Accidental Actions : Fire.
Connection between
Parametric temperature-time curves and Equivalent time of fire exposure
(Annexes B and E of ENV 1991-2-2).

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SUMMARY

The concept of parametric temperature-time curves presented in Annex B of Eurocode 1 : part 2-2. [1] and the concept of equivalent time of fire exposure presented in Annex E of the same document are briefly described. A nomogram is presented as a graphic help for the application of each method. Starting from a reference compartment, some parameters are modified and the two methods are applied. Via the calculation of maximum temperatures in 3 structures, it is possible to compare the two methods with regard to their severity.

1. Introduction

Beyond the application of the nominal ISO temperature-time curve, Eurocode 1 proposes 2 different methods which consider more realistically the influence of some parameters on the severity of the fire such as the fire load, the geometry of the compartment and the nature of the surrounding walls. One method, proposed in Annex B, leads to parametric temperature-time curves for the air in the compartment and the other one, proposed in Annex E, leads to an equivalent time of exposure to the ISO fire supposed to have the same severity as a real fire in the compartment.

For practical situations, the designer or the authority will face the choice between one of the two methods and no indication is given in [1] concerning the correlation between them, except some limitations for the applicability of the methods. For situation where both methods are applicable, will they lead to the same "severity" ? If not, is one of the methods systematically more severe? How are different parameters taken into account in the methods?

To give some answers to those questions, a parametrical study has been undertaken on a reference case. Both methods have been applied under the same conditions and the severity of the fire has been defined as the maximum temperature obtained in a structure submitted either to the temperature-time curve given by Annex B, or to the ISO fire during the equivalent time given by Annex E.

2. Annex B of ENV 1991-2-2: Natural Fire Curve

2.1 Introduction

This Annex is based on a paper of U. Wickström [1]. In case of a compartment with O = $0{,}04m^{1/2}$ and b = $1160J/(m^2s^{1/2}K)$, the parametric curve is almost exactly the ISO curve. The nomogram explained hereafter has been developed to make easier the use of this Annex

2.2 Nomogram of Parametric temperature time curves (Annex B of ENV 1991-2-2)

The first step in finding the time dependent progress of temperature is to calculate the opening factor, $O[m^{1/2}]$, found on the upper x axis. This is done by solving the following definition:

$$O = \left[A_v \frac{\sqrt{h}}{A_t} \right]$$

A_v= area of vertical openings (m^2)
h = height of vertical openings (m)
A_t = total area of enclosure, walls, ceiling and floor (including openings) (m^2) (1)

limits being: $0{,}02 \leq O \leq 0{,}2\ [m^{1/2}]$.
This value is found on the upper x axis and a vertical line is extended downwards (1) from this point until it meets the corresponding materials value line, b.
The value of b is calculated by the equation:

$$b = \sqrt{(\rho, c, \lambda)}$$

ρ = density of enclosure [kg/m^3]
c = specific heat of enclosure (J/kgK] (2)
λ = thermal conductivity of enclosure (W/mK)

To account for enclosures with different layers of material or for different materials in walls, ceiling and floor, see points 4 and 5 of Annex B ENV 1991-2-2. [2]

For this step in the procedures the equation $\Gamma = [O/b]^2 \Big/ \left(\frac{0.04}{1160}\right)^2$ is used. (3)

From this point on the materials line a horizontal line is charted across from left to right (2) to cross the time lines which emanate from the upper zero on the y axis. This line forms a new artificial time axis, the scale based upon the points where the time lines cross that artificial axis. Thus with the temperature line, the temperature path of the fire with time can be easily charted.
The original equation for the temperature against time is taken from

$$\theta_g = 1325\left(1 - 0{,}324e^{-0{,}2t^*} - 0{,}204e^{-1{,}7t^*} - 0{,}472e^{-19t^*}\right) \quad (4)$$

The next step is to find the position of maximum temperature and the time that it occurs. This is done by recommencing with the initial value for the opening factor, but this time starting on the O values found on the lower portion of the y axis.
From this point a horizontal line is charted to the corresponding fire load line (3) then charted vertically up to the lower x axis (4). Passing through this intersection, a new line starting from the upper zero on the y axis is drawn. This line continues along this path (5) until it strikes the new artificial time axis (this point being t_d). From this point a vertical line is charted up through the lower x (time) axis (this point being t_d^*) until it crosses the temperature curve (6). This point is defined by the time t_d and the maximum temperature θ_{max} provided by the horizontal line 7.

