# Thermal response

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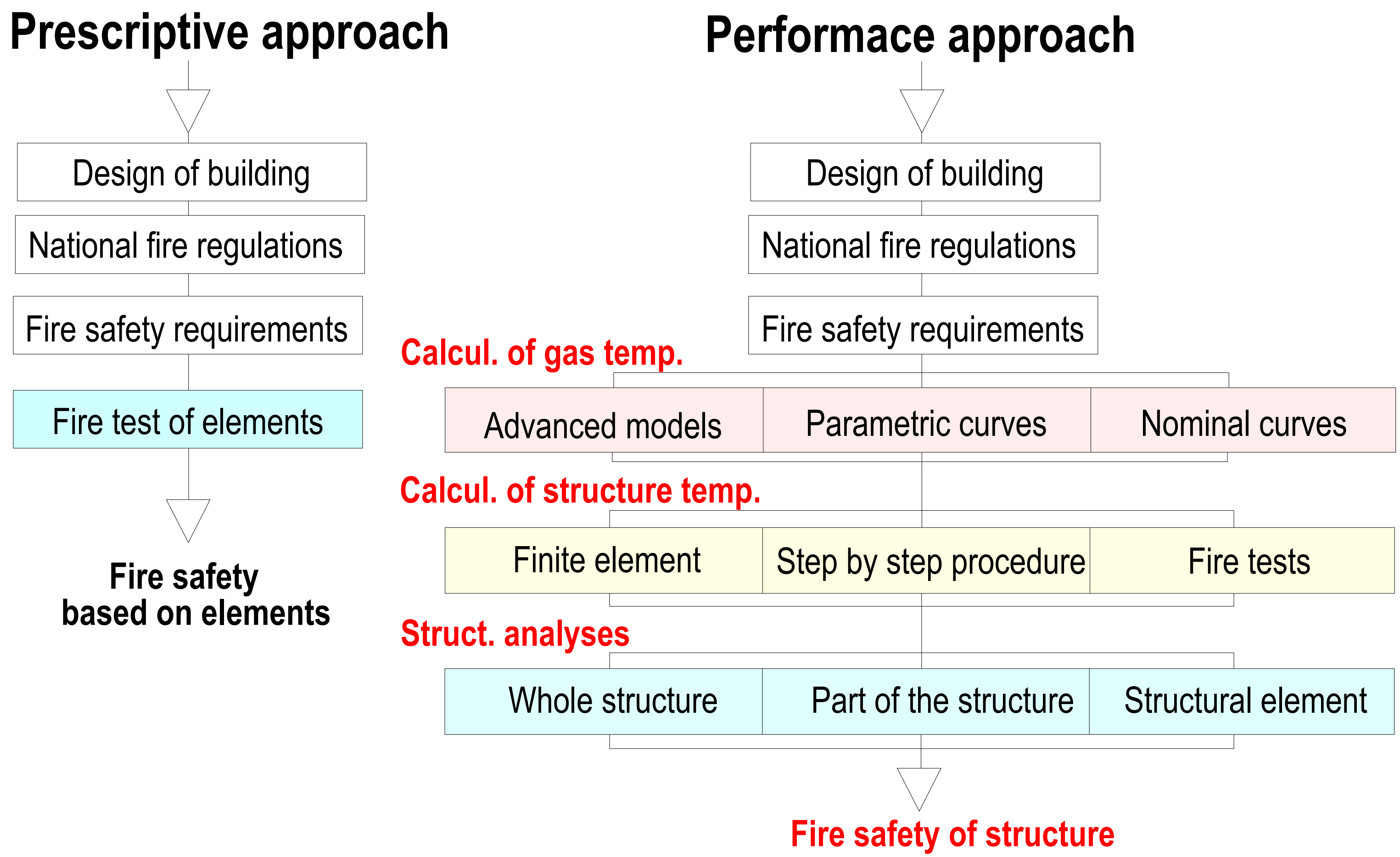
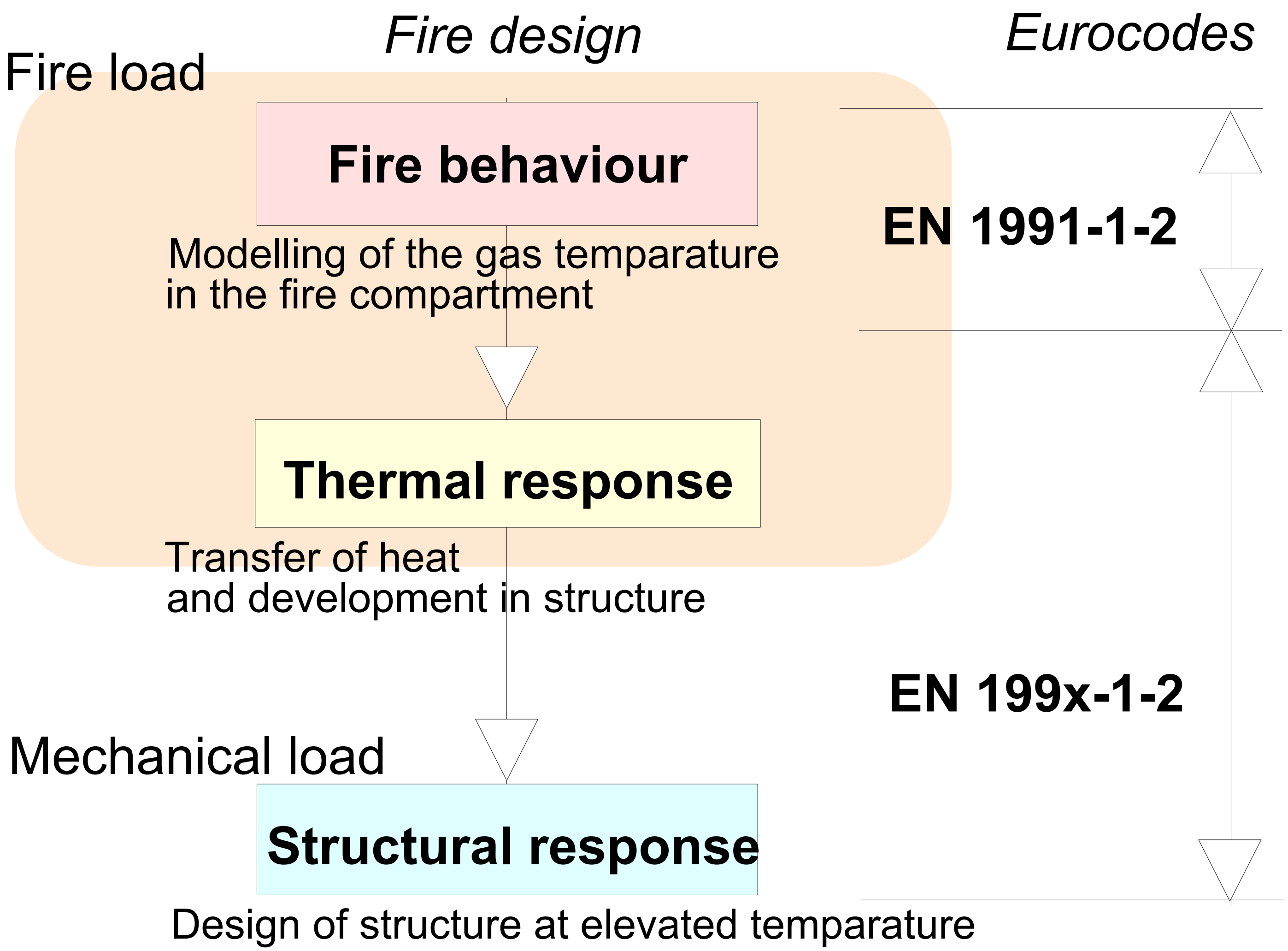
Lecture 3: 1/04/2014

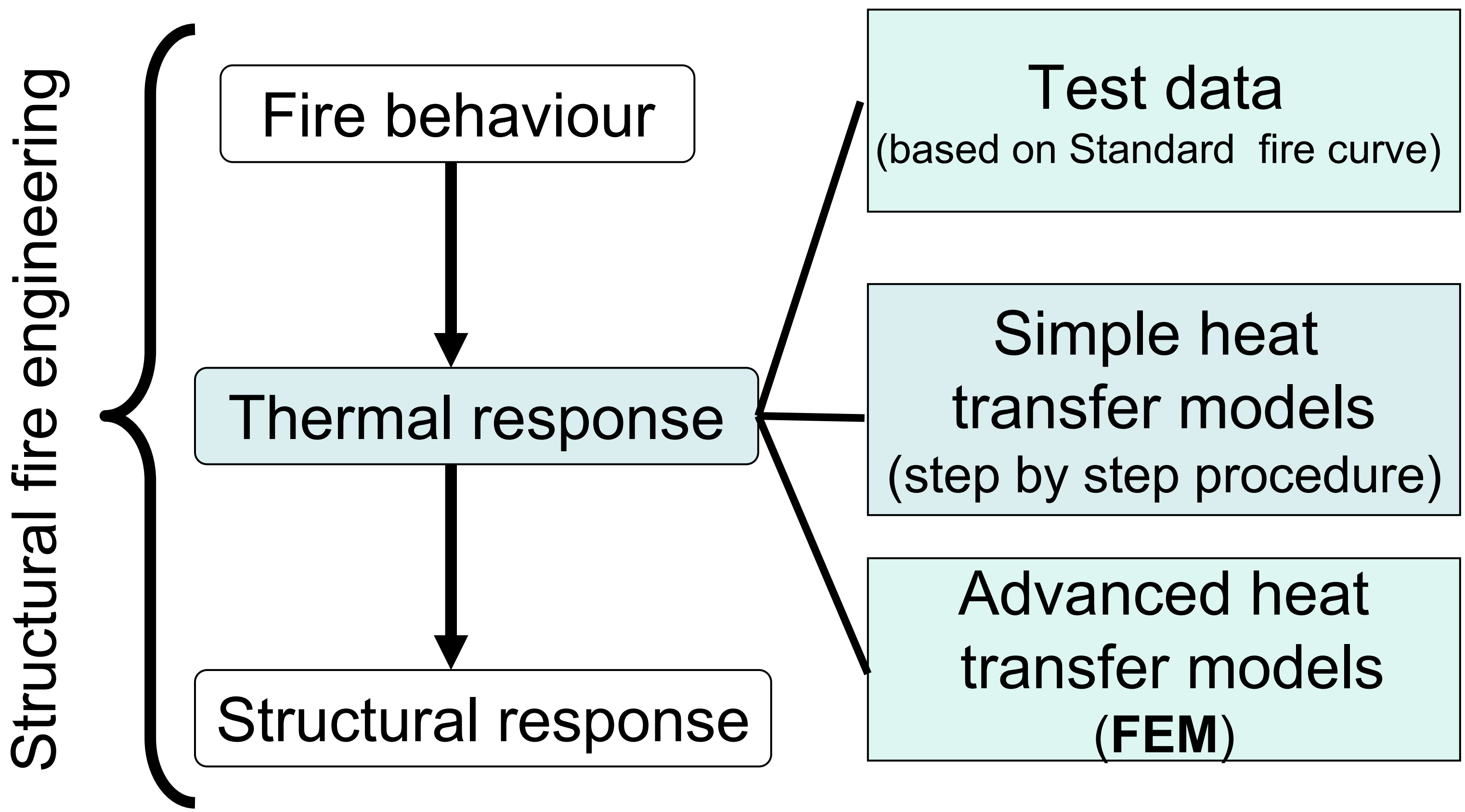
European Erasmus Mundus Master Course
Sustainable Constructions
under Natural Hazards and Catastrophic Events
520121-1-2011-1-CZ-ERA MUNDUS-EMMC


Prescriptive approach
Design of building
National fire regulations
Fire safety requirements
Fire test of elements
Fire safety
based on elements
Performace approach
Design of building
National fire regulations
Fire safety requirements
Calcul. of gas temp.
Advanced models
Parametric curves
Nominal curves
Calcul. of structure temp.
Finite element
Step by step procedure
Fire tests
Struct. analyses
Whole structure
Part of the structure
Structural element
Fire safety of structure



