J. Construct. Steel Research 9 (1988) 111–135

Characterization of an Insulating Material With Regard to ECCS Recommendations for the Fire Safety of Steel Structures

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(Received 1 July 1987 revised version received 30 September 1987; accepted 29 October 1987)

SYNOPSIS

The aim of this paper is to derive a practical way to characterize an insulating material, applied to steel profiles, in a fire. The proposed method is based directly on the European Recommendations for Fire Safety of Steel Structures. By consideration of three series of fire tests on three different insulating materials, an analysis is made of the practical influence of some assumptions or some parameters. The influence of the temperature dependent thermal capacity of steel, the thermal capacity of the insulation, the way to estimate this thermal capacity, the cross-section type and the temperature dependent thermal conductivity of the insulating material are examined successively. The proposed method can be used for design purposes and makes it possible to consider mean or characteristic properties.

1 INTRODUCTION

This paper deals with the heating of steel profiles protected against fire by insulating materials, with particular respect to the calculation method proposed by the Technical Committee 3 of the ECCS, *European Recommendations for the Fire Safety of Steel Structures.*[1]

The aim is to consider three series of fire-tests made with three different

J. Construct. Steel Research 0143-974X/88/$03·50 © 1988 Elsevier Applied Science Publishers Ltd, England. Printed in Great Britain

insulating materials in order to define how the ECCS recommendations could be practically applied when it is intended to characterize an insulating material.

In this method, as well as in practically all of the simplified methods for the calculation of steel profiles submitted to the fire, the thermal problem is considered to be totally separated from the structural aspect of the question. The variations of the mechanical properties of steel with temperature are assumed to be well known. Figure 1 shows the variation of the effective yield stress $\sigma_y(\theta)$, according to Reference 1. It will be noted that the right part of the curve is a dotted line because steel properties beyond 600°C are not so well known, yet detailed knowledge of the steel properties in this temperature region is not essential since normally critical conditions will be reached at temperatures lower than 600°C. Figure 1 also makes it clear that, due to the partial safety factor at ambient temperature, the failure will normally not occur at temperatures below 400°C.

Thus, it can be concluded that, due to the mechanical behaviour of steel at high temperatures, the heating of steel profiles must be analysed up to temperatures of steel in the region 400°C to 600°C.

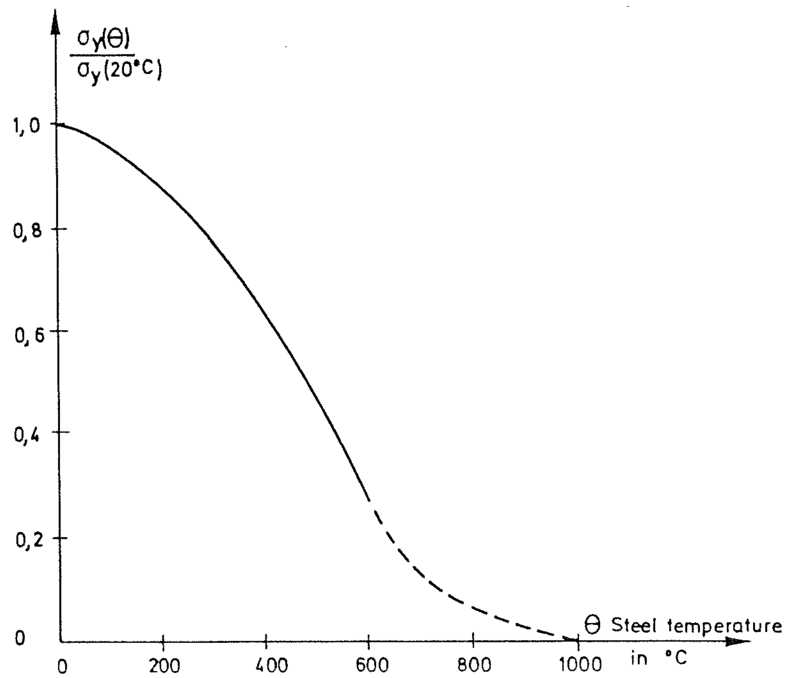

Fig. 1. Variation of the effective yield stress.

2 CALCULATION METHOD OF THE ECCS

The main hypotheses of this method are:

(i) the temperature of a steel profile is uniform,
(ii) the temperature gradient in the insulating material between the fire-exposed surface and the inner surface next to the steel is linear,
(iii) the resistance to heat flow between the inner surface of the insulating material and the steel is negligible.

Heat flow can therefore be calculated as one-dimensional, which leads to very simple and easy to handle equations.

The ambient gas temperature θ_t used in the calculation is the same as that specified in ISO 834[2] and given by

$$\theta_t - \theta_0 = 345 \log\left(\frac{8}{60}\, t + 1\right) \tag{1}$$

where t = time (s), θ_t = furnace temperature at time t (°C), and θ_o = furnace temperature at time $t = 0$ (°C).

The heat flow transmitted from the fire compartment to unit length of the steel member is given by

$$Q = KF(\theta_t - \theta_s) \tag{2}$$

where Q = heat flow (W/m), K = coefficient of total heat transfer (W/m^2 °C), F = surface area of the member per unit length exposed to heating (m^2/m), and θ_s = temperature of the steel member (°C).

The coefficient of heat transfer K is calculated by

$$\frac{1}{K} = \frac{1}{\alpha_c + \alpha_r} + \frac{d_i}{\lambda_i} \tag{3}$$

where α_c = coefficient of heat transfer due to convection from the fire to the exposed surface of the member (α_c = 25 W/m^2 °C), α_r = coefficient of heat transfer due to radiation from the fire to the exposed surface of the member (W/m^2 °C), λ_i = thermal conductivity of the insulation material (W/m °C), and d_i = thickness of the insulation (m).

In eqn (3), the coefficient of heat transfer due to radiation α_r is calculated by

$$\alpha_r = \frac{5{\cdot}77 \times 10^{-8} \epsilon_r}{\theta_t - \theta_s}\left[(\theta_t + 273)^4 - (\theta_S + 273)^4\right] \tag{4}$$

where ϵ_r = resultant emissivity of the flames, combustion gases and exposed surface (= 0·5).

