Fire design of slim-floor beams

Slim-floor beams are a well-known and cost-effective solution that permits a significant reduction of floor thickness, and are increasingly used in industrial and commercial buildings. Since only their lower flange is exposed to fire, slim-floor beams may also achieve higher fire resistance, in comparison to other types of composite beams that are not fully embedded in the concrete floor. Simplified models are available in Eurocode 4 Parts 1-2 to evaluate the temperature distribution for partially encased and non-encased composite beams. However this standard does not provide any simplified model to evaluate the cross-sectional temperature field of slim-floor beams. In this sense, different proposals have been evaluated in recent years in order to provide simplified models for temperature evaluation. The currently available models in the literature have shown their accurate behaviour providing results on the safe side, and are recommended for use in practice. Finally, this work shows that slim-floor composite beams can provide good performance during a fire event. Specifically, 60 min of standard fire rating can be achieved for load levels lower than 0.5–0.6. Improved behaviour to achieve 90 or 120 min of standard fire exposure may also be reached by using innovative solutions, advanced materials or external protection.

Keywords slim-floor beams; fire resistance; fire design; simplified design methods

1 Introduction

In composite construction, slim-floor beams are a well-known and cost-effective solution that permits a significant reduction of floor thickness, increase of working space and simpler underfloor technical equipment installation. Due to these advantages, slim-floor beams are being increasingly used in industrial and commercial buildings.

Slim-floor beams can be used in combination with different flooring systems, such as in-situ concrete slabs, profiled steel decks or precast concrete slabs. Moreover, the slab configuration itself changes the incidence of the thermal action to the composite beam, i.e. the hot air between the ribs in a profiled steel deck facilitates the increase of temperatures in the beam section compared to a floor configuration with concrete slabs.

In practice, two main types of slim-floor beams can be recognized: Integrated Floor Beam (IFB, Fig. 1b) and Shallow Floor Beam (SFB, Fig. 1a). The former type is made of a half I-section where a wider bottom plate is attached and welded to its lower flange. The latter consists of a full I-section with a bottom plate welded to the web as a replacement of the lower flange. The latter consists of a full I-section with a bottom plate attached and welded to its lower flange. Other configurations have been made available in the construction market such as the “Thor-beam” [1] or the “Delta-beam” [2] systems developed in Scandinavia, the “Ultra Shallow Floor Beam” [3] in the UK, or more recently shallow floor beams with small web openings (CoSFB) [4], where the composite action between steel and concrete is ensured by means of transverse reinforcing bars through the beam web openings.

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Due to the fact that the steel beam is totally embedded within the concrete floor, the fire behaviour of slim-floor beams is remarkable. Being exposed to fire only from their lower flange, in contrast with other types of composite beams not fully embedded within the concrete floor, slim-floor beams can achieve higher fire resistance times. Moreover, the SFB configuration presents the additional advantage in a fire situation of a thermal gap that appears between the lower flange of the steel profile and the bottom plate, which delays the temperature rise of the steel profile, as observed experimentally by Newman [3], Fellinger and Twilt [5] suggested that this thermal gap should be ensured when manufacturing SFB in order to enhance the slim-floor fire resistance.

A great number of experimental studies were carried out in the nineties on partially encased beams under fire conditions, but the study of slim-floor beams is more recent. In particular, the flexural behaviour of slim-floor beams exposed to fire has been studied in several experimental campaigns performed in recent years [6]. Two standard fire tests were conducted by the Warrington Fire Research Center [7] with a SLIMDECK system using an IFB configuration. Significant fire resistance times of 75 and 107 min were achieved for load ratios of 0.43 and 0.56, respectively. Fire tests were also reported by Ma and Mäkeläinen [6] using an IFB configuration under different load ratios. It was observed that fire resistance periods of over 60 min could only be reached for load ratios under 0.5 without additional fire protection.

Previous parametric studies carried out by the authors [8, 9] with a validated finite element model showed the improvement in terms of fire resistance which may be achieved with the SFB solution, as compared to an equivalent IFB configuration with the same load bearing capacity at room temperature or in terms of equal steel area. This numerical investigation confirmed that a good strategy for enhancing the fire resistance of composite beams embedded in floors is to split the lower steel flange into two steel plates. This solution creates a reduced but thermally significant gap between the lower flange and the bottom plate that delays the temperature rise and therefore lengthens the fire response of the beam.