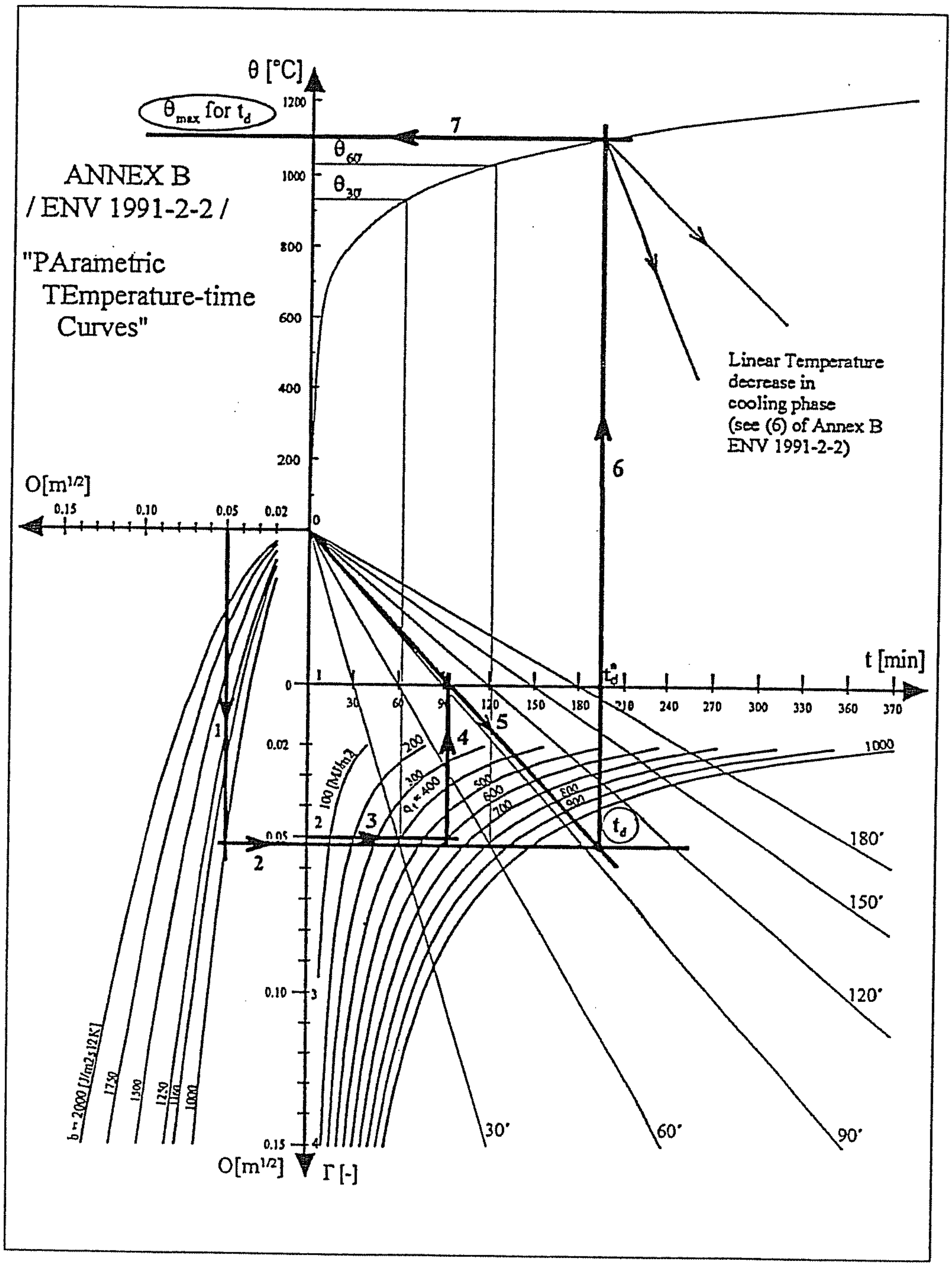

Fig. 1: Annex B Nomogram

For this step the equation base is defined by

$$t_d^* = \left(0,13 \times 10^{-3} \cdot q_{t,d} \cdot \Gamma\right)/O \text{ and } t_d^* = \Gamma \cdot t_d \quad (5)$$