2.1 Non-insulated members

In this particular case, the coefficient of heat transfer K is given by

$$K = \alpha_c + \alpha_r \tag{5}$$

The equation of the heating of the steel member becomes in differential form

$$Q\,dt = C_s \rho_s V d\theta_s \tag{6}$$

where Q = heat flow according to eqn (2) (W/m), C_s = specific heat of steel (J/kg °C), ρ_s = density of steel (kg/m^3), and V = volume of the member per unit length (m^3/m).

The introduction of finite differences in eqn (6) provides

$$\Delta\theta_s = \frac{\alpha}{C_s \rho_s} \frac{1}{V/F} (\theta_t - \theta_s) \Delta t \tag{7}$$

where $\alpha = \alpha_c + \alpha_r$

2.2 Insulated members

In practice, the value of $1/(\alpha_c + \alpha_r)$ is small compared with the value d_i/λ_i. Then, for insulated members the coefficient of heat transfer K of eqn (3) reduces to:

$$K = \frac{\lambda_i}{d_i} \tag{8}$$

This simplification can lead to too conservative solutions for very small values of d_i/λ_i.

2.2.1 Members with lightweight and dry insulation

The insulation is considered lightweight if

$$C_i \rho_i F_i d_i < 0{\cdot}5 C_s \rho_s V \tag{9}$$

where C_i = specific heat of the insulation material (J/kg °C), ρ_i = density of the insulation material (kg/m^3), F_i = area of inner surface of the insulation material per unit length of the steel member (m^2/m).

If this condition is met, the calculation of the temperature increase $\Delta\theta_s$ during a time interval Δt is based on the following simplified equation:

$$\Delta\theta_s = \frac{\lambda_i}{d_i}\frac{1}{C_s/\rho_s}\frac{1}{V/F_i}(\theta_t - \theta_s)\Delta t \qquad (10)$$

2.2.2 Members with moist insulation materials

In that case, a delay time t_v in the increase of temperatures takes place because of the evaporation of moisture. This delay time can be estimated (see Reference 1) and is proportional to the moisture content p.

2.2.3 Members with intumescent materials

Equation (10) can be used, where the insulation capacity of the material is expressed in terms of an effective d_i/λ_i value for each nominal thickness of application (the thickness of the foam-like layer may vary during fire exposure).

2.2.4 Members with heavyweight insulation

If the condition in eqn (9) is not met, the temperature increase of the heavily insulated member may be based on the following, approximate equation:

$$\Delta\theta_s = \frac{\lambda_i}{d_i}\frac{1}{V/F_i}(\theta_t - \theta_s)\Delta t\left(\frac{1}{C_s\rho_s + \dfrac{C_i\rho_i d_i}{2V/F_i}}\right) \qquad (11)$$

In this equation, the thermal capacity of the steel has been increased by one half of the thermal capacity of the insulation material.

3 INFLUENCE OF SOME PARAMETERS OF THE EQUATIONS

3.1 General considerations

Some hypotheses or approximations have already been mentioned.

—The heat flow is calculated as one-dimensional,
—$1/(\alpha_c + \alpha_r)$ is small compared with the value of d_i/λ_i.
—The thickness of the insulating material is uniform.
—Equation (11) is a simplified approximation.

Some other approximations of the equations have to be underlined here.

—The thermal capacity of the insulation material being equal to $C_i\,\rho_i\,d_i\,F_i$ in eqn (11) is not valid for high thickness d_i.

—The thermal capacity of the insulation material is divided by 2 in eqn (11) because it is supposed that

$$\theta_i = \frac{\theta_s + \theta_t}{2}$$

In reality, there is a high thermal gradient in the insulation and the temperature in this material is not uniform. Even if the temperature of the insulating material has to be represented by its mean value, the only certain thing is that, due to the thermal capacity of the material, the thermal gradient is not linear and the mean temperature of the insulation is not equal to $(\theta_s + \theta_t)/2$.

—The thermal properties of steel (C_s and ρ_s) and of the insulating material (C_i and ρ_i) may vary with temperature.

—In heavily insulated members, no differentiation is made between dry and moist materials.

—The shape of the cross-section of the profile is not taken into account, whereas it is clear that the radiative flux must be influenced by that factor. In Fig. 2, every cross-section is not heated in the same manner due to the shadow effect that will play a role in the concave sections.

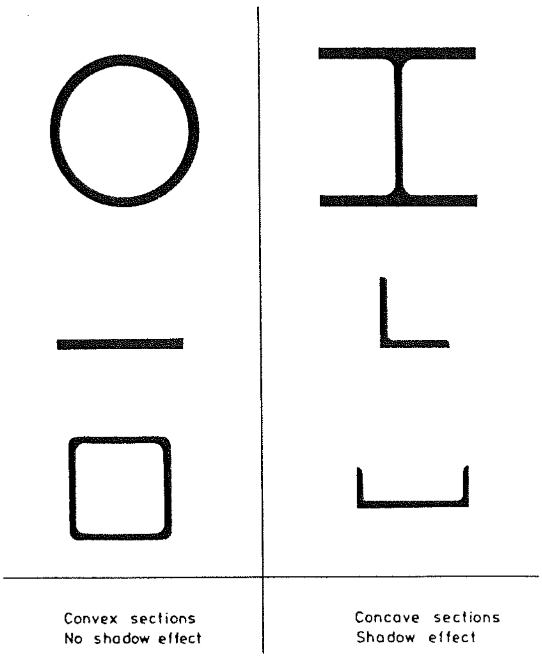

Fig. 2. The shadow effect.

It is therefore very clear, and clearly underlined in the ECCS recommendations, that the thermal conductivity of the insulation material λ_i is not identical with the conventional thermal conductivity as given in the handbooks on heat transfer. It must be regarded as a conventional parameter, the value of which must be determined experimentally, generally by means of small-scale experiments with unloaded test specimens. Thus λ_i will be referred to as the apparent thermal conductivity. It is very clear that this value depends on the type of fire tests and on the way these tests are interpreted.

When analysing a fire test in order to determine the conventional thermal conductivity of the insulation material, there are two different possible approaches.

First approach

For every test, the variation of the mean temperature of the steel member can be noted (see Fig. 3a). The time is divided into finite increments Δt, and from eqn (10) or eqn (11), the value of λ_i can be calculated during each time step (Fig. 3b). Introducing the hypothesis

$$\theta_i = \frac{\theta_s + \theta_t}{2}$$

makes it possible to present the values of λ_i versus θ_i (Fig. 3c). A curve can also be drawn through those points, so every test leads to a particular curve of λ_i as a function of θ_i.

