A Simplified Prediction Method of Real Fire Exposure as a Basis for an Analytical Structural Fire Design

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ABSTRACT

This paper presents a method for predicting the fire temperature -time curve in compartments as a part of a analytical approach for the determination of fire behaviour and loadbearing capacities of structures and structural elements.
Existing data in the basis of graphs were analysed and equations derived on the basis of results of analysis are suggested for the calculation of the temperature-time curve in compartments.

KEYWORDS: fire behaviour, real fire, temperature-time curves, fire load, opening factor.

INTRODUCTION

A fully analytical evalution procedure of fire behaviour of structural elements and structures with the consideration of real fire exposure can be subdivided into three main steps: prediction of; compartment fire temperature-time curve, temperature-time fields in the structure and the reduction rate in load-carrying capicity of the structure until reaching a limit state condition.

If the prediction of fire resistance for elements is made on the basis of the standard temperature-time curve,then the first step (prediction of compartment fire temperature-time curve) is deleted, since using the standard temperature-time curve is a traditional practice in solving fire resistance design problems.

Observations of and research on the consequences of real fires in different objects show [1-5], that their gas temperature-time curves can be very different from the standard curve. This necessitates such supplements to the evalution procedure of fire behaviour of structural elements and structures, that permit the consideration of the whole "thermal" history of fire development in compartments.

DEVELOPMENT AND MAIN CHARACTERISTICS OF FIRE BEHAVIOUR

According to the fire engineering design approach suggested in references [9, 10]the real fire exposure, depends upon three main parameters:

Ψ - coefficient of fire intensity, which expresses the ratio of gastemperature in compartment in any moment of fire exposure to the temperature of the standard fire at the some time;

τ_m - the time to reach the maximum gastemperature in compartment t_m , min in a real fire exposure;

V_c - a parameter, which characterizes the descending rate of gastemperature in compartment in the stage of fire decay, °C/min.

The existing data on fire exposure models in compartments [2, 3, 4] are given in a system of tables and nomograms. In this form, these data are used with some difficulty for calculation purposes.

The aim of this contribution is to get a system of equations for the determination of the real fire parameters, which permits their direct use in calculations of the structural fire behaviour.

To achieve this aim, it became necessary to evalute how the parameters Ψ , τ_m and V_c depend upon the fire load in compartments, the conditions of ventilation and other factors.

As widely acknowledged [2-5], the main factors, which determine the fire temperature-time curve in compartments, are the fire load density q (MJ/m^2), the conditions of ventilation and the thermal properties of the structures enclosing the compartment. These influences are expressed by the following factors:

$$K_1 = \frac{A_2 \sqrt{H}}{A_3} \qquad (1)$$

$$K_2 = \frac{A_1 \sqrt{H_1}}{A_2 \sqrt{H}} \qquad (2)$$

$$K_{1,red} = f_1 \cdot f_2 \cdot K_1 \qquad (3)$$

$$q_{red} = f_1 \cdot q \qquad (4)$$

where

K_1 and K_2 - opening factors for vertical and horizontal openings, respectively, $m^{1/2}$;

A_1 and A_2 - area of vertical and horizontal opening of the compartment, respectively, m^2;

A_3 - total boundary surface area of the compartment, openings areas included, m^2;

H - average height of vertical openings of the compartment, m;

H_1 - the distance from the plane of horizontal opening to the centre of the vertical openings, m;

$K_{1,red}$ - equivalent opening factor, $m^{1/2}$;

q_{red} - equivalent fire load density, MJ/m^2.

The value of coefficients f_1 and f_2 are determined by using tabels 1 and 2 respectively [3, 4].