$$t_d = 0,13 \times 10^{-3} \cdot q_{t,d} / O \quad (6)$$

The value of $q_{t,d}$ is the design value of the fire load density related to the surface area A_t of the enclosure

$$q_{t,d} = q_{f,d} \cdot A_f/A_t \text{ [MJ/m}^2\text{]} \quad (7)$$

$q_{f,d}$ = design value of the fire load density related to the surface area A_f of the floor [MJ/m²]

At the point (t_d, θ_{max}) the linear temperature decrease will begin, this being defined by point 6 of Annex B ENV1991-2-2 as a function of t_d^*

3. Annex E of ENV 1991-2-2: Equivalent Time

3.1 Description of the method

Annex E of Eurocode 1 offers a simple equation (8) to determine the required fire resistance time $t_{e,d}$ for a compartment, equivalent to the same duration of an ISO curve fire.

$$t_{e,d} = q_d \, k_b \, w_f \quad (8)$$

Before starting the calculation, it is necessary to determine the floor area of the compartment A_f as well as the total fire load $Q_{fi,k}$,mainly depending on the combustibility of the component parts and of the stored material. Annex D of [2] can be applied for this purpose. The design fire load density $q_{f,d}$ can be obtained from the multiplication of the characteristic fire load q_k by the safety factors γ_n and γ_q for the accepted failure risk in the case of fire and the influence of active fire measures, eq. 9.

$$q_d = \gamma_q \, \gamma_n \, q_k = \gamma_q \, \gamma_n \frac{Q_{fi,k}}{A_f} \quad (9)$$

The conversion factor k_b in equation (8) accounts for the heat transfer in the neighbouring component parts of the compartment. It depends on the thermal properties of the walls and ceilings of the enclosure, see table E.1 of [2].

The ventilation factor w_f can be calculated by the following equation ;

$$w_f = \left(\frac{6}{H}\right)^{0.3} \left(0.62 + 90\left(0.4 - \alpha_v\right)^4 / \left(1 + b_v \, \alpha_h\right)\right) \geq 0.5 \quad (10)$$

This equation depends on the height of the compartment H and on the ratios of the vertical (α_v) and horizontal (α_h) opening areas to the floor area A_f.
The dimensionless factor b_v can be determined by the following equation ;

$$b_v = 12.5\left(1 + 10\,\alpha_v - \alpha_v^2\right) \geq 10 \quad (11)$$

In case of small compartments, A_f < 100 m², Annex E allows to use the more simple equation 12. to calculate the ventilation factor ;

$$w_f = O^{-1/2}\ A_f/A_t \tag{12}$$

with the opening factor O being calculated according to Annex B, see eq. 1.

3.2 Nomogram of Equivalent time method (Annex E of ENV 1991 2-2)

Two nomograms are presented in figure 2. The first one (upper two drawings) can be used when there is no horizontal openings in the compartment (α_h=0). The second one (lower two drawings) is made considering that the compartment has the minimum of vertical opening (α_v=2.5%). The left drawings enable to calculate w_f (equation 10) in function of the dimensionless factor α_v (upper left drawing) or α_h (lower left drawing) and in function of the height of the compartment H. The right drawings enable to calculate the equivalent time in function of the w_f factor found on the left figure and in function of the design fire load density times the conversion factor k_b (equation 8).

