FIRE DESIGN OF A NEW SLIM FLOOR BEAM SYSTEM USING FEM-ANALYSIS

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ABSTRACT

This paper deals with the application of general calculation models in structural fire design. Computer simulations enable new possibilities in assessing fire resistance of load bearing composite members.

The finite element modelling of the heating and its effects on the load bearing capacity are demonstrated and discussed via the example of a new slim floor beam system. The cross section features a cavity and special regard is paid to the modelling of heat transfer by radiation in this cavity. Typical pitfalls are regarded and checking methods are suggested. The influences of several parameters are studied and an evaluation of these parameters has been worked out.

It will be demonstrated that the radiative heat transfer in the cavity is of significant influence on the temperature development and as a consequence on the load bearing capacity of the cross section. Neglecting the radiation in the cavity can be conservative or unsafe depending on the fire duration. The effects of possible future modifications in the Eurocodes are presented, concerning the surface emissivity of the member.

KEYWORDS

Fire design, composite structure, slim floor beam, FEM, fire resistance, Eurocodes, configuration factor, cavity radiation

INTRODUCTION

In the past, the fire resistance of load carrying members was determined only by tests. The test conditions referred to the standard fire tests. In the last two decades, computer models have been developed for the simulation of structural members and even global structures exposed to fire. The improvements concerning numerical methods were forced particularly by research work on composite steel and concrete structures.
This development may also be recognised in the "hot Eurocodes". Thus, the assessment of structural behaviour in a fire design situation according to Eurocode 4 Part 1-2 [8] (EC4-1-2) shall be based on one of the following approaches:

- level 1:
  recognised design solutions called tabular data for specific types of structural members,
- level 2:
  simple calculation models for specific types of structural members,
- level 3:
  general calculation models to simulate the behaviour of the global structure, of parts of the structure or only of a structural member.

Only in those cases where none of the above mentioned approaches is applicable, it is necessary to use a method based on test results.
Up to now, general calculation models for practitioners are less important than tabular data or simple calculation models. There are two main reasons for this. First, the use of sophisticated computer programs requires a high level of education and training. The second reason is that even if these conditions are fulfilled, the application of general calculation models is costly. Thus, general calculation models are mainly used to develop tabular data or simple calculation models. On the other hand the cost of general calculation models are less than that of fire tests, so that computer simulation supersedes more and more traditional fire tests for structural fire design.
In the following, as an example for the application of general calculation models, the finite element modelling of a new slim floor beam system is presented.

GENERAL CALCULATION MODELS

The basic requirements for general calculation models are written down in the "hot Eurocodes" [4,6,8]. Generally these calculation models comprise adequate numerical models for both the thermal and the mechanical response under the action of fire. An important improvement was the definition of temperature-dependent material properties of structural steel, reinforcement steel and concrete in the Eurocodes. According to the new European codes, general calculation models may be used for individual members, for subassemblies or for entire structures. The numerical analyses presented in this contribution are carried out with the finite element computer program ABAQUS®.
Verification of the programme for heat transfer analysis has been carried out, using the evaluation scheme presented in [11].

MODELLING OF A NEW SLIM FLOOR BEAM CROSS-SECTION

General

Kuhlmann & Fries & Leukart [10] designed a new single span slim-floor beam for multi-storey buildings with spans up to 10 m. The development was initialised and supported by the German steel producer Salzgitter AG. The cross section comprises a two-part, welded steel section connected to the concrete slab by shear stud connectors. The steel section is assembled welding a U-profile to a steel plate by a fillet weld, so that it forms the shape of a hat. Therefore this beam is called hat-profile.
Both, the cold and the fire design of this beam, has been performed on the basis of the Eurocodes. A level-3 method (general calculation model) was applied to calculate the temperature distributions in the beam cross section. The calculation of the load bearing capacity was based on these temperature distributions using a level-2 method. The authors were involved checking the results of the calculation.
First, the temperature distribution in the cross section was calculated at different standard fire durations (ISO-fire): 30, 60, 90 and 120 minutes. Second the plastic bending moment M_{pl} and the shear resistance V_{pl} of the composite beam was calculated, considering the reduction of strength caused by elevated temperatures. A detailed discussion is given further on. At the end, a series of more than 100 sections has been studied. Figure 5 shows the example presented in this report.

