Characterization of Fire Protection Materials of Steel Elements - Sensitivity Study of a Simplified Assessment Method

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ABSTRACT

The use of calculation methods for verifying the fire resistance of insulated metal (steel or aluminium) structures requires data on the thermal properties of fire protection materials. A testing methodology has been developed within CEN TC 127 "fire in buildings" and one of the possible assessment methods provides a method for deriving the thermal conductivity of protection materials from fire test results performed on insulated sections.
To check the accuracy of this assessment method, a theoretical study has been carried out using products with well-defined material properties.
It was found that the thermal conductivity obtained by this assessment method is slightly different from the "measured" values, and a better consistency between calculated and experimental data could be reached by improving the definition of the section factor and using a corrected thickness for fire protection materials.
KEYWORDS
Fire resistance, structural behaviour, steel structure, fire protection, protection material, testing standard, Eurocode, calculation method.

1. INTRODUCTION

Within the standard prENV YYY5-4 developed by CEN/TC 127 [1] a testing methodology for fire protection of steel elements is given as well as 4 possible assessment methods of the test results to characterise fire protection materials.

Two of these assessment methods are based on the differential equation given in Eurocode 3 - part 1.2 (structural fire design of steel structure) [2], and originally used in Sweden [3,4] for calculating the temperature of insulated steel section, when exposed to fire:

$$\Delta\theta_{a,t} = \frac{\lambda_p A_p/V}{d_p c_a \rho_a} \frac{(\theta_{g,t} - \theta_{a,t})}{(1+\phi/3)} \Delta t - (e^{\phi/10} - 1)\Delta\theta_{g,t} \qquad (1)$$

with:

$$\phi = \frac{c_p \rho_p}{c_a \rho_a} d_p A_p/V$$

where :

$\Delta\theta_{a,t}$	steel temperature increase	[K]
A_p/V	section factor	[m^{-1}]
c_a	specific heat of steel	[J/kgK]
c_p	specific heat of the fire protection material	[J/kgK]
d_p	thickness of the fire protection material	[m]
Δt	time step	[s]
$\theta_{a,t}$	steel temperature at time t	[°C]
$\theta_{g,t}$	ambient gas temperature at time t	[°C]
$\Delta\theta_{g,t}$	increase of the ambient gas temperature during the time step Δt	[K]
λ_p	thermal conductivity of the fire protection material	[W/mK]
ρ_a	unit mass of steel	[kg/m^3]
ρ_p	unit mass of the fire protection material	[kg/m^3]

From test results giving ambient gas temperature and steel section temperature as a function of time, one of the assessment method (annex G of prENV YYY5-4 [1]) allows, using the above formula, the calculation of the thermal conductivity of fire protection materials as a function of temperature.

However, with contour protection (figure 1-a), this differential equation is a rough estimation of a one-dimensional heat transfer mechanism to an insulated steel section. The estimation is more important with box protection (figure 1-b) in which air gaps exist between the protection material and some parts of the insulated section. This clearly leads to some errors when determining the thermal characteristics of a protection material from experimental time-temperature relationships.

FIGURE 1 : Contour (a) and box (b) protection of steel sections

However, it is difficult to quantify these errors since there are a number of uncertainties in the experimental results. For instance, with sprayed materials on contour protection, the density may not be uniform, the thickness varies, the moisture content of the material is not homogeneous [5].

In order to eliminate uncertainties due to experimental data and to quantify the scatter due to the differential equation itself and to have a better estimation of the limits of this calculation method, a theoretical study based on numerical simulations for representative fire protection materials has been made [6].

This study has been carried out with 4 different parts :

a. Representative thermal characteristics for several insulation materials have been chosen.
b. The time-temperature relationships of steel sections protected by each insulation material is calculated using a numerical model based on 2D-finite elements, when exposed to the standard fire.
c. The derived time-temperature relationships have been used as input data to calculate the "effective" thermal conductivity of the chosen materials and the results have been compared with the initial thermal characteristics.
d. The influence of some relevant parameters has been analysed in order to have better consistency between initial and calculated thermal characteristics.