2 Code provisions and available fire design methods

It is well known that the assessment of the load-bearing capacity of any structural member during a fire event requires three different models: the fire model, the heat transfer model and the mechanical model at elevated temperatures.

In the first instance, the fire model involves the thermal action definition, which may be represented by nominal time-temperature curves or more sophisticated natural fire models. Usually, for construction products, the fire model is defined simply through the standard time-temperature (ISO-834) curve, which is provided in EN 1991-1-2 [10].

Secondly, once the thermal action is defined, the heat transfer model should provide a way to calculate the temperature field within the cross-section. While simplified models are available in EN 1994-1-2 [11] to evaluate the temperature distribution for partially encased (Annex F) and non-encased (Clause 4.3.4.2.2) composite beams, this standard does not provide any simplified heat transfer model to evaluate the temperature field of slim-floor beams.

The third stage of the fire resistance assessment is the mechanical (bending) capacity calculation at elevated temperatures, which may be addressed by means of a fibre-based model by discretizing the cross-section into a finite number of differential strips (for which the realistic temperature gradient is first needed), or alternatively by dividing the cross-section into a number of zones with known temperatures, which allows the ultimate bending moment to be obtained by “hand calculation”.

In the absence of any specific method for assessing the temperature development in slim-floor beams, it is a common practice to apply the method in Annex F for partially encased composite beams with different assumptions, such as adopting an infinite width for the concrete part [12].

In this sense, different proposals have been developed during recent years in order to provide models that permit the prediction of the temperature field in slim-floor composite beams.

The first work worth mentioning is the model by Zaharia and Franssen [13]. This model provides detailed formulas, validated against SAFIR software, to obtain the temperature evolution of the main slim-floor beam cross-section parts. Specifically, the authors provide formulas for the assessment of the temperature at the bottom part (1), web profile and reinforcing bars (2) (Fig. 2).

\[ T = A \cdot t_{pl}^2 + B \cdot t_{pl} + C \]  

(1)

In this equation, \( t_{pl} \) is the bottom plate thickness in mm, \( T \) is the temperature of the bottom part and coefficients \( A, B \) and \( C \) are tabulated in [13] depending on the fire exposure time, as shown in Table 1.
The formulas for evaluating the temperature along the web of the steel profile and reinforcing bars show the following aspect:

\[ T = k \cdot e^{k'z} \]  

(2)

where \( z \) is the distance along the height of the web measured from the top of the bottom plate and \( k, k' \) are provided in [13] and depend on fire exposure time and bottom plate thickness.

It should be highlighted that these formulas were developed by taking into account the standard ISO-834 time-temperature curve as the thermal action. More details about the formulas described above, which could be useful for their practical application, can be found in [13].

More recently, Hanus et al. [14] developed an additional simplified formula for the temperature assessment of reinforcing bars. In this case, the formula was developed based on the temperature evolution within concrete slabs provided by EN 1992-1-2 [15], but including some corrections to take into account the possible horizontal heat flux in steel-deck composite floors.

From the literature review, it was noticed that the main emphasis of the developed thermal models is the prediction of the temperatures of the longitudinal reinforcing bars. In fact, different models exist for the temperature assessment of reinforcing bars, while for the bottom plate and web profile prediction the model from Zaharia and Franssen [13] is widely accepted. It should also be underlined that only steel parts are under evaluation in these simplified thermal models. The reason for this aspect comes from the fact that in the tension zone (i.e. the bottom part, when the cross-section is evaluated under sagging moment), only the steel parts contribute to the bending moment resistance. The tensile strength of concrete may be safely neglected. In turn, the compression zone, located in this case at the top part of the section, may be assumed to be unaffected by a fire in slim-floor beams exposed only from their lower surface.

As previously mentioned, the third model needed for slim-floor beam assessment during a fire is the mechanical model, which takes into account the evolution of the mechanical properties of steel and concrete at elevated temperatures. The reduction of strength and stiffness at elevated temperatures can be obtained from EN 1994-1-2 [11]. Different approaches may be used to address this mechanical calculation. The easiest consists of the evaluation of the plastic bending resistance by splitting the cross-section into different parts composed of different materials at different representative temperatures. The plastic neutral axis position is then evaluated by applying the corresponding equilibrium equations and in this way the bending moment resistance can be easily obtained. An example of this methodology is explained in the following section, where a worked example is used to illustrate its application.