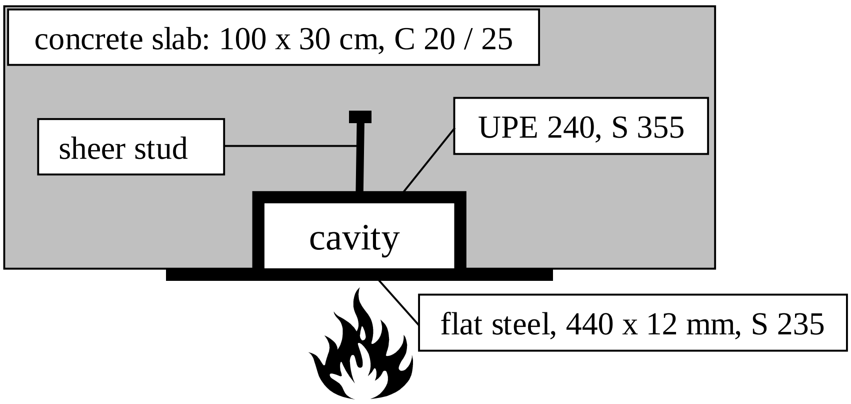


Figure 1:
Cross section of the slim-floor composite beam

Thermal analysis

The temperature dependant thermal material properties like specific heat, thermal conductivity and mass density of steel and concrete was implemented according to the Eurocodes. To produce conservative results moisture content of the concrete was neglected. In order to satisfy German building regulations the German National Application Documents for the Eurocodes [5,7,9] had to be considered.
To analyse the heat transfer the calculations were performed with a two dimensional model of the cross section. Four-node linear solid elements (DC2D4) were applied. Figure 2 shows the FEM-mesh of the model.

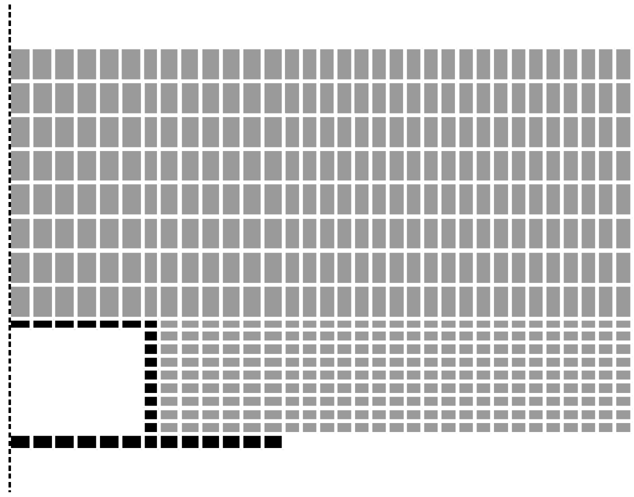


Figure 2:
FEM-mesh of the cross-section used in the ABAQUS® analysis

The axial symmetry was used to reduce the number of elements so that only one half of the cross section was modelled. Normal to the symmetry axis no heat is transferred. Therefore adiabatic boundary conditions were applied on the vertical borders of the model. To model the heat transfer by radiation a special radiation symmetry boundary condition was used, which is discussed later on. Special attention was paid to the heat transfer within the cavity and the effect on the heating process of the beam section.
On the fire-exposed underside of the section the heat transfer due to convection and radiation had to be considered. For the fire-exposed steel and concrete surfaces the emissivity is