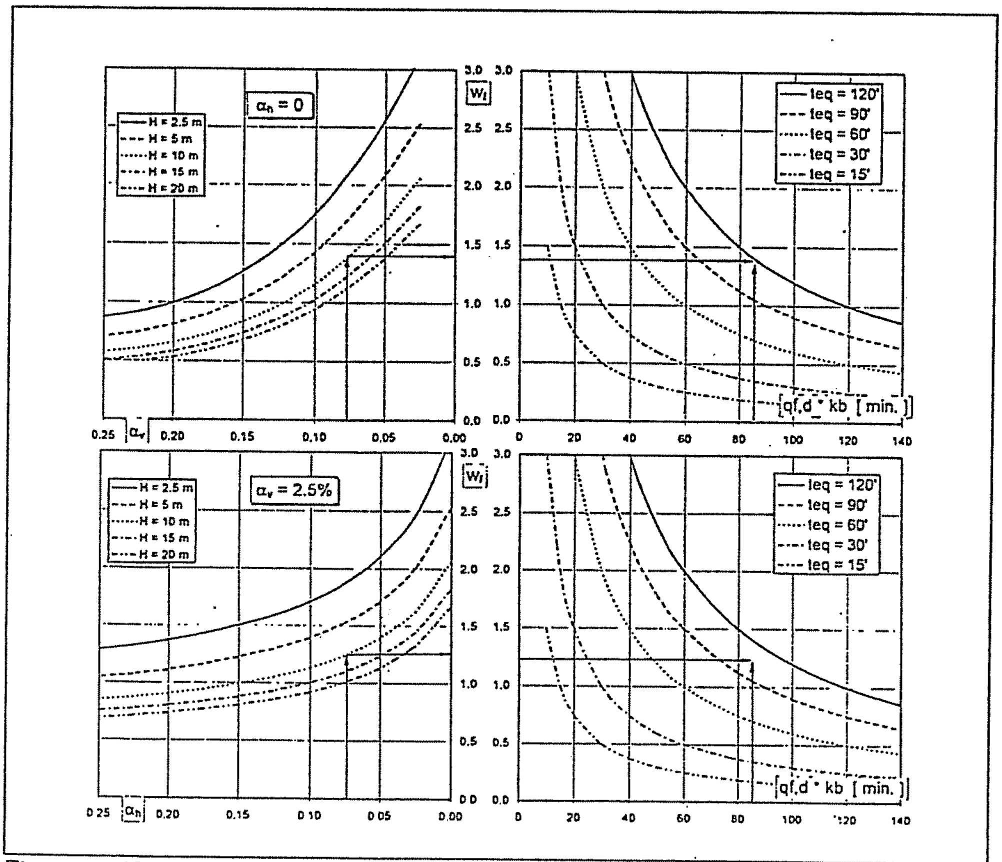

Figure 2. : Nomogram of Equivalent time

4. Comparison between Annex B and Annex E

4.1 First look on the equations of the 2 methods

It is interesting to notice that t_d^* from Annex B can be considered as an equivalent ISO time which is related to the temperature of a very light steel element (with a very big section factor, see EC3 Part 1.2). In other words, an element whose temperature is very close to the gas temperature. In Annex B, t_d^* is proportional to the opening factor O (eq 5 & 3) while in Annex E $t_{e,d}$ is proportional to $O^{-1/2}$. It will be verified by the parametrical study whether this apparent contradiction has practical effects.

4.2 Parametrical study

A parametrical study has been made with the 2 methods. 7 parameters are taken into account:

- the floor area of the compartment, A_f in m² 16, 25, **36**, 64, 100, 144, 256, 324, 400
- the height of the compartment, H in m 2.4, 2.5, **3.0**, 3.5, 4.0, 4.5, 5.0
- the design fire load density, q_d in MJ/m² 250, 500, **750**, 1000, 1250, 1500, 1750, 2000
- the opening height, h in m 0.2, 0.5, **1.0**, 1.5, 2.0, 2.5
- the position of the sill of the opening, h_s in m 0.0, **0.5**, 1.0
- the width of the opening, w in m 0.5, 1.0, 2.0, 3.0, **4.0**, 5.0
- the characteristics of the walls, b in $J/m^2s^{0.5}K$ 500, 1000, **1300**, 1600, 2000

The bold values are those of the reference case. The variation is made separately on the parameters. While one of them is allowed to vary from the reference case, the values of the other parameters remain fixed to the values of the reference case. This leads to 38 different cases. For the reference case we have the 7 bold values of the parameters and for the 37 other cases we have 6 bold values and one non bold value.