TABLE 1

Description of enclosing construction	value of coefficient f_1 when K_1 equals					
	0.02	0.04	0.06	0.08	0.1	0.12
Standard fire compartment	1	1	1	1	1	1
Concrete	0.85	0.85	0.85	0.85	0.85	0.85
Light weight conrete	3	3	3	3	3	2.5
Concrete (50%) and light weight concrete (50%)	1.35	1.35	1.35	1.5	1.55	1.65
Concrete (33%), light weight concrete(50%) and other components (17%)	1.65	1.5	1.35	1.5	1.75	2
from the inside outwards						
Plaster board penel (13 mm)						
Mineral wool(100 mm)						
Brickwork (200 mm)						
Uninsulated steel sheeting (80%) and concrete (20%)	1-0.5	1-0.5	0.8-0.5	0.7-0.5	0.7-0.5	0.7--0.5

TABLE 1 (continued)

Description of enclosing construction	value of coefficient f_1 when k_1 equals					
	0.02	0.04	0.06	0.08	0.1	0.12
Concrete (20%), two plasterboad panels (2x13 mm)	1.5	1.45	1.35	1.25	1.15	1.05
Sheet steel - diabase wool (100 mm) - sheet steel	3	3	3	3	3	2.5

TABLE 2

K_2	f_2	K_2	f_2
0	1	1	3,2
0.5	2.1	1.5	4.6

ANALYSIS AND RESULTS

In order to establish a relation between parameters Ψ , τ_m, V_c and the values q_{red} and $K_{1,red}$, the graphs of fire temperature-time curves (Fig. 1) [2, 3, 4], which were derived by solving the energy and mass balance equations of the compartment fire and verified by experimental results, were carefully analysed. The results of the analysis showed that:

- the coefficient of fire intensity Ψ does not depend upon the fire load density q_{red} , but is influenced by the opening factor $K_{1,red}$ (Fig. 2);

- the time to reach the maximum value of gastemperature in compartment τ_m is directly proportional to the fire load density and inversely proportional to the opening factor (Fig 3);

- when the fire load density increases, the value of parameter V_c decreases (Fig. 4).

After the mathematical approximation of the results of analysis (Fig. 2-4), the following equations are suggested for Ψ , τ_m and V_c ($K_{1,red}$ in $m^{1/2}$ and q_{red} in MJ/m^2):

$$\Psi = 1.37 - \frac{150\, K_{1,red} - 0.65}{(K_{1,red})^2 \times 10\,000} \tag{5}$$

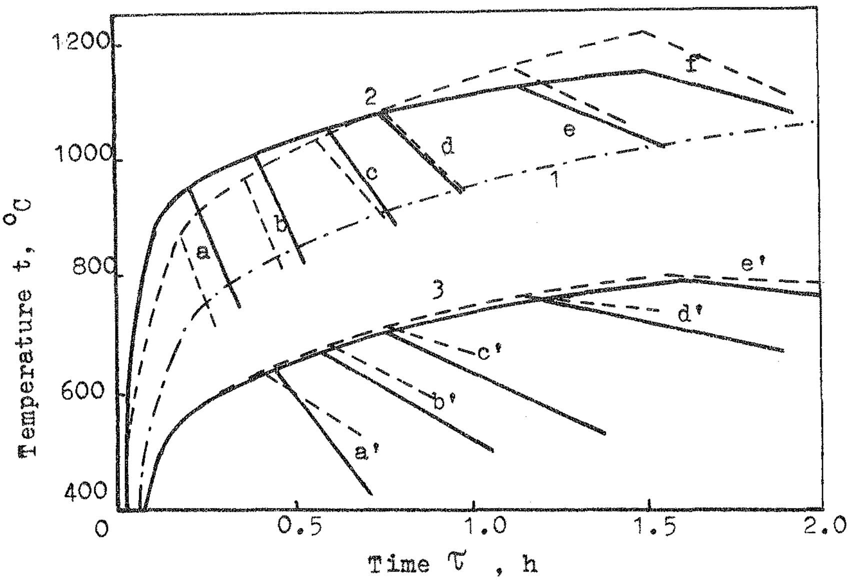

FIGURE 1. Fire gastemperature-time curves in compartment for different values of factor of opening $K_{1,red}$ (m$^{1/2}$) and fire load q_{red} (MJ/m^2):
1. The standard temperature-time curve. 2. Fire temperature-time curves for $K_{1,red}$ = 0.08 and: a - q_{red} = 151, b - 251, c - 377, d - 502, e - 754, f - 1004. 3. Fire temperature-time curves for $K_{1,red}$ = 0.02 and: a' - q_{red} = 62.8, b' - 94,2, c' - 126, d' - 188, e' - 251.
———— data of ref. [2], _ _ _ _ calculation results by the suggested method.

