Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 74 (1996)

Artikel: Input data for the natural fire design of building structures

Autor: Twilt, Leen / Leur, Peter van de / Cajot, Luis-Guy

DOI: https://doi.org/10.5169/seals-56090

Input data for the natural fire design of building structures

TWILT, Leen
VAN DE LEUR, Peter
TNO Bouw
Delft
The Netherlands

CAJOT, Luis-Guy
SCHLEICH, Jean-Batist
Profil ARBED Research
Esch/Alzette
Luxembourg

JOYEUX, Daniel
KRUPPA, Joël
CTICM
Paris
France

1. INTRODUCTION

Traditionally, structural fire safety design is based on conventionally rather than on physically based thermal actions. This certainly holds for the international standards in the field, see e.g. [1]. Therefore, the release of Eurocode 1, part 2-2: "Actions on structures exposed to fire" [2], should be seen as a turning point: for the first time in international standardization, the natural fire concept is presented as an - for the time being -informative option. This option opens the possibility for a more nuanced and functionally based design, enabling to achieve rational and uniform fire safety levels.

It should be noted however that the Eurocode approach is a first and still incomplete attempt to arrive at more physically based thermal actions. Hence, the aim of this paper is:
- to identify the input data, necessary for a natural fire design;
- to critically discuss the input data, required by EC1, part 2-2;
- to demonstrate the potential of the natural fire design.

2. THE VARIOUS FIRE MODELS AND NECESSARY INPUT DATA

In order of increasing level of complexity, the following models are distinguished:

- **Nominal Fire Curves**

These are fire models in which the gas temperature time relationships are set by convention, i.e. no physical parameters are taken into account. In some models of this kind, the fire duration is related to the fire load density. Differentiation with respect to the type of combustible materials (e.g. cellulosic vs. hydrocarbon based curves).

- **One Zone Models**

In One Zone Models, the temperature in the fire compartment is assumed to be uniformly distributed. Gas temperature development is calculated by solving the heat and mass balance for the system consisting of the fire compartment (= fire zone) with its boundary structure including ventilation openings. Input data are the amount of combustible materials (representative for the total available heat of combustion), the ventilation conditions (representative for the rate of heat release) and the thermal inertia of structural elements bounding the fire compartment (representative for the convective heat losses to the environment).

- **Multi Zone Models**

These models are used when the fire is localized, e.g. in the growth phase of a fire. The fire compartment is divided into a hot zone, with a uniform temperature, above a fresh air zone and a fire plume which feeds the hot zone just above the fire. For each of the zones, the heat and mass balance is solved. (Semi-) empirical relations govern plume entrainment, radiative heat exchange between zones and mass flow through openings to adjoining compartments. Besides the input data necessary for one zone models, the (growth of the) fire size should be known. Only some of the available models can handle oxygen-starved conditions.

- **C(omputational) F(luid) D(ynamics) Models**

CFD models are based on two- or three-dimensional heat and mass transport, solving the equations of conservation of mass, momentum and energy for discrete points in the enclosed compartment and are, therefore, commonly referred to as "field models". Input data as for the multi zone models, however a more nuanced approach is viable. E.g., material properties and boundary conditions may be defined as function of the temperature, if necessary.

3. INPUT DATA REQUIRED BY EUROCODE 1, PART 2-2

Of the various fire models reviewed in the above section, only the Nominal Temperature-Time Curves and the One Zone Models are recognized in Eurocode 1, part 2-2.

Three types of Nominal Fire Curves are specified: the ISO standard curve, the hydrocarbon curve and a curve representative for external fire exposure. See Fig. 1. None of these curves require physical input data.

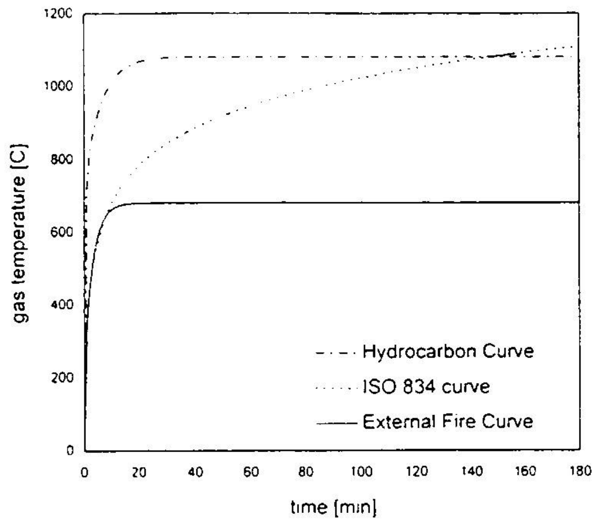

Fig. 1: Nominal fire curves.