The results of this study are in case of annex B a set of temperature-time curves and in case of annex E a set of equivalent time. Figure 3 shows the results obtained by the 2 methods for the variation of the parameter A_f.

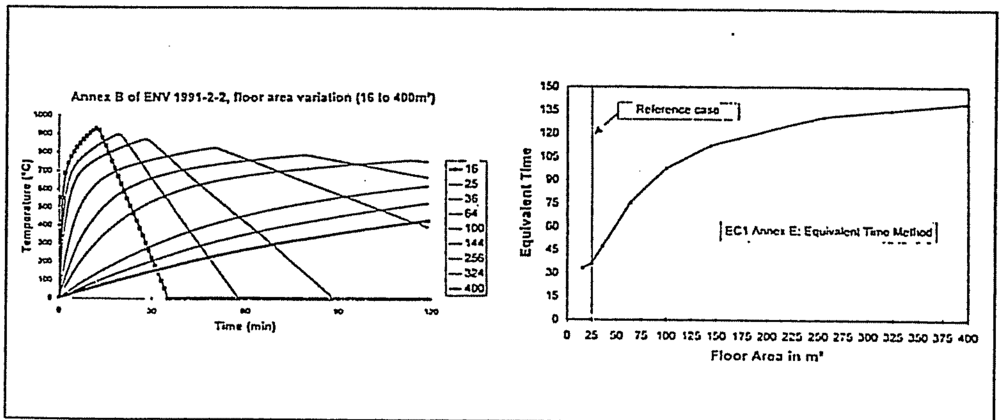

Fig. 3. Results obtained by the 2 methods.

4.3 Link between the two methods

In order to make a comparison between those methods we have to transform the results obtained with Annex B into equivalent times. This is done by calculations of temperatures in a structure and observation of the maximum temperature reached by this structure. Three structures have been chosen here;

- *Unprotected steel section.* In this case, the calculation of the uniform temperature is made by the method described in § 4.2.5.1. of Eurocode 3 : Part 1-2 [3]. A massivity of 211 m^{-1} was chosen corresponding, for example, to a HE 200 A section.
- *Protected steel section.* The same massivity is taken as for the unprotected section. The lightweight insulating material has the following properties: c_P = 850 J/(kgK); λ_P = 0.15 W/(m²K); ρ_P = 300 kg/m³ ; thickness = 20 mm. Those characteristics are similar to, say, vermiculite. Here the calculation of the uniform temperature is made by the method described in § 4.2.5.2. of Eurocode 3 : Part 1-2 [3].
- *Concrete structure.* The temperature is calculated in a semi-infinite concrete volume, at a penetration depth of 3 cm. The calculations are made with the non linear finite element code SAFIR of the University of Liège.

For the thermal calculations, steel and concrete thermal properties are taken from Eurocode 4 : part 1-2 [4].

The temperature in the structures submitted to the ISO curve is first calculated as a function of time. The same calculation is made for the same structures submitted to the natural fire curves obtained from annex B. In each case, the maximum temperature obtained in a structure submitted to a parametric temperature-time curve is reported on the corresponding curve obtained by the first calculation when the structure was submitted to the ISO curve. The moment when this temperature was obtained is defined as the equivalent time.