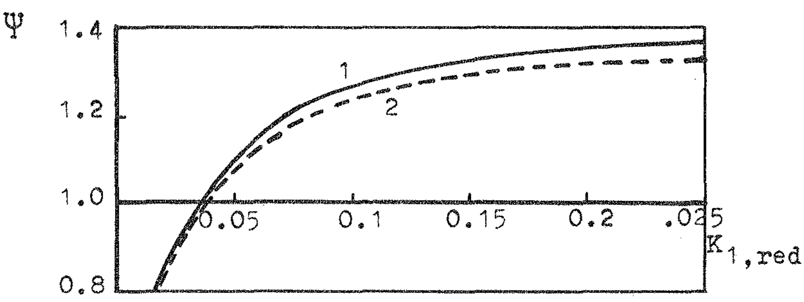

FIGURE 2. Relationship between coefficient of fire intensity and factor of opening $K_{1,red}$ (m$^{1/2}$):
1. data of ref. [2];
2. calculation results by using equation (5).

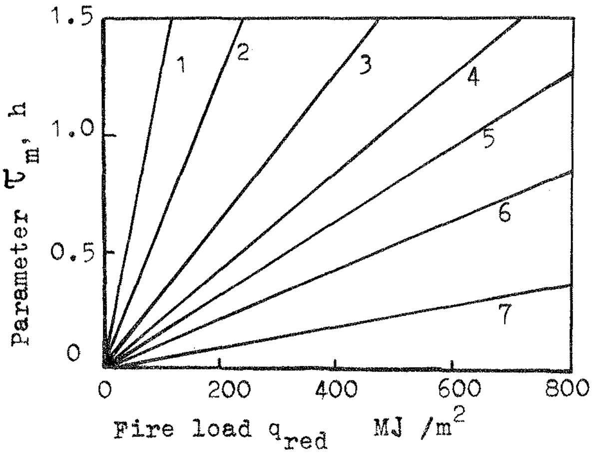

FIGURE 3. Relationship between time τ_m of reaching the maximum gastemperature in compartment fire and fire load q_{red} for different values of factor of opening $K_{1,red}$ ($m^{1/2}$) - analysis of data of ref [2].
1 - $K_{1,red}$= 0.01, 2 - 0.02, 3 - 0.04, 4 - 0.08, 5 - 0.12, 6 -0.03

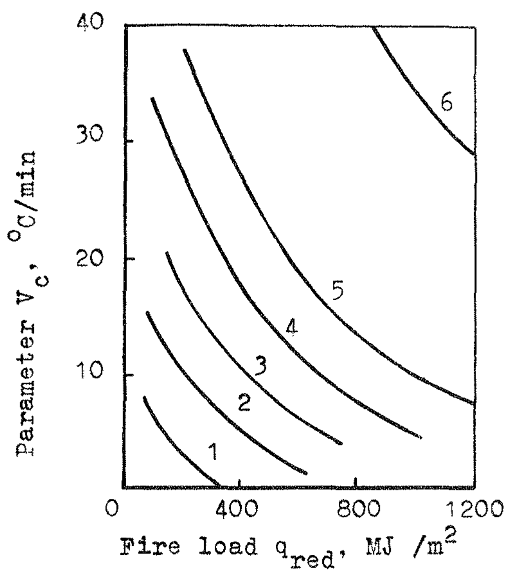

FIGURE 4. Relationship between the descending velocity V_c of fire gastemperature in compartment in the stage of fire decay and fire load q_{red} for different values factors of openings $K_{1,red}$ ($m^{1/2}$) - analysis of data of ref [2]:
1 - $K_{1,red}$ = 0.02, 2 - 0.04, 3 - 0.06, 4 - 0.08, 5 - 0.12, 6 - 0.3.

$$\tau_m = \frac{60\ q_{red}}{8318\ K_{1,red} - 4021\ (K_{1,red})^2} \qquad (6)$$

$$V_c = \frac{98\ 000\ K_{1,red} - 1500}{q_{red}} \qquad (7)$$

The value of gastemperature t_f in compartment at time τ_i (min) of fire exposure can be determined by the following equations:

$$\text{when } \tau_i < \tau_m ,\ t_f\ (\tau) = \Psi \cdot 345 \log(8\tau_i + 1) + t_o \qquad (8)$$

$$\text{when } \tau_i > \tau_m ,\ t_f\ (\tau) = \Psi \cdot 345 \log(8\tau_i + 1) - V_c(\tau_i - \tau_m) + t_o \qquad (9)$$

where

t_o - temperature of compartment at $\tau_i = 0$, ^oC.