The main results of this study are as follows.

2. THERMAL CHARACTERISTICS OF INSULATION MATERIALS

Four different fire protection materials have been chosen. In each case the density chosen is 0.35.

The thermal characteristics of protection materials were selected in order to cover a wide range of application. These are (see figure 2 and 3):

Case 1

- thermal conductivity is constant as a function of the temperature of the insulation : λ_p = 0.13 W/m.K,
- specific heat is constant as a function of the temperature of the insulation : C_p = 1 000 J/kg.K.

Case 2

- thermal conductivity varies linearly as a function of the temperature between 100°C (λ_p = 0.05 W/m.K) and 900°C (λ_p = 0.21 W/m.K) and is constant before and after this range of temperatures.
- specific heat is constant as a function of the temperature : C_p = 1 000 J/kg.K.

Case 3

- thermal conductivity varies linearly as a function of the temperature (see case 2).
- specific heat varies linearly as a function of the temperature between 100°C (C_p = 800 J/kg.K) and 900°C (C_p = 1 200 J/kg.K).

Case 4

- thermal conductivity has a parabolic variation as a function of the temperature between 100°C (λ_p = 0.05 W/m.K) and 900°C (λ_p = 0.20 W/m.K) with intermediary values of 0.07 at 500°C, 0.08 at 700°C and 0.12 at 800°C and is constant before 100°C and after 900°C.
- specific heat varies linearly as a function of the temperature as for case 3.

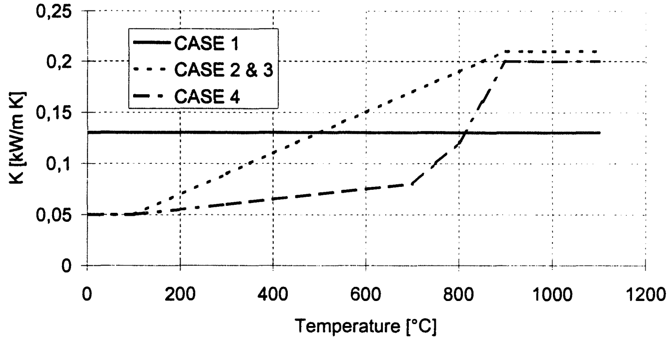

FIGURE 2 : Thermal conductivity for finite element calculations

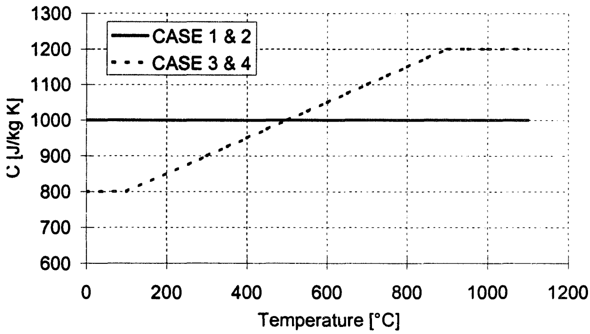

FIGURE 3 : Specific heat for finite element calculations

3. TEMPERATURE-TIME RELATIONSHIPS OF STEEL SECTIONS

In the testing methodology [1] experimental data have to be obtained for 10 different sections insulated by various thickness of protection material (table 1).

TABLE 1 : Data needed for assessment

THICKNESS OF PROTECTION	SECTIONS					
	HEM 280	*HEB 450*	*HEB 300*	*HEA 300*	*HEA 200*	*IPE 200*
Minimum	X		X	X	X	
Medium	X					X
Maximum		X		X	X	X

It was assumed that minimum thickness is 20 mm of protection, maximum thickness is 60 mm and consequently mid thickness is 40 mm.

According to the thermal properties given above and with the use of a 2D-finite element software [7], the temperature-time curves of these 10 insulated steel sections were calculated.

From the calculation results, the average temperature of steel sections obtained in similar to the test results i.e. equal to (4 * temperature of flange + 1*temperature of web) / 5

The results of the average temperature of the 10 steel sections for the thermal properties described in cases 1 and 4 are given in figures 4 and 5.