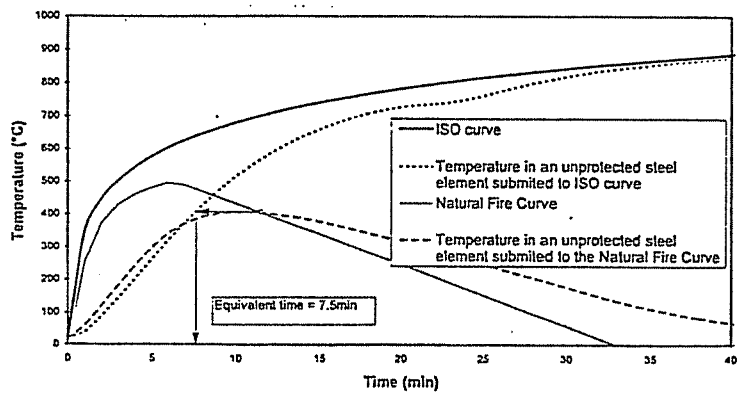

Fig. 4: Link between Natural Fire Curve and Equivalent Time

In other words, the equivalent time is the time during which a defined structure has to be submitted to the ISO fire curve in order to obtain, in the structure, the same effect (maximum temperature) as the natural fire curve would have produced.

4.4 Results

The position of the sill of the opening has no influence on the results,.for the annex B method as well as for the annex E method. The 6 other results of the parametrical study are shown on the figures 5.a and 5.b. The equivalent time is given in minutes as a function of the different parameters. Dotted lines are segments linking at least one point which is out of the field of application of the method used to obtained this point. The zones which are beyond the applicability limits of the methods have been shaded in grey on the figures.

It appears that the equivalent times calculated with a concrete structure and with a protected steel structure are very close to each other. This is because those two structure have the same thermal behaviour, i.e. a delay in time between the increase of temperature in the air and the temperature increase in the structure. Whether the delay is caused by a thermal protection or by a cover of concrete does not make a difference. It is also observed that these two curves are generally very similar to the equivalent time curves given by Annex E.

In some cases, the variation of the equivalent time calculated from the results of the Annex B with a parameter is different for the unprotected steel element than for the two protected elements. This is due to the fact that the maximum temperature calculated in the unprotected steel is mainly influenced by the maximum temperature in the air, whereas the maximum temperature in the protected elements is also influenced by the duration of the fire. Going from a severe but short fire to a less severe but longer one is generally favourable for a pure steel section, but it can be more critical for a protected element.
The same effect also explains why the apparent contradiction between Annex B and Annex E mentioned in § 4.1. disappears when temperatures are calculated in protected elements, but not in unprotected elements.

5. Conclusions

Two different methods are proposed in ENV 1991-2-2 [2] to take into account the influence of physical parameters on the severity of the fire. Those parameters are the fire load, , the geometry of the compartment and the thermal properties of the surrounding material.
This study shows that, despite apparent contradiction in the equations, the methods proposed in Annex B and in Annex E are coherent while evaluating the temperature in a protected steel element or in a concrete element.
When considering an unprotected steel element, these two methods have lead in some cases to very different results. None of two methods is systematically safer than the other.
If it is considered that Annex B provides a good approximation of the air temperature-time curve in the compartment, based on more refined models, thus allowing the calculation of the temperature in each structure type, whereas Annex E is an attempt to simplify the solution even further and to propose equivalent time irrespective of the structure, then this study tends to indicate that the approximation is valid in case of protected elements, but may not be valid in case of unprotected steel elements.
It can be noticed that the method of Annex E gives equivalent times which in each case are higher than 30 minutes. Nevertheless 30 minutes of ISO curve heating is an upper bearing limit for an unprotected steel element.