### 3 Advanced models

A more precise approach to address the solution of the problem consists of the evaluation of the bending resistance through the cross-section discretization in cells (Fig. 3). Each cell of the mesh is characterized by its position and its temperature. Using the mechanical properties at elevated temperature, the plastic bending resistance of the cross-section can be computed by applying equilibrium equations. This methodology is very similar to that previously described, but in this case the finer discretization of the section permits a more accurate assessment. However, the drawback of this model is that simplified temperature formulas for different parts of the cross-section cannot be used in this case. Instead, a previous evaluation of the heat transfer problem by means of a finite differences model is needed to obtain a detailed temperature field with information about the temperatures of all the cross-section cells.

Additionally, the most sophisticated way to evaluate the thermo-mechanical behaviour of slim-floor beams is by means of finite element (FE) models. In recent investigations, some authors [16], [8] have developed detailed FE models, using the commercial package ABAQUS, where a sequentially coupled thermal-stress analysis is performed (Fig. 4). The first step consists of a thermal analysis to compute the temperature field. Secondly, the temperatures are imported into a mechanical FE model with the non-linear behaviour of the materials (steel and concrete) at elevated temperatures being taken into account. For concrete and steel, the temperature-dependent properties recommended in EN 1994-1-2 [11] were considered: specific heat and thermal conductivity. The upper thermal conductivity limit was used for concrete, which is
a safe assumption. Moreover, the mechanical properties at elevated temperatures (i.e. thermal elongation and strength reduction factors) were also considered. The stress-strain relationships for steel and concrete at elevated temperatures given in EN 1994-1-2 [11] were employed.

Additionally, it is also worth noticing that the cavity radiation model from ABAQUS was used to compute the heat transfer through the voids of the hollow core concrete slabs. This cavity model directly solves the calculation of view factors of all the element faces which adjoin the voids.

Through this type of model, other three-dimensional phenomena can be assessed, apart from the simple cross-section evaluation, such as the concrete cracking or the development of the composite effect between steel and concrete, as well as possibility of applying non-uniform heating conditions or taking into account the effect of the voids in the floor system in a more realistic way.

Now all the available models have been described, it is considered useful at this point to compare the validated FE model developed by authors [8] against the simplified temperature formulas developed by Zaharia and Franssen [13] and Hanus et al. [14]. Specifically, the bottom plate, the reinforcing bars and the web profile temperature evolution have been compared (Figs. 5, 6).

The developed FE model has been used to reproduce the thermal behaviour of a SFB cross-section made of an HEB200 profile welded to a bottom plate of 15 mm thickness (Fig. 7) exposed to the standard ISO-834 time-temperature curve. In this case, the thickness of the bottom steel part will be 30 mm at the central position (i.e. vertical axis of the profile) and 15 mm at the sides. The reinforcing bars are located 30 mm above the top face of the lower steel flange and at horizontal distance of 40 mm from the web of the steel profile.

The results of this comparison show that the bottom plate simplified formula developed by Zaharia and Franssen [13] provides accurate results when compared with the temperature at points T1 and T2 from the FE model (Fig. 5). The formula has been applied for 15 mm and 30 mm bottom plate thickness in order to take into account the influence of the thickness of the bottom plate. It should also be highlighted that point T3, placed in the lower flange, shows a significant lower temperature. The reason for this difference comes from the previously de-
The differences observed in the comparison of temperatures in the web of the steel profile may come from the fact that the previously described simplified formula [13] was developed for an IFB cross-section configuration. However, the developed model shows the temperature field of an SFB. Therefore, the thermal gap described above, which appears between bottom plate and lower flange, may affect the temperature evolution along the web of the steel profile. In any case, the simplified model provides higher temperatures than the FE model.

4 Worked example

In this section, a worked example is presented to illustrate the calculation of the bending capacity of slim-floor beams in case of fire. Specifically, the process to obtaining the sagging moment resistance at elevated temperature is detailed.

According to EN 1994-1-2 [11], the fire resistance of a structural member for a certain fire exposure time $t$ is verified by checking that:

$$E_{fi,d,t} \leq R_{fi,d,t}$$

where $E_{fi,d,t}$ is the design effect of the loads in the fire situation and $R_{fi,d,t}$ is the corresponding design resistance. This expression has to be verified for the relevant duration of fire exposure, which would be defined in the project for the structural member under evaluation.

