9-2. Fire behaviour and thermal response

František Wald

Czech Technical University in Prague

EQUESTA
Electronic Quality Assured
Steel Training & Assessment

Education and Culture
Lifelong learning programme
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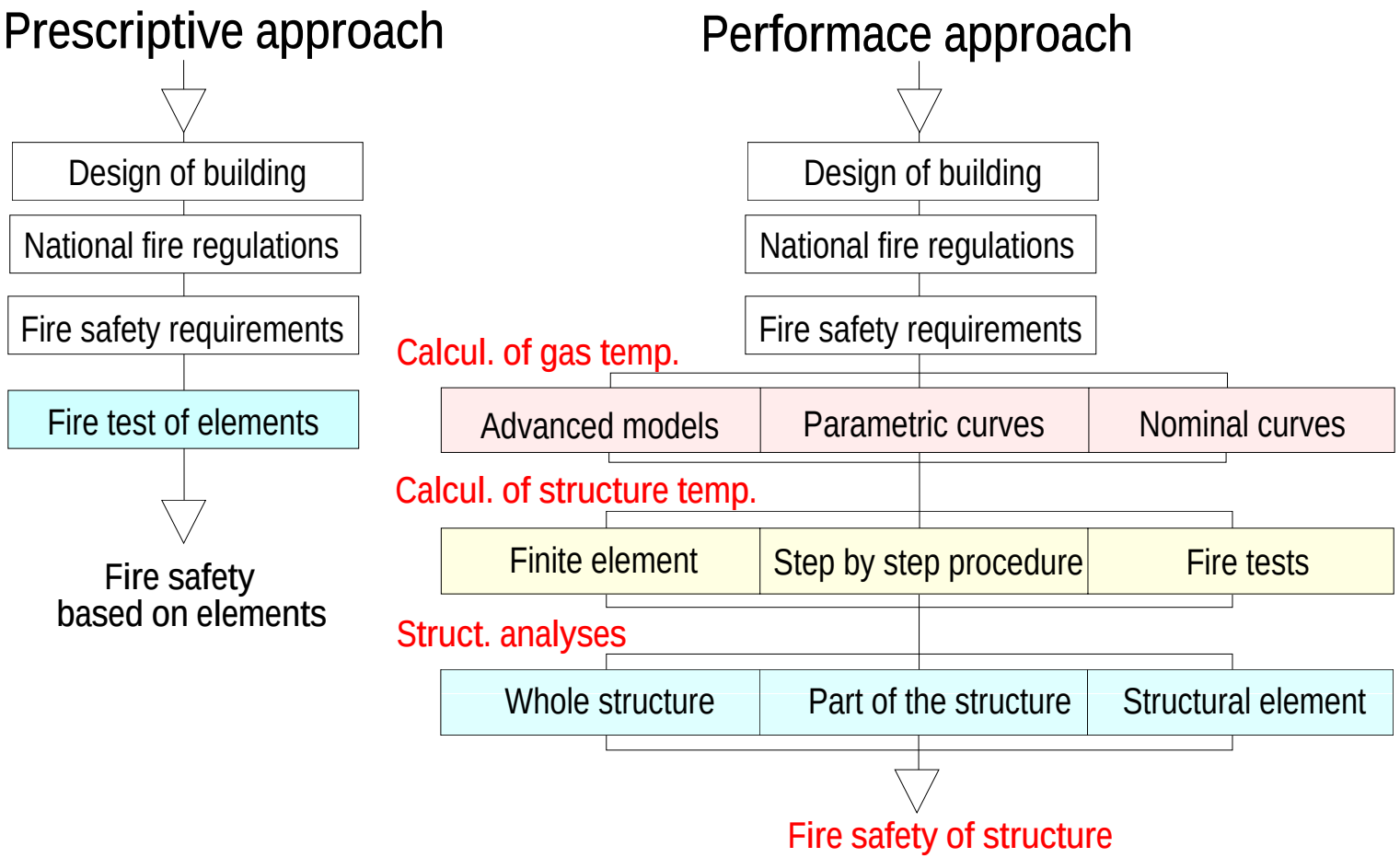
Objectives of the lecture