As an alternative to nominal fire curves, thermal actions for internal members may be based on a One Zone Model ("Parametric Fire Exposure"). See Fig. 2. This requires the following input data:

- the total amount of combustion energy per unit of floor area, represented by the fire load density (see section 4);
- the so-called opening factor, representative for the rate of heat release (see section 5) and the heat loss through the ventilation flow (see section 6);
- the thermal inertia of the boundary enclosure, representative for the convective heat losses through the solid boundaries (see section 6).

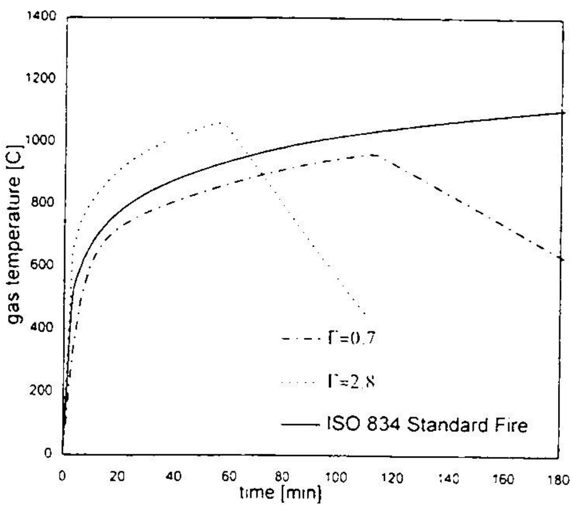

Fig. 2: Parametric fire curves

The thermal actions for external members may, alternatively, be based on an external fire exposure model in which size and temperature distribution of the flames from the openings of the fire compartment are determined. In essence the underlying fire model is a One Zone Model. In principle similar input data as for the Parametric Fire Exposure play a role, complemented with some geometrical parameters . However, especially the rate of heat release is treated in a somewhat different manner. See section 5.

4. FIRE LOAD DENSITY

The fire load Q in a fire compartment is defined by the total energy liable to be released. Building components such as wall and ceiling linings, and building contents, such as furniture constitute the fire load. Divided by a reference area (generally the floor area), the fire load Q gives the fire load density q_f. The fire load density is the source of the fire development and is also the production-source term in the heat balance equation solved by calculation models.

In the EC 1, the characteristic fire load density is defined by the following equation:

$$q_f = \frac{1}{A_f} \sum_i \psi_i \, m_i \, H_{ui} \, M_i \qquad (1)$$

where: M_i = the mass of the material i (kg)
H_{ui} = the net calorific value of the material i (MJ/kg)
m_i = the factor describing the combustion behaviour of the material i
ψ_i = the factor of assessing protected fire load of the material
A_f = the floor area of the fire compartment

M_iH_{ui} represents the total amount of energy contained in material and released assuming a complete combustion.

The 'm' factor is a non-dimensional factor between 0 and 1, representing the combustion efficiency: m = 1 corresponds to complete combustion and m = 0 to the extreme situation in which a combustible material contributes no heat at all to the fire process. The m-factor is a function of the type of fuel (solids, liquids) and its geometrical properties (porosity, massivity), its position in the fire compartment (exposed area to radiation) and the fire characteristics (temperature, oxygen content, etc.). So far, no international agreement exists on the way to determine the m-factor. Apparently, the m-factor may be assumed conservatively as m = 1.

The ψ-factor in equation (1) is introduced to take into account protection of the fire load, for example by putting it inside a cabinet. It has a value between 0 (complete protection for the full fire duration) and 1 (the protection has no influence on the energy release). The protection may reduce the energy release, but often does so for a limited period of time, which depends on the fire conditions (radiation, temperature). This is not reflected in the present concept of the ψ-factor which is time independent. For many practical applications, ψ = 1.0 is a realistic value.

According to EC 1, the fire load density may be determined from a national fire load classification system, or - for an individual project - by performing a fire load survey. The classification on the basis of the occupancy of the fire compartment calls for a statistical approach. A summary of statistics available in Europe is well represented in a CIB/W14 workshop report [3]. Operational guidance on application for non specialists is however lacking. This should be provided for the next version of EC 1.