$$\varepsilon_{res} = 0.56 \tag{1}$$

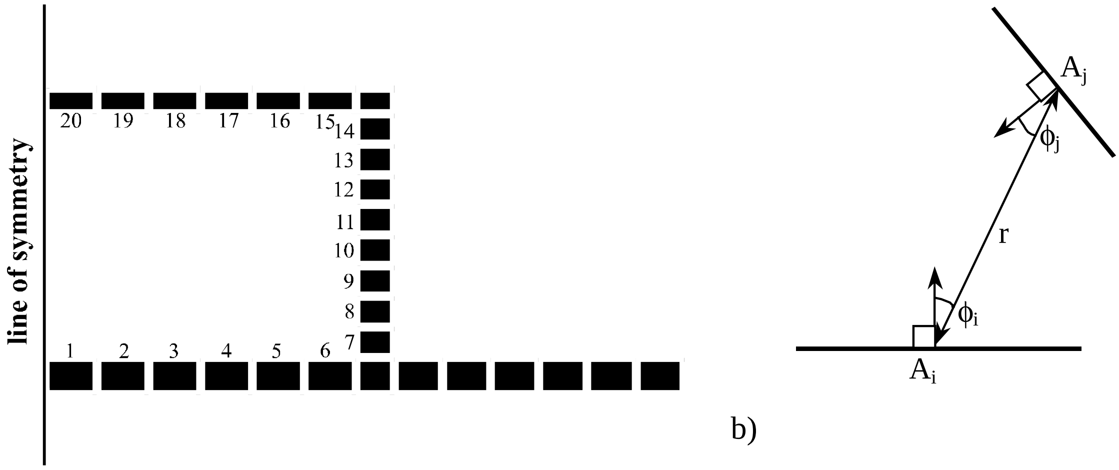
for the fire-exposed steel and concrete surfaces corresponding to Eurocode 1 Part 2-2 (EC1-2-2) and EC4-1-2. And the convective heat transfer coefficient is

$$\alpha_c = 25\ \mathrm{W/(m^2K)}. \tag{2}$$

According to EC1-2-2 a convective heat transfer coefficient of

$$\alpha_c = 9\ \mathrm{W/(m^2K)} \tag{3}$$

on the unexposed top of the slab is assumed. The heat flow due to radiation has been neglected on this side. The studies showed, that in this case the heat loss at the unexposed slab side is of minor influence and an adiabatic boundary condition on the upper edge of the slab could have been applied.
Heat transfer by radiation between the interior surfaces was calculated. The value of $\varepsilon_{res} = 0.56$ is also assumed for the interior surfaces of the steel section which are not directly exposed to fire.



a)

b)

Figure 3:
a) Numbering of the surfaces composing the cavity
b) Radiative heat transfer between two surfaces

The thermal conductivity of the air and the heat transfer by convection in the cavity was neglected.
Cavity radiation is active when surfaces of the model can "see" each other, see Figure 3a). Such heat exchange depends on viewfactors that measure the relative interaction between the surfaces composing the cavity. The viewfactor F_{ij} between two surfaces A_i an A_j, see Figure 3b), is calculated as

$$F_{ij} = \int_i \int_j \frac{\cos\phi_i \cos\phi_j}{\pi r^2} dA_i dA_j, \quad F_{ij} = F_{ji}, \tag{4}$$

where r is the distance between the two areas and ϕ_i, ϕ_j are the angles between r and the normals to the surfaces of the areas. The viewfactor is a purely geometrical quantity. The symmetry line acts like a mirror, so that a radiation symmetry boundary condition could be implemented. In an ABAQUS® analysis the configuration factor is calculated and used specifying the radiative heat leaving the emitting surface and the radiative heat arriving at the receiving surface. According to ECCS Model code on Fire engineering [2] the configuration factor is calculated as

$$\Phi_{ij} = \frac{1}{A_i} F_{ij}, \quad \Phi_{ij} \neq \Phi_{ji}. \tag{5}$$

By definition, the configuration factor is between zero and unity. The configuration factors of the system are written in a matrix. In this example there are 20 surfaces composing the cavity, see Figure 3a), which leads to a 20 x 20 configuration factor matrix. This matrix can be used to control the accuracy of configuration factor calculation. In a completely enclosed cavity any ray from surface A_i in whatever direction it leaves the surface will reach another surface. Therefore the sum of each line in the matrix must be 1:

$$\sum_j \Phi_{ij} = \frac{1}{A_i} \sum_j F_{ij} = 1 \tag{6}$$

and the total sum of all lines must be the number of elementary surfaces composing the cavity, which in this example is 20.
The matrix of viewfactors (Equation 4) can be calculated from the configuration factor matrix using Equation 5 by multiplying the values in each line with the corresponding elementary surface area A_i. The resulting matrix must be symmetric, see also Equation 4.
The influence of heat transfer in the cavity is shown in Figure 4. The heating curves of the top and the bottom flange of the hat-profile are compared. The black curves show the results with and the grey curves without cavity radiation. Figure 5 illustrates the temperature gradients in the beam cross section without (a, c) and with cavity radiation (b, d) for fire duration of 30 and 90 minutes.

