FIRE RESITANCE OF COMPOSITE SLABS ACCORDING EN1994-1-2

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Abstract: Using composite steel and concrete slabs is an interesting solution compared with the traditional concrete slabs, because it's less expensive and shows a straightforward implementation. In a fire scenario, the profiled steel sheeting remains in direct contact with the fire, reducing its resistance. As a solution to that problem, generally, a reinforced bar is used in the middle of the ribs to increase the slab resistance during the fire. In the scope of this thesis, an Excel program (*toolkit*) was developed in order to evaluate the fire resistance of composite slabs. Safety procedures mentioned in Eurocode 4, part 1-2 (fire part) was taken into account. Inside this Eurocode there are different approaches regarding calculation methods that are studied, however, simple calculation methods are the main focus, once there were in the bases of the toolkit. Starting with input parameters, such as steel sheeting's geometry and the material's class, the toolkit classifies the composite slab regarding three main parameters: load bearing (Criterion R), integrity (Criterion E) and thermal isolation (Criteria I). From this tool that was developed, a result analysis is carried by the mean of a graphic component and programming language in *VisualBasic*. The main objective is to achieve some conclusions about the most important parameters in the terms of fire resistance.

Keywords: Structures, Fire safety, Fire, Composite slab, Eurocode, Toolkit

1. Introduction

During the civil engineering course, there were few curricular units addressing the subject of fire safety in buildings. One of the main reasons as to do with the frequency of this scenarios (a fire may not occur during the lifetime of a building) and its importance compared with other actions (earthquake, wind and snow). Despite of this fact, structures subject to fire can result in the loss of human lives and several material damages. Structural integrity is the last line of defence when other measures fail. It's essential for all civil engineers to have the basic knowledge about this subject in order to apply it correctly during the building design. This study will provide the necessary background information for a rational fire design of composite concrete and steel structures (more specifically, slabs). In the past, "the most common method of designing a steel structure for fire condition is to design the building for ambient temperature loading condition and then, to cover the steel members with proprietary fire protection materials to ensure that specific temperature is not exceeded" (Franssen e Vila Real, 2012). As this study will reveal, fire parts of Eurocode gives the designer much more flexibility to achieve more economic solutions compared with the prescriptive approach.

2. COMPOSITE SLABS WITH PROFILED STEEL SHEETING

The utilization of composite slabs with profiled steel sheeting in buildings has been increasing in Portugal. Overall, it's a good alternative compared with the traditional concrete slabs because it´s a solution that shows a very simple and easy way to assembly at the construction site. Once the profiled sheeting is placed (supported by the beams), it will work as a platform and simultaneously, as a formwork when concreting. In fact, this solution allows cost reduction associated to the absence of inferior reinforcement, struts, formworks and low storage space. Multiple levels of the building can be done at the same time when using composite structurers. (Calado & Santos 2009)

Typically, composite slabs with profiled steel sheeting has a reinforcement mesh placed in the top face (Figure 1). This mesh will work as the main reinforcement for the hogging moment ($M_{fi,Ed}^{-}$). It improves the slab resistance in the case of fire and distribute punctual loads. Figure 1 also shows some shear studs (they ensure the connection between the beam and the steel sheeting) and other construction details, such as, an end tape / foam to cover the openings during concreting, and a restrain strap.