Fire design
Eurocodes
Fire load
Fire behaviour
Modelling of the gas temparature
in the fire compartment
EN 1991-1-2
Thermal response
Transfer of heat
and development in structure
EN 199x-1-2
Mechanical load
Structural response
Design of structure at elevated temparature

# Thermal response



# Basics of heat transfer

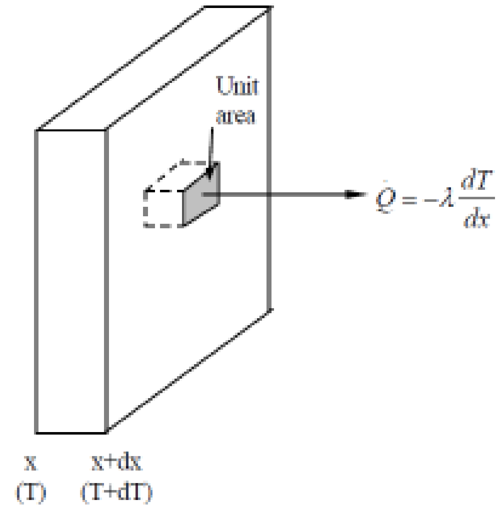
**Three basic mechanisms**

- **CONDUCTION – Heat transferred within an object or between two objects in contact**

- **CONVECTION – Heat transferred by movement of currents within fluids or air**

- **RADIATION – Transfer of energy by electromagnetic waves (does not require matter to transfer thermal energy)**

# Heat conduction




**Fourier's law of heat conduction**

$$\dot{Q} = -\lambda \frac{dT}{dx}$$

***dT*** **- is the temperature difference across an infinitesimal thickness *dx***

$\dot{Q}$ **- is the rate of heat transfer (heat flux) across the material thickness (the amount of energy that flows through a unit area per unit time – W/m$^2$)**

$\lambda$ **- is the conductivity (W/mK)**

**The minus sign in equation indicates that heat flows from the higher temperature side to the lower temperature side.**

# Radiant heat transfer of black body surfaces

**The total amount of thermal radiation emitted by a black body surface is a function of its temperature only**

$$E_b = \sigma T^4$$

**where**

$\sigma$ **is the Stefan-Boltzmann constant = $5.67 \times 10^{-8}$ W/($m^2K^4$)**
$T$ **is the temperature in K**

# Radiant heat transfer of grey body surfaces

**No real material emits and absorbs radiation according to laws of the black body.**

**The total radiant energy emitted by a general surface**

$$E = \varepsilon \sigma T^4$$

**where**

$\varepsilon$ **is the emissivity**

$\sigma$ **is the Stefan-Boltzmann constant = $5.67 \times 10^{-8}$ W/($m^2K^4$)**

$T$ **is the temperature in K**

# Net heat flux

**Thermal actions are given by the net heat flux to the surface of the element.**

**The net heat flux** $h_{net}$ **is given as the sum of effects of** convection **and** radiation

**The design value is given by**

$$h_{\mathrm{net,d}} = h_{\mathrm{net,c}} + h_{\mathrm{net,r}}$$

**where**

$h_{net,c}$ **is the heat flux from convection [W/m²]**

$h_{net,r}$ **is the heat flux from radiation [W/m²]**

## Convective heat flux

The net convective heat flux **[W/m²] is given by**

$$h_{\mathrm{net,c}} = \alpha_{\mathrm{c}}\left(\theta_{\mathrm{g}} - \theta_{\mathrm{m}}\right)$$

**where**

$\alpha_c$ **is the coefficient of heat transfer by conduction**

- $\alpha_c$ **= 25 W/m²K for standard curve**
- $\alpha_c$ **= 35 W/m²K for parametric curve**
- $\alpha_c$ **= 50 W/m²K for hydrocarbon curve**
- $\alpha_c$ **= 35 W/m²K for zone models and localized fires**

$\theta_g$ **is the gas temperature in the vicinity of the fire exposed element [°C]**

$\theta_m$ **is the surface temperature of the element [°C]**

# Radiative heat flux

The net radiative heat flux **[W/m²] is given by**

$$h_{\text{net,r}} = \phi \;\; \varepsilon_{\text{res}} \;\; 5{,}67 \cdot 10^{-8} \left[ (\theta_r + 273)^4 - (\theta_{\text{m}} + 273)^4 \right]$$

**where**

**$\phi$ is the configuration factor, usually $\phi$ = 1,0 (a lower value may be considered, to take into account the shadow effects – see Annex G of EN1991-1-2)**

**$\varepsilon_{\text{res}}$ is the resulting emissivity, see next page**

**$\theta_{\text{r}}$ is the radiating temperature [°C ], which can be taken equal to the gas temperature $\theta_{\text{g}}$**

**$\theta_{\text{m}}$ is surface temperature of the element [°C ]**

**$5{,}67 \cdot 10^{-8}$ is Stefan-Boltzmann constant [$W/(m^2K^4)$]**

# Resulting emissivity

**The emissivity is changing during the fire, influenced by the amount of carbon particles and dust in the smoke, the colour and the temperature of the surface.**

**Its value has a significant effect on the accuracy of the solution**

$$\varepsilon_{\mathrm{res}} = \varepsilon_{\mathrm{f}}\ \varepsilon_{\mathrm{m}}$$

**where**

$\varepsilon_f$ **is the emissivity of the fire, usually** $\varepsilon_f = 1{,}0$

$\varepsilon_m$ **is the emisivity of the material surface**

- **carbon steel element, concrete** $\varepsilon_m = 0{,}7$
- **stainless steel element** $\varepsilon_m = 0{,}4$
- **aluminum alloys** $\varepsilon_m = 0{,}3$

# Heat transfer

**Equilibrium between the quantity of energy (heat) that penetrates in a body through its surface and the energy used to modify the temperature of the body in a given time period *Δt***

Increase of body temperature

$$mc\Delta\theta = A_{\mathrm{m}} \; h_{\mathrm{net,d}} \; \Delta t$$

The heat received on surface

**or** $$\rho V c \Delta\theta = A_{\mathrm{m}} h_{\mathrm{net,d}} \Delta t \qquad \Rightarrow \Delta\theta = \frac{A_{\mathrm{m}}/V}{\rho c} h_{\mathrm{net,d}} \Delta t$$

**where**

***m*** **is the mass of the body**

***V*** **volume of the body [$m^3$]**

***$A_m$*** **surface area of the body [$m^2$]**

***c*** **specific heat of body [J/kgK]**

***$\rho$*** **density of body [$kg/m^3$]**

***$h_{net,d}$*** **net heat flux received by the surface of the body [$W/m^2$]**

***Δt*** **time period**

# Step by step procedure

for the fire unprotected steel elements in EN1993-1-2

## 4.2.5 Steel temperature development

### 4.2.5.1 Unprotected internal steelwork

(1) For an equivalent uniform temperature distribution in the cross-section, the increase of temperature $\Delta\theta_{a,t}$ in an unprotected steel member during a time interval $\Delta t$ should be determined from:

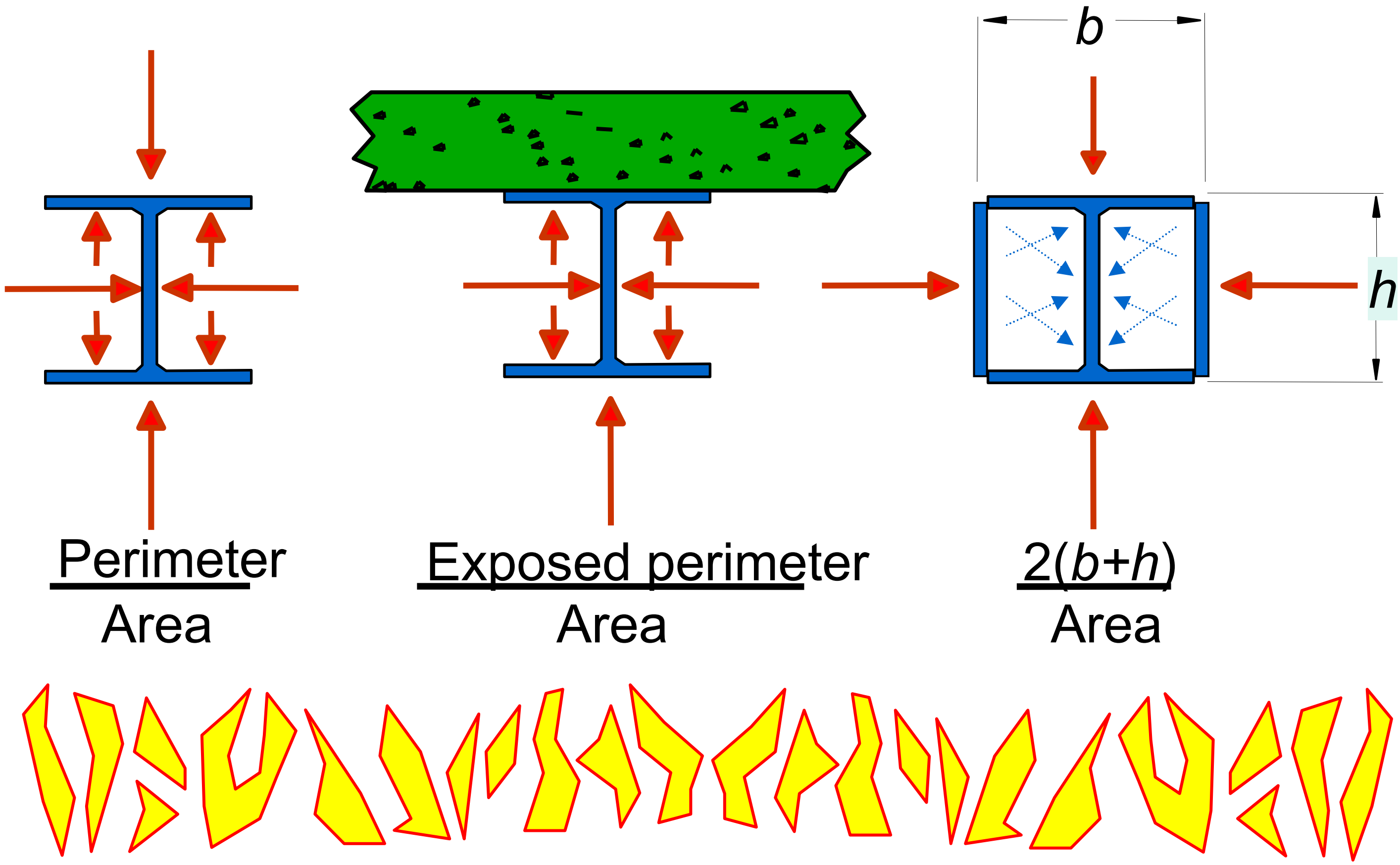
$$\Delta\theta_{a,t} = k_{sh} \frac{A_m / V}{c_a \rho_a} \dot{h}_{net,d} \Delta t \quad (4.25)$$

where:

| | | |
|---|---|---|
| $k_{sh}$ | is | correction factor for the shadow effect, from 5.2.5.1(2) |
| $A_m / V$ | is | the section factor for unprotected steel members; |
| $A_m$ | is | the surface area of the member per unit length [m²]; |
| $V$ | is | the volume of the member per unit length [m³]; |
| $c_a$ | is | the specific heat of steel, from section 3 [J/kgK]; |
| $\dot{h}_{net,d}$ | is | the design value of the net heat flux per unit area [W/m²]; |
| $\Delta t$ | is | the time interval [seconds]; |
| $\rho_a$ | is | the unit mass of steel, from section 3 [kg/m³]. |

# Section factor $A_m/V$

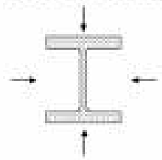
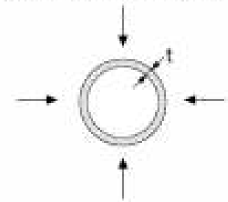
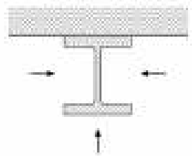
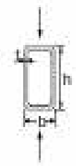
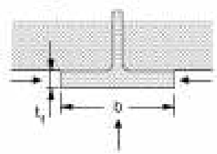
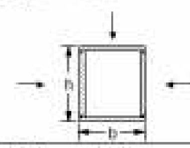
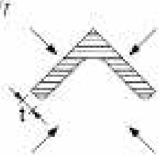
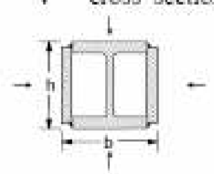
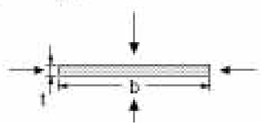
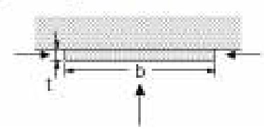
for the fire unprotected steel element




The surface area of the element per unit length of the member divided
by the volume of the member per unit length .