This worked example is only focused on determining the design resistance of a slim-floor beam in the fire situation $R_{fi,d,t}$. The effect of the loads under fire conditions $E_{fi,d,t}$ depends on other project aspects which are outside the scope of this analysis.

Although it can only be achieved with lower load ratios, the fire exposure time in this worked example is considered as 120 min of standard time-temperature curve. The procedure would be exactly equal for other exposure times.

Once the general context of the analysis has been defined, the assessment of the slim-floor beam fire resistance is focused on the evaluation of the sagging bending moment capacity after 120 min, $R_{fi,d,t} = M_{fi,Rd,120}$.

The section analysed in this worked example is an SFB configuration composed of a HEB200 steel profile welded to a bottom plate of 15 mm thickness. Cross-sectional details are shown in Fig. 7.

In this example, the following values for the material strengths are considered:

- Steel profile and bottom plate: $f_y = 355$ MPa
- Concrete: $f_c = 50$ MPa
- Reinforcing bars: $f_s = 500$ MPa
To begin the calculation process, the temperature of each cross-section part should be determined in the first instance. For this purpose, the simplified model from Zaharia and Franssen [13] is used. Additionally, the model from Hanus et al. [14] is also applied to obtain the temperature of the reinforcing bars. In this calculation, any positive effect of the thermal gap between bottom plate and lower flange is neglected.

Specifically, the slim-floor beam cross-section is divided into 8 parts (Fig. 8). Part 1 considers the lower flange of the steel profile and a portion of the bottom plate with the same width. Therefore, the thickness of part 1 is 30 mm in this example. In turn, part 2 comprises the rest of the bottom plate, which is 15 mm thick.

Regarding the web of the steel profile, it is divided into two parts: part 3, where the temperature remains over 400 °C after 120 min of standard fire exposure, and part 4, which is below 400 °C. This temperature limit is defined based on the fact that the structural steel yield strength is unaffected under 400 °C according to EN 1994-1-2 [11]. The 400 °C isotherm (s. Fig. 8) is located 100 mm above the lower flange of the steel profile according to the simplified model of Zaharia and Franssen [13] (eq. 2).

Finally, part 5 is the upper flange of the steel profile, while part 6 is the top concrete compression zone and the part denoted as <R> comprises the longitudinal reinforcing bars embedded in concrete.

Once each cross-section part temperature – θ (°C) – has been obtained from the previously described simplified models [13, 14] (Table 2), the corresponding strength reduction factor \( k_\theta \) can be obtained from EN 1994-1-2 [11].

By doing so, the resultant force at elevated temperature for each cross-section part can be calculated as follows:

\[
F_{i\theta} = A_i k_\theta f_y
\]

It should be highlighted that the Zaharia and Franssen model [13], as was described in previous section, provides specific temperature values for bottom plate and reinforcing bars. However, the web profile temperature is provided as a temperature function along the web. In this case, the temperature for the part 3, the web over 400 °C, was assumed as the average value of this temperature evolution.

The plastic neutral axis position can be obtained by using the equilibrium equation:
The sagging plastic bending moment at elevated temperature can be calculated by multiplying the resultant force of each part times the distance \( z_i \) of its centroid measured from the bottom face.

\[
M_{L,Rd,120} = \sum F_{i,\theta} = 118.9 \text{ kN}\cdot\text{m}
\]

Additionally, the result obtained above can be compared with the advanced model developed by the authors, explained in detail in the previous section. Alternatively, Fig. 9 shows the cross-sectional temperature field obtained by means of the finite element model. The computed stress distribution at elevated temperature is also indicated.

The sagging plastic bending moment obtained by means of the developed finite element model is 133.2 kNm, differing only by 9% from the result obtained by applying the simplified calculation method. The prediction of the simplified thermal model lies on the safe side, as the value obtained by hand calculation produces results lower than the more accurate one provided by the numerical model. The explanation of this safer response is attributed to

\[
\sum F_{i,\theta} \leq 0
\]
It can be noticed (Fig. 10) that even with a dramatic increment of the reinforcing bar diameter (note that a 32 mm diameter is not common in practice), the fire resistance for moderate load ratios cannot achieve more than 90 min. Therefore, new innovative solutions should be developed to reach a further increase of fire resistance.