As different tests are performed for various shape factors of the steel member V/F_i and various thicknesses of the insulating material d_i, different curves $\lambda_i = \lambda_i(\theta_i)$ can be drawn (Fig. 3d) and a mean or a characteristic curve can be calculated, which finally characterize the insulating material

$$\lambda_i = \lambda_i(\theta_i) \tag{12}$$

Second approach

If the temperature corresponding to the failure of the steel member is known (eq. $\theta_s^f = 500°C$ or $\theta_s^f = 540°C$), the apparent thermal conductivity λ_i of the insulating material can be considered as not temperature dependent. From each test, the time corresponding to the failure temperature is noted (t^f corresponding to θ_s^f—see Fig. 4). The apparent thermal conductivity of the insulating material in that test must be determined in order to obtain also the failure temperature θ_s^f after a duration t^f by the application of eqn (10) (or eqn (11))—see Fig. 4.

That way, the moisture is not explicitly taken into account. Instead, it is implicitly introduced in the apparent thermal conductivity. Figure 4 shows that the local phenomenon of evaporation in the test is considered in the calculated apparent thermal conductivity.

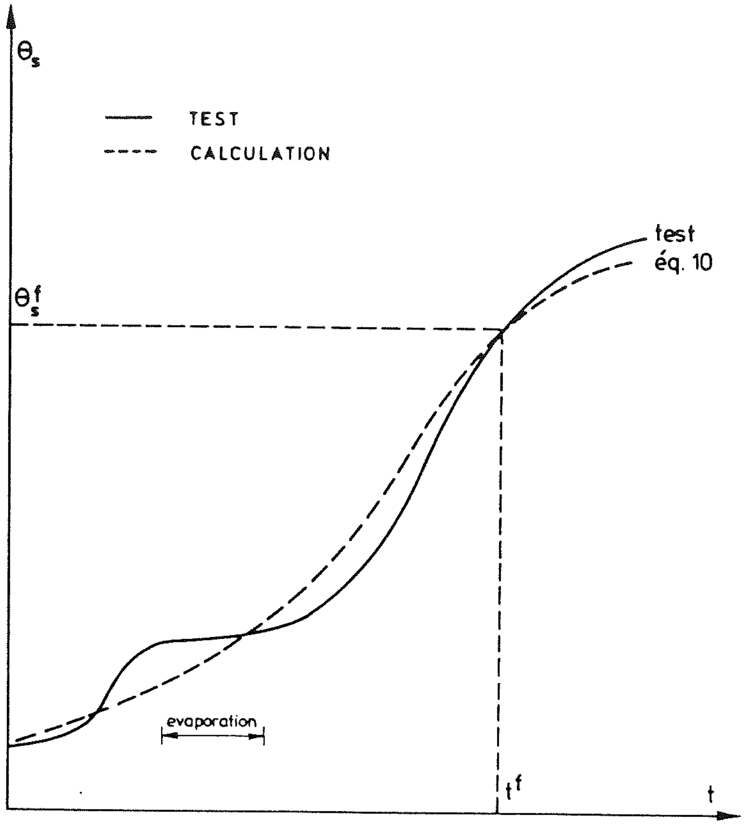

Fig. 4. Second approach to analysing a fire test.

As different tests are performed, different values of λ_i can be calculated, which leads to a mean or a characteristic value *for that particular failure temperature of the steel members.*

If the insulating material has to be characterized for different failure temperatures, the same calculation has to be performed for various failure temperatures which finally leads to a curve

$$\lambda_i = \lambda_i(\theta_s^f) \tag{13}$$

In this paper, the second approach has been used because it has the advantage that every fire test can be represented by one single number, i.e. the apparent thermal conductivity of the insulating material. It is more practical, when comparisons have to be made between several tests, to handle numbers rather than curves.

The comparisons in this study are based on three series of fire tests.

In Table 1 are given the main parameters of 11 fire tests performed at the University of Gent[3] with asbestos silicate sheets as insulating material. The specific mass of that material is 750 kg/m^3 (assumed to be constant). In this table, the times t^f corresponding to θ_s^f = 500°C are also given.

In Table 2 are given the main parameters of 8 fire tests performed at the TNO in Delft[4] with sprayed mineral fibre as insulating material. The specific mass of that material is 400 kg/m^2 (assumed to be constant).

TABLE 1

Test no.	d_i *(mm)*	*Profile*	$\frac{V}{F_i}$ *(mm)*	$\frac{\theta_s^f = 500°C}{t^f}$ *(min)*
1	10	IPE 300	6·0	41
2	12	IPE 300	6·0	49
3	20	IPE 300	6·0	78
4	2 × 15 = 30	IPE 300	6·0	102
5	20 + 15 = 35	IPE 300	6·0	138
6	12	HEA 300	9·6	59
7	25	HEA 300	9·6	118
8	8	HEB 300	12·4	49
9	10	HEB 300	12·4	60
10	2 × 25 = 50	HEB 300	12·4	280
11	8	HEM 300	23·3	87

TABLE 2

Test no.	d_i *(mm)*	*Profile*	$\frac{V}{F_i}$ *(mm)*	$\frac{\theta_s^f = 500°C}{t^f}$ *(min)*
1	13	IPE 200	4·8	54
2	20	IPE 200	4·8	65½
3	30	IPE 200	4·8	89
4	13	HEA 300	9·6	78
5	20	HEA 300	9·6	101½
6	30	HEA 300	9·6	134
7	20	HEM 200	16·0	129
8	13	HEM 300	23·2	135

In Table 3 are given the main parameters of 14 fire tests performed at the CSTB in France[5] with sprayed mineral fibre as insulating material. The specific mass of that material is 250 kg/m^3 (assumed to be constant).

These series of tests are going to be interpreted in different ways. For every type of interpretation, for every equation utilized, for every hypothesis, it is possible to calculate for the apparent thermal conductivity of an insulating material:

(i) the mean,
(ii) the standard deviation.