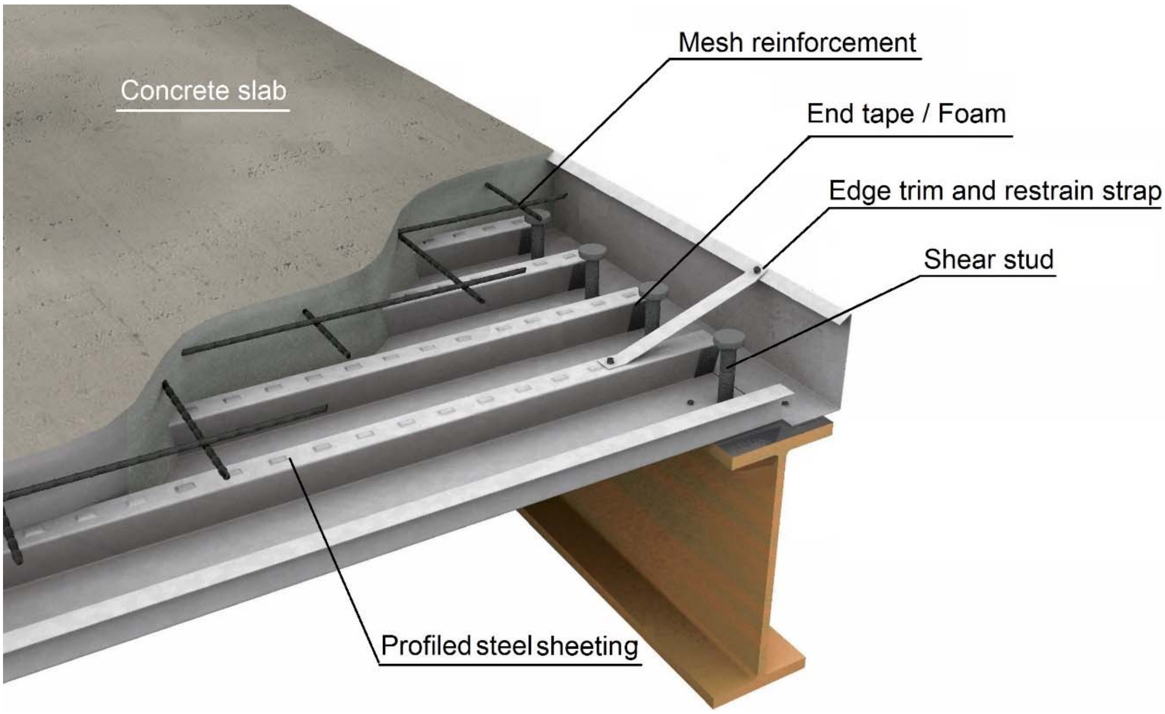


Figure 1 - Schematization of a composite slab with profiled steel sheeting.

It's very clear that this type of solution can save time and money to the constructers. However, its behaviour during a fire scenario is worst than a traditional concrete slab because it's the profiled sheeting that remains in contact with the fire. The steel and the concrete show a very different behaviour at high temperatures. For example, the thermal conductivity of steel is 50/60 times higher than the concrete, in other words, the steel temperature will increase much faster than the concrete. This dissertation focus on this matter and will try to achieve some conclusions about this type of structure and how can designers improve their resistance to fire. It was only considered simply supported slabs and so, the programme that was developed only evaluate the sagging moment $M_{fi,Ed}^{+}$. The verification process that was considered was based on Eurocode 4 part 1-2, chapter 4.3.2 (Unprotected composite slabs).

3. EUROCODE APPROACH

"Fire parts of the Eurocodes set out a new way of approaching structural fire design" (Franssen & Vila Real, 2012). Eurocode 1 allows the designers to choose between several fire model and calculation methods. First, it's essential to understand the difference between "nominal temperature-time curves" and "natural fire models" (Figure 2). A nominal temperature-time curve is often used for prescriptive requirements, for example, a structure must survive 90 minutes to the standard curve. This curve represents a fully developed fire without any cooling phase. It's very conservative and often can result in more expensive solutions. In the other hand, a "natural fire curve" has several phases. Starting with the ignition until the cooling phase. Research's results show that "real fire can be more or less severe than the standard fire test depending on the characteristics of the fire enclosure". Using this type of approach, it's called a performance based design because it takes into account the performance of the structure during all stages of the fire. Nevertheless, for this study, it was considered the standard curve.

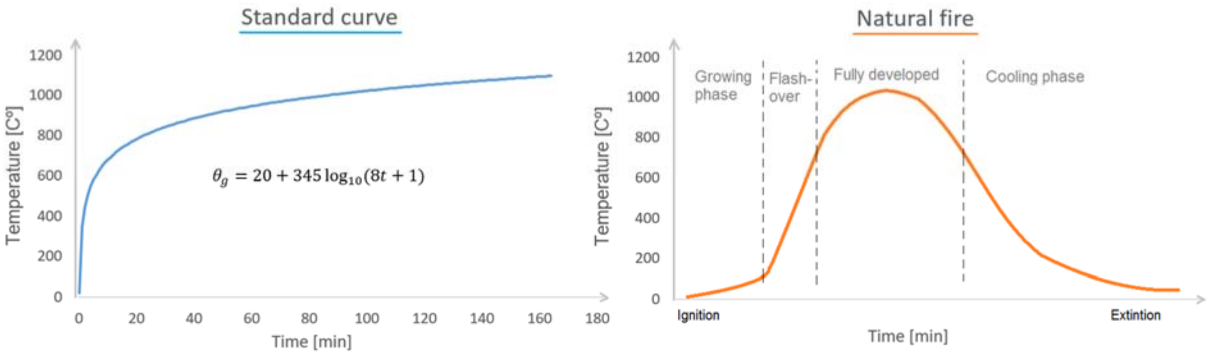


Figure 2 - Temperature over time curves: Standard curve vs Natural fire's curve.