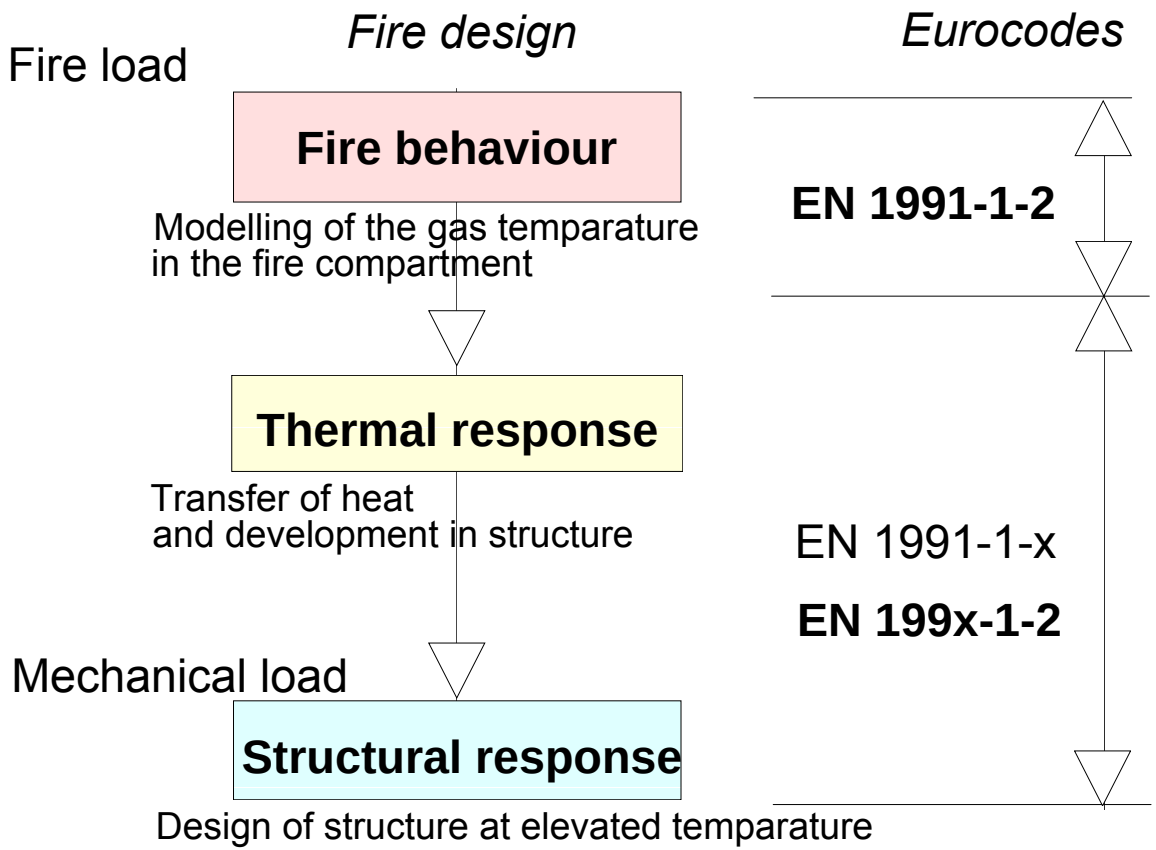
- Models of fire
- Software supports
- Models of transfer of heat into structure
- Software supports
- Example of test on building