TABLE 3

Test no.	d_i (mm)	Profile	$\frac{V}{F_i}$ (mm)	$\frac{\theta^f = 500°C}{t^f}$ (min)
1	25	plate 120 × 6	2·9	39
2	48	plate 120 × 6	2·9	63
3	61	plate 120 × 6	2·9	87
4	76	plate 120 × 6	2·9	129
5	47	IPE 270	4·4	125
6	62	IPE 270	4·4	226
7	80·5	IPE 270	4·4	297
8	14	H305 × 127 × 42	5·5	43
9	45	H305 × 127 × 42	5·5	172
10	25	HEB 260	7·9	92
11	26·4	HEB 260	7·9	89
12	45	HEB 260	7·9	169
13	74	HEB 260	7·9	336
14	80·5	plate 300 × 20	9·4	267

Of course, the mean is likely to depend on the type of interpretation that is made. Yet, this is of no practical influence because, once the hypotheses used in the interpretation of the tests are chosen, the same hypotheses should be made in the design situation. More significant is the standard deviation or, better, the coefficient of variation, here defined as the standard deviation divided by the mean. Indeed, using a bad fit would lead to high discrepancies between the tests and the calculations and thus to a high coefficient of variation. If the theory could perfectly describe the reality, the coefficient of variation would tend to zero. The coefficient of variation is a parameter indicating the accuracy of the interpretation that is made.

3.3 Variation of the thermal capacity of steel

It is well known that the specific heat of steel is a function of temperature and, according to the ECCS,[1] the following equation can be used

$$C_s = 470 + 0{\cdot}20\theta_s + 38 \times 10^{-5}\theta_s^2 \qquad (\mathrm{J/kg\,°C})$$

The calculations have then been made with the use of the very simple eqn (10), this time taking into account the variation of C_s with temperature.

This time, the calculated apparent thermal conductivities are slightly higher but, more important, the coefficients of variation are practically unchanged. For example, they have been found to be as follows:

16·9% instead of 16·7% for material 1,
16·5% instead of 16·6% for material 2,
29·9% instead of 29·6% for material 3.

The same has been found even with higher failure temperatures of the steel members ($\theta_s^f = 600$°C).

The fact that the coefficient of variation is not affected by the hypothesis on the specific heat of steel indicates that it has no practical effect on the final result and that it is not useful to consider the temperature-dependence of the specific heat of steel. In all the following calculations, the constant value recommended by the ECCS

$$C_s = 520 \ \mathrm{J/kg\,°C}$$

has been considered.

3.4 Simplified consideration of the thermal capacity of the insulating material

It is of more importance to know whether eqn (10) or eqn (11) has to be used, i.e. whether the thermal capacity of the insulation has to be taken into account. Condition (9) is not practically applicable because, in a series of tests on the same insulating material, it is met for some tests but not for some others.

For material 1, 6 members out of 11 are heavily insulated.
For material 2, 1 member out of 8 is heavily insulated.
For material 3, 10 members out of 14 are heavily insulated.

Applying eqn (10) for some tests and eqn (11) for the others would lead to two different values of the apparent thermal conductivity λ_i, one for members with lightweight insulation and another for heavily insulated members, with all the problems of discontinuity between the two situations.

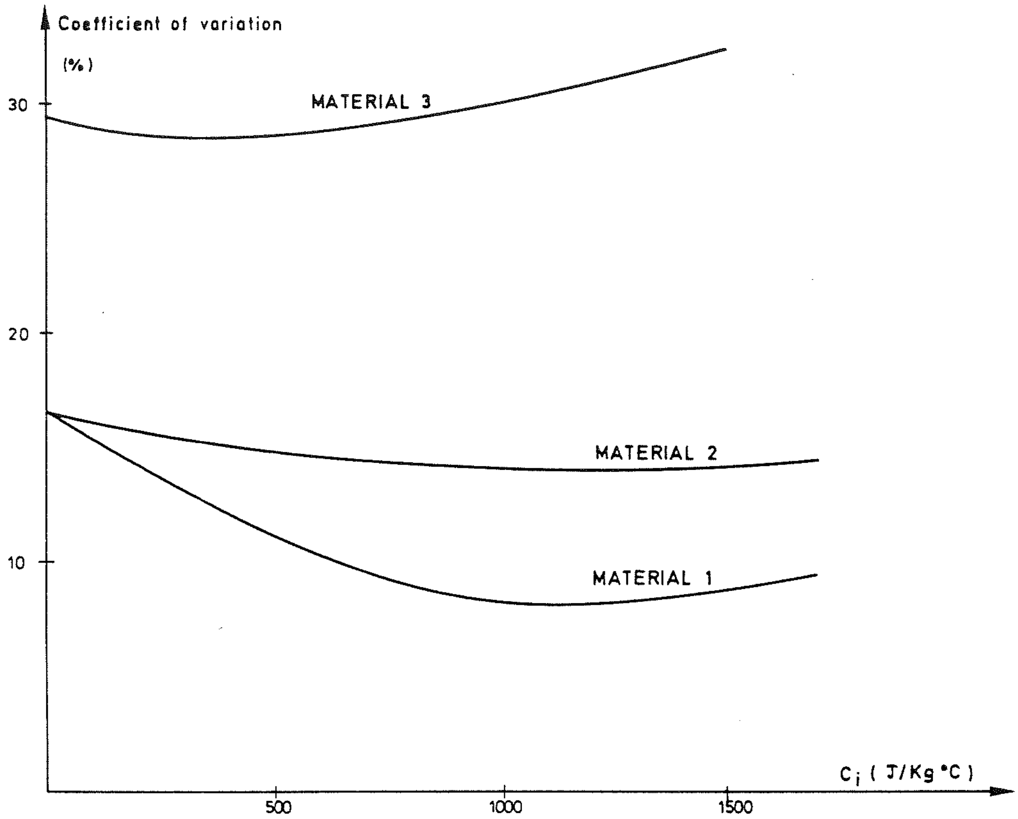

Fig. 5. Influence of the thermal capacity of the insulation.

Thus, the thermal conductivity of the insulating materials has been calculated according to eqn (11) with the specific heat C_i varying from 0 to 1500 J/kg°C. Figure 5 shows the calculated coefficients of variation for different values of C_i.

For the first material, the improvement is significant, whereas for materials 2 and 3, the influence is not important, which confirms the comment of the ECCS that, for most insulating materials with usual specific weight, the thermal capacity of the insulation could be neglected.