Fire design process mentioned in the Eurocode (EN1991-1-2) "can be described in to three components consisting of the characterisation of the fire model, a consideration of the temperature distribution within the structure and assessment of the structural response to the fire. (…) Eurocode allows designers to choose in a very wide range of methods. The options available range from a simple consideration of isolated member behaviour subjected to a standard fire to a consideration of the physical parameters influencing fire development coupled with an analysis of the entire building".

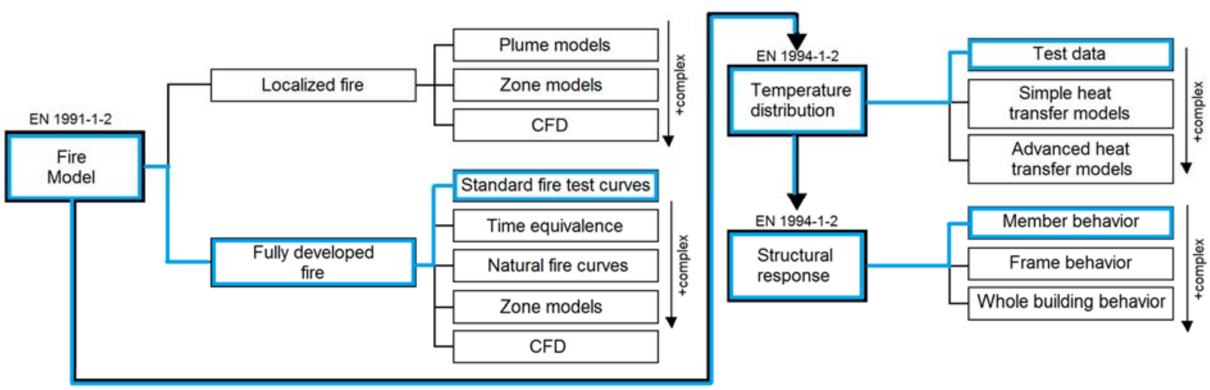


Figure 3 - Eurocode approach: The three stages of the fire design process.

4. SIMPLE CALCULATION MODEL

The toolkit development was based in safety procedures mentioned in the annex D of Eurocode 4 part 1-2. This simple calculation model (EN 1994-1-2, 4.3) is valid for unprotected slabs in which section is class 1 or 2 and the design bending resistance shall be determined by plastic theory. The following rules apply only to simply supported concrete slabs with profiled steel sheeting (Figure 4), heated from below subjected to the standard temperature-time curve (CEN 2005). Temperature in both materials are obtain by the mean of tables within the EN1994-1-2 annex D. Indirect action, resulted by the interaction with the rest of the structure, are not considered (isolated member analysis).

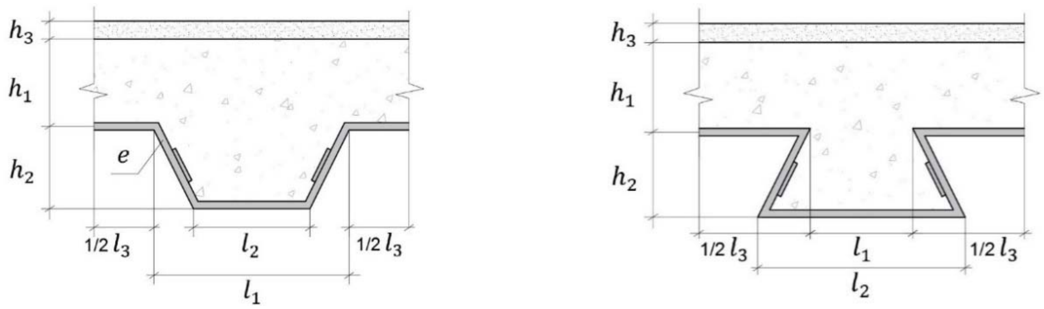


Figure 4 - Composite slab with profiled sheeting: trapezoidal and re-entrant sheeting.

Starting with input parameters, such as the profiled steel sheeting's geometry and the material's class, the toolkit classifies the composite slab regarding three criterions (Figure 5): Load bearing (Criterion R), Integrity (Criterion E) and thermal isolation (Criteria I).