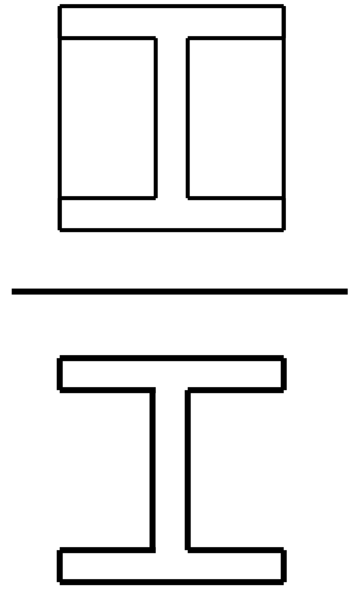
The figure – I. Burgess, STESSA project

**Table 4.2: Section factor $A_m/V$ for unprotected steel members.**

| | |
|---|---|
| Open section exposed to fire on all sides:<br>$$\frac{A_m}{V} = \frac{\text{perimeter}}{\text{cross- section area}}$$<br> | Tube exposed to fire on all sides: $A_m/V = 1/t$<br> |
| Open section exposed to fire on three sides:<br>$$\frac{A_m}{V} = \frac{\text{surface exposed to fire}}{\text{cross- section area}}$$<br> | Hollow section (or welded box section of uniform thickness) exposed to fire on all sides:<br>If $t \ll b$: $A_m/V \approx 1/t$<br> |
| I-section flange exposed to fire on three sides:<br>$A_m/V = (b + 2t_f)/(bt_f)$<br>If $t \ll b$: $A_m/V \approx 1/t_f$<br> | Welded box section exposed to fire on all sides:<br>$$\frac{A_m}{V} = \frac{2(b+h)}{\text{cross- section area}}$$<br>If $t \ll b$: $A_m/V \approx 1/t$<br> |
| Angle exposed to fire on all sides:<br>$A_m/V = 2/t$<br> | I-section with box reinforcement, exposed to fire on all sides: $$\frac{A_m}{V} = \frac{2(b+h)}{\text{cross- section area}}$$<br> |
| Flat bar exposed to fire on all sides:<br>$A_m/V = 2(b+t)/(bt)$<br>If $t \ll b$: $A_m/V \approx 2/t$<br> | Flat bar exposed to fire on three sides:<br>$A_m/V = (b+2t)/(bt)$<br>If $t \ll b$: $A_m/V \approx 1/t$<br> |

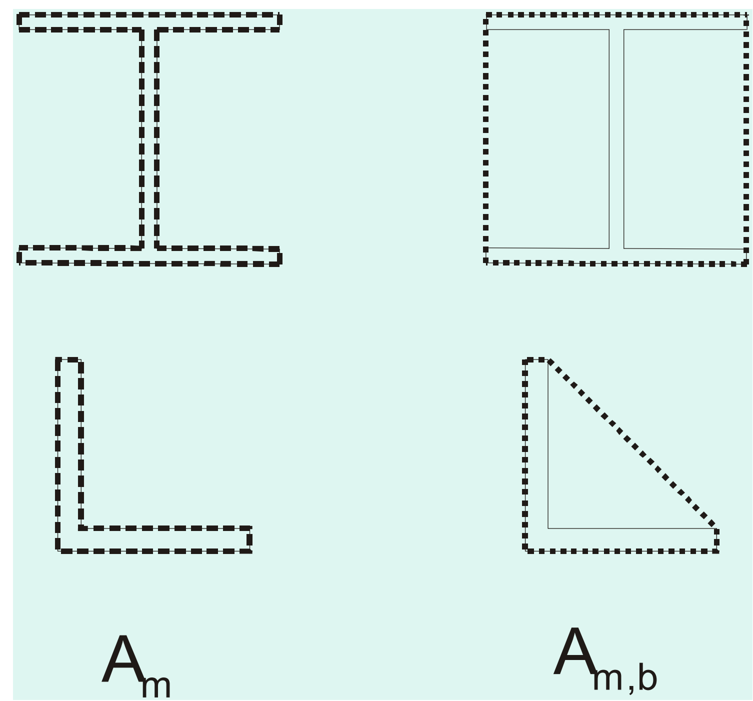
# Shadow effect

$$k_{sh} = \frac{\left[A_m/V\right]_b}{\left[A_m/V\right]} =$$



The shadow effect takes into account that there cannot be more radiation reaching the surface of the member than the radiation travelling through the smallest box surrounding the section.

For temperatures normally encountered in a fire, the radiation is the dominant heat transfer mode to the elements.



# Shadow effect

(2) For I-sections under nominal fire actions, the correction factor for the shadow effect may be determined from:

$$k_{sh} = 0.9\,[A_m/V]_b/[A_m/V] \quad (4.26a)$$

where:

$[A_m/V]_b$ is box value of the section factor

In all other cases, the value of $k_{sh}$ shall be taken as:

$$k_{sh} = [A_m/V]_b/[A_m/V] \quad (4.26b)$$

**NOTE (1)**: For cross sections with a convex shape (e.g. rectangular or circular hollow sections) fully embedded in fire, the shadow effect does not play role and consequently the correction factor $k_{sh}$ equals unity.

**NOTE (2)**: Ignoring the shadow effect (i.e.: $k_{sh} = 1$), leads to conservative solutions.

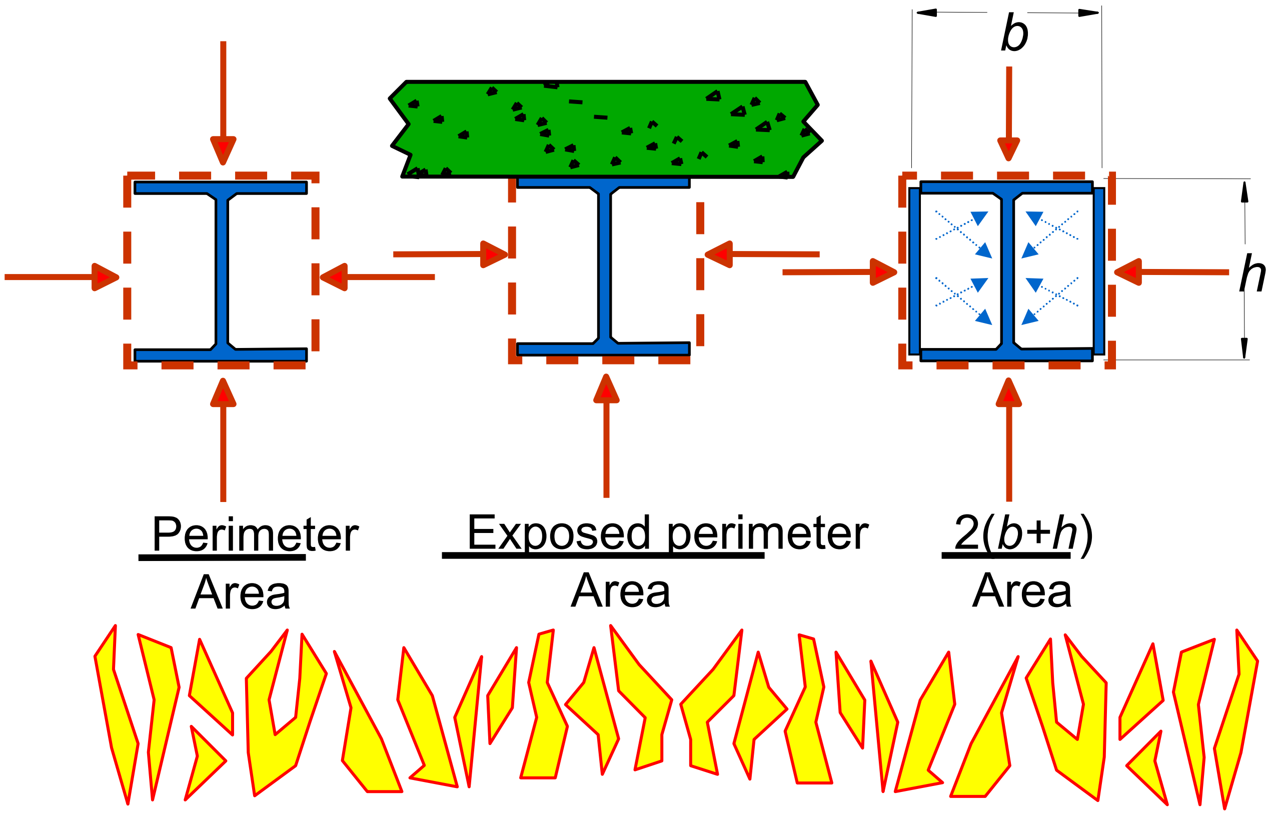
(4) The value of $\dot{h}_{net,d}$ should be obtained from EN 1991-1-2 using $\varepsilon_f = 1,0$ and $\varepsilon_m$ according to 2.2(2), where $\varepsilon_f$, $\varepsilon_m$ are as defined in EN 1991-1-2.

(5) The value of $\Delta t$ should not be taken as more than 5 seconds.

(6) In expression (4.26) the value of the section factor $A_m/V$ should not be taken as less than $10\,m^{-1}$.

# Section factor $(A_m/V)_b$

for shadow effect, unprotected steel element




$$\frac{\text{Perimeter}}{\text{Area}} \qquad \frac{\text{Exposed perimeter}}{\text{Area}} \qquad \frac{2(b+h)}{\text{Area}}$$

