CALCULATION OF THE TEMPERATURE OF A PROTECTED STEEL ELEMENT EXPOSED TO FIRE ACCORDING A PARAMETRIC CURVE

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Abstract: *In this study the problem of evaluation the temperature of a protected steel element exposed to fire according EN 1991-1-2 and EN 1993-1-2 is considered. A macros for MS Excel is developed for this purpose. The input data are :*

- *the section factor of the element -* A_p/V;
- *the specific heat of the insulation -* c_p;
- *the thickness of the insulation material -* d_p;
- *the thermal conductivity of the fire protection material -* λ_p;
- *the design fire load density -* $q_{f,d}$;
- *opening factor - O;*
- *the thermal properties of fire sector enclosure - b*

The obtained results are presented in graphical and a tabular form.

A proposition for a smoother transition between fuel controlled and ventilation controlled cases is made

Key words*: fire situation, protected steel sections, MS Excel, parametric curve.*

1. Calculation the temperature of a steel element in fire

The temperature of a steel element increase in time interval Δt(recommended 20 seconds) by $\Delta\Theta_{a,t}$:

(1.1) $$\Delta\theta_{a.t} = \frac{\lambda_p / d_p}{c_a \rho_a} \frac{A_p}{V} \left(\frac{1}{1 + f/3} \right) \left(\theta_{g.t} - \theta_{a.t} \right) \Delta t - \left(e^{f/10} - 1 \right) \Delta\theta_{g.t} \;\; (but\ \Delta\theta_{a.t} = 0,\ if\ \Delta\theta_{g.t} > 0)$$

(1.2) $$\varphi = \frac{c_p \rho_p}{c_a \rho_a} d_p \frac{A_p}{V}$$

when:

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C_a the temperature dependant specific heat of steel, J/kgK

C_p the temperature independant specific heat of the fire protection material , J/kgK

ρ_a , ρ_p the unit mass of the steel and protection material, kg/m^3

A_p/V section factor , m^{-1}

d_p the thickness of the fire protection material, m

Δt the time interval , sec;

λ_p is the thermal conductivity of the fire protection system , W/mK;

$\theta_{g.t}, \theta_{a.t}$ the steel and the ambient temperature at time , ^0C

$\Delta\theta_{g.t}$ the increase of the ambient temperature during the time interval Δt , K;

$\Delta\theta_{a.t}$ the increase of the steel element temperature during the time interval Δt, K;

The section factor Ap/V is evaluated according the recommendations given in table 4.3 [2]

2. Calculation of the ambient temperature in a fire compartment according a parametric curve (Appendix A of EN 1991-1-2 [1]).

The ambient temperature expressed by parametric curve depends on:
design fire load density related to the surface area A_t , $q_{t,d}$, the opening factor of the fire compartment O, thermal absorptivity b , duration of heating phase in fuel controlled fire t_{lim}.

These parameters are calculated by:

(2.1) $q_{t,d} = q_{f,d} \, . A_f \, / \, A_t \; , \; MJ / m^2$

(2.2) $O = A_V \sqrt{h_{eq}} \, / \, A_t \quad , \quad m^{1/2}$

(2.3) $b = \sqrt{\rho\lambda c} \quad , \quad J/m^2 \, s^{1/2} \, K$

When:

$q_{f,d}$ design fire load density related to the floor area A_f , MJ/ m^2;
A_f floor area of the fire compartment A_f , m^2;
A_v total area of vertical openings on all walls , m^2;
h_{eq} weighted average of window heights on all walls , m;
A_t total area of enclosure (walls, ceiling and floor, including openings), m^2;
ρ Density, kg/m^3;
λ thermal conductivity, W/m/K;
c specific heat, J/kg K;

The time t_{max}, at which the maximum temperature is reached, is given by:

(2.4) $t_{\max} = \max[0, 2.10^{-3}.q_{td} \, / \, O; \; t_{\lim}]$

The duration of t_{lim} is in the case of: slow fire growth rate - 25 minutes, average fire growth rate - 20 minutes and fast fire growth rate - 15 minutes. In equations for calculation of the ambient temperature in the fire compartment is used parameter t* expressed by:

(2.5) $$t^* = \Gamma . t$$

In case of ventilation controlled fire, the coefficient Γ is given by:

(2.6) $$\Gamma = \frac{(O/0,04)^2}{(b/1160)^2}$$

In fuel controlled fire for heating phase O_{lim} is used instead O :

(2.7) $$O_{\lim} = \frac{0,1.10^{-3}.q_{t,d}}{t_{\lim}}$$

The parametric curves consist of two parts: a heating phase - exponential curve and a cooling phase - a linear one.
In the heating phase the relationship " Temperature – time " is :