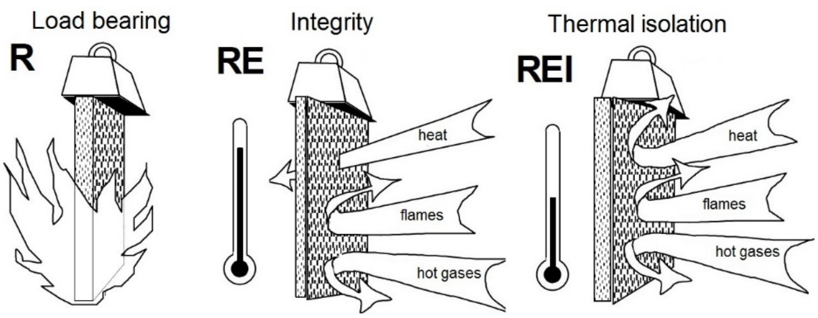


Figure 5 – For standard fire exposure, members shall comply with criteria R, E and I.

To use the annex D of EN1994-1-2 to check the fire resistance regarding criteria I and criteria R, the profiled sheeting's geometry must comply with the following range:

Table 1 - Field of application for unprotected composite slabs (EN1994-1-2)

Trapezoidal steel sheeting profiles	Re-entrant steel sheeting profile
$80,0 \leq l_1 \leq 155,0\ mm$	$77,0 \leq l_1 \leq 135,0\ mm$
$32,0 \leq l_2 \leq 132,0\ mm$	$110,0 \leq l_2 \leq 150,0\ mm$
$40,0 \leq l_3 \leq 155,0\ mm$	$38,5 \leq l_3 \leq 97,5\ mm$
$50 \leq h_1 \leq 125,0\ mm$	$50 \leq h_1 \leq 130,0\ mm$
$50 \leq h_2 \leq 100\ mm$	$30 \leq h_2 \leq 60\ mm$

4.1 Criterion "I"

"Thermal isolation may be assumed to be satisfied where the average temperature rise over the whole of the non-exposed surface is limited to 140ºC and the maximum temperature rise at any point of that surface does not exceed 180 ºC" (EN1994-1-2, 2.1.2 (3)). There are two ways to check for this criterion, according Eurocode 4 part 1-2. The first one is based on the relation of the fire resistance respect to thermal isolation and the minimum effective thickness h_{eff} (Table 2):

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

$$h_{eff} = h_1 \left[1 + 0{,}75 \left(\frac{l_1 + l_2}{l_1 + l_3}\right)\right] \qquad \text{for } h_2/h_1 > 1{,}5 \text{ and } h_1 > 40 \text{ mm} \qquad (2)$$

Table 2 - Minimum effective thickness as a function of the standard fire

Thermal isolation	Min. h_{eff} [mm]
I 30	60 - h_3
I 60	80 - h_3
I 90	100 - h_3
I 120	120 - h_3
I 180	150 - h_3
I 240	175 - h_3

Alternatively, according the annex D of EN1994-1-2, fire resistance with respect to thermal isolation can be obtained by the following expression:

$$t_i = a_0 + a_1 h_1 + a_2 \Phi + a_3 \frac{A}{L_r} + a_4 \frac{1}{l_3} + a_5 \frac{A}{L_r}\frac{1}{l_3} \qquad (3)$$

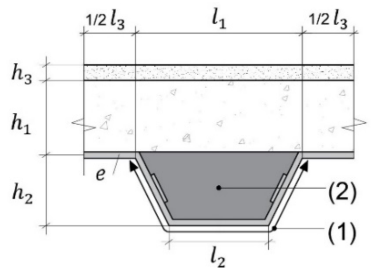
Where:

t_i - Fire resistance with respect to thermal isolation [min]

Φ - The view factor of the upper flange [-]

1 - Exposed surface: L_r [mm]

2 - Concrete volume of the rib per meter of rib length: A [mm³/mm]



$$\frac{A}{L_r} = \frac{h_2 \frac{l_1 + l_2}{2}}{l_2 + 2\sqrt{{h_2}^2 + \left(\frac{l_1 - l_2}{2}\right)^2}} \qquad (4)$$

$$\Phi = \left(\sqrt{{h_2}^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2} - \sqrt{{h_2}^2 + \left(\frac{l_1 - l_2}{2}\right)^2}\right) \Big/ l_3 \qquad (5)$$

Table 3 – Coefficients for determination of the fire resistance with respect to thermal insulation

Concrete	a_0 [min]	a_1 [min/mm]	a_2 [min]	a_3 [min/mm]	a_4 [min.mm]	a_0 [min]
Normal concrete	-28,8	1,55	-12,6	0,33	-735	48
Light weight concrete	-79,2	2,18	-2,44	0,56	-542	52,3

4.2 Criterion "R"

As mentioned before, the design bending resistance ($M_{fi,Rd}$) shall be obtain by the plastic theory. In order to calculate the plastic neutral axis of the composite slab, first, it shall be obtained the forces felted by the concrete and the steel sheeting during the fire. Both materials will suffer tensile strength reduction caused by the increase of the temperature during the fire exposure. The steel sheeting's temperatures within the flanges and the web can be obtained through the expression (6) Table 4:

$$\theta_a = b_0 + b_1.\frac{1}{l_3} + b_2.\frac{A}{L_r} + b_3.\Phi + b_4.\Phi^2 \quad (6)$$

Regarding the concrete temperature felt during the fire, there isn't any mathematical expression in the Eurocode. It's required to use the Table 5 that express a temperature distribution in a solid slab of 100 mm thickness composed of normal weight concrete. The "x" coordinate is measured from the bottom face of the slab (exposed to the fire).