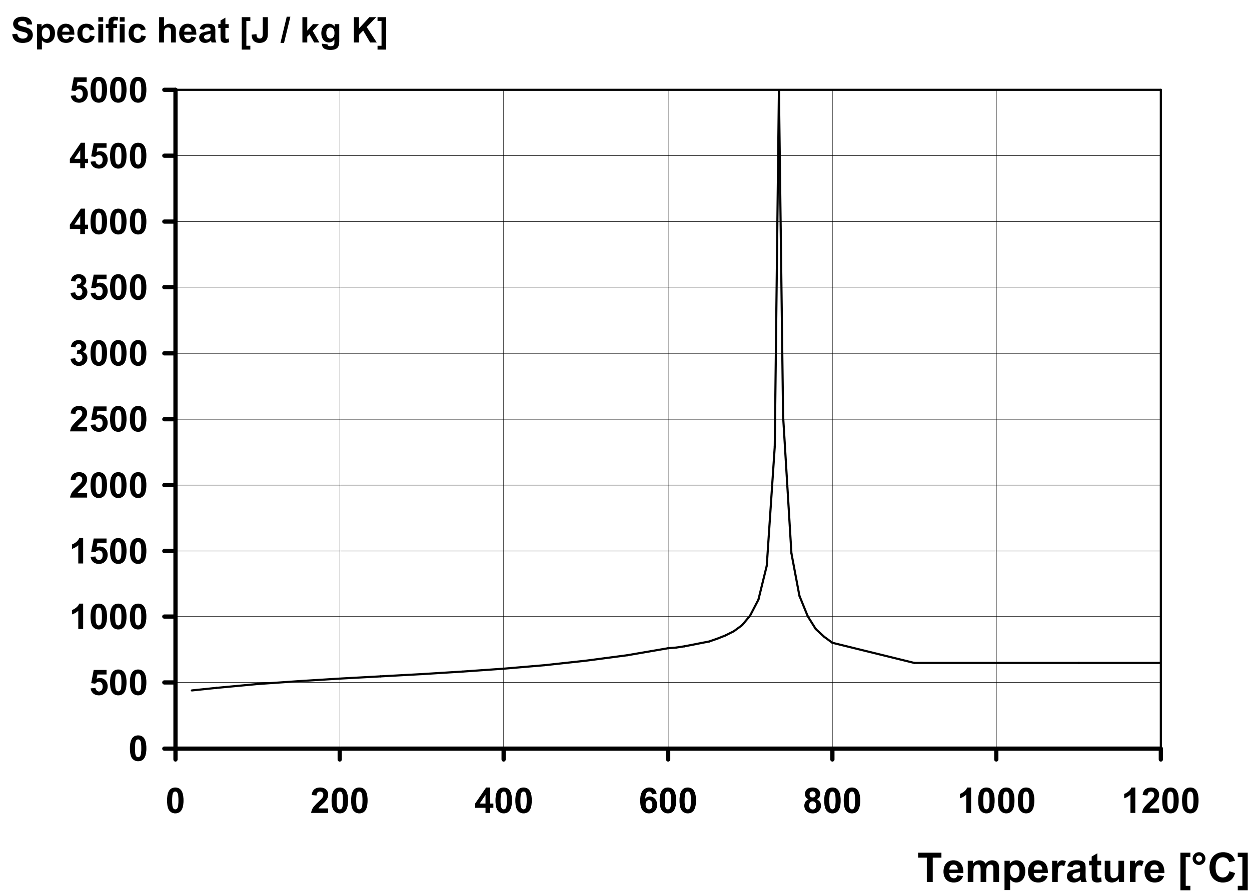
The figure – I. Burgess, STESSA project

# Thermal properties

of carbon steel at elevated temperatures

## Specific heat

Model in EN1993-1-2:2005



for $20\,°C \leq \theta_a < 600\,°C$

$c_a = 425 + 7{,}73 \times 10^{-1}\,\theta_a - 1{,}69 \times 10^{-3}\,\theta_a^2 + 2{,}22 \cdot 10^{-6}\,\theta_a^3$ J/kgK

for $600\,°C \leq \theta_a < 735\,°C$

$c_a = 666 +$ J/kgK

for $735\,°C \leq \theta_a < 900\,°C$

$c_a = 545 +$ J/kgK

for $900\,°C \leq \theta_a \leq 1200\,°C$

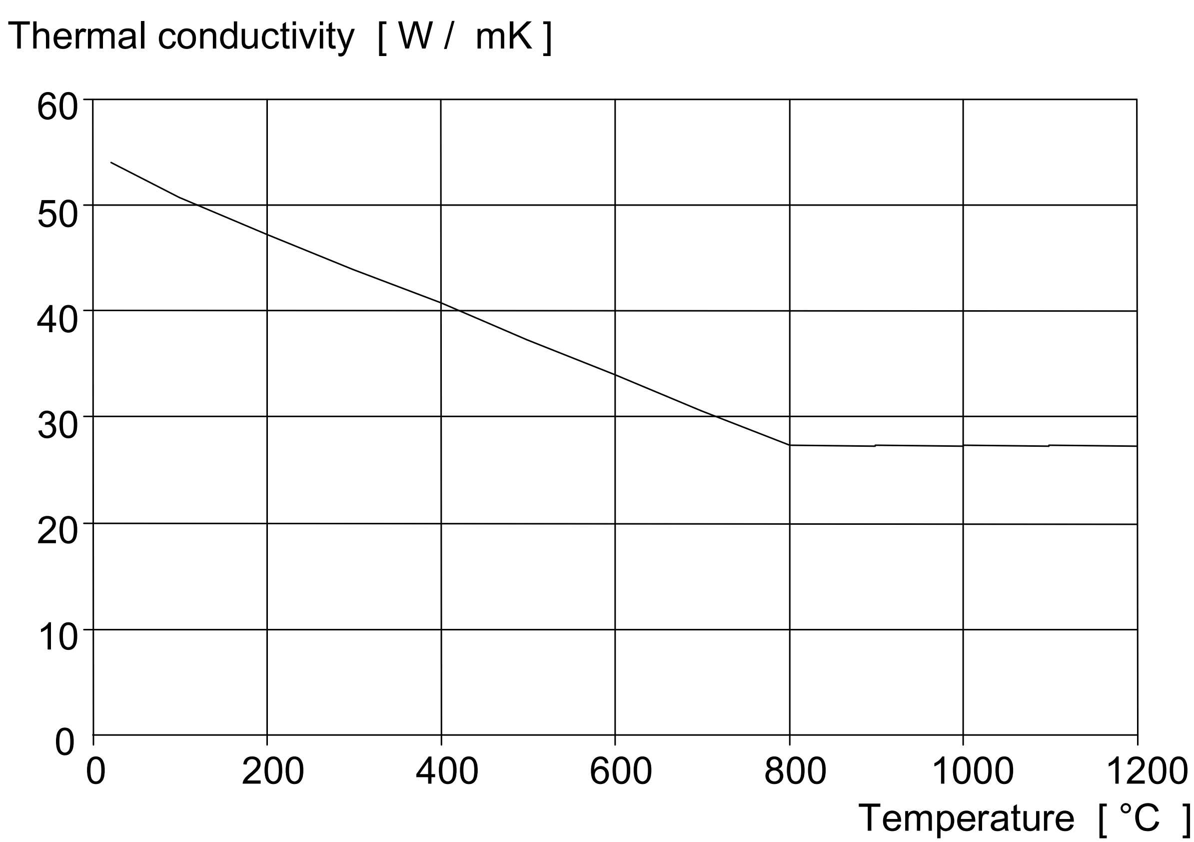
$c_a = 650$ J/kgK

where:

$\theta_a$ is the steel temperature [°C]

## Thermal conductivity

Model in EN1993-1-2:2005



for $20\,°C \leq \theta_a < 800\,°C$

$$\lambda_a = 54 - 3{,}33 \cdot 10^{-2}\,\theta_a \text{ W/mK}$$

for $800\,°C \leq \theta_a \leq 1200\,°C$

$$\lambda_a = 27{,}3 \text{ W/mK}$$

where:

$\theta_a$ is the steel temperature [°C]

# Technique of step by step precedure

$$\Delta\theta_{a,t} = k_{sh}\,\frac{A_m / V}{c_a\ \rho_a}\,h_{net,d}\ \Delta t$$

Spreadsheet technique (excel, etc.)

Temperature increment

Gas temperature (according to temperature-time curve)

Temperature of the element at time *t*

Components of the heat flux

Specific heat of steel

Time

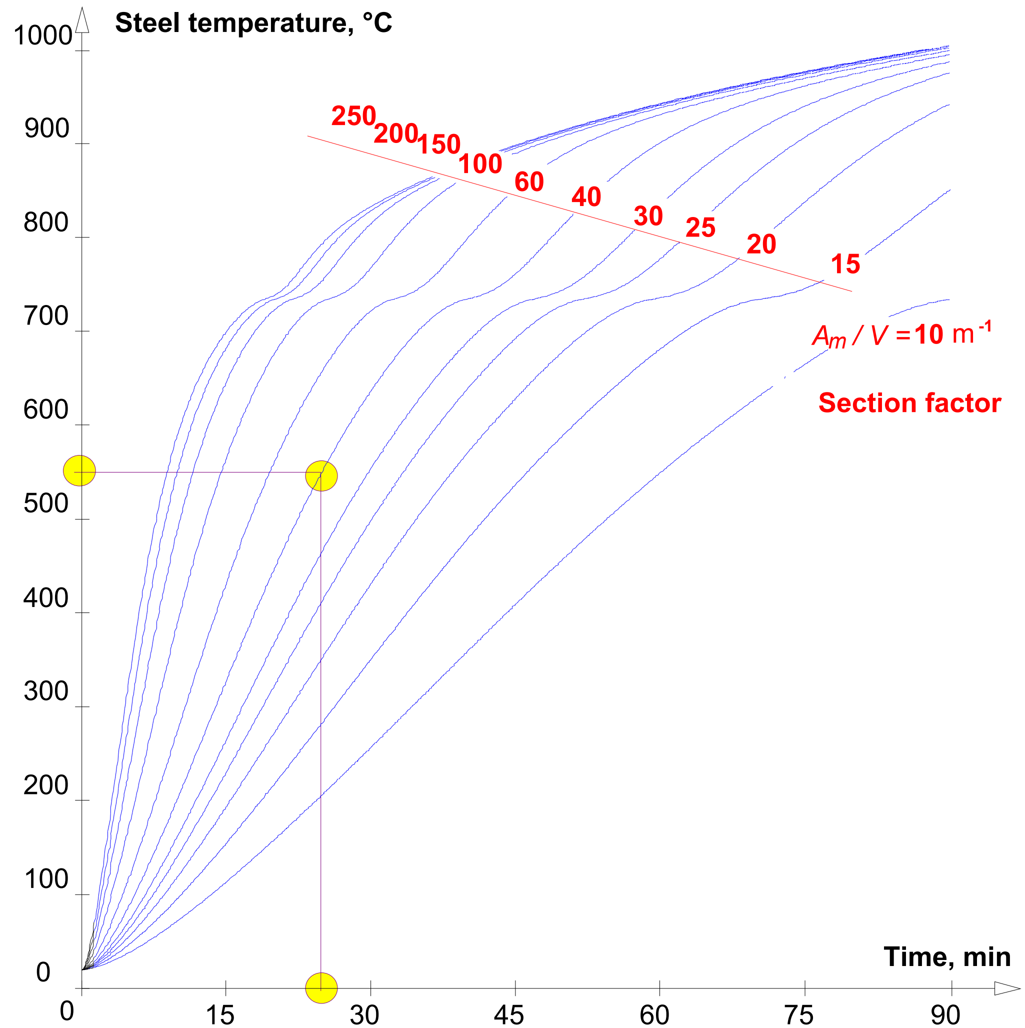
| $t$ | | $t$ | $\Theta_g$ | $h_{net,r}$ | $h_{net,c}$ | $h_{net,d}$ | $c_a$ | $\Delta\Theta_{a,t}$ | $\Theta_{a,t}$ |
|---|---|---|---|---|---|---|---|---|---|
| min | sec | min | 20,0 | | | | J/kg K | | 20,0 |
| 0 | 0 | 0 | 20,0 | 0 | 0 | 0 | 440 | 0,00 | 20,0 |
| 0 | 5 | 0,083 | 96,5 | 448 | 2679 | 3126 | 440 | 1,18 | 21,2 |
| 0 | 10 | 0,167 | 147,0 | 937 | 4402 | 5339 | 441 | 2,00 | 23,2 |
| 0 | 15 | 0,250 | 184,6 | 1435 | 5650 | 7085 | 442 | 2,65 | 25,8 |
| 0 | 20 | 0,333 | 214,7 | 1928 | 6610 | 8538 | 444 | 3,18 | 29,0 |
| 0 | 25 | 0,417 | 239,7 | 2412 | 7374 | 9787 | 446 | 3,63 | 32,6 |
| | | | | | | | | | |
| 0 | 30 | 0,500 | 261,1 | 2885 | 7998 | 10882 | 449 | | |

# Result of step by step precedure

Temperature
of the fire
unprotected steel
$\theta_{a,t}$

as function
of time *t*

and
section factor
$A_m / V$



# Tables and graphs – unprotected steel

[http://www.ct.upt.ro/users/RaulZaharia/Introduction_fire_design.pdf](http://www.ct.upt.ro/users/RaulZaharia/Introduction_fire_design.pdf)