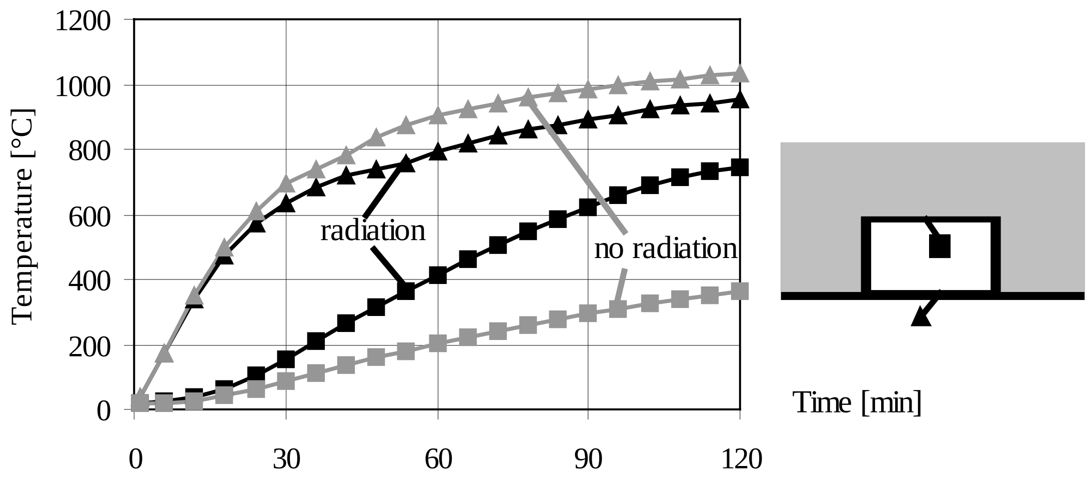
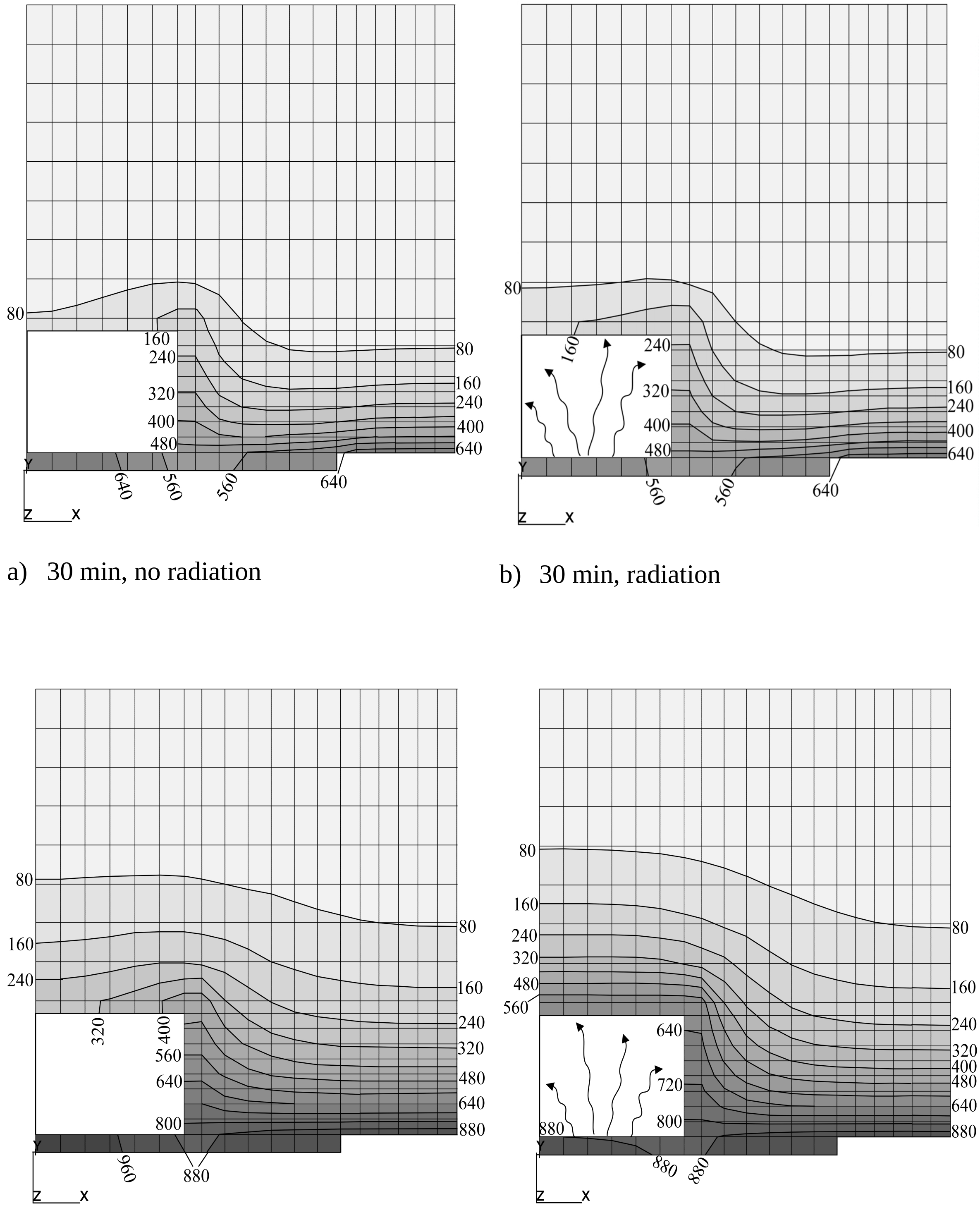