In fact, there is no real difficulty in using eqn (11) instead of eqn (10) and it is reasonable to do so, whatever the thickness and the specific weight of the insulation.

Very important is the fact that the curves of Fig. 5 are very flat near their minimum value. For the following calculations, the value

$$C_i = 1100 \text{ J/kg °C}$$

has been chosen and we now know that a slight approximation on that parameter would not affect the results very much. It can also be concluded that the hypothesis

$$\theta_i = \frac{\theta_t + \theta_s}{2}$$

which leads to one half of the specific heat of the insulation being taken into account is not of significant importance. For example, if the hypothesis

$$\theta_i = \frac{\theta_t + 2\theta_s}{3}$$

was made, it would have the same effect (see eqn (11)) as to multiply the thermal capacity of the insulation by a factor 4/3. Figure 5 indicates that this would not have a significant influence.

As a conclusion to this paragraph, the hypothesis $\theta_i = (\theta_t + \theta_s)/2$ can be accepted for the temperature of the insulation when the thermal capacity of the insulation material which can be recommended is taken into account.

3.5 Exact consideration of the thermal capacity of the insulating material

The influence of the thermal capacity of the insulation is significant mostly in the case of very thick materials.

In that case, the approximation of eqn (11)

$$K_i = C_i \rho_i d_i F_i$$

is no more suitable and the correct expression should be used. Generally

$$K_i = C_i \rho_i d_i F_i + 4d_i^2$$

If, instead of the inner surface of the insulation material F_i, the surface at mid-level of the insulation was considered (F_m—see Fig. 6), one could write

$$K_i = C_i \rho_i d_i F_m \tag{14}$$

and eqn (11) would stand

$$\Delta\theta_s = \frac{\lambda_i}{d_i} \frac{1}{V/F_i} (\theta_t - \theta_s) \Delta t \left(\frac{1}{C_s \rho_s + \dfrac{C_i \rho_i d_i}{2V/F_m}} \right)$$

This, however, would mean the introduction of a new parameter, every steel member being characterized by F_i and by F_m. Indeed, it is suitable to consider that not only the thermal capacity of the insulation but also the heat

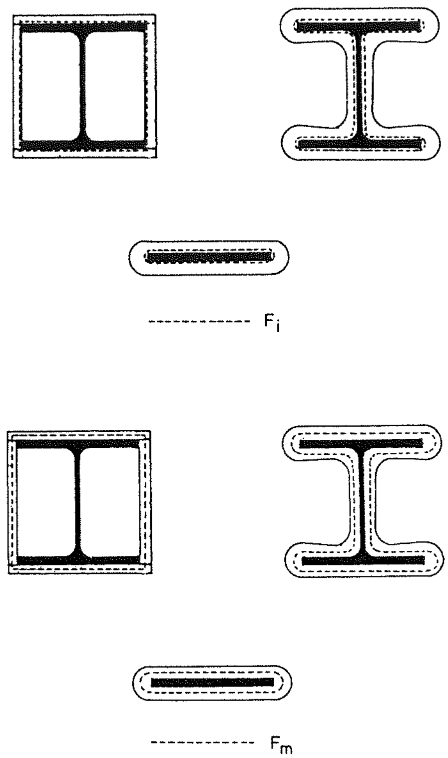

Fig. 6. Consideration of the thermal capacity of the insulation.

flow is proportional to F_m (see Fig. 5). This is an hypothesis, as was the fact that the heat flow is proportional to F_i. That way, eqn (15) could be used, which is similar to eqn (11) except that F_m is used instead of F_i

$$\Delta\theta_s = \frac{\lambda_i}{d_i}\frac{1}{V/F_m}(\theta_t - \theta_s)\Delta t\left(\frac{1}{C_s\rho_s + \dfrac{C_i\rho_i d_i}{2V/F_m}}\right) \quad (15)$$

This introduces no difficulty in the determination of the thermal conductivity of the insulating material. In the design situation, however, the fact that F_m depends on the thickness of the insulation d_i leads to very few (generally one) iterations. Table 5 shows the value of the coefficient of variation in the three different cases, defined as follows

1. $C_i = 0$
2. $C_i = 1100$ J/kg K and $K_i = C_i\rho_i d_i F_i$
3. $C_i = 1100$ J/kg K and $K_i = C_i\rho_i d_i F_m$

TABLE 5

	Case 1	*Case 2*	*Case 3*
Material 1	16·7%	8·2%	8·8%
Material 2	16·6%	14·1%	13·1%
Material 3	29·6%	30·6%	23·5%

Of course, the improvement from case 2 to case 3 is significant mostly in material 3, because of the high thicknesses and of the presence of the rectangular steel sections.

It can be concluded that when the thermal capacity of the insulation is taken into account, the surface at mid-level of the insulation should be considered.

3.6 Influence of the cross-section type

As suggested by Fig. 2, the shape of the cross-section of the steel members influences the radiant heat flow, whereas this phenomenon is not taken into account by eqn (10), (11) or (15). With material 3 applied on I profiles as well as on plate rectangular cross-section, the shadow effect, i.e. the protection of the web from the radiative flow due to the presence of the flanges, will cause an additional resistance to the heating of the I profile and this additional resistance will be interpreted by eqn (10), (11) or (15) as a lower thermal conductivity of the insulating material.

Material 3

$C_i = 1100$ J/kg K

$K_i = C_i \rho_i d_i F_m$ (eqn (15))

TABLE 6

	I and— *(14 tests)*	*I* *(9 tests)*	*—* *(5 tests)*
λ_{im}	0·110	0·100	0·129
$\dfrac{\Delta\lambda_i}{\lambda_{im}}$	23·5%	25·4%	11·1%

Table 6 shows the big difference between the two different types of cross-section and the importance to consider them separately.

The reason why the variation for the I profiles is so high (25·4%) is to be found in Table 3. For some tests, the steel member has reached 500°C after a very long time (more than 5 hours!). This situation is not realistic and leads to very low calculated thermal conductivities, as can be seen in Fig. 7 where the apparent thermal conductivities corresponding to $\theta_s^f = 500°C$ are plotted against the time needed to obtain that temperature.

In the interpretation of fire tests, different types of steel members should be considered separately. Moreover, tests leading to unrealistic fire resistances should be avoided.

