations on its top surface. The model is shown from an isometric perspective. In the top right corner, there is text: ANSYS 2021 R1 ACADEMIC MAY 21 2021 16:35:21. In the top left corner, there is text: 1 ELEMENTS MAT NUM.</p>			

Model 40 - Thermal Analysis with ANSYS - (2/3)			
ANSYS Element	Convection Coef. ( $\alpha_c$ )	View Factor ( $\phi$ )	Emissivity ( $\varepsilon$ )
Steel Deck: SHELL131 Concrete: SOLID70 Steel Bars: LINK33	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00	Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7
Temperature Curve	Convergence Parameters	Convergence Criteria - Heat Flow	
Exposed Surface: ISO-834	Simulation Time: 7200 s	Tolerance Value: $1 \cdot 10^{-3}$	
	Time Step Size: 60 s		
Unexposed Surface: $20^\circ\text{C}$	Minimum Time Step: 1 s	Min. Reference Value: $1 \cdot 10^{-6}$	
	Máximum Time Step: 60 s		
Boundary Conditions		Finite Element - Temperature Distribution at 7200 s	
Additional Data		Temperature Graph	

**Model 40 - Thermal Analysis with MATLAB - (3/3)**

<b>MATLAB Element</b>	<b>Convection Coef. (<math>\alpha_c</math>)</b>	<b>View Factor (<math>\phi</math>)</b>
Steel Deck: Triangular Concrete: Triangular Steel Bars: Triangular	Exposed Surface: $25 \text{ W/m}^2\text{K}$ Unexposed Surface: $9 \text{ W/m}^2\text{K}$	Upper flange: 0.12 Web: 0.09 Lower Flange: 1.00
<b>Emissivity (<math>\varepsilon</math>)</b>	<b>Temperature Curve</b>	
Steel Deck: 0.7 Concrete: 0.7 Steel Bars: 0.7	Exposed Surface: ISO-834 Unexposed Surface: $20^\circ\text{C}$	

**Boundary Conditions**



**Additional Information**

In the temperature graph, (N) corresponds to the temperature curves obtained through MATLAB, while the term (air) refers to the simulations concerning the debonding effect. The term "S" represents the temperatures using the Eurocode Simplified Method. Upper, Web, Lower, and Rebar refer to the average temperature calculated in each of the following steel components, Upper flange, Web, Lower flange, and Rebar, respectively.

**(a) Finite Element - Temperature Distribution at 7200 s and (b) Temperature Graph**