**Table I-1 : temperature in unprotected sections subjected to the ISO fire**

| $A^{*}_{m}/V$ [$m^{-1}$] | 400 | 200 | 100 | 60 | 40 | 25 |
|---|---|---|---|---|---|---|
| $V/A^{*}_{m}$ [mm] | 2.5 | 5.0 | 10.0 | 16.7 | 25.0 | 40.0 |
| Time [min.] | Steel temperature in °C | | | | | |
| 0 | 20 | 20 | 20 | 20 | 20 | 20 |
| 5 | 430 | 291 | 177 | 121 | 90 | 65 |
| 10 | 640 | 552 | 392 | 276 | 204 | 142 |
| 11 | 661 | 587 | 432 | 308 | 228 | 159 |
| 12 | 678 | 616 | 469 | 340 | 253 | 177 |
| 13 | 693 | 642 | 503 | 371 | 278 | 194 |
| 14 | 705 | 663 | 535 | 402 | 303 | 212 |
| 15 | 716 | 682 | 565 | 432 | 328 | 230 |
| 16 | 725 | 698 | 591 | 460 | 353 | 249 |
| 17 | 732 | 711 | 616 | 487 | 377 | 267 |
| 18 | 736 | 721 | 638 | 513 | 401 | 286 |
| 19 | 743 | 729 | 658 | 538 | 425 | 304 |
| 20 | 754 | 734 | 676 | 561 | 447 | 323 |
| 21 | 767 | 738 | 692 | 583 | 470 | 341 |
| 22 | 780 | 744 | 706 | 604 | 491 | 360 |
| 23 | 790 | 754 | 717 | 623 | 512 | 378 |
| 24 | 799 | 767 | 726 | 641 | 532 | 396 |
| 25 | 807 | 780 | 732 | 658 | 551 | 414 |
| 26 | 813 | 792 | 735 | 674 | 570 | 431 |
| 27 | 820 | 803 | 740 | 688 | 588 | 449 |
| 28 | 826 | 813 | 746 | 701 | 604 | 466 |
| 29 | 831 | 821 | 756 | 712 | 621 | 482 |
| 30 | 837 | 828 | 767 | 721 | 636 | 498 |
| 31 | 842 | 835 | 780 | 728 | 651 | 514 |
| 32 | 847 | 841 | 793 | 733 | 665 | 530 |
| 33 | 852 | 846 | 805 | 736 | 678 | 545 |
| 34 | 856 | 851 | 816 | 740 | 690 | 559 |
| 35 | 861 | 856 | 827 | 745 | 701 | 573 |
| 36 | 865 | 861 | 836 | 753 | 711 | 587 |
| 37 | 870 | 866 | 844 | 763 | 719 | 601 |
| 38 | 874 | 870 | 852 | 774 | 726 | 614 |
| 39 | 878 | 874 | 859 | 786 | 731 | 626 |
| 40 | 882 | 878 | 865 | 798 | 734 | 638 |
| 41 | 885 | 882 | 871 | 810 | 737 | 650 |
| 42 | 889 | 886 | 876 | 822 | 740 | 661 |
| 43 | 893 | 890 | 881 | 832 | 745 | 672 |
| 44 | 896 | 893 | 885 | 842 | 752 | 683 |
| 45 | 900 | 897 | 890 | 852 | 761 | 692 |

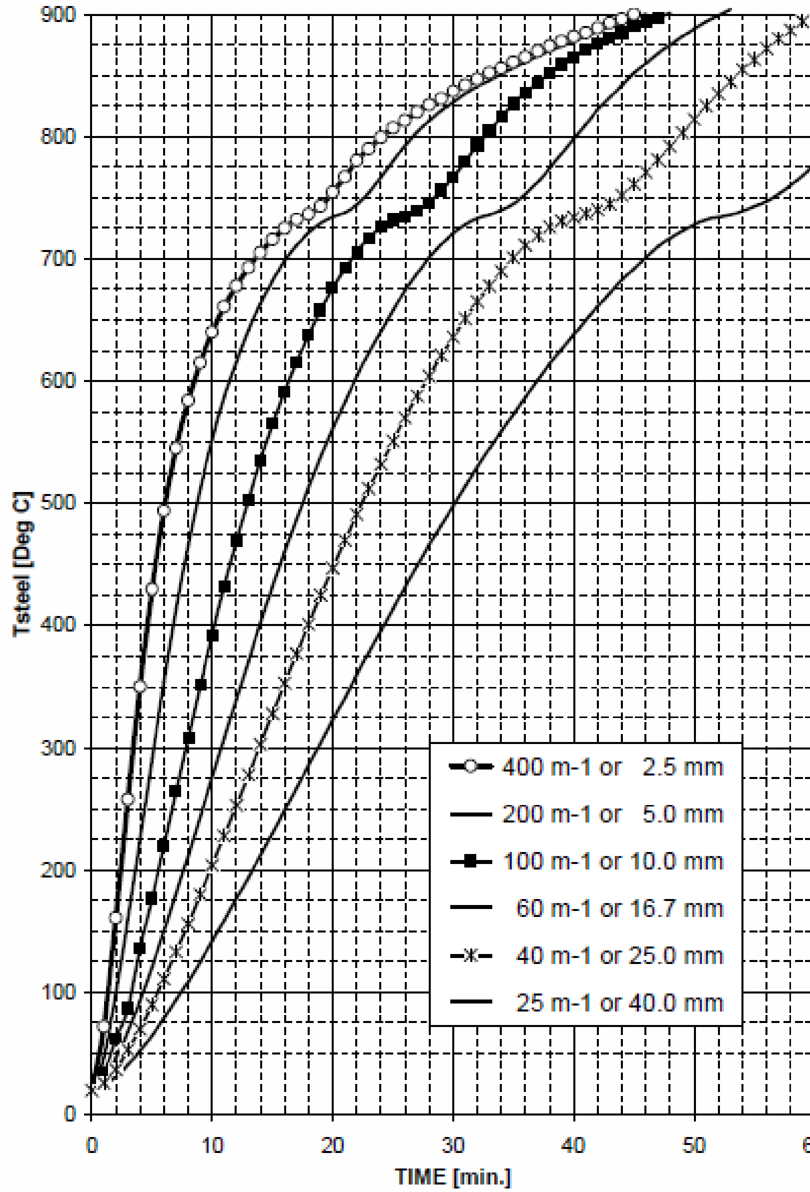



**Figure I-3 : temperatures as a function of time for various section factors**

## Passive structural fire protection

- Composite steel and concrete structures
  - In the past lining by bricks, embedding in concrete
  - Today preferable with structural function as well
- Insulating Boards
  - Gypsum, Mineral fiber, Vermiculite

  + Easy to apply, aesthetically acceptable

  - Difficulties with complex details
- Cementations Sprays
  - Mineral fiber or vermiculite in cement binder

  + Economy

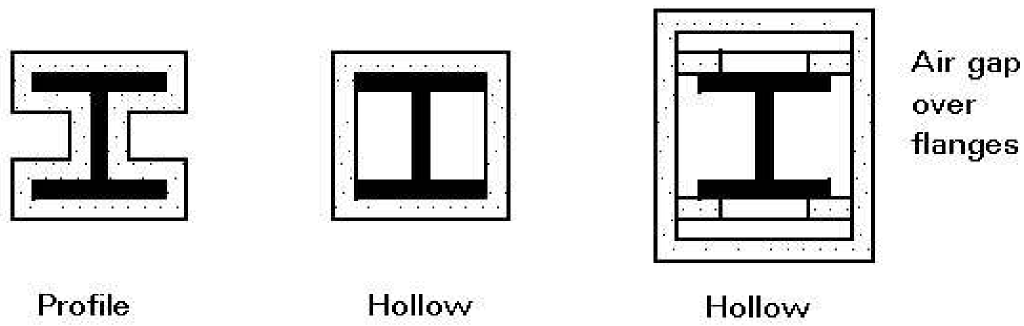
  - Esthetics; normally used behind suspended ceilings.
- Intumescent Paints
  - Expands on heating to produce insulating layer