3.7 Variation of the thermal conductivity with temperature

In all the previous comparisons, the apparent thermal conductivity of the insulating material was assumed to be independent of temperature.

The question whether a more sophisticated approach would lead to better results must now be discussed. The tests made with material 1 have been examined with the use of eqn (15).

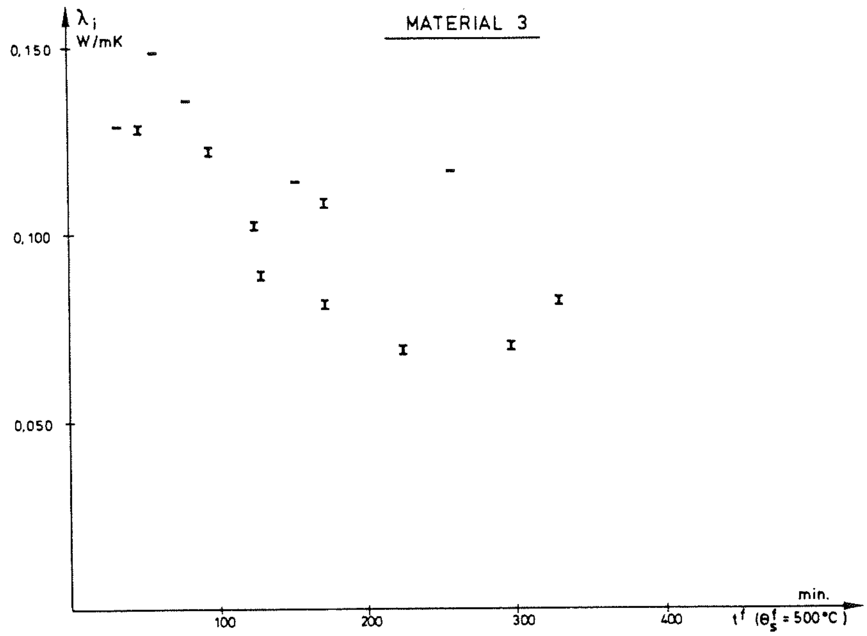

Fig. 7. Influence of the duration of the test.

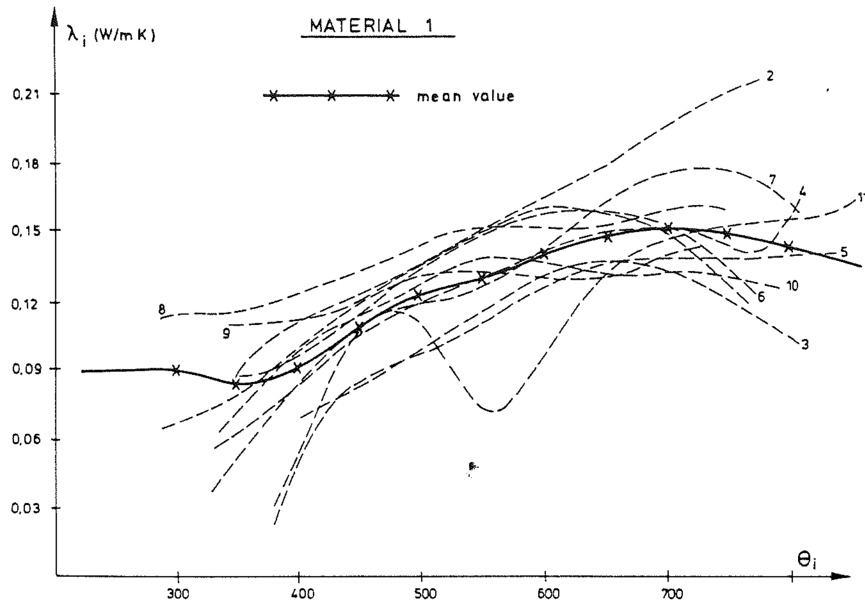

Fig. 8. Temperature dependent conductivity.

Figure 8 shows the eleven curves $\lambda_i = \lambda_i(\theta_i)$ that have been drawn. For various temperatures θ_i, the mean value of λ_i has been calculated, which leads to the curve

$$\lambda_i = \lambda_i(\theta_i)$$

characterizing the insulating material (first approach).

By the second approach (λ_i non temperature dependent), the apparent thermal conductivity has been calculated for various failure temperatures (θ_s^f = 400°C, 500°C and 600°C). The values of the calculated mean thermal conductivities are given in Table 7.

In material 1, the apparent thermal conductivity varies by only 5% for a 100°C variation of the failure temperature of the steel member. The value of λ_{im} for θ_s^f = 600°C has been extrapolated and is chosen equal to 0·129 W/m°C.

TABLE 7

λ_{im}	*Material 1*	*Material 2*	*Material 3*
θ_s^f = 400 °C	0·119	0·095	0·096
500 °C	0·124	0·103	0·110
600 °C	—	0·110	0·125