The EC option for a specific study of the fire load may be extended to give a general procedure as follows:

- The net calorific value of numerous materials is known. A limited overwiew is presented in EC 1, part 2-2. If necessary, H_{ui} can be determined on basis of a generally accepted test method (calorific bomb, ISO 1716).
- In addition, the m-factor should be known. As mentioned earlier however, an internationally accepted test method is not available. A concept of such a method is under development within the scope of ECCS project "Natural Fire Safety Concept" (NFSC). Basic ideas behind that work are, that the conditions under which the m-factor is determined should follow real fire conditions closely, and that modern measuring techniques should be applied. Until such a method is available, a conventional value for the m-factor of 0.7 is proposed.

- The fire model of Annex C determines whether the fire is fuel or ventilation controlled, and then uses the appropriate relationship to calculate the RHR.

$$R = \min \left(\frac{L}{\tau_F} \; ; \; 0.18 \, (1 - e^{-0.036 \cdot \eta}) \, A_w \sqrt{h . W/D} \right) \qquad \textbf{(2)}$$

where:

R	=	rate of burning (kg of wood/s)
L	=	fire load ($=A_F.Q$) (kg of wood)
τ_F	=	free burning fire duration (assumed to be 1200 s)
A_w	=	sum of window area on all walls ($A_w = \sum_i A_{wi}$) (m^2)
h	=	weighted average of window height on all walls ($h = \sum_i A_i h_i / A_w$) (m)
W	=	width of wall containing window(s) (m)
D	=	depth of fire compartment (m)
η	=	$A_T / A_w \sqrt{h}$ ($m^{-1/2}$)
A_T	=	all surfaces minus windows (m^2)

The first term in equation (2) relates to fuel controlled fires and the second to ventilation controlled fires. The expression for fuel control is only approximate as it assumes that all fuel controlled fires have a duration of twenty minutes.

For the ventilation controlled regime, various sets of equations exist for the RHR but the differences are small. This can be seen in graphical form in Fig. 4, which compares expressions for RHR from different sources with experimental data [4,5].

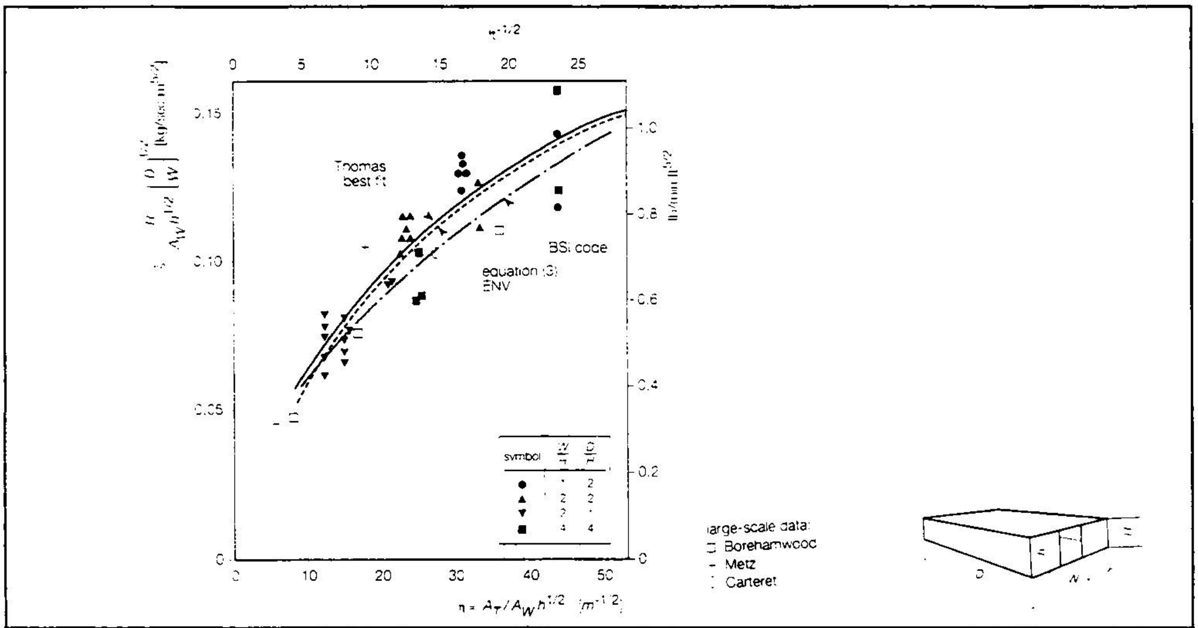

Fig. 4: Rate of heat release, ventilation controlled fires.