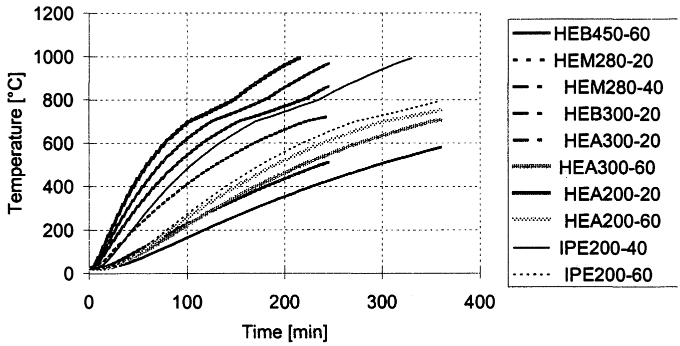

FIGURE 4 : Average steel temperatures obtained by calculation – Material case 1

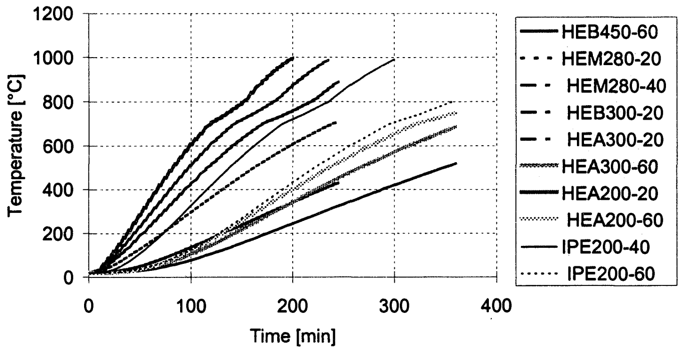

FIGURE 5 : Average steel temperatures obtained by calculation – Material case 4

4. ASSESSMENT OF RESULTS

The assessment was made according to annex F of the CEN TC 127 testing methodology [1]. The following equation was used to calculate the value of the thermal conductivity as a function of the average temperature of the protection materials (equal to 1/2 of the steel temperature + 1/2 of the fire temperature for each time increment exposed to fire) :

$$K=\lambda_i=d_i\left[\frac{d\theta_a}{dt}+(e^{u/10}-1)\frac{d\theta_{fs}}{dt}\right]\frac{V}{A_i}\rho_a c_a\left[\frac{1+\mu/3}{\theta_{fs}-\theta_a}\right] \qquad (2)$$

In every case the specific heat of the protection material (C_p) was taken as 1000J/kg°C and independent on temperature since it is unlikely this method will be used in conjunction with a temperature dependent specific heat relationship.

According to ENV 1993-1.2 [2] and the schematisation of the sections used for numerical calculations, the section factors given in table 2 were used.

TABLE 2 : Section factors

	HEM 280	HEB 450	HEB 300	HEA 300	HEA 200	IPE 200
SECTION FACTOR (A/V in m^{-1})	73,76	97,87	124,49	165,90	228,60	289,49

Consequently for each insulated section the thermal conductivity is calculated for each time step and an arithmetic mean value is obtained from the 10 sections insulated by a given material, as a function of time.

According to the assessment method, the average value of λ_p at each step of temperature has to be modified in order to satisfy the validity criteria given in [1] with respect to the ratio :

$$\frac{t_{\theta,c}}{t_{\theta,m}}$$

where :

$t_{\theta,c}$ is the time to reach the steel temperature θ (for 350°C to 800°C with a step of 50°C), obtained by calculation according to the formula (1)

$t_{\theta,m}$ is the time to reach the same steel temperatures, obtained by measurement in fire test (or here obtained by numerical modelling).