Table 4 – Coefficients for the determination of the temperature of the parts of the steel decking.

Time [min]	Steel sheeting part	b_0 [°C]	b_1 [°C]·mm	b_2 [°C]·mm	b_3 [°C]	b_4 [°C]
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
90	Lower flange	1018	-839	-1,55	65.1	-108,1
	Web	816	-959	-2,21	464.9	-340,2
	Upper flange	618	-2786	-1,79	767.9	-472
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

Table 5 – Temperature distribution in a solid slab of 100 mm thickness of normal concrete

x [mm]	θ_c [°C] after a fire duration of [min]:			
	30	60	90	120
5	535	705	-	-
10	470	642	738	-
15	415	581	681	754
20	350	525	627	697
25	300	469	571	642
30	250	421	519	591
35	210	374	473	542
40	180	327	428	493
45	160	289	387	454
50	140	250	345	415
55	125	200	294	369
60	110	175	271	342
80	80	140	220	270
100	60	100	160	210

Through these temperatures, it's possible to obtain the reduction factors ($k_{y,\theta,f\_inf}, k_{y,\theta,f\_sup}, k_{y,\theta,w}, k_{c,\theta}$) of the material's tensile strength for a given time of exposure to the standard fire:

Table 6 - Tensile strength reduction of the Steel

Steel temperature θ_a [ºC]	$k_{y,\theta} = \frac{f_{ay,\theta}}{f_{ay}}$
20	1
100	1
200	1
300	1
400	1
500	0,78
600	0,47
700	0,23
800	0,11
900	0,06
1000	0,04
1100	0,02

Table 7 – Tensile reduction of the concrete

Concrete temperature θ_c [ºC]	$k_{c,\theta} = \frac{f_{c,\theta}}{f_c}$	
20	1	1
100	1	1
200	0.95	1
300	0.85	1
400	0.75	0.88
500	0.60	0.76
600	0.45	0.64
700	0.30	0.52
800	0.15	0.40
900	0.08	0.28
1000	0.04	0.16
1100	0.01	0.04

Once a plastic analysis is considered, the tensioned concrete below the plastic neutral axis (Z_{pl}) must be neglected. An iterative process was used to obtain the reduction factor of concrete's tensile strength ($k_{c,\theta}$). This coefficient depends on the position of plastic neutral axis (Z_{pl}) and therefore, Z_{pl}, depends on the coefficient $k_{c,\theta}$. So, for a 1st iteration, it's consider that the concrete doesn't suffer any reduction on the tensile strength ($k_{c,\theta} = 1$). From equilibrium between compression and tension forces within the cross section of the composite slab, ($A_c = Z_{pl} \times b$ – compressed concrete area; $A_{f\_sup}/A_{f\_inf}/\ A_w$ – upper, lower flange and web areas; $\alpha_{slab} = 0.85$ - rectangular tension block) it's possible to obtain the plastic neutral axis position. Table 5 may be used to obtain the location of the isotherm as a conservative approximation. In this case, the coordinate "x" result from this expression: $Z_{pl} = h_{eff} - x$

From the coordinate "x", the concrete temperature can be obtained and, therefore, the new coefficient $k_{c,\theta}$ is calculated (Table 7). This process is repeated until the value of the coefficient $k_{c,\theta}$ converge.

$$-\sum F_h = 0 \qquad \sum_{i=1}^{n} A_i k_{y,\theta,i} \left(\frac{f_{y,i}}{\gamma_{M,fi,a}} \right) + \alpha_{slab} \sum_{j=1}^{m} A_j k_{c,\theta,j} \left(\frac{f_{c,j}}{\gamma_{M,fi,c}} \right) = 0 \tag{7}$$