Pre-flashover fires are not dealt with in the Eurocode, but they are important in egress analysis and in the design of heat and smoke extraction systems. They will also gain relevance for structural fire safety when the concept of localised fire is accepted. For pre-

- The Eurocode parametric fire models use $\sum_i \psi_i \ m_i \ H_{ui} \ M_i$ but more advanced models use the rate of heat release directly (see next section).

5. RATE OF HEAT RELEASE AND VENTILATION CONDITIONS

An essential parameter in a fire is the rate of heat release (RHR). It is the source of the gas temperature rise, and the driving force behind the spreading of gas and smoke.

A typical fire starts small and goes through a growth phase. Two things can then happen: either during the growth process there is always enough oxygen to sustain combustion. In that case, when the fire size reaches a maximum, the RHR is limited by the available fire load (fuel controlled fire). Or, the size of openings in the compartment enclosure is too small to allow enough air to enter the compartment. Then, the RHR is limited by the available oxygen and the fire is said to be ventilation controlled. Both ventilation and fuel controlled fires can go through flashover. This important phenomenon marks the transition from a localised fire to a fire involving all the exposed combustible surfaces in the compartment.

The two regimes are illustrated in Fig. 3, which presents graphs of the rate of burning (kg/s) vs. the ventilation parameter $A\sqrt{h}$, with A being the opening area and h being the opening height. Graphs are shown for different fire load densities. Starting on the left side of the figure in the ventilation controlled regime, with increasing ventilation parameter the rate of burning grows up to the limiting value determined by the fire load density and then remains approximately constant (fuel controlled region).
The models described in the annexes to EC 1 treat the RHR in different ways.

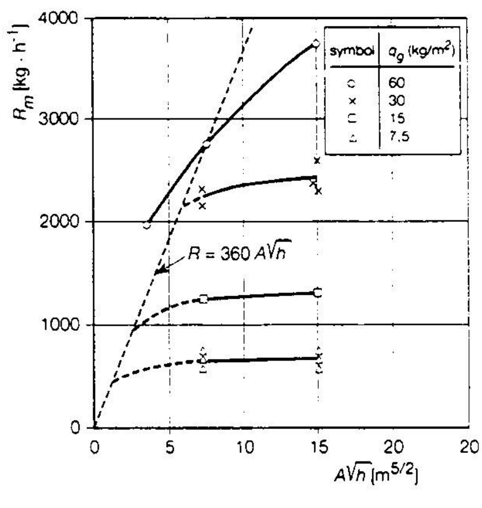

Fig. 3: Rate of heat release for different ventilation regimes.

- The parametric fires of Annex B do not deal with the RHR explicitly. Implicit in the model however, a ventilation controlled post-flashover fire is assumed and the RHR is calculated proportional to $A\sqrt{h}$.

flashover fires one method of calculating the RHR uses conventional or calculated values of the RHR per unit area, and estimates the rate of fire spread (i.e. the rate of growth of the area involved in fire) to calculate RHR as a function of time. In other cases it may be acceptable to simply assume a fixed area involved in fire and find a corresponding value for the rate of heat release. In all cases the RHR per unit floor surface must be available. A British draft standard [6] only states two values as a guideline, depending on the building occupancy:

Building use is "retail" : 0.5 MW/m^2
Building use is "offices" : 0.25 MW/m^2

The Belgian standard for the design of heat and smoke venting systems [7] contains tables with values of the RHR density for specified combustibles in storage halls. As default values to be used when the exact nature of the combustible is unknown, 0.5 and 0.25 MW/m^2 are mentioned for mechanical and natural ventilation respectively.

6. HEAT LOSSES

The heat losses suffered by the combustion gases are important factors to the temperature development of a compartment fire. Heat losses occur to the compartment boundaries by convection and radiation. A substantial amount of heat can also be removed from the compartment by the ventilation flow. This last contribution to the heat loss is quite easy to model. In this paper, attention will be focused on the heat losses to the compartment boundaries.