5 Current trends and future research

Following the worked example presented above and the description of the available models explained in previous sections, this part intends to summarize current knowledge of the fire performance of slim-floor beams in order to help practitioners with future design work. These guidelines are related to aspects like an improved cross-section configuration to improve the composite beam fire resistance or the advisable use of advanced materials such as stainless steel or lightweight concrete.

5.1 Thermal Gap

The thermal gap, described previously for SFB, works as an insulation barrier to the heat flow conducted upwards along the web profile from the lower exposed surface. The thermal contact conductance, which appears at the contact interface between different materials or cross-section members, is a well-known phenomenon [19] that has been already studied in other structural elements like concrete-filled steel tubular (CFST) columns [20]. Recent experimental tests were also carried out by the authors [9] in the testing facilities of Universitat Politècnica de València, Spain, as part of a wider experimental campaign currently underway. These tests provided evidence of the different thermal behaviour between SFB and IFB due to the thermal contact resistance in the gap between the bottom plate and lower flange, proving the previous findings (Fig. 11).
5.2 High Strength Steel

Advanced materials such as high strength steel (HSS) may be used to further increase the fire performance of slim-floor beams. Previous research work [21] has shown that in case high strength steel is used, it should be reserved for the steel profile rather than in the bottom plate (Fig. 12). Its use in the bottom plate does not provide a significant increase of the bending resistance, as it is directly exposed to fire and thus its strength is rapidly affected by high temperatures. Fig. 12 shows the evolution of the bending capacity under a standard fire for different locations of HSS in the SFB cross-section (Plate – Profile), supporting the previous findings.

5.3 Lightweight Concrete

The use of lightweight concrete in the slim-floor beam encasement has been also assessed in previous investigations [9] concluding that, for this typology of composite beam, the advantage provided by this type of concrete depends on the degree of reinforcement. The lower thermal conductivity of lightweight concrete and its consequent delay of the temperature rise in the concrete mass cause a localized temperature increase in the bottom steel plate and thus a reduction of its contribution to the bending moment capacity. In turn, lightweight concrete provides additional heat insulation for the reinforcing bars and therefore increases their mechanical contribution in case of fire. Thus, in shallow floor beams configurations where the amount of reinforcement is significant, the additional protection offered by lightweight concrete may counteract the unfavourable effect of the reduction of strength of the bottom plate and help increasing the total bending capacity of the cross-section in fire.

5.4 Stainless Steel

The performance of stainless steel under fire conditions has been assessed with extensive research in recent years [22, 23], showing better strength retention at elevated temperatures and lower emissivity, which can delay the cross-section heating. Therefore, it seems a favourable material to use in the bottom plate of slim-floor beams [24]. Apart from a better fire performance, it also provides improved durability and an aesthetic finishing to the ceiling.

5.5 Composite action

Finally, it should be highlighted that the composite action in slim-floor beams during a fire may be guaranteed provided that sufficient shear connectors are placed in the cool cross-section zone. For instance, shear studs welded to the upper flange of the steel profile would be in a good position to be protected from fire action. Additionally, when slim-floor beams are used supporting precast units, the local bending moment of the bottom plate, which works as a cantilever in the transverse direction, should be checked. Specific reinforcing tie bars should be provided in the concrete encasement so as to work in the transverse direction.

6 Concluding remarks

The fire behaviour of slim-floor beams has been reviewed in this paper, showing that such composite beams provide good performance in the event of a fire. Specifically, current slim-floor beam configurations can achieve 60 min of standard time-temperature curve exposure with a load level lower than 0.5–0.6. It has been noticed that reaching the goal of 90 or even 120 min of fire exposure with these load levels may require the use of advanced materials such as stainless steel at the exposed bottom plate of HSS at the inner profile, or alternatively increasing the reinforcing bars diameter or using external fire protection.

Moreover, it has been highlighted in this work that based on previous studies available in the literature, the SFB configuration can provide a better fire performance than IFB due to the thermal gap which appears between bottom plate and steel profile lower flange. Some authors have even suggested that this gap should be ensured during manufacture of the steel beam.

Finally, from the assessment of the current design guidelines, it has been concluded that application of the simplified formulas developed by Zaharia and Franssen [13] and Hanus et al. [14] provide accurate temperature results, higher than those from advanced FE models. Therefore they should be recommended in practice to predict the cross-sectional temperatures of slim-floor beams exposed to the standard ISO-834 time-temperature curve. However, it should be noted that these equations are no longer valid when external protection is used.
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