DISCUSSION

The calculation results of fire temperature-time curves by using formules (1-9), are shown by dashed lines in Fig. 1, compared with data in ref.[2]. The comparison shows that equations (1-9) are sufficiently accurate for practical purposes.

Example: given - dimensions of compartment: 11.8 x 6.05x 3 m; area of vertical openings; A = 0.9 x 2 + 2 (1.5 x 1.5)= 6.3 m^2 ; average height of vertical openings: H = 1.615 m; fire load density: q = 272 MJ/m^2 ; material of bounding structures: normal concrete.

Determine the values of the parameters of real fire. Solution - 1. area of bounding structures A_3 = 2 (11.8x6.05+ 6.05 x 3 + 11.8 x 3) = 249,88 m .
2. determine the opening factor K_1 by equation (1):

$$K_1 = \frac{6.3\ \sqrt{1.615}}{249.88} = 0.032\ m^{1/2}$$

3. by using table 1 coefficient f_1 = 0.85
4. by using table 2 coefficient f_2 = 1
5. determine the equivalent opening factor by equation (3):

$$K_{1,red} = 0.85 \times 0.032 = 0.0272\ m^{1/2}$$

6. determine the equivalent fire load density by equation(4):

$$q_{red} = 0.85 \times 272 = 231\ MJ/m^2$$

7. determine parameter Ψ , τ_m and v_c by equations (5-7):

$$\Psi = 1.37 - \frac{150 \times 0.0272 - 0.65}{(0.0272)^2 \times 10\ 000} = 0.907$$

$$\tau_m = \frac{60 \times 231}{8318 \times 0.0272 - 4012 \times (0.0272)^2} = 62 \text{ min}$$

$$v_c = \frac{98000 \times 0.0272 - 1500}{231} = 5.05\ ^{\circ}\text{C/min}$$

CONCLUSIONS

Together with the method given in references [9, 10] equations (1-9) enable an efficient prediction of fire behaviour and load bearing capicity of structural elements to be carried out with the consideration of real fire exposure (and not only standard fire). The method can also used for research purposes and an estimation of the structural safety of buildings after fires and other engineering problems.

REFERENCES

1. Lie, T.T., Characteristic Temperature Curves for Various Fire Severities, Fire Technology, 10:4, 315-326, 1974.

2. Magnussen, S.E., Thelanderson, S., "Temperature-Time Curces for the Complete Process of fire Development. A Theoritical Study of Wood Fuel Fires in Enclosed Spaces", Acta Polytechnica Scandinavica, Ci 65, Stockholm, 1970.

3. Pettersson, O., Magnusson, S.E., Thor, J., Fire Engineering Design of Steel Construction, Stockholmm 1976 (Swedish end., 1974).

4. Barthelemy, B., Kruppa, J., Resistance an Feu des Structures Beton-Acier-Bois, Edition Eyrolles, Paris, 1978.

5. Harmathy, T.Z., Mchaffey, J.R., Post-Flashover Compartment Fires, Fire and Material, 7:2, 1983.

6. Kordina, K., Aktuelle Problems des vorbeugenden baulichen Brandschuts, Betonwerk, Fertigteil, Tech., 48:8, 509-517, 1982.

7. Wickstörm, U., Application of the Standard Fire Curve for Expressing Natural Fires for Design purposes, Fire Safety Science and Engineering, ASTM STP 882, Phyladelphia, 145-159, 1985.

8. Pettersson, O., Practical Need of Scientific Material Models for Structural Fire Design - General Review, Fire Safety Journal, 13:1, 1-8, 1988.

9. Roitman, V.M., With Account of the Real Fire Impact, Pozharnoe delo (Fire Engineering), 3, 19-20, 1988.

10, Roitman, V.M., Yesterday Stereotypes or New Approach? On the Theory of the Structural Fire Resistanc Analysis, Pozarnoe delo (Fire Engineering), 9, 8-10, 1989.