The three validity criteria to be fulfilled are:

- maximum value of $\frac{t_{\theta,c}}{t_{\theta,m}}$: 1.3 (meaning that the maximum unsafe error has to be limited to 30% of the experimental data)

- maximum number of value $\frac{t_{\theta,c}}{t_{\theta,m}} > 1$: equal or less than 20 % (meaning that within all the calculated data not more than 20% can be on the unsafe side),

- sum of all ($t_{\theta,c}$ - $t_{\theta,m}$) : less than 0 (meaning that, in average, the calculated data are on the safe side).

The modification of λ_p is made by increase α in the following equation :

$$\lambda_{p,\text{final}} = \lambda_{p,\text{initial}} + \alpha \cdot d \qquad (3)$$

where :
d is the standard deviation of $\lambda_{p\ \text{initial}}$ at each step of 50°C,

The agreement between calculated time and "measured" time to reach 350 to 850°C for the 10 sections of table 1 is shown in figure 6. To evaluate the level of accuracy between calculated and "measured" data it is possible to refer to the coefficients of the regression line going through the points. These coefficients are :

a_1 slope of the line (the best coefficient is when this slope is equal to 1, equal to the diagonal),

r regression coefficient expressing the scatter of the results (the best coefficient is when all the points are on the same line leading to a value of 1).

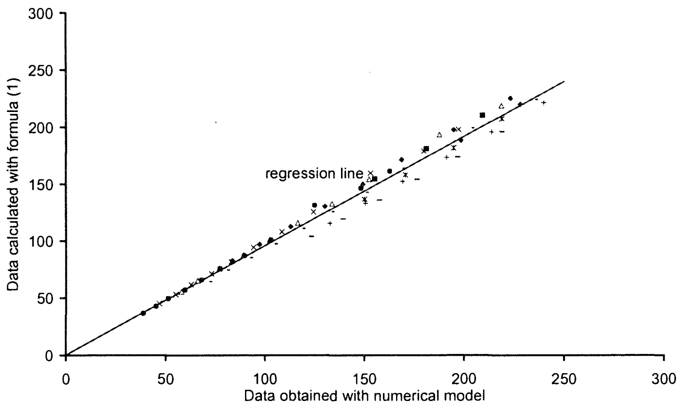

FIGURE 6 : Comparison between initial data and calculated data using formula (1)

The values of the thermal conductivity λ_p used for initial calculation and resulting from the assessment method are given in figures 7 to 10. The overestimation at low temperature may be due to the approximation in the formula given in Eurocode [2] and the underestimation at high temperature is mainly due to the fact that the shadow effect for radiative heat flux to the section, due to the flanges, can not be explicitly taken into account here.