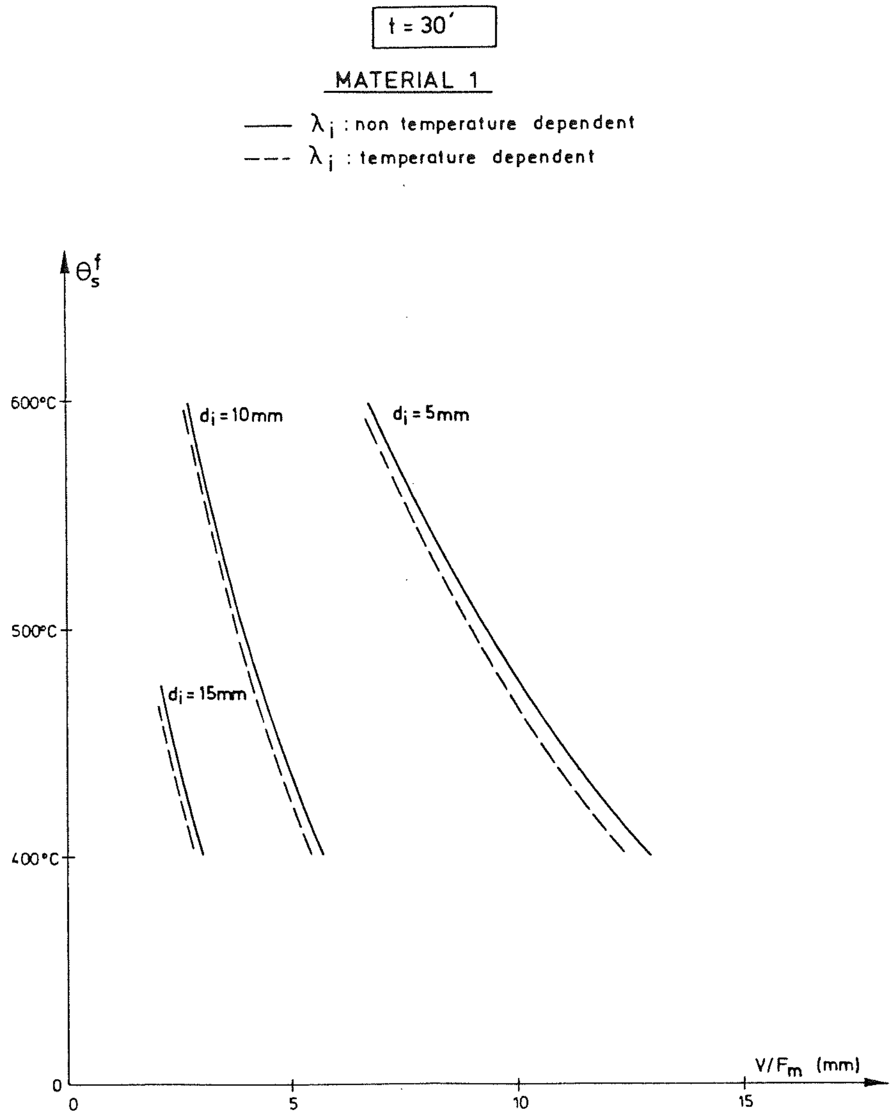

Fig. 9a. Design graph.

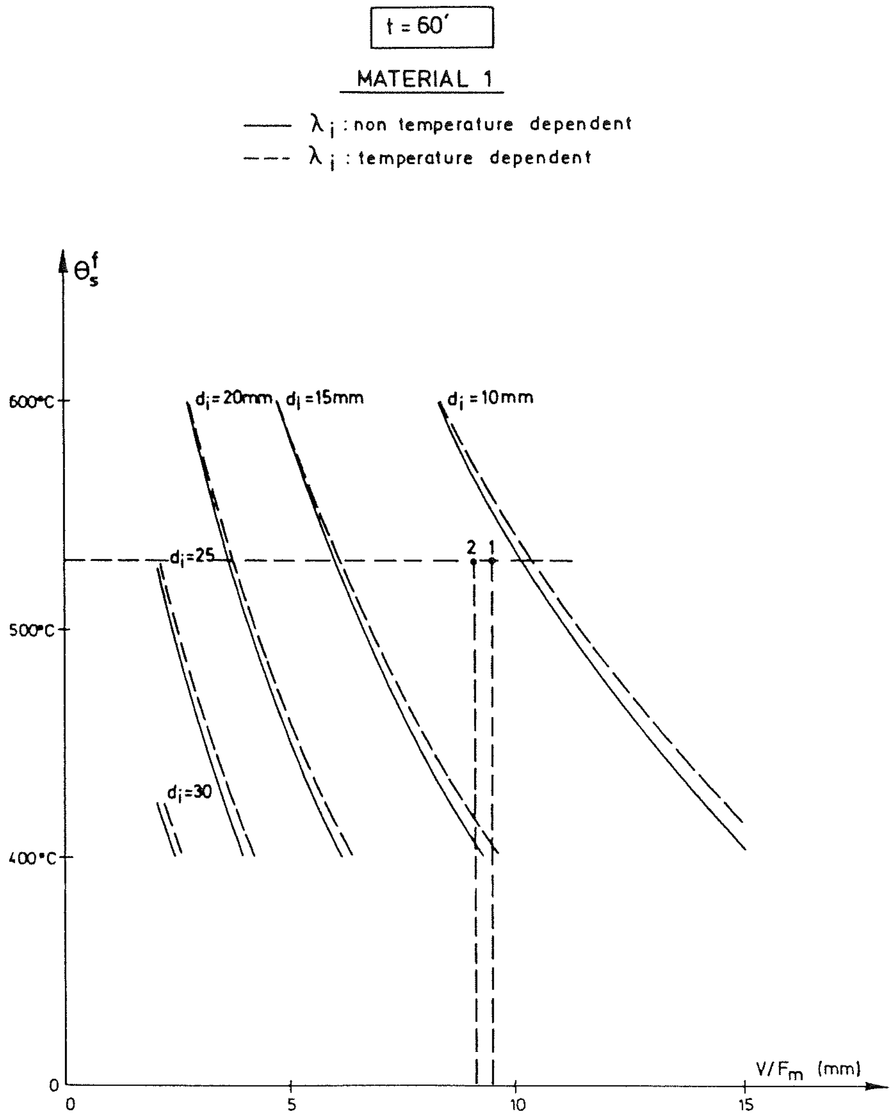

Fig. 9b. Design graph.