(2.8) $$\Theta_g = 20 + 1325 \left(1 - 0,324\, e^{-0,2t*} - 0,204\, e^{-1,7t*} - 0,472\, e^{-19t*}\right)$$

when:
Θ_g is the ambient temperature in the fire compartment, ^{0}C
In the cooling phase the relationships are :

(2.9)
$$\Theta_g = \Theta_{max} - 625\,(t^* - t^*_{\max}.\,\mathrm{X})\ за\ t^*_{max} \le 0,5$$
$$\Theta_g = \Theta_{max} - 250\,(3 - t^*_{\max}.\,X)\,(t^* - t^*_{max}.\,\mathrm{X})\ за\ 0,5 < t^*_{max} < 2$$
$$\Theta_g = \Theta_{max} - 250\,(t^* - t^*_{max}.\,X)\ за\ t^*_{max} \ge 2$$

In equations (2.9) t^* , $t^*_{\max}$ and X are respectively :

(2.10) $$t^* = t.\Gamma$$

(2.11) $$t^*_{max} = (0,2\,.\,10^{-3}.q_{t,d}\,/\,O)\,.\Gamma$$

(2.12) $$\mathrm{X} = 1,0 \text{ if } t_{\max} > t_{lim} \quad or\ \mathrm{X} = t_{lim}.\Gamma /\ t^*_{max} \quad \text{if } t^*_{max} = t_{\lim}$$

3. Description of the program:
The program uses 3 functions and one subroutine specially developed for this purpose. The first function is FtitagISO834(t As Double) As Double which calculates the ambient temperature according nominal curve ISO834 given by [1] :

(3.1) $$\Theta_g = 20 + 345.log_{10}(8t+1)$$

The second function is deltaAapr(ftitag As Double, titam As Double) As double - calculates changes in the temperature of the element for time interval Δt , according equation (1.1).

The third function is TITA_G(t As Double) As Double. It performs this part of the calculations of parametric curve which are time depending on according: (2.8) and (2.9).The procedure Parametric() is only used for that part of the calculations of the parametric curve which does not depend on the time.

The essential part of the program is implemented in procedure Main () in the beginning at the program. The input parameters are read. They can by divided in two groups. The first one is related to the parametric curve : $q_{t,d}$, O, t_{lim} , b. The second part of input data is related to steel sections and their protections: A_m/V, λ_p, d_p, ρ_p, c_p and Δt.

The procedure Parametric() starts after the reading of the input data. The calculation of the temperature of the element is realized in two nested loops. In the inner loop time interval of five minutes (300) seconds is divided in to intervals Dt (recommended) 20 seconds. The differences in the the elements temperature for fire actions according Parametric and ISO834 curves for each interval are calculated.The interval in which the maximum value of the temperature of the steel element caused by parametric curve is reached is the last one in which the difference of the temperature is positive. The outer loop covers a period corresponding to $3*t_{20}$ (three time the duration of heating plus cooling phases of the parametric curve).

In outer loop every five minutes the temperatures in the element corresponding to parametric and ISO834 curves are recorded in two arrays. The t_{ef} is the time when the temperature in the element in the case of the fire action according ISO834 is equal to maximum of the steel element temperature in case of a parametric curve. It is a measure of the effects of the fire impact on parametric curve compared to the nominal curve ISO834.The time period t_{eff} can be determined with two nested loops similar in the above described algorithm.

4. Numerical example :

A steel element with cross section HE 240A is protected with 20mm gypsum board for a fast fire growth rate t_{lim}=15 min.

The enclosure of fire compartment is made from normal weight concrete.

The input data and results are presented on Fig. 1

5. Proposition for smoother transition between fuel controlled and ventilation controlled cases

The gas temperature in the fire compartment is calculated in both cases – fuel and ventilation controlled fire by the equation 2.8 and 2.9. However the Opening factor O is replaced by O_{lim} in the case of fuel controlled fire. This leads to a difference of 20 to 30% in the maxima of the steel element temperature when $t_{max} = t_{lim}$ and when it is a little bit greater – see Fig. 2.To avoid this differences an additional code in subroutine Parametric() is proposed :

```
dt02 = (tlim - 0.2 * 10 ^ -3 * qtd / O) / tlim
If  dt02 >  -1E-10  And  dt02 < 0.1 Then
        kcor = 4 - 30 * dt02
Else
        kcor = 1
```

```
End If
Gamalim = Gamalim * kcor
```