Figure 4:
Comparison of the heating curves of the bottom an the top flange of the steel section with (black) and without (grey) cavity radiation

The effect of different assumptions concerning the radiation in the cavity is limited to the local area of the steel section. The concrete temperatures differ only marginally. As shown in Figure 4 the cavity radiation leads to dramatic higher temperatures in the top flange (black square) and lower temperatures in the bottom flange (black triangle). The different heating of the member causes a different performance of the load bearing capacity. This effect is discussed in detail in the following section.

Calculation of the load bearing capacity

Plastic theory has been used to determine the load bearing capacity. A level 2 approach was applied to calculate the bending and shear resistance. The temperature distributions were analysed using a self-made post-processing tool. The basis for the calculations are the temperature dependent mechanical material properties according to EC4-1-2 [8]. The calculation tool consists of a spreadsheet programmed in MS Excel®. The mean values of nodal temperatures related to each element are calculated and used to specify the temperature reduction factors k_θ for the material strength.



a) 30 min, no radiation

b) 30 min, radiation

c) 90 min, no radiation

d) 90 min, radiation

Figure 5:
Temperature gradient in °C in the beam cross section
without (a, c) and with cavity radiation (b, d)

The plastic neutral axis is determined from

$$\sum_{a=1}^{n} A_a k_{max,\theta,a} \frac{f_{y,a}}{\gamma_{M;fi}} + 0.8 \sum_{l=1}^{m} A_l k_{c,\theta,l} \frac{f_{c,20,l}}{\gamma_{M,fi,c}} = 0\,, \tag{7}$$

where:

A_a, A_l	are the elemental areas in the steel and concrete parts of the cross section.
$k_{max,\theta,a}$	is the reduction factor for the yield strength of steel related to the steel elemental area A_a.
$k_{c,\theta,l}$	is the reduction factor for the compressive strength of concrete related to the concrete elemental area A_l.
$f_{y,a}$	is the nominal yield strength f_y for the elemental steel area A_a and
$f_{c,20,l}$	the design strength $f_{c,20,}$ of concrete at a temperature of 20°C for the elemental concrete area A_l. For concrete parts A_l tension is ignored.
$\gamma_{M,fi}$, $\gamma_{M,fi,c}$	are the partial safety factors for the material strength of steel and concrete in the fire design situation ($\gamma_{M,fi}$, = $\gamma_{M,fi,c}$. = 1.0).