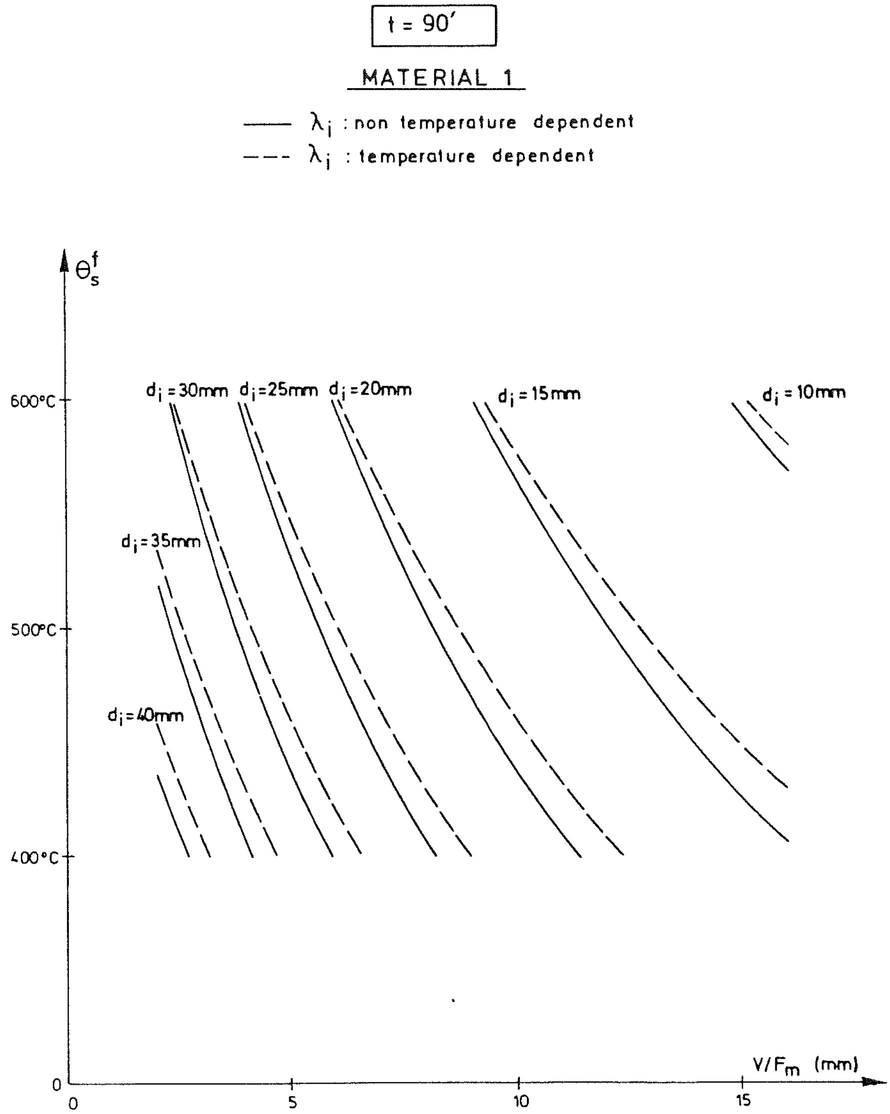

Fig. 9c. Design graph.

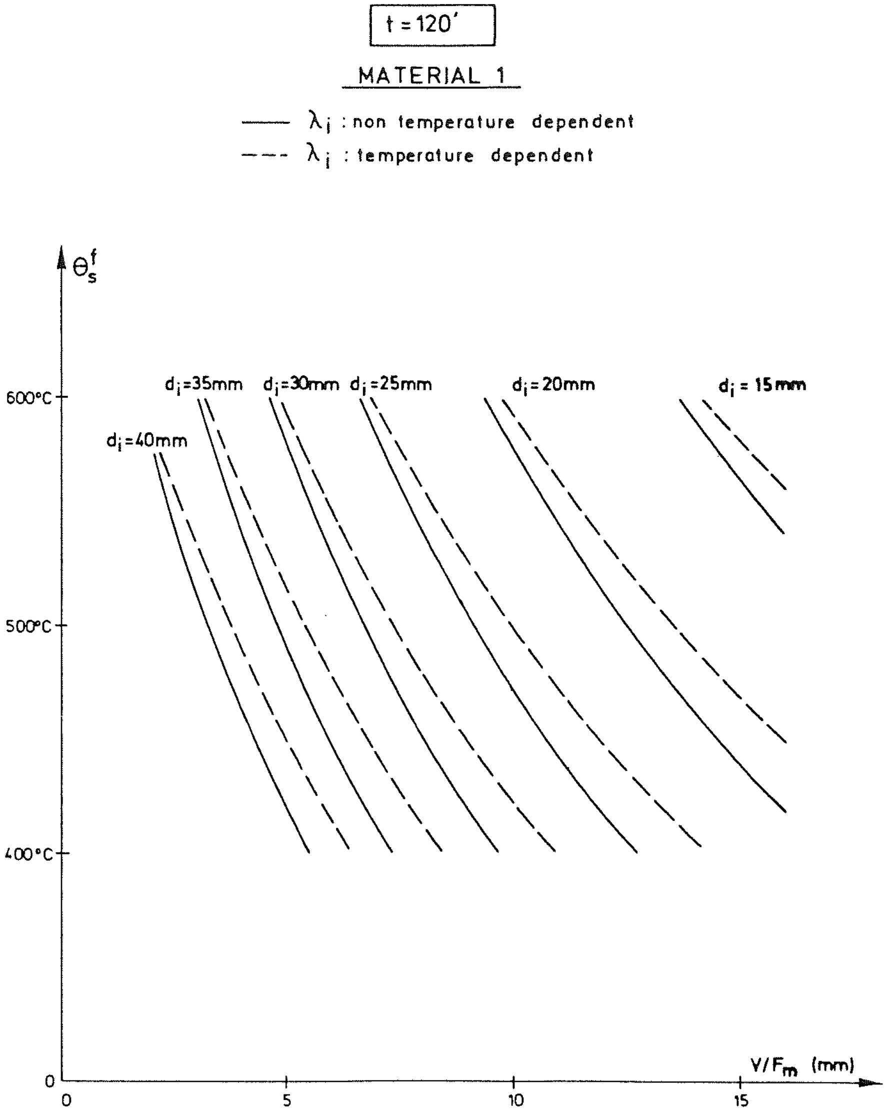

Fig. 9d. Design graph.

the apparent thermal conductivity corresponding to a failure temperature of 500°C. Of course, in the design diagrams which look like Fig. 9, the variation of λ_i with the failure temperature should be considered.

Such diagrams can be used for design purposes. For example, if a fire resistance of 60 minutes is required, Fig. 9b should be used. If the design at ambient temperature leads to a HE 300 A, and if the stress level combined with Fig. 1 indicates that the temperature should not reach 530°C, the following can be calculated.

1st iteration

$$V/F_i = \frac{A_s}{2(h+b)} = \frac{112{\cdot}50}{2(300+290)} = 9{\cdot}53\ \text{mm}$$

In Fig. 9b, point 1 corresponds to $d_i = 11$ mm, whatever the approach used.

2nd iteration

$d_i = 12$ mm is chosen

and

$$V/F_m = \frac{A_s}{2(h+b+2d_i)} = 9{\cdot}16\ \text{mm}$$

In Fig. 9b, point 2 is found and there is no need to reiterate because it corresponds well to $d_i = 12$ mm.

The question of whether a mean or a characteristic value of the apparent thermal conductivity must be considered has still to be discussed.

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