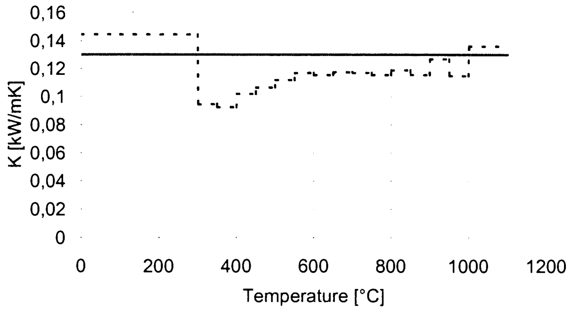

FIGURE 7 : Thermal conductivity for material case 1

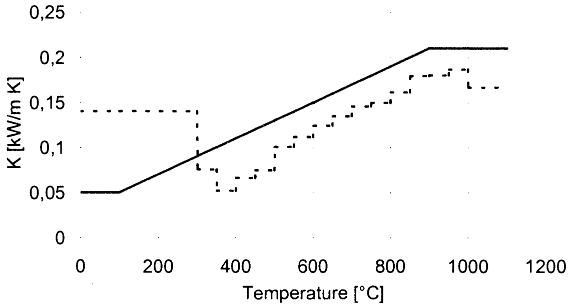

FIGURE 8 : Thermal conductivity for material case 2

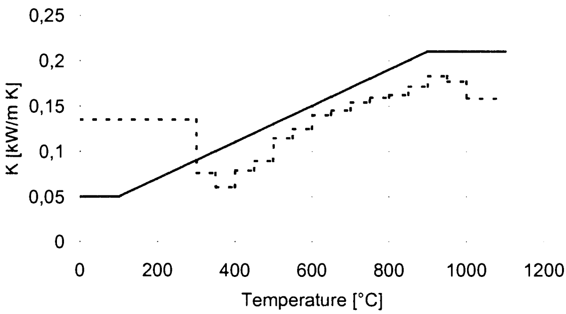

FIGURE 9 : Thermal conductivity for material case 3

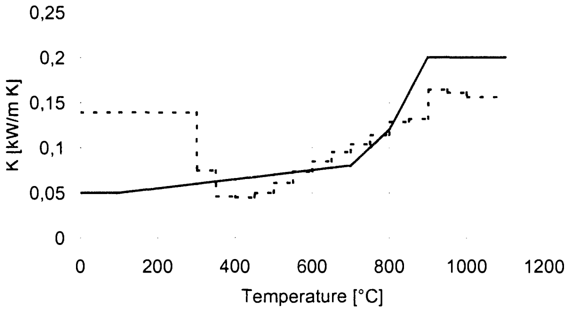

FIGURE 10 : Thermal conductivity for material case 4

In figure 11 an example of some comparisons is given between initial temperature-time curves of steel sections and those obtained by using formula (1) and $\lambda_{p,final}$ for material case 4.

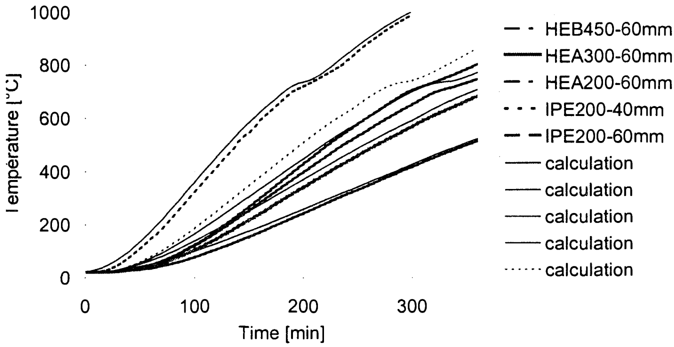

FIGURE 11 : Comparison between calculated and "measured" temperatures of steel sections

5. EFFECT OF SOME PARAMETERS

Even if agreement between calculated and "measured" temperature-time curves is rather good, it is obvious that errors are made by using formula (1) for determining the temperature of steel sections.

In this respect, the two main parameters are :
- section factor (A/V),
- thickness of the insulation (d).

5.1 Effect of Section Factor

In the formula given in equation (1), it is assumed that the heat transfer from surrounding hot gases to insulated steel section is (for contour protection) proportional to the heated perimeter of the steel section (A). In fact it could also be assumed that this heat flux is :

- proportional to the external perimeter of the insulating material or,
- proportional to the average perimeter of the insulating material.

Both assumptions lead to a modification of the section factor. In table 3 these section factors are given as well as the name of the data file (QSA31-ηa, ηb or ηc, where η represents the material case (1,2,3 or 4)).

TABLE 3 : Values of section factors

ASSUMPTION FOR A/V	THICKNESS OF PROTECTION [mm]	SECTIONS					
		HEM 280	*HEB 450*	*HEB 300*	*HEA 300*	*HEA 200*	*IPE 200*
Initial value (files QSA31-ηa)*	whatever	73,76	97,87	124,49	165,90	228,60	289,49
External perimeter of protection (files QSA31-ηb)*	20	77,16	-	130,09	173,43	244,27	-
	40	80,56	-	-	-	-	348,21
	60	-	109,20	-	188,48	275,61	377,57
Average perimeter of protection (files QSA31-ηc)*	20	75,46	-	127,29	169,66	236,43	-
	40	77,16	-	-	-	-	318,85
	60	-	103,53	-	177,19	252,11	333,53

* *with η = 1 to 4 according to the thermal characteristics*

With these new section factors the values of λ_p, are slightly modified however they do not lead to an improved consistency between calculated and "measured" temperatures. This is shown in figures 12 and 13 for material cases 1 and 2, by referring to the coefficients (a_1 and r) of the regression line (as presented in figure 6).