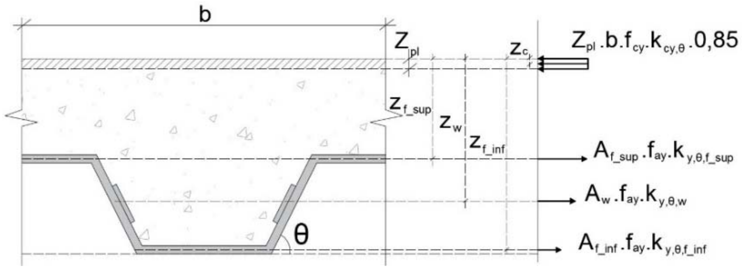


Figure 6 – Plastic analysis of a generic rib of a composite slab

The design bending resistance $M_{fi,Rd}$ is obtained from the top face of the cross section:

$$-\sum M_{top} = M_{fi,Rd} \qquad M_{fi,Rd} = \sum_{i=1}^{n} f_i \cdot z_i \cdot + \alpha_{slab} \sum_{j=1}^{m} Z_{pl} \cdot b \cdot z_c \cdot k_{c,\theta,j} \cdot 0.85 \cdot \left(\frac{f_{c,j}}{\gamma_{M,fi,c}} \right) \tag{8}$$

For slabs with longer periods of time exposed to the standard fire, usually a reinforced bar is places inside the rib (Figure 7). This reinforced bar is covered with concrete and therefore, it won't be in direct contact with the fire. Its temperature (θ_s) will depend on its the position inside the rib (u_3).

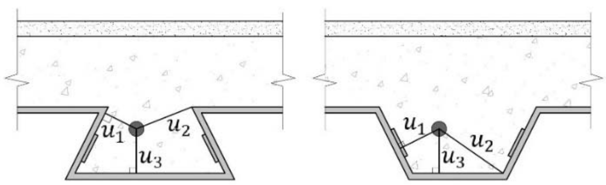


Figure 7 – Position of the reinforced bar u_i

$$\frac{1}{z} = \frac{1}{\sqrt{u_1}} + \frac{1}{\sqrt{u_2}} + \frac{1}{\sqrt{u_3}} \tag{9}$$

$$\theta_s = c_0 + \left(c_1 \times \frac{u_3}{h_2} \right) + (c_2 \times z) + \left(c_3 \times \frac{A}{L_r} \right) + (c_4 \times \alpha) + \left(c_5 \times \frac{1}{l_3} \right) \tag{10}$$

Table 8 – Coefficients for the determination of the temperatures of the reinforced bars in the rib

Concrete	Fire Resistance [min]	c_0 [˚C]	c_1 [˚C]	c_2 [˚C].mm$^{0.5}$	c_3 [˚C].mm	c_4 [˚C/˚]	c_5 [˚C].mm
Normal	60	1191	-250	-240	-5.01	1.04	-925
	90	1342	-256	-235	-5.30	1.39	-1267
	120	1387	-238	-227	-4.79	1.68	-1326

For a slab with a reinforced bar inside the rib, the process to obtain the coefficient $k_{c,\theta}$ is the same as described before for a non-reinforced slab. The only difference relays on the fact that the equilibrium of horizontal forces in the cross section has one more force. Therefore, once the tension force of the reinforced bar is significantly higher $(A_{\phi s} \cdot f_{sy} \cdot k_{y,\theta,\phi s})$ compared with the steel sheeting tension forces $(A_i \cdot f_{ay} \cdot k_{y,\theta,i})$, the plastic neutral axis will be closest to the profiled sheeting. The coefficient $k_{y,\theta,\phi s}$ is also obtained by the mean of Table 6, the same table used for the profiled sheeting coefficient.

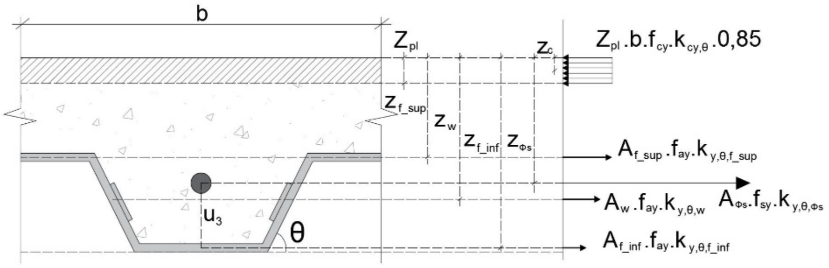


Figure 8 - Plastic analysis of a generic rib of a composite slab

The design bending resistance $M_{fi,Rd}$ is obtained from the top face of the cross section (Figure 8):

$$M_{fi,Rd} = \sum_{i=1}^{n} f_i \cdot z_i + \alpha_{slab} \sum_{j=1}^{m} Z_{pl} \cdot b \cdot z_c \cdot k_{c,\theta,j} \cdot 0{,}85 \cdot \left(\frac{f_{c,j}}{\gamma_{M,fi,c}}\right) + f_{\phi\_s} \cdot z_{\phi\_s} \qquad (11)$$

Regarding criterion "E" (integrity), EN1994-1-2 refers that if the composite slab was design according EN1991-1-1, this criterion is assumed to be satisfied.