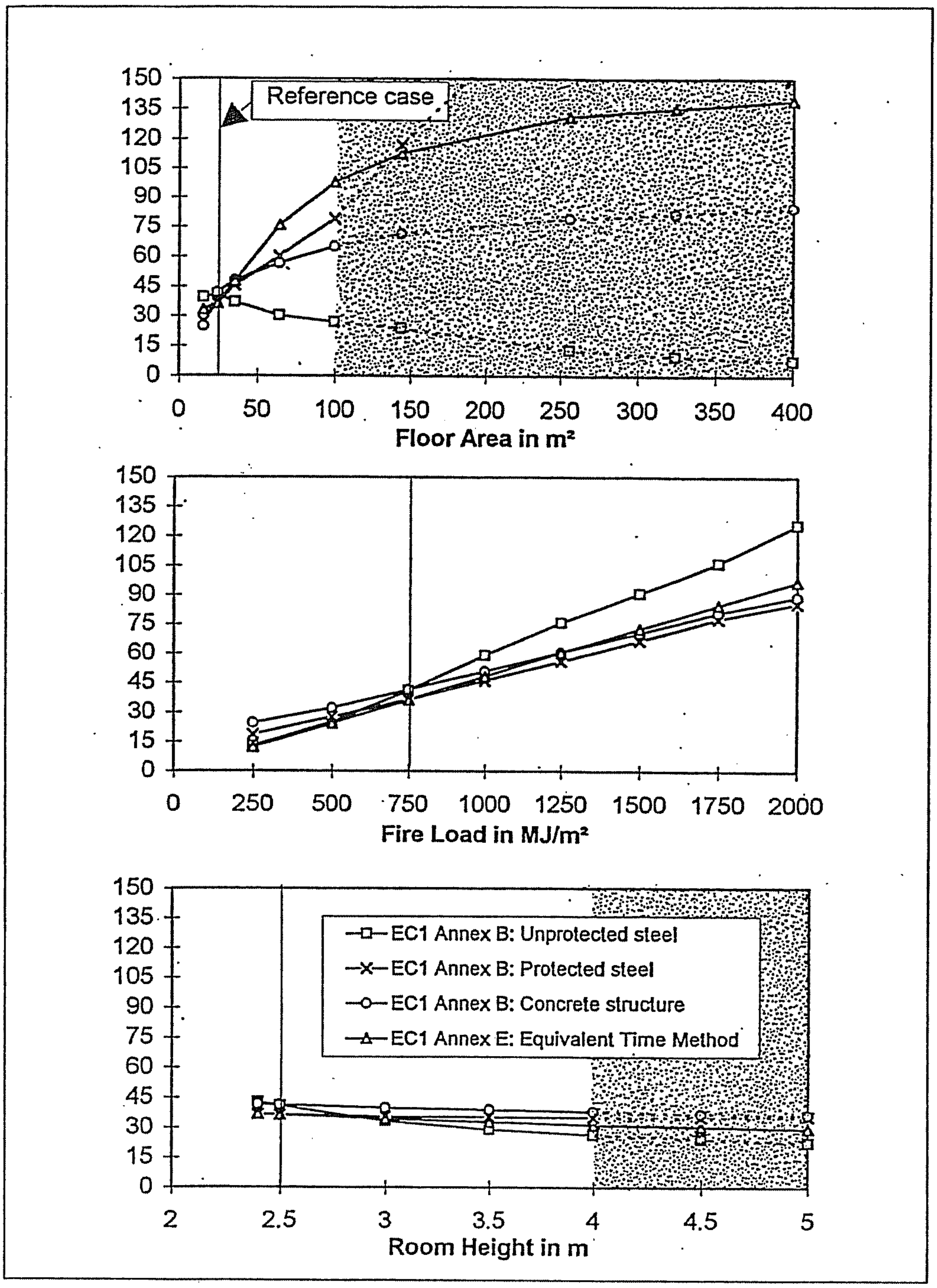

Fig.5.a: Results of the parametrical study

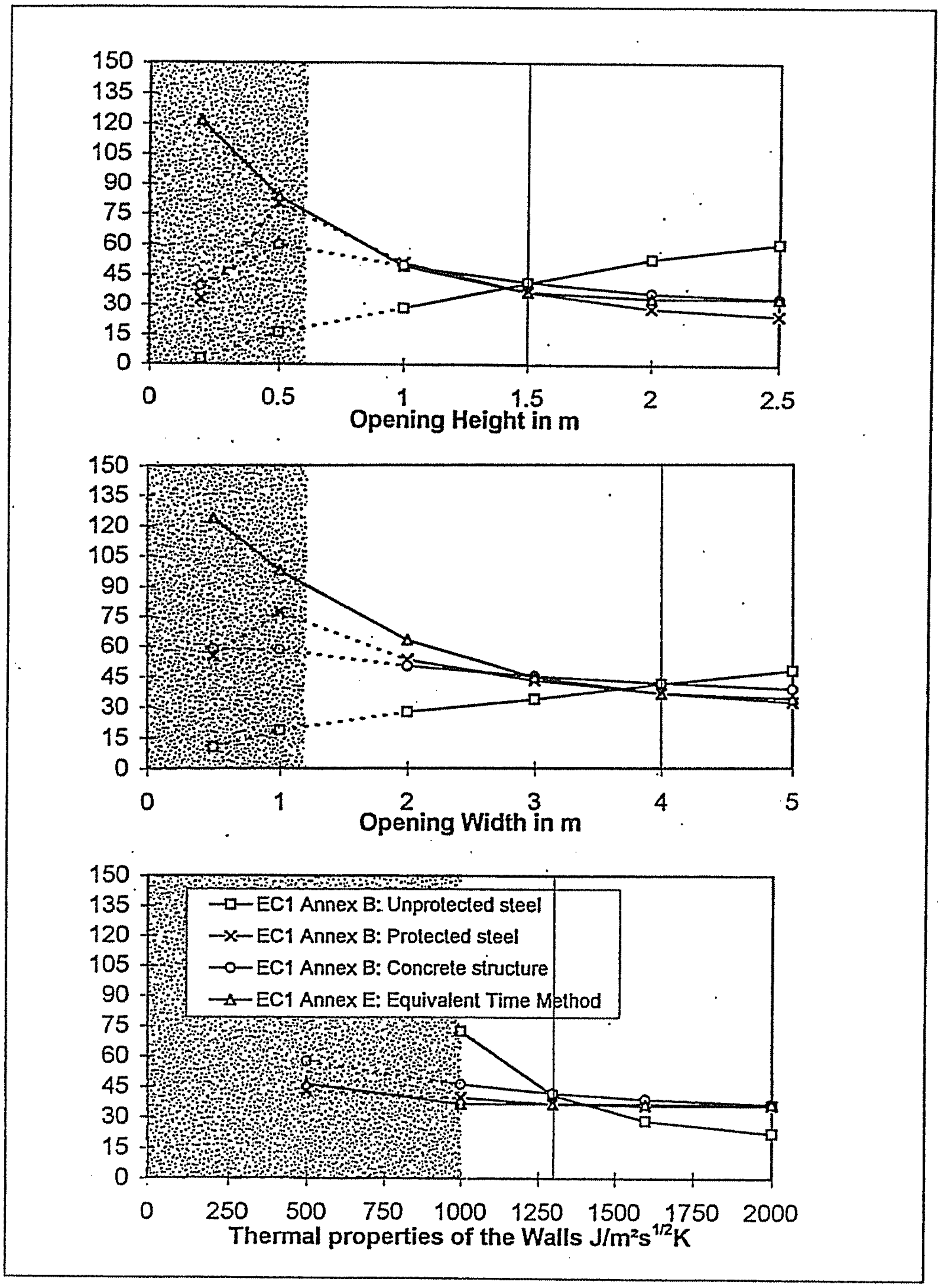

Fig. 5.b: Results of the parametrical study

6. Acknowledgement

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7. References

[1] Wickström, "Application of the Standard Fire curve for Expressing Natural Fires for Design Purposes".
[2] Eurocode 1: Basis of design and actions on structures. Part 2-2: Actions on structures exposed to fire, ENV 1991-2-2.
[3] Eurocode 3: Design of steel structures Part 1.2: General rules Strucural fire design, DRAFT ENV 1993-1-2.
[4] Eurocode 4. Design of Composite Steel and Concrete Structures. Part 1.2 : Structural Fire Design, prENV 1994-1-2, CEN , April 1994.
[5] J.B. Schleich, L.G. Cajot, M. Pierre, CEC Agreement 7210-SA / 125, 126, 213, 214, 323, 423, 522, 623, 839, 937 "Competitive Steel Buildings Through Natural Fire Safety Concept" Technical Report n° 1 Semestrial Report (01.07.1994 to 31.12.1994)
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