The coefficient 0.8 is an additional reduction factor for the compressive strength of concrete. It is applied when calculating the bending moment capacity of composite slabs, using stress blocks without limiting the concrete strains. The plastic bending moment resistance is determined from

$$M_{fi,t,Rd} = \sum_{a=1}^{n} A_a z_a k_{max,\theta,a} \frac{f_{y,a}}{\gamma_{M,fi}} + 0.8 \sum_{l=1}^{m} A_l z_l k_{c,\theta,l} \frac{f_{c,20,l}}{\gamma_{M,fi,c}}\,, \tag{8}$$

where z_a and z_l are the moment arms of the steel and concrete elemental areas, measured from the centroids of the elemental areas. Only the vertical parts of the steel cross section forming the two webs are considered to calculate the transverse shear resistance of the beam:

$$V_{fi,t,Rd} = \sum_{a=1}^{n} A_a k_{max,\theta,a} \frac{f_{y,a}}{\gamma_{M,fi}\sqrt{3}}\,. \tag{9}$$

Table 1 shows the plastic load bearing capacities according to different fire resistance classes. It demonstrates clearly, that neglecting the radiation effect leads to unsafe results, in spite of higher temperatures in the bottom flange.

TABLE 1:

CALCULATED PLASTIC BENDING AND SHEAR RESISTANCE
WITH CAVITY RADIATION TAKEN INTO ACCOUNT
AN WITHOUT CAVITY RADIATION

			Fire duration [min]				
			0	30	60	90	120
radiation	$V_{fi,t,Rd}$	[kN]	434	421	255	103	49
	$M_{fi,t,Rd}$	[kNm]	498	393	252	125	65
no radiation	$V_{fi,t,Rd}$	[kN]	434	421	306	194	129
	$M_{fi,t,Rd}$	[kNm]	498	389	265	212	182

The influence of cavity radiation increases with higher fire resistance classes. This performance is explained regarding the temperature gradients in Figure 5. After a fire exposure of 30 minutes the temperature in the bottom flange without cavity radiation is higher than that with cavity radiation (see also Figure 4), because there is no heat loss due to radiation. At this time the material strength of the bottom flange is of significant influence on the plastic bending resistance of the beam section. The influence of temperature and material strength of the top flange is not so important because the moment arm of the corresponding force is small compared to that of the bottom flange. Because of the lower temperatures in the bottom flange, the plastic bending moment capacity resulting from the calculation with cavity radiation taken into account is a little bit higher than calculated without cavity radiation (see Figure 6). For a fire exposure of 30 minutes neglecting the influence of cavity radiation produces conservative results.

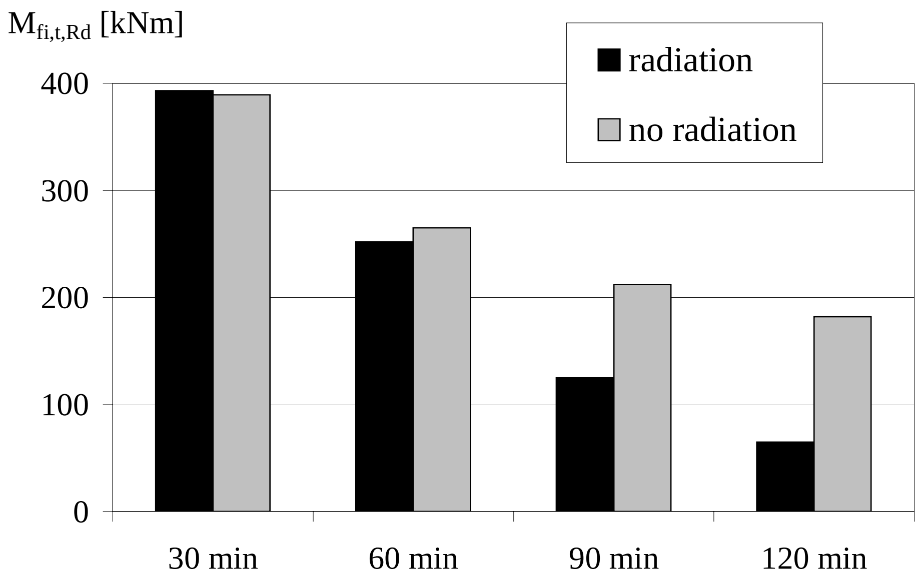


Figure 6:
Comparison between the calculated plastic bending resistance
with and without cavity radiation