5. Parametric Study

From this simple calculation model, an excel programme was developed in order to automatize this procedure. The user only has to introduce the geometry of the composite slab, the class of the materials and the time of exposure to the standard fire. The programme will return the thermal isolation time, and the design bending resistance of the slab. Once the programme was ready and properly tested, the goal was to study which parameters, in terms of geometry or class of the materials, are more relevant to obtain a superior fire resistance. In this next section, it is shown a graphic analysis. Starting with a comparison of different times of exposure to the standard fire (60, 90 and 120 minutes). In this two graphics, the class of the concrete is increasing and different classes of steel are compared.

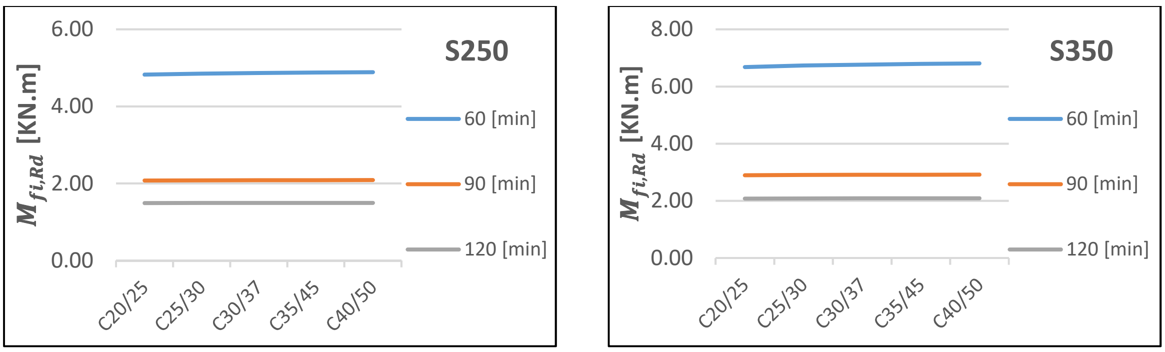


Figure 9 – Influence of the class of the material for different times of exposure

The reason for the gap between the line of 60 minutes and the line of 90 or 120 minutes (Figure 9) as to do with the tensile strength coefficient of the steel and with the progress of the standard fire curve. At 60 minutes, steel only has 17% of its tensile strength while at 90 and 120 minutes it has 6% and 4% respectively. Besides this, it’s possible to see that the class of the steel has a more relevant role than the class of the concrete regarding fire resistance.

In the next two graphs is shown an increase of the height h_1 and h_2. Different class of materials (Steel and concrete) are tested. All other geometric parameters are constant during this analysis

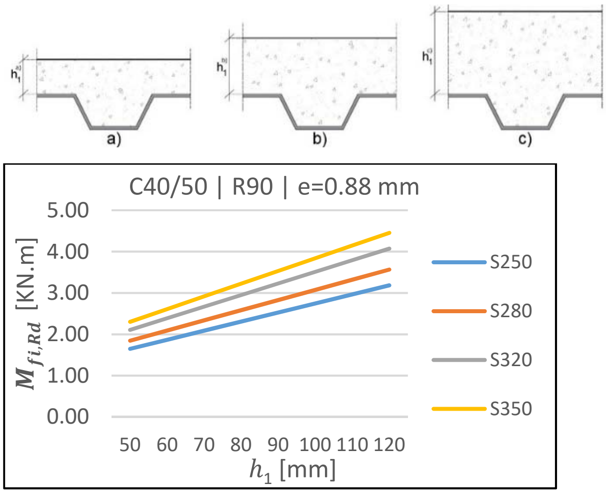


Figure 10 - h_1 for different classes of steel

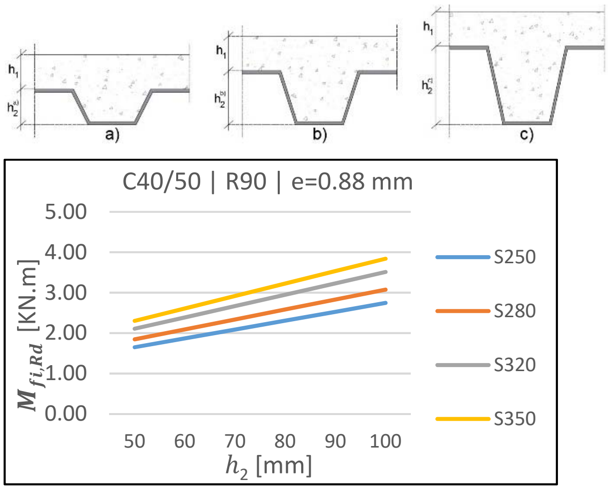


Figure 11 - h_2 for different classes of steel

The design bending resistance increase for higher values of h_1 although the self-weight of the slab increases too. In terms of thermal isolation, h_1, is one of the most relevant parameter to achieve longer periods of exposure to fire