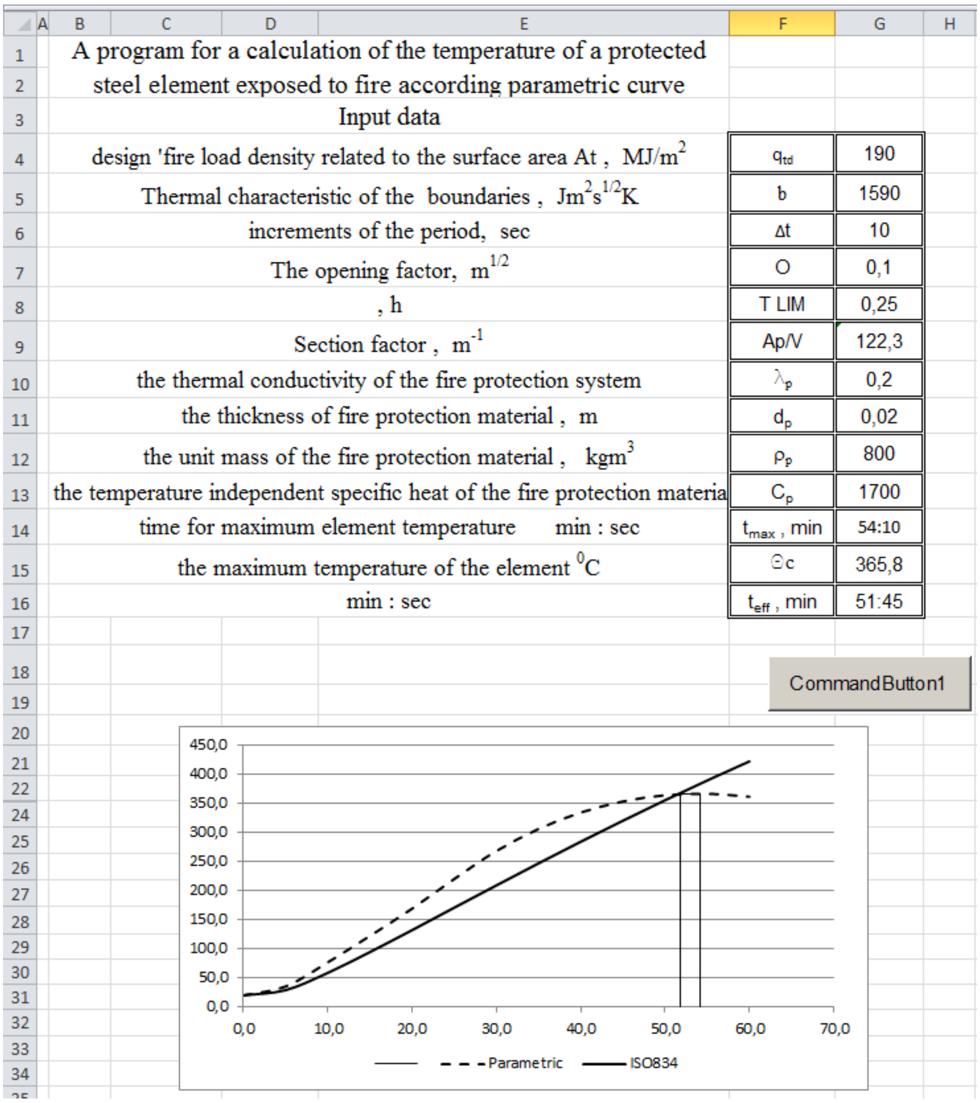

Fig. 1 Worksheet of the numerical example

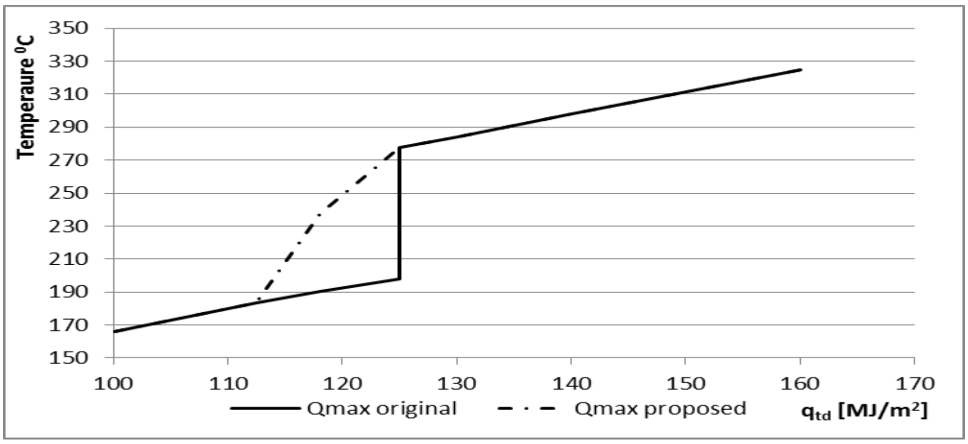

Fig. 2 Relationship between $q_{t,d}$ and Θ_{max} before and after smoother.

6. Conclusions

The fire model based on parametric curves is more realistic. Its take in to account:fire loads, the opening in the walls and the material of the fire compartment.

The developed macros for MS Excel has a user-friendly interface. The results are presented in a tabular and graphical form.

The proposed method for smooth transition between fuel controlled and ventilation controlled fire gives results in favor of security.

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