It has long been known that the heat losses to the compartment boundaries can play a decisive part in determining whether a given fire will develop to flash over or not. This is why even the simpler approaches to fire modelling take this aspect into account.
The most popular way to do that is through the concept of the "thermal inertia" b of the wall material. This factor is defined for a homogeneous wall construction by:

$$b = \sqrt{\lambda \cdot \rho \cdot c} \qquad (3)$$

where: λ = heat conductivity (W/mK)
ρ = mass density (kg/m^3)
c = heat capacity (J/kgK)

It can be shown that under certain conditions (among others, "thermally thick" wall, constant surface temperature) the heat flux into the wall depends on b only.

The parametric fire models in the Eurocode have b as the single parameter to account for the convective heat losses. For the important case of walls consisting of multiple layers of different materials, an effective value of b is calculated from the contributions of the different layers, according to:

$$b = \sqrt{\sum s_i \cdot c_i \cdot \lambda_i \Big/ \sum \frac{s_i \cdot c_i \cdot \lambda_i}{b_i^2}} \qquad (4)$$

where: λ_i = heat conductivity of material i (W/mK)
s_i = thickness of material i (m)
c_i = heat capacity of material i (J/kgK)
b_i = b-factor of material i ($J/m^2s^{1/2}K$)

The expression has some obvious shortcomings:

- The sequence of the different materials is not accounted for; a brick wall insulated with wood panels gives the same result as a wood panel 'insulated' with a brick wall.
- In extreme but practical cases, the expression leads to an unrealistic value for b. Consider a wall consisting of two layers of different materials. If the first layer (heated side) is thermally thick, the other layer will have no influence on the heat flux through the surface (example: well insulated brick). The effective b should be equal to b_1. On the other side, if the first layer is thermally very thin, the effective b should be equal to b_2 (e.g. thin steel sheet covering an insulating layer). The weighing procedure in the expression does not follow these relationships.

To illustrate the consequences of the use of the b-factor, in Fig. 5 the temperature development in a fire compartment (Γ-fires), calculated by means of EC1 for different b-factors, is compared with the results of calculations based on a rigorous treatment of the 1-dimensional heat conduction equation. For the boundary construction of the fire compartment - floor area 5 x 5 m^2 - various practical sandwich constructions have been chosen. Conclusion is that use of the EC1 rule for calculating effective b-factors is not recommended. Work is currently under progress to establish an alternative 'rule of thumb' to calculate the effective b-factor. For the time being, as a first (safe) approach it is proposed to take the smallest b-factor of the materials in the sandwich construction as the effective b-factor.