The situation changes completely after 90 minutes of fire exposure. In both cases, with and without cavity radiation, the bottom flange has reached high temperatures and the material strength is reduced strongly. Therefore the strength of the bottom flange is of minor influence on the bending capacity. Now the temperature reduced material strength of the top flange is responsible for the bending resistance of the beam section. The plastic bending moment capacity calculated with cavity radiation is about 60 % of that calculated, neglecting the effect of radiation. The effect is even stronger for a fire exposure of 120 minutes. Neglect of radiation in the cavity leads to higher calculated resistance and therefore is unsafe for higher fire resistance classes.
Further calculations with cavity radiation were carried out to quantify the influence of the emissivity ε_{res} on the load bearing capacity. In one calculation the emissivity of the fire exposed surfaces and the interior surfaces of the cavity were increased to $\varepsilon_{res} = 0.70$ and in another case the emissivity was $\varepsilon_{res} = 0.80$. The second assumption corresponds to a new proposal discussed in the project team of Eurocode 4 part 1-2. Figure 7 shows a comparison of the resulting plastic bending moment resistance. It is obvious, that a higher emissivity leads to higher temperatures and as a consequence to lower load bearing capacities. For a fire duration of 30 minutes and an emissivity of $\varepsilon_{res} = 0.80$ the plastic bending moment resistance is

reduced to 88 % of the value calculated with $\varepsilon_{res} = 0.56$. The reduction is even stronger for higher fire durations. For instance after 90 minutes the bending moment capacity is reduced to 66 %.

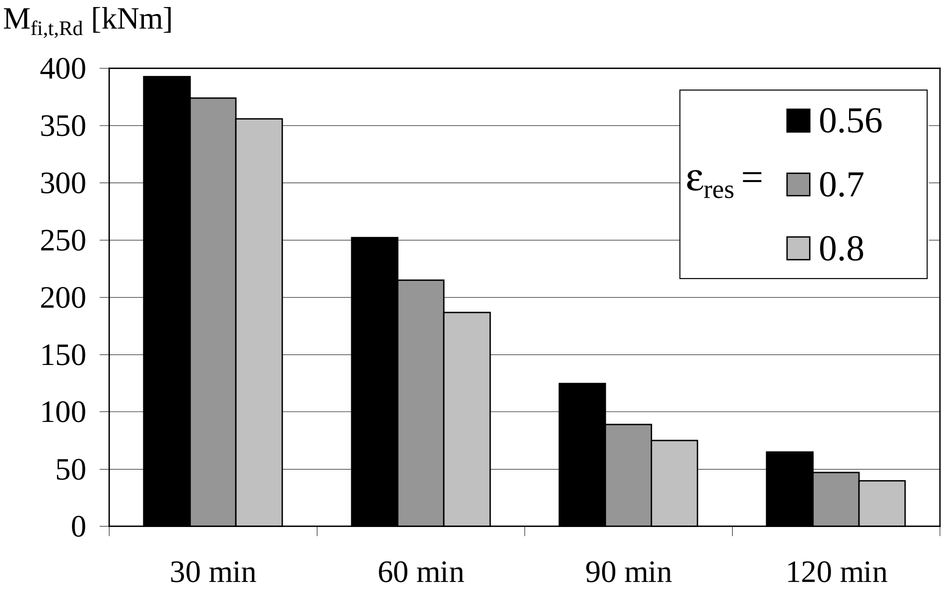


Figure 7:
Comparison of the plastic bending moment resistance resulting from different assumptions for the emissivity ε_{res}

In general the demand for a higher value of emissivity results in more restrict requirements of the members, especially for higher fire resistance classes. It should be mentioned, that using the same value of emissivity for the interior surfaces as for the surfaces directly exposed to fire, is only an assumption. There is no regulation in the Eurocodes concerning this subject. Anyway it would be difficult to find a value for the emissivity in cavities, which is conservative for all possible types of applications. As shown in the example of Figure 6, considering the radiation in a cavity can be conservative or unsafe, depending on the duration of fire exposure.

Another aspect of the studies was to identify out the influence of different steel grades used for the UPE-profile and the flat steel to assemble the hat-profile. Three additional sections were studied supplementary to the section presented in Figure 1 (section 1). Based on this cross section only the steel grades were modified (see Table 2). Cavity radiation was considered with $\varepsilon_{res} = 0.56$. Table 2 illustrates that higher steel grades (especially for the flat steel forming the lower flange) lead to higher bending moment capacities at ambient temperatures.

