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 an 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 evaluation 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 capacity 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 evaluation 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 gas temperature in compartment in any moment of fire exposure to the temperature of the standard fire at the same time;

\( \tau_m \) - the time to reach the maximum gas temperature in compartment \( \tau_m \), min in a real fire exposure;

\( V_c \) - a parameter, which characterizes the descending rate of gas temperature 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 evaluate how the parameters \( \Psi \), \( \tau_m \) 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/m²), the conditions of ventilation and the thermal properties of the structures enclosing the compartment. These influences are expressed by the following factors:

\[
K_1 = \frac{A_2 \sqrt{H}}{A_3} \quad (1)
\]

\[
K_2 = \frac{A_1 \sqrt{H}}{A_2 \sqrt{H}} \quad (2)
\]

\[
K_{1,\text{red}} = f_1 \cdot f_2 \cdot K_1 \quad (3)
\]

\[
q_{\text{red}} = f_1 \cdot q \quad (4)
\]

where

\( K_1 \) and \( K_2 \) - opening factors for vertical and horizontal openings, respectively, m²/m²;

\( A_1 \) and \( A_2 \) - area of vertical and horizontal opening of the compartment, respectively, m²;
A₃ - total boundary surface area of the compartment, openings areas included, m²;

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

H₁ - the distance from the plane of horizontal opening to the centre of the vertical openings, m;

K₁, red - equivalent opening factor, m²/2;

gₐ₀ - equivalent fire load density, MJ/m².

The value of coefficients f₁ and f₂ are determined by using tables 1 and 2 respectively [3, 4²].

TABLE 1

<table>
<thead>
<tr>
<th>Description of enclosing construction</th>
<th>value of coefficient f₁ when K₁ equals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Standard fire compartment</td>
<td>1</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.85</td>
</tr>
<tr>
<td>Light weight concrete</td>
<td>3</td>
</tr>
<tr>
<td>Concrete (50%) and light weight concrete (50%)</td>
<td>1.35</td>
</tr>
<tr>
<td>Concrete (33%), light weight concrete(50%) and other components (17%)</td>
<td>1.65</td>
</tr>
<tr>
<td>from the inside outwards</td>
<td></td>
</tr>
<tr>
<td>Plaster board panel (13 mm)</td>
<td></td>
</tr>
<tr>
<td>Mineral wool (100 mm)</td>
<td></td>
</tr>
<tr>
<td>Brickwork (200 mm)</td>
<td></td>
</tr>
<tr>
<td>Uninsulated steel sheeting (80%) and concrete (20%)</td>
<td>0.5</td>
</tr>
</tbody>
</table>
TABLE 1 (continued)

<table>
<thead>
<tr>
<th>Description of enclosing construction</th>
<th>value of coefficient $f_1$ when $k_1$ equals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Concrete (20%), two plasterboard panels (2x13 mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Sheet steel - diabase wool (100 mm) - sheet steel</td>
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</tr>
</tbody>
</table>

TABLE 2

<table>
<thead>
<tr>
<th>$K_2$</th>
<th>$f_2$</th>
<th>$K_2$</th>
<th>$f_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>3.2</td>
</tr>
<tr>
<td>0.5</td>
<td>2.1</td>
<td>1.5</td>
<td>4.6</td>
</tr>
</tbody>
</table>

ANALYSIS AND RESULTS

In order to establish a relation between parameters $\Psi$, $T_m$, $V_c$ and the values $q_{red}$ and $K_{i,red}$, 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 $\Psi$ does not depend upon the fire load density $q_{red}$, but is influenced by the opening factor $K_{i,red}$ (Fig. 2);

- the time to reach the maximum value of gas temperature in compartment $T_m$ 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 $\Psi$, $T_m$ and $V_c$ ($K_{i,red}$ in m/² and $q_{red}$ in MJ/m²):

$$\Psi = 1.37 - \frac{150 K_{i,red} - 0.65}{(K_{i,red})^2 \times 10000}$$  \hspace{1cm} (5)
FIGURE 1. Fire gas temperature-time curves in compartment for different values of factor of opening $K_{i, red}$ (m$^2$/h) and fire load $q_{red}$ (MJ/m$^2$):
1. The standard temperature-time curve. 2. Fire temperature-time curves for $K_{i, red} = 0.08$ and: $a - q_{red} = 151$, $b - 251$, $c - 377$, $d - 502$, $e - 754$, $f - 1004$. 3. Fire temperature-time curves for $K_{i, red} = 0.02$ 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 $K_{i, red}$ (m$^2$/h):
1. data of ref. [2];
2. calculation results by using equation (5).
FIGURE 3. Relationship between time $\tau_m$ of reaching the maximum gas temperature in compartment fire and fire load $q_{red}$ for different values of factor of opening $K_{i,red}$ (m$^2$) - analysis of data of ref [2].

$1 - K_{i,red} = 0.01, 2 - 0.02, 3 - 0.04, 4 - 0.08, 5 - 0.12, 6 - 0.2$.

FIGURE 4. Relationship between the descending velocity $V_c$ of fire gas temperature in compartment in the stage of fire decay and fire load $q_{red}$ for different values factors of openings $K_{i,red}$ (m$^2$) - analysis of data of ref [2].

$1 - K_{i,red} = 0.02, 2 - 0.04, 3 - 0.06, 4 - 0.08, 5 - 0.12, 6 - 0.3$. 

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The value of gas temperature $T_m$ in compartment at time $T_m$ (min) of fire exposure can be determined by the following equations:

When $T_i < T_m$, $t_f (T_i) = \Psi \cdot 345 \log(3T_i + 1) + t_o$ (8)

When $T_i > T_m$, $t_f (T_i) = \Psi \cdot 345 \log(3T_i + 1) - V_c (T_i - T_m) + t_o$ (9)

where

$t_o$ - temperature of compartment at $T_i = 0$, $^\circ C$.

DISCUSSION

The calculation results of fire temperature-time curves by using formulas (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 6.05 x 3 m; area of vertical openings: $A = 0.9 \times 2 + 2 (1.5 \times 1.5) = 6.3 \text{ m}^2$; average height of vertical openings: $H = 1.615$ m; fire load density: $q = 272 \text{ MJ/m}^2$; material of bounding structures: normal concrete.

Determine the values of the parameters of real fire. Solution - 1. area of bounding structures $A_b = 2 (11.8 \times 6.05 + 6.05 \times 3 + 11.8 \times 3) = 249.88 \text{ m}^2$.

2. determine the opening factor $K_1$ by equation (1):

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

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):

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

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

$$q_{\text{red}} = 0.85 \times 272 = 231 \text{ MJ/m}^2$$
7. determine parameter $\Psi$, $T_m$ and $v_c$ by equations (5-7):

\[
\Psi = 1.37 - \frac{150 \times 0.0272 - 0.65}{(0.0272)^2 \times 10000} = 0.907
\]

\[
T_m = \frac{60 \times 231}{8318 \times 0.0272 - 4012 \times (0.0272)^2} = 62 \text{ min}
\]

\[
v_c = \frac{98000 \times 0.0272 - 1500}{231} = 5.05 \text{ °C/min}
\]

CONCLUSIONS

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

REFERENCES