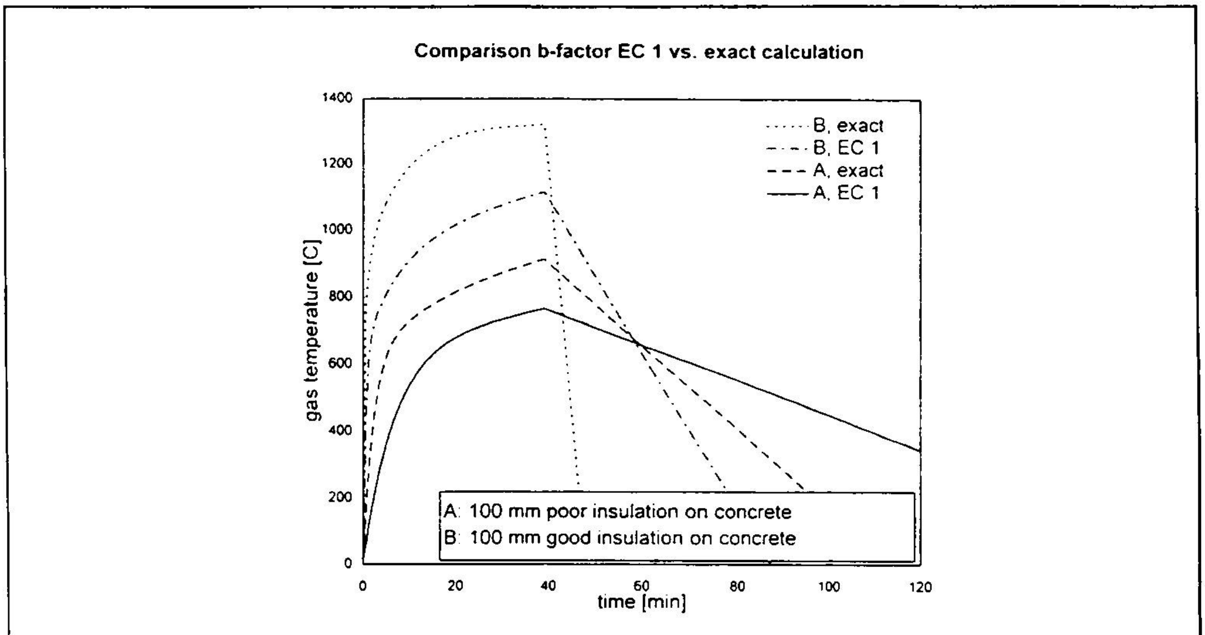

Fig. 5: Parametric fire curves: comparison of calculation methods of the thermal inertia of the boundary construction.

7. PRACTICAL EXAMPLES

7.1 Fires in open car parks

As a basis for the theoretical simulation of the effect of fires in open car parks, tests have been carried out in the scope of the ECSC-project "Fire Safety in Open Car Parks" [8,9]. During these tests, the rate of heat release was measured and the following "Car Fire Model" was deduced. See also Fig. 6.
During the tests flames emerged from the car mainly through the windscreen and the rear window. The hot gases in the flames move upwards due to the buoyancy. This buoyant flow is referred to as " fire plume". Two plumes are distinguished, referred to as the "front fire plume" and the "rear fire plume". The axis of these fire plumes are assumed to be 2 m apart corresponding to the dimensions of ordinary passenger cars. The rate of heat release as function of time of both the front and the rear fire plume was deduced for the measured RHR. Time integration over the RHR curves gives the total energy release (= 4.0 GJ).

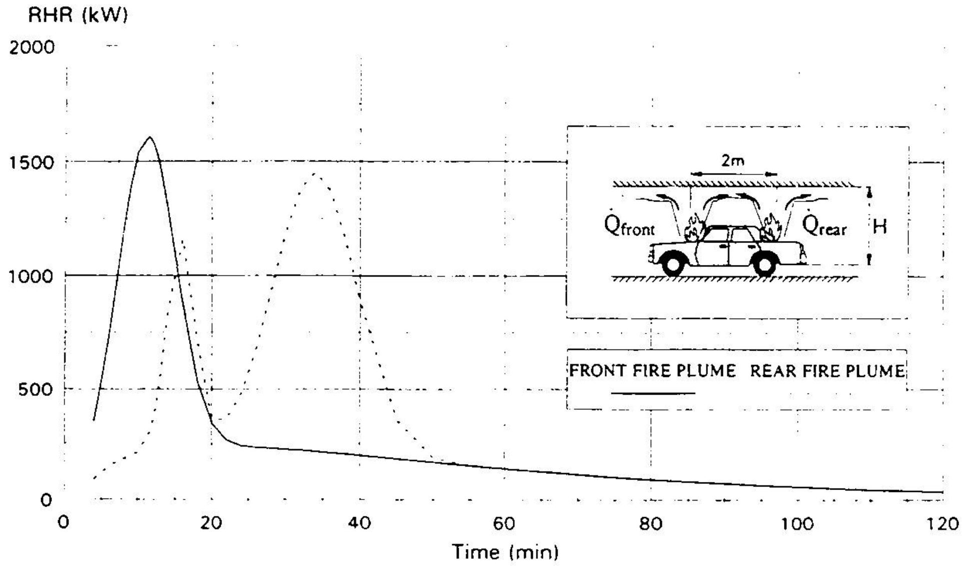

Fig. 6: Car fire model used for Open Car Parks.

The above "car fire model" was fed into a CFD model which allowed to obtain the gas temperature field. The temperatures inside the sections and the structural behaviour during the fire were analysed using advanced thermal and mechanical response models (CEFICOSS, TASEF and SISMEF). The numerical simulations have shown that composite steel concrete beams can safely be used, without any fire protection on the structural steelwork.

7.2 Fires in large compartments

In 1994 a series of two full scale fire tests have been performed in a large exhibition hall (dimensions 144 x 65 x 28 m) at the "Parc des Expositions de la Porte de Versailles", Paris

[10]. The fire load, consisting of appr. 3,500 kg wood in the form of pallets, was concentrated on a surface of 5 x 6 m^2. During one of the tests the rate of heat release was assessed by monitoring the mass loss during the fire. Also, radiative flux in the vicinity of the fire and both gas temperatures and steel temperatures at various spots in the load bearing structure have been measured. The fires were extinguished after approximately 20 minutes.