TABLE 2:
STEEL CROSS SECTIONSAND BENDING MOMENT RESISTANCE
AT AMBIENT TEMPERATURES

	UPE-profile	Flat steel	$M_{fi,Rd,0}$ [kNm]
section 1	S 355	S 235	498
section 2	S 235	S 235	451
section 3	S 235	S 355	543
section 4	S 355	S 355	572

Figure 8 shows the bending moment resistances of the different sections under fire conditions. For a comparison, the bending moment resistances are given in % of the corresponding values at ambient temperature.

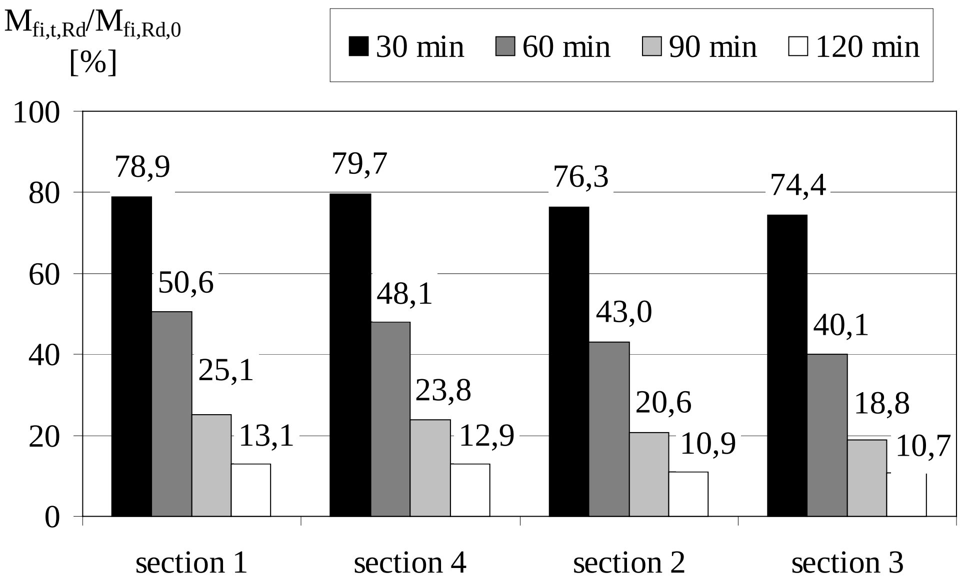


Figure 8:
Bending moment resistance for different fire duration in % of the corresponding values at ambient temperature

Regarding the remaining bending moment resistance after certain duration of fire exposure, section 1 with a steel grade S 355 for the UPE-profile and an S 235 for the directly fire-exposed flat steel, shows the best performance. Section 4 with S 355 for both, the UPE-profile and the flat steel, ranges on the second position. This counts for all studied duration of fire exposure except 30 minutes. Compared to section 1 in section 3 the steel grades are inverted and now the directly fire-exposed flat steel has the higher steel grade. This leads to worse performance of section 3 compared to that of section one. This study shows that, concerning the bending moment capacity, a hat profile featuring a lower steel grade for the directly fire-exposed lower flange, shows a better performance in case of fire.

CONCLUSION

This paper deals with the application of general calculation models in structural fire design. Computer simulations enable new possibilities in assessing fire resistance of load bearing composite members.
The finite element modelling of the heating and its effects on the load bearing capacity of a new slim floor beam system are demonstrated and discussed. The cross section features a cavity and the radiative heat transfer in this cavity is of significant influence on the temperature development and as a consequence, on the load bearing capacity of the cross section. The emissivity of such cavity surfaces which are not directly exposed to fire is not regulated by the Eurocodes. In the presented example the same emissivity as for the directly fire exposed surfaces was assumed for the interior surfaces of the cavity. The calculations showed, that it would be difficult to find a value for the emissivity in cavities which is conservative for all possible types of applications. Neglecting the radiation in the cavity can be conserva-

tive or unsafe depending on the fire duration.
In general the demand for a higher value of the emissivity of fire exposed surfaces results in more restrict requirements of the members, especially for higher fire resistance classes.

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