This means that, according to the assumptions made, modifying the section factor is not the parameter which will lead to providing an improvement in consistency.

5.2 Effect of the Effective Thickness

In the formula (1), the heat content of the insulation material is proportional to its volume which is assumed to be :

A . d

where :
A is the perimeter of the steel section (for contour protection),
and
d the average thickness of the protection from recorded measurement.

In fact, due to the shape of I steel section, this formula is not right. To be able to use the correct volume in the formula, it is necessary to use an effective thickness :

$$\frac{\text{actual volume of insulating material}}{\text{heated perimeter}}$$

The heated perimeter (A) is one of the possibilities mentioned in § 5.1.

Concerning the 3 assumptions for the calculation of A/V, the effective thickness given in table 4 has to be used accordingly :

TABLE 4 : Effective thickness of protection materials

ASSUMPTION FOR A/V	THICKNESS OF PROTECTION [mm]	SECTIONS					
		HEM 280	*HEB 450*	*HEB 300*	*HEA 300*	*HEA 200*	*IPE 200*
Initial value (files QSA31-ηd)*	20	20,9	-	20,9	20,9	21,4	-
	40	43,7	-	-	-	-	48,1
	60	-	66,9	-	-	72,3	78,3
External perimeter of protection (files QSA31-ηb)*	20	20	-	20	20	20	-
	40	40	-	-	-	-	40
	60	-	60	-	-	-	60
Average perimeter of protection (files QSA31-ηe)*	20	20,5	-	20,4	20,4	20,7	-
	40	41,8	-	-	-	-	43,7
	60	-	63,3	-	-	65,6	67,9

* *with η = 1 to 4 according to the thermal characteristics*

Regarding A/V obtained with the external perimeter of protection, the assumption made on the influence of the effective thickness has no effect, which means that the results are the same as those obtained in § 5.1.

For material cases 1 and 2 figures 12 and 13 show that the use of this effective thickness, for A/V related to internal or average perimeter of protection, leads to a better consistency between calculated and "measured" temperature of steel sections. With material cases 3 and 4 the results are similar.

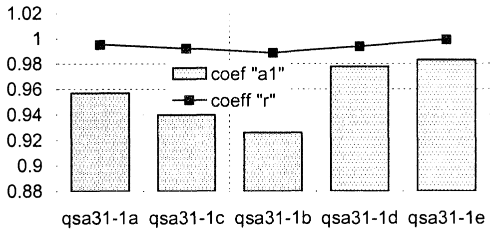

FIGURE 12 : Coefficients of linear regression for 5 different assumptions (see tables 3 and 4) – Material case 1

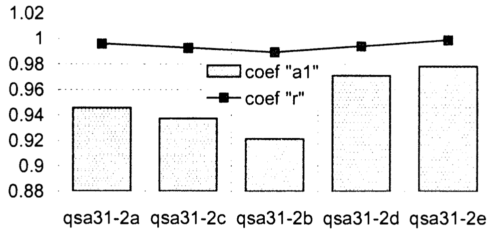

FIGURE 13: Coefficients of linear regression for 5 different assumptions (see tables 3 and 4) – Material case

6. CONCLUSION

This theoretical study on the assessment of the thermal conductivity of fire protection material of steel section has demonstrated that it is possible to obtain good agreement between calculated and "measured" temperature data by using the differential equation method [1]. However the thermal conductivity derived is a little bit different of the one to be used in numerical models based, for instance, on finite elements.

Additionally, comparing to what it currently described in Eurocode 3 – part 1.2 [2], a better agreement between calculated and "measured" results could be obtained by using :

- the section factor (A/V) related to average thickness of protection (for contour protection), instead of that related to the internal perimeter of the protection material,
- an effective thickness of protection in order to take into account the heat content of the protection material itself.

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