  + Decorative finish under normal conditions
  + May be done off-site

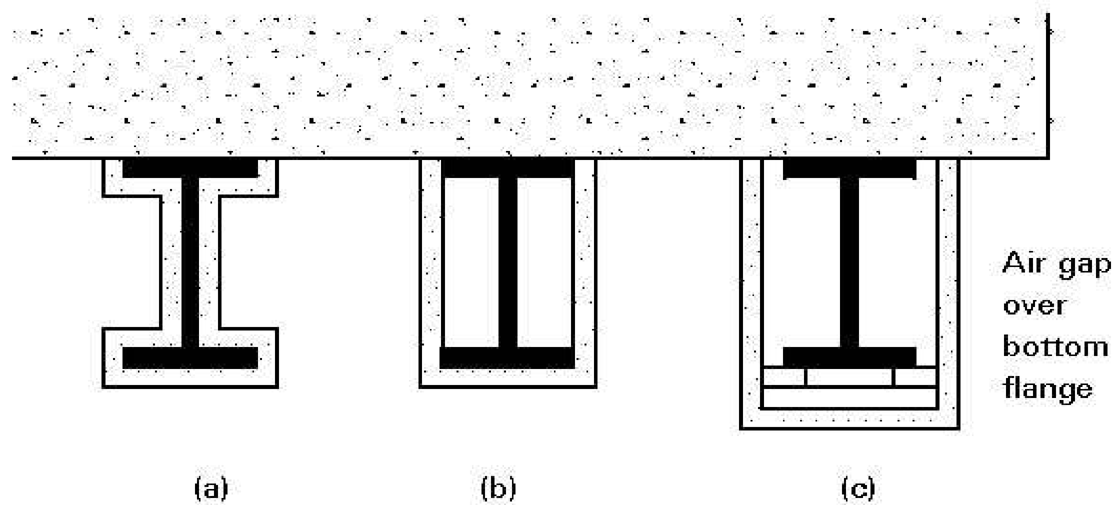
  - Durability

# Exposed from three/four sides

**Columns:**



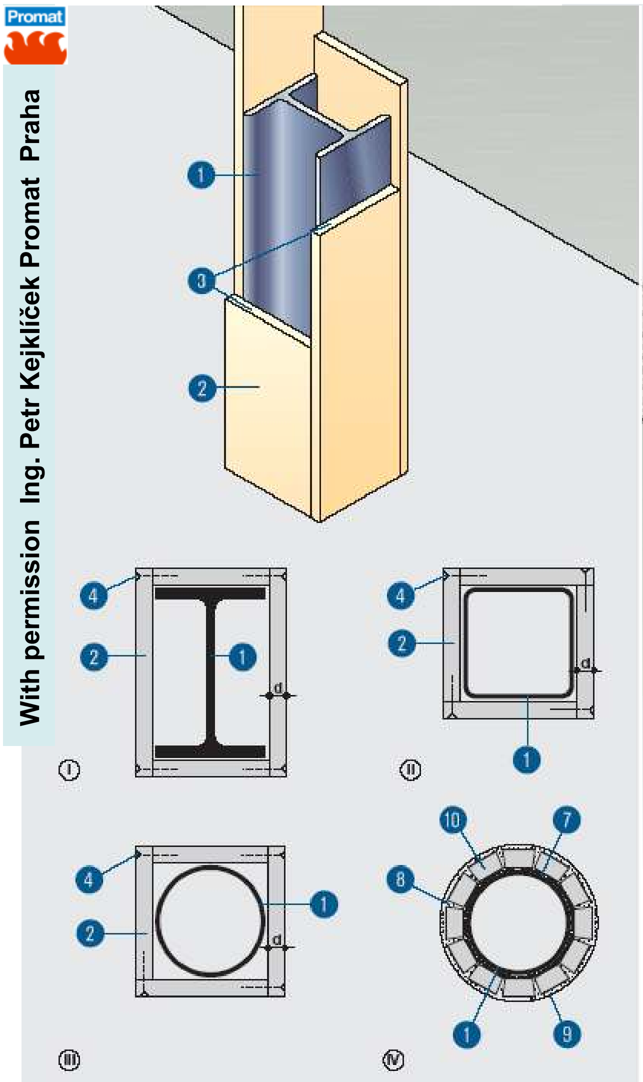

**Beams:**

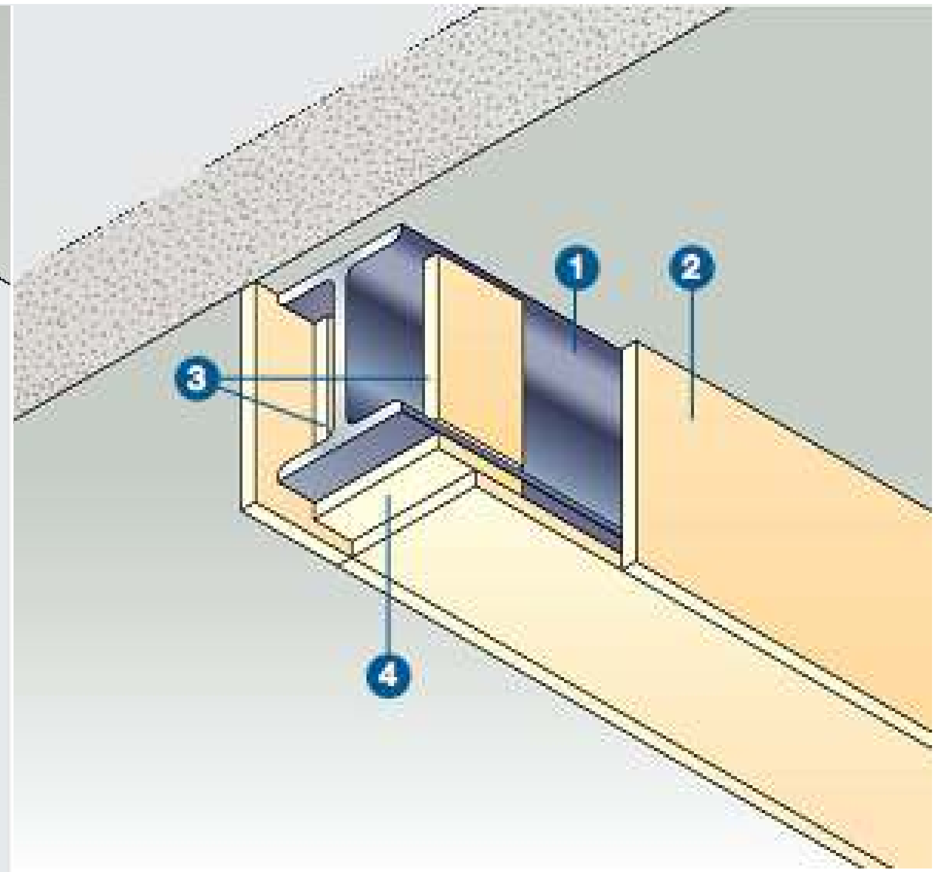



(a) - Spray or intumescent
(b) - Board
(c) - Board

# Insulating Boards







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# Cementations Sprays

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# Intumescent Paints


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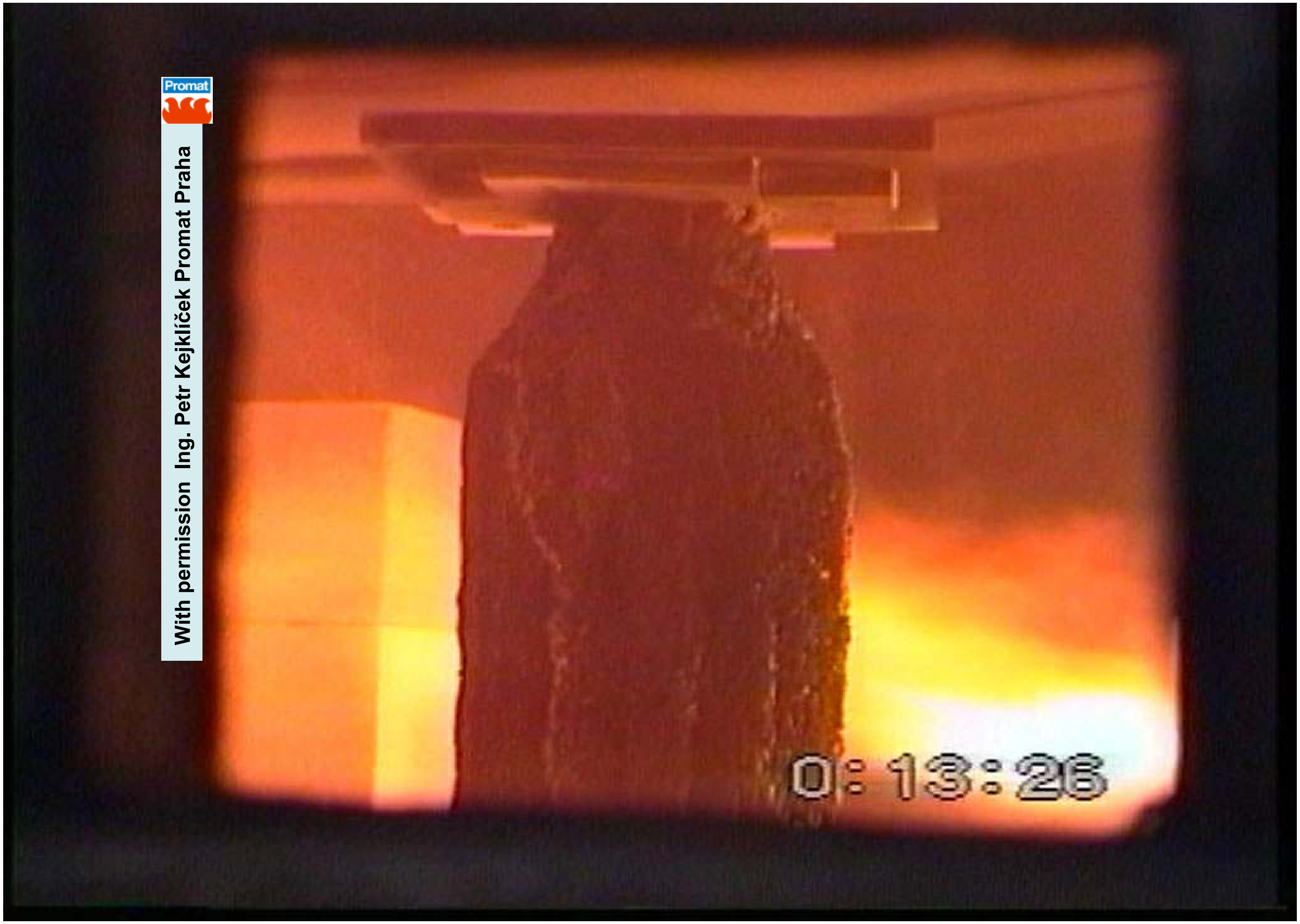
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#### 4.2.5.2 Internal steelwork insulated by fire protection material

(1) For a uniform temperature distribution in a cross-section, the temperature increase $\Delta\theta_{a,t}$ of an insulated steel member during a time interval $\Delta t$ should be obtained from:

$$\Delta\theta_{a,t} = \frac{\lambda_p A_p / V}{d_p c_a \rho_a} \frac{(\theta_{g,t} - \theta_{a,t})}{(1+\phi/3)} \Delta t - (e^{\phi/10} - 1)\Delta\theta_{g,t} \qquad (\text{but } \Delta\theta_{a,t} \geq 0 \text{ if } \Delta\theta_{g,t} > 0) \qquad (4.27)$$

with:

$$\phi = \frac{c_p \rho_p}{c_a \rho_a} d_p A_p / V$$

where:

| | | |
|---|---|---|
| $A_p/V$ | is | the section factor for steel members insulated by fire protection material; |
| $A_p$ | is | the appropriate area of fire protection material per unit length of the member [m²]; |
| $V$ | is | the volume of the member per unit length [m³]; |
| $c_a$ | is | the temperature dependant specific heat of steel, from section 3 [J/kgK]; |
| $c_p$ | is | the temperature independent specific heat of the fire protection material [J/kgK]; |
| $d_p$ | is | the thickness of the fire protection material [m]; |
| $\Delta t$ | is | the time interval [seconds]; |
| $\theta_{a,t}$ | is | the steel temperature at time $t$ [°C]; |
| $\theta_{g,t}$ | is | the ambient gas temperature at time $t$ [°C]; |
| $\Delta\theta_{g,t}$ | is | the increase of the ambient gas temperature during the time interval $\Delta t$ [K]; |
| $\lambda_p$ | is | the thermal conductivity of the fire protection system [W/mK]; |
| $\rho_a$ | is | the unit mass of steel, from section 3 [kg/m³]; |
| $\rho_p$ | is | the unit mass of the fire protection material [kg/m³]. |

(2) The values of $c_p$, $\lambda_p$ and $\rho_p$ should be determined as specified in section 3.

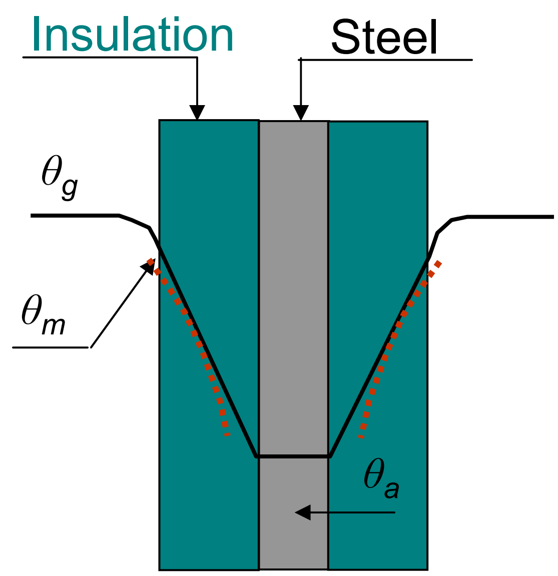
(3) The value of $\Delta t$ should not be taken as more than 30 seconds.

(4) The area $A_p$ of the fire protection material should generally be taken as the area of its inner surface, but for hollow encasement with a clearance around the steel member the same value as for hollow encasement without a clearance may be adopted.

Principle for equation 4.27:

The surface temperature of fire protection is considered to be the same as the gas temperature (no shadow effect)