Repetition

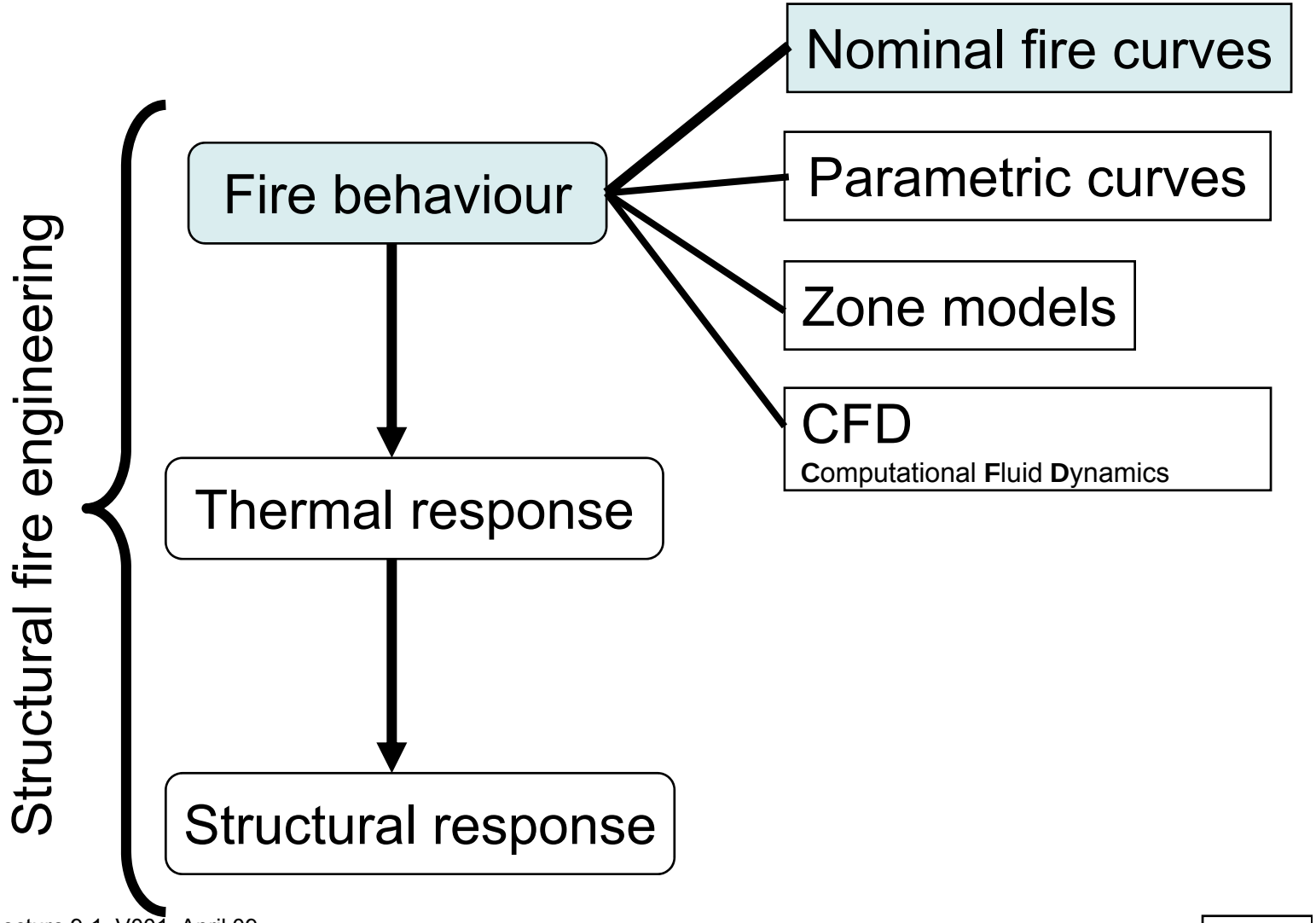


Repetition

The major steps of the fire design

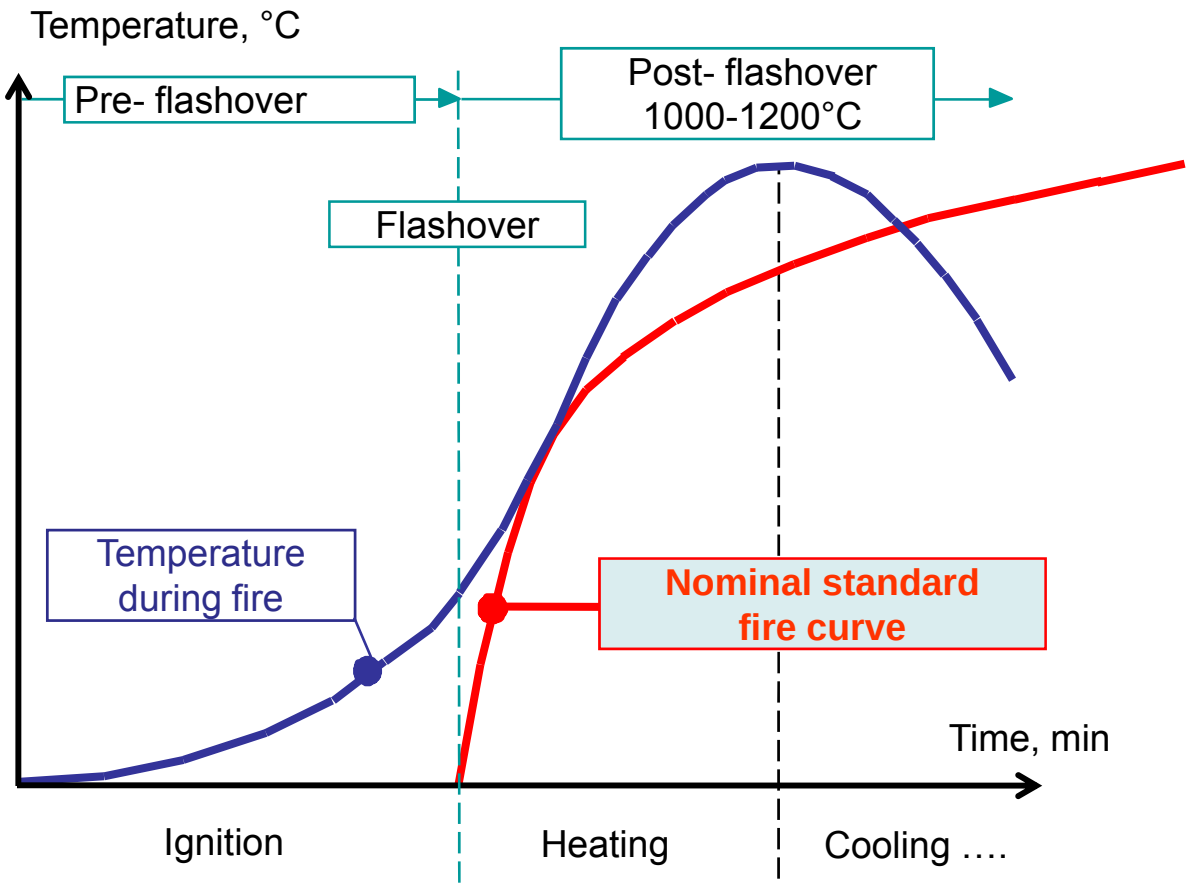


Fire behaviour



Nominal fire curves

The simplest fire modelling