The tests allowed to evaluate the application of multi-zone models for localized fires in extremely large halls. Refer to Fig. 7 for a comparison between test results and calculation results. The agreement is satisfactory.

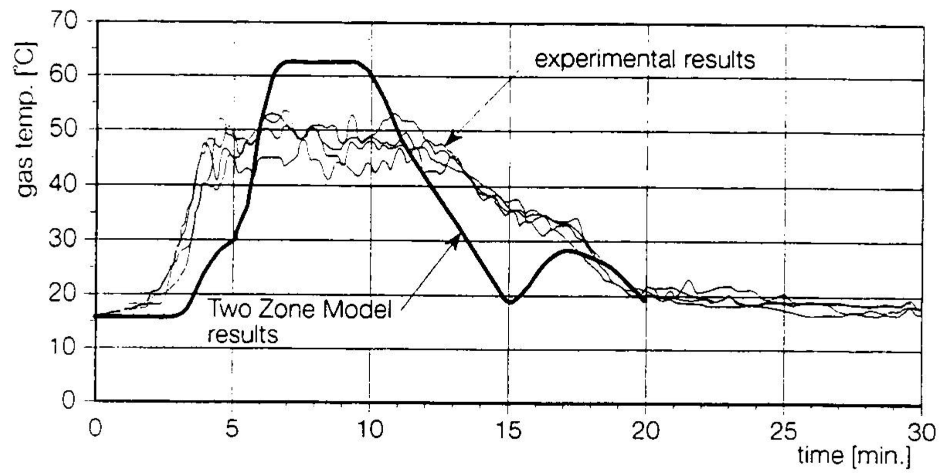

Fig. 7: Localised fire in a large compartment: comparison between test and multi zone calculation results.

8. CONCLUSIONS

The increase of knowledge within the last decade allows performance-based codes for structural fire design. This will lead to design assumptions beyond the conventional ISO-fire approach, explicitly taking into account more realistic fire conditions.

A first step ahead is the Eurocode 1, part 2.2 which has been agreed as ENV in 1994. However, in view of the lack of operational data and the references made to national guidelines, the rules given in this first version of the document are not fully adequate.

As explained in this paper, substantial efforts are still necessary to introduce more complete and operational rules in the next version of Eurocode 1, part 2-2. This next version is expected by the middle of the year 2000.

Within the ECCS project "Natural Fire Safety Concept", efforts are under way to contribute to this goal.

9. BIBLIOGRAPHY

[1] ISO TC 92: “Fire Resistance Tests - Elements of Building Construction”. International Standard ISO 834, 1st edition, 1975.

[2] Eurocode1, part 2-2: “Basis of design and actions on structures: Actions on structures exposed to fire”. ENV 1991-2-2, November, 1994.

[3] CIB W14: “Design Guide for Structural Fire Safety”. Fire Safety Journal, vol. 10 (2), 1986.

[4] Thomas, P.H.: “Fires in Model Rooms”; CIB research programmes, Building Research Establishment current paper CP 32/74, BRE, Borehamwood, 1974.

[5] Law, M.: “Fire Safety of External Building Elements - The Design Approach”; AISC Engineering Journal, 2nd Quarter/1978, p. 59-74.

[6] BSI: "Draft code of practice for the application of fire safety engineering principles to fire safety in buildings". Bsi 94/340340 DC, (draft for public comment), June 1994.

[7] Belgian Normalization Institute: “Protection incendie dans les batiments-Conception et calcul des installations d’évacuation de fumées et de chaleur-Partie 1: Grands espaces intérieurs non cloisonnés s’étendant sur un niveau”. Belgian Standard NBN S21-208, 1st edition, August 1993.

[8] ECCS - Technical Committee 3 - Fire Safety of Steel Structures: “Fire Safety in Open Car Parks-Modern Fire Engineering”. Technical Note N°75, first edition, 1993.

[9] Mangs, J. and Keski-Rahkonen, O.: “Characterization of the fire behaviour of a burning passenger car. Part I : Car fire experiments”. Fire Safety Journal, vol. 23, (1994), p. 17-35.

[10] Joyeux , D:“Simulation of Tests in ‘Parc des Expositions’”. CTICM- report no. INC 95/34-DJ/IM, February 1995.

Leere Seite
Blank page
Page vide