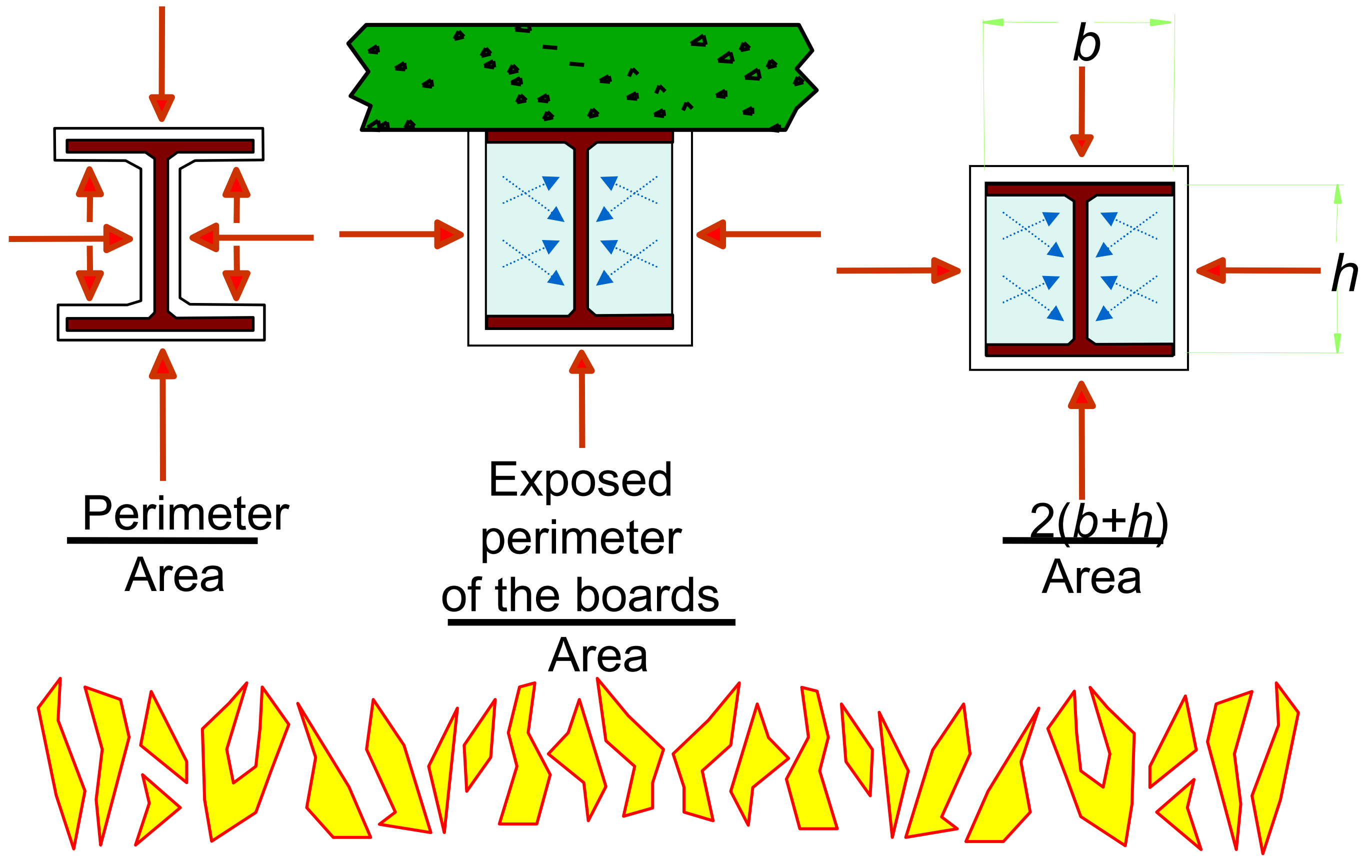
θg - θm << θm - θa




The heat transfer is performed through the fire protected layer.

## Section factor $A_p/V$

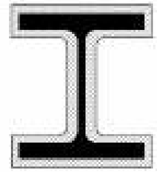
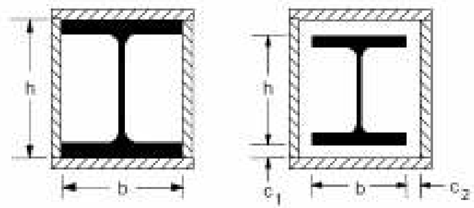
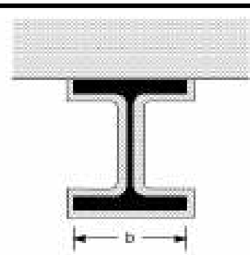
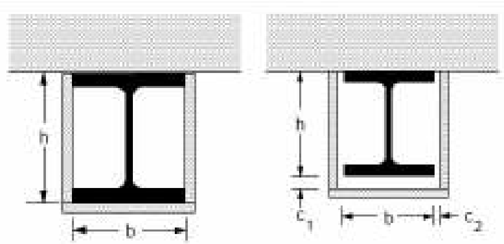
for the fire protected steel element




The appropriate area of fire protection material per unit length of the member
divided by the volume of the member per unit length .

The figure – I. Burgess, STESSA project

**Table 4.3: Section factor $A_p/V$ for steel members insulated by fire protection material**

| Sketch | Description | Section factor $(A_p/V)$ |
|---|---|---|
|  | Contour encasement of uniform thickness | $\dfrac{\text{steel perimeter}}{\text{steel cross-section area}}$ |
|  | Hollow encasement of uniform thickness)[1] | $\dfrac{2(b+h)}{\text{steel cross-section area}}$ |
|  | Contour encasement of uniform thickness, exposed to fire on three sides | $\dfrac{\text{steel perimeter} - b}{\text{steel cross-section area}}$ |
|  | Hollow encasement of uniform thickness, exposed to fire on three sides )[1] | $\dfrac{2h+b}{\text{steel cross-section area}}$ |

)[1] The clearance dimensions $c_1$ and $c_2$ should not normally exceed $h/4$

If the specific heat of the protection material cp is conservatively neglected, Eq. 4.27 reduces to

$$\Delta\theta_{a,t} = \frac{\lambda_p A_p}{d_p V} \frac{(\theta_{g,t} - \theta_{a,t})}{c_a \rho_a} \Delta t$$

All parameters that define the steel section and the protection may be grouped into one single factor :

$$k_p = \frac{\lambda_p}{d_p} \frac{A_p}{V}$$

For a defined fire, it is quite convenient to perform the integration of the equation above once for various values of this factor *kp* and to build design aids in the form of tables or graphs.

## Tables and graphs – protected steel

http://www.ct.upt.ro/users/RaulZaharia/Introduction_fire_design.pdf

Table I-2 : temperature in protected sections subjected to the ISO fire

| $k_p$ [W/m³K] | 200 | 400 | 600 | 800 | 1200 | 2000 |
|---|---|---|---|---|---|---|
| Time [min.] | Steel temperature in °C | | | | | |
| 0 | 20 | 20 | 20 | 20 | 20 | 20 |
| 10 | 37 | 54 | 70 | 85 | 113 | 163 |
| 20 | 60 | 97 | 130 | 160 | 215 | 304 |
| 30 | 84 | 139 | 188 | 232 | 306 | 421 |
| 40 | 108 | 181 | 244 | 298 | 388 | 514 |
| 50 | 132 | 222 | 296 | 359 | 459 | 589 |
| 60 | 156 | 260 | 345 | 414 | 520 | 650 |
| 70 | 179 | 298 | 391 | 465 | 573 | 699 |
| 80 | 202 | 333 | 433 | 510 | 620 | 730 |
| 90 | 225 | 367 | 472 | 552 | 661 | 743 |
| 100 | 247 | 399 | 509 | 589 | 695 | 773 |
| 110 | 268 | 430 | 542 | 623 | 721 | 816 |
| 120 | 289 | 459 | 573 | 654 | 734 | 859 |
| 130 | 310 | 486 | 602 | 681 | 744 | 900 |
| 140 | 330 | 512 | 629 | 705 | 765 | 935 |
| 150 | 349 | 537 | 654 | 723 | 795 | 965 |
| 160 | 368 | 560 | 677 | 733 | 828 | 990 |
| 170 | 386 | 582 | 697 | 739 | 861 | 1013 |
| 180 | 404 | 603 | 714 | 751 | 892 | 1032 |
| 190 | 422 | 623 | 727 | 769 | 921 | 1049 |
| 200 | 439 | 642 | 734 | 792 | 948 | 1065 |
| 210 | 455 | 660 | 738 | 817 | 972 | 1078 |
| 220 | 471 | 677 | 747 | 843 | 993 | 1090 |
| 230 | 487 | 692 | 760 | 869 | 1013 | 1101 |
| 240 | 502 | 706 | 777 | 893 | 1031 | 1112 |

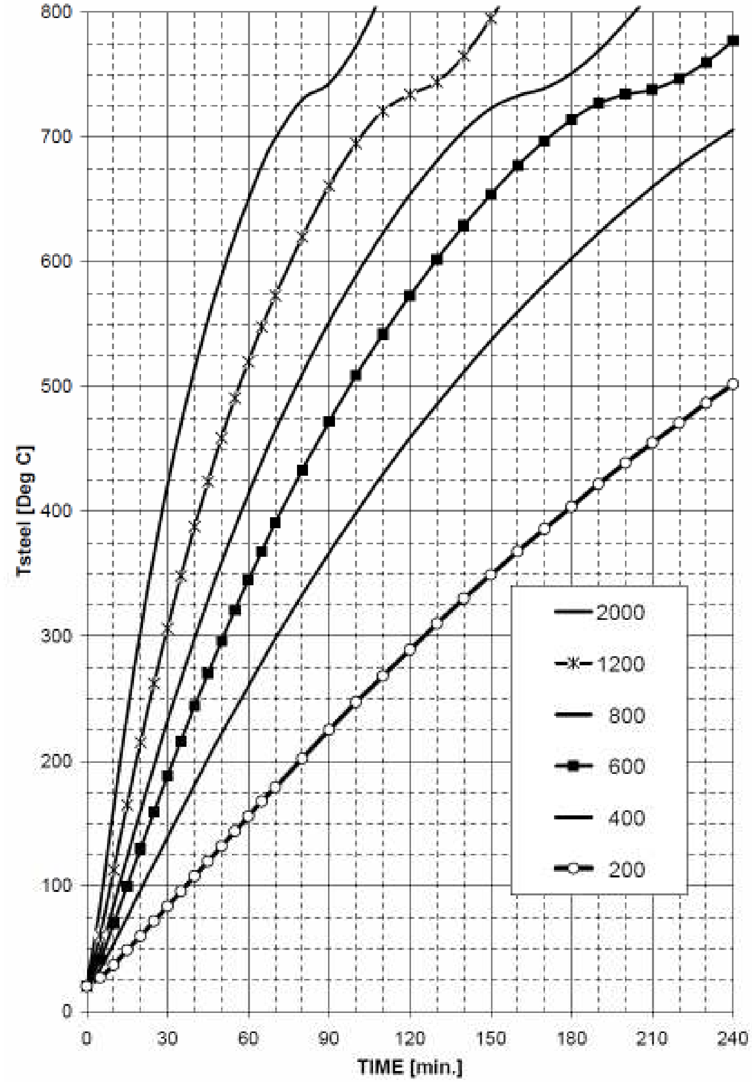
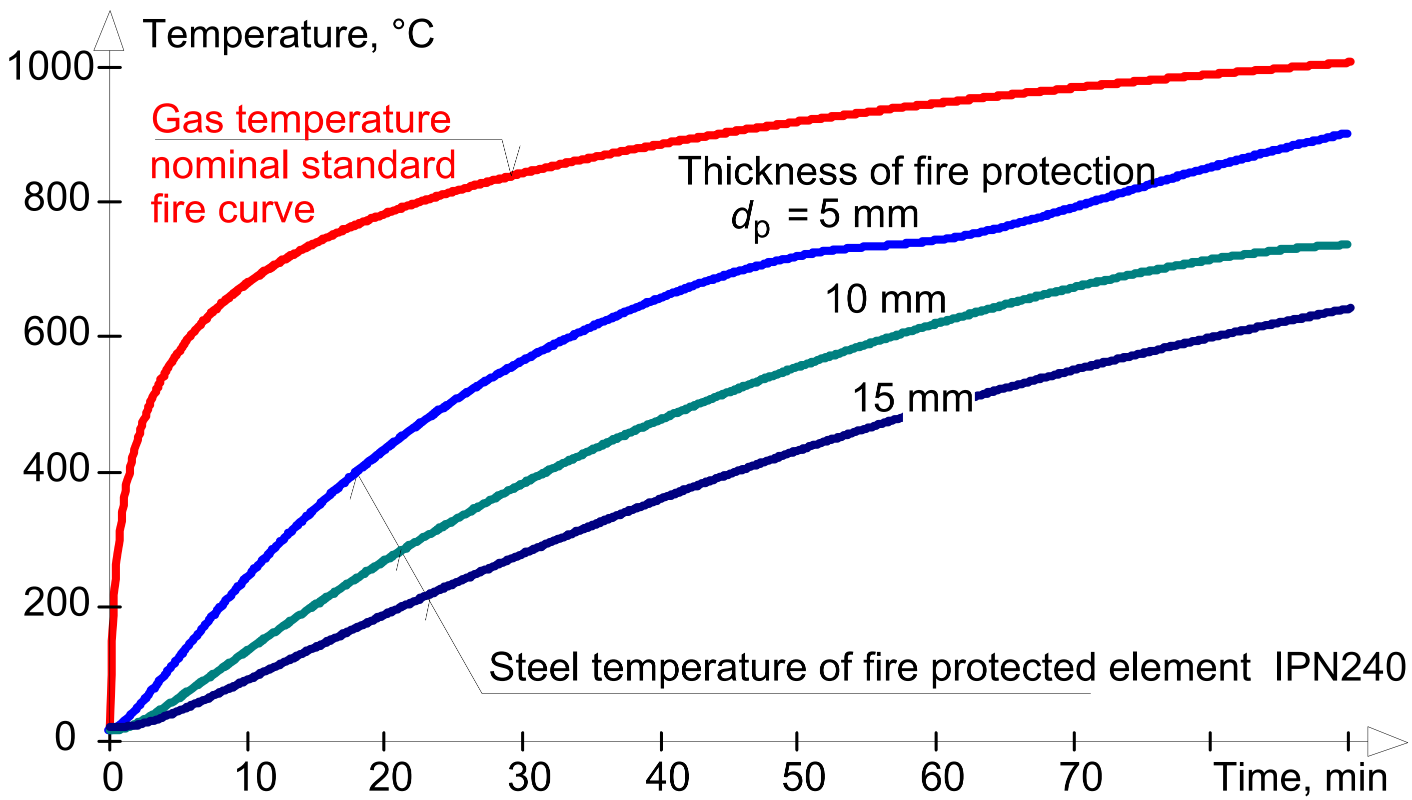



Figure I-5 : temperatures as a function of time for various values of the factor $k_p$

# Result of step by step procedure

Temperature of the fire protected steel element
heated by nominal standard curve



## Caution !

A common error that must be avoided is to consider the values of the thermal properties for the fire protection derived at ambient temperature, typically for applications such as thermal insulation in buildings.