Table 9 - Influence of the height h_1 (thermal isolation)

h_1 [mm]	50	60	70	80	90	100	110	120
Thermal Isolation	I60	I60	I90	I90	I120	I120	I120	I180

In the other hand, increasing h_2 also increase the self -weight of the slab but not as the same rate as h_1. This fact as to do with the geometry of the rib and with the quantity of concrete inside of it. In terms of thermal isolation, is not so effective as h_1.

Table 10 - Influence of the height h_2 (thermal isolation)

h_2 [mm]	50	60	70	80	90	100	110
Thermal Isolation	I60	I60	I90	I60	I90	I90	I90

This analysis was carried for a non-reinforced slab. As mentioned before, for longer periods of exposure to fire, usually, a reinforced bar is placed inside of the rib. This reinforced bar will drastically increase the design bending resistance of the slab.

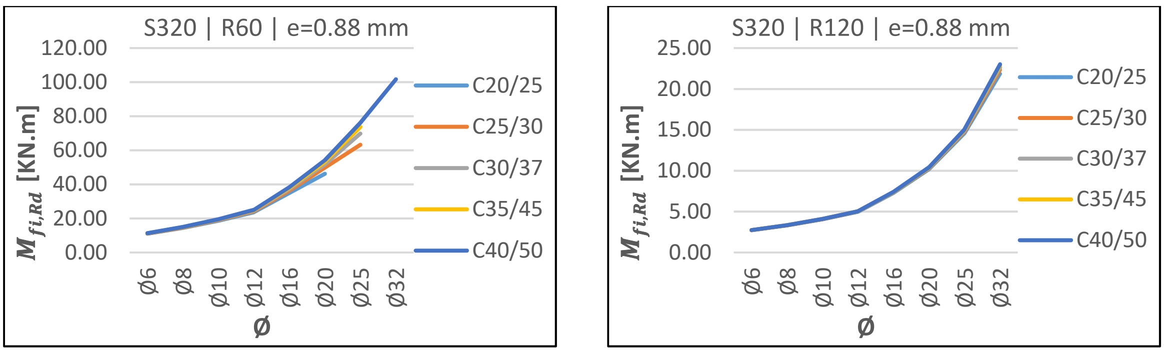


Figure 12 – Influence of the reinforced bar area for different classes of concrete

From this last two graphics, it's very clear that the bending resistance has suffer a major improve comparing with a non-reinforced slab. Regarding the first graphic, there are few points, more specifically, the bending resistance for larger diameters that the programme didn't calculate. The reason for this as to do with plastic neutral axis. Once the reinforced bar is very close to this line, it doesn't reach its yield strength and so, a plastic analysis is not possible. This points are not in the range of this programme.

6. Conclusions

The calculation programme that was developed allowed the automatization of the simple calculation model mentioned on the EN1994-1-2. Even though this method is based on standard fire curve and therefore, it doesn´t consider all the stages of the fire, this programme allows the designer to achieve satisfactory results in terms of composite slabs. On the other hand, this programme has some limitations. It only calculates the sagging moment resistance ($M^{+}_{fi,Rd}$), the mesh reinforced placed on the concrete slab is neglected and the membrane effect is not considered (for more information about this effect, the full document shall be requested).

From the parametric analysis, it was possible to achieve some conclusions. First, the reinforced bar is clearly the most effective way to increase the bending resistance in a fire scenario. This bar will be covered with concrete and so, the temperature felt by the steel will be inferior, compared with the temperature felt by the steel sheeting. For longer periods of fire exposure and when the designer wants to satisfy the criterion "R", this measure gives very satisfactory results.

Regarding Criterion "I", adding a reinforced bar doesn´t improve the thermal isolation. For this criterion, the most effective measure is to increase the height of concrete h_1, despite knowing that this parameter also increase the self-weight of the slab.

In terms of the materials, the graphics clearly show that is more advantageous to invest on a higher-class steel then a higher-class concrete.

7. References

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