Nominal fire curves

Nominal standard curve

$$\theta_g = 20 + 345 \log_{10}(8\,t + 1)$$

Nominal external curve

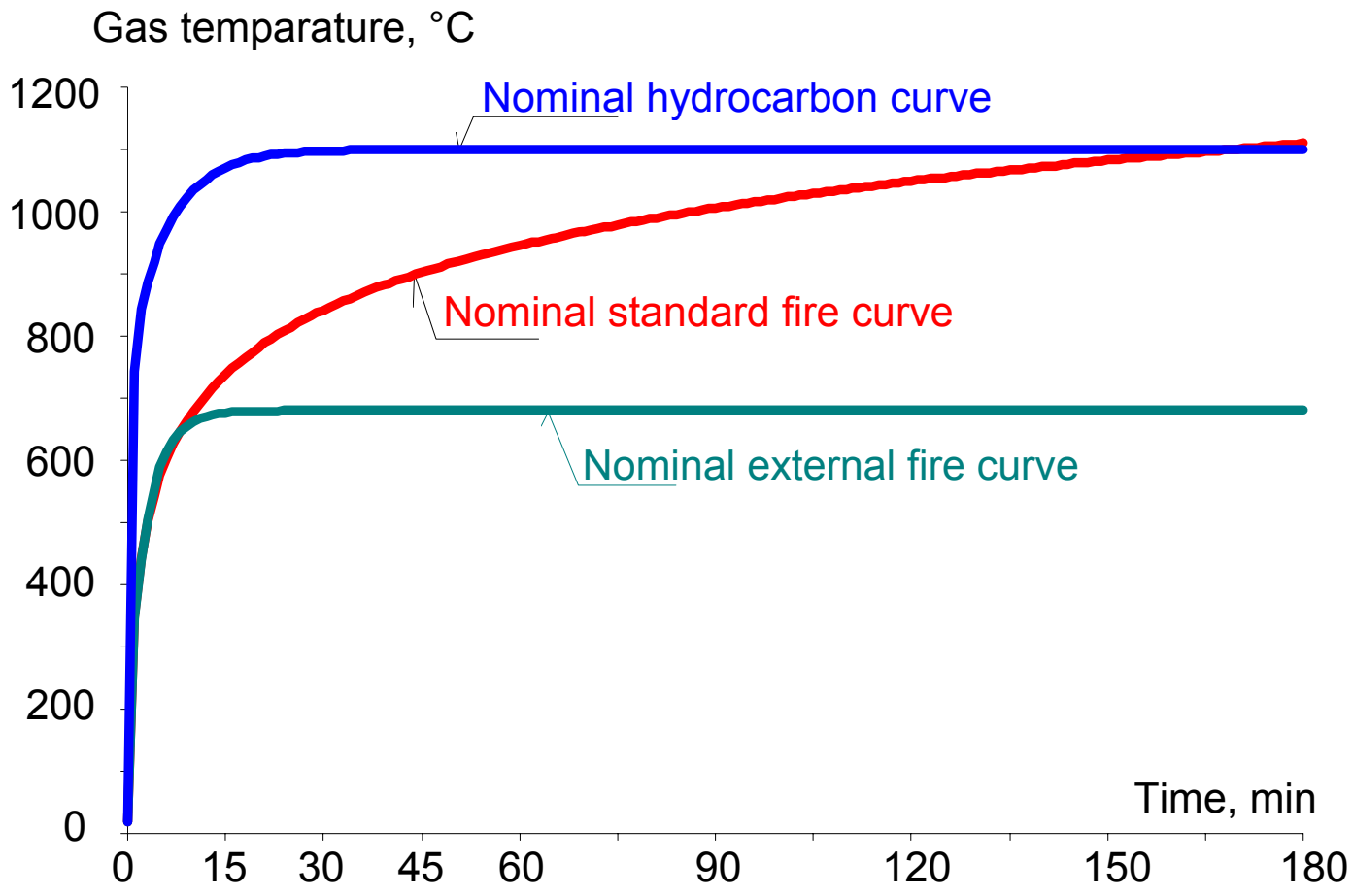
$$\theta_g = 20 + 660\left(1 - 0{,}687\,e^{-0{,}32\,t} - 0{,}313\,e^{-0{,}38\,t}\right)$$

Nominal hydrocarbon curve

$$\theta_g = 20 + 1080\left(1 - 0{,}325\,e^{-0{,}167\,t} - 0{,}675\,e^{-2{,}5\,t}\right)$$

Nominal standard fire curve