This would lead to unsafe results in the fire situation, because the thermal conductivity has a tendency to increase with increasing temperature in most insulating materials.

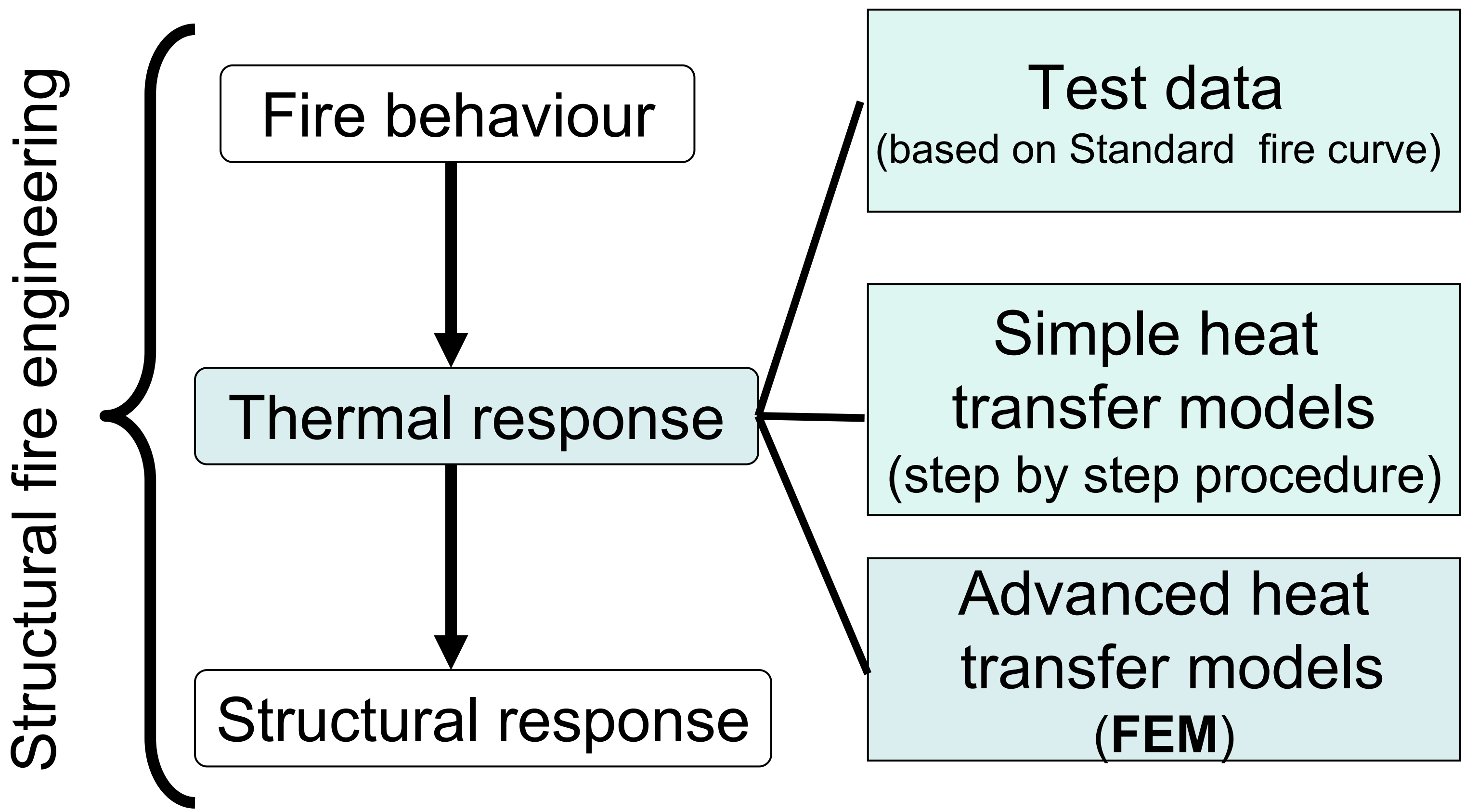
# Material properties for preliminary design

| Material | Unit mass $\rho_p$ [kg/m$^3$] | Thermal conductivity $\lambda_p$ [W/(m.K)] | Specific heat $c_p$ [J/(kg.K)] |
|---|---|---|---|
| SPRAYS | | | |
| **- mineral fibre** | **300** | **0,12** | **1200** |
| **- vermiculite cement** | **350** | **0,12** | **1200** |
| **- perlite** | **350** | **0,12** | **1200** |
| **HIGH-DENSITY SPRAYS** | | | |
| **- vermiculite (or perlite) and cement** | **550** | **0,12** | **1100** |
| **- vermiculite (or perlite) and gypsum** | **650** | **0.12** | **1100** |
| BOARDS | | | |
| **- vermiculite (or perlite) and cement** | **800** | **0,2** | **1200** |
| **- fibre-silicate or fibre calcium-silicate** | **600** | **0,15** | **1200** |
| **- fibre-cement** | **800** | **0,15** | **1200** |
| **- gypsum board** | **800** | **0,20** | **1700** |
| **COMPRESSED FIBRE BOARDS** | | | |
| **- fibre-silicate, mineral- & stone-wool** | **150** | **0,2** | **1200** |
| **Concrete** | **2300** | **1,60** | **1000** |
| **Light weight concrete** | **1600** | **0,80** | **840** |
| **Concrete bricks** | **2200** | **1,00** | **1200** |
| **Bricks with holes** | **1000** | **0,40** | **1200** |
| **Solid bricks** | **2000** | **1,20** | **1200** |

EN 13381-4 “Test methods for determining the contribution to the fire resistance of structural members - Applied protection to steel members”

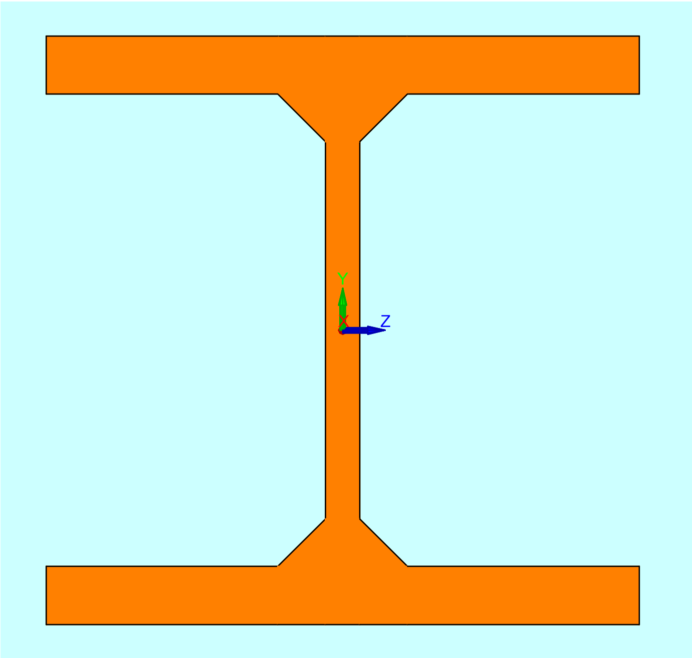
# Thermal conductivity models of common fire protection materials

| *Material* | *Density ρ, kg/m³* | *Base value of specific heat, J/kg.K* | *Thermal conductivity, W/m.K* |
|---|---|---|---|
| Rock fibre | 155–180 | 900 | $\lambda_{rock\ fibre} = 0.022 + 0.1475\left(\frac{T}{1000}\right)^3$ |
| Mineral wool | 165 | 840 | $\lambda_{mineral\ wool} = 0.03 + 0.2438\left(\frac{T}{1000}\right)^3$ |
| Calcium silicate | Various | 900 | $\lambda^* = \lambda_0^* + CT^3$<br>$\lambda_0^* = 0.23\frac{\rho}{1000}$<br>$C = 0.08 \times \frac{(2540-\rho)}{2540}$ |
| Vermiculite | Various | 900 | $\lambda^* = \lambda_0^* + CT^3$<br>$\lambda_0^* = 0.27\frac{\rho}{1000}$<br>$C = 0.18 \times \frac{(1000-\rho)}{1000}$ |

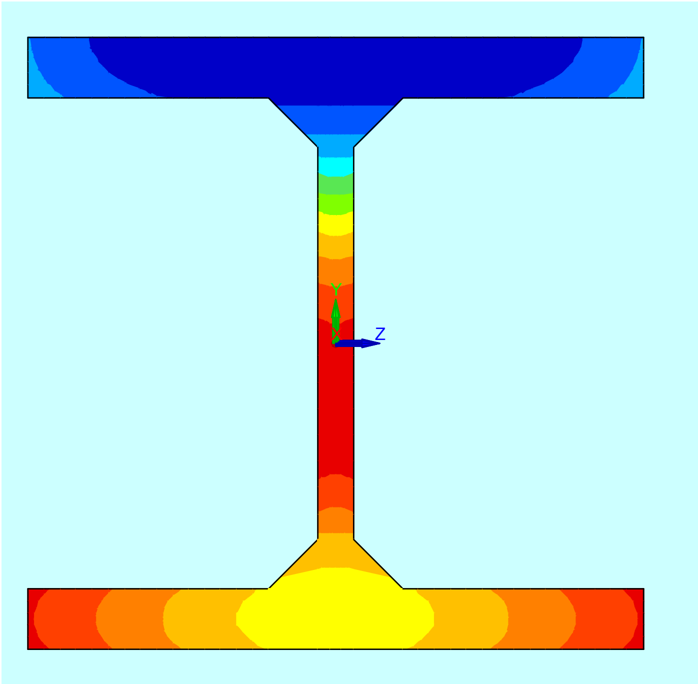

Structural fire engineering
Fire behaviour
Thermal response
Structural response
Test data
(based on Standard fire curve)
Simple heat transfer models
(step by step procedure)
Advanced heat transfer models
(FEM)

# Thermal gradient on elements

Uniform temperature



Non uniform temperature



# Temperatures development in structure during CTU edge bay test in Cardington






## Recapitulation

- Describe the three models of heat transfer.
- Describe the major components of the net heat flux.
- What is influencing the emissivity during the fire?
- Which is the principle of the step by step procedure of heat transfer for the fire protected steel element?
- Which are the material thermal properties of fire protection that are taken into account in the evaluation of transfer of heat to the fire protected elements?
- Which is the difference in the calculation of the section factor for the fire protected and unprotected steel elements?

# Thank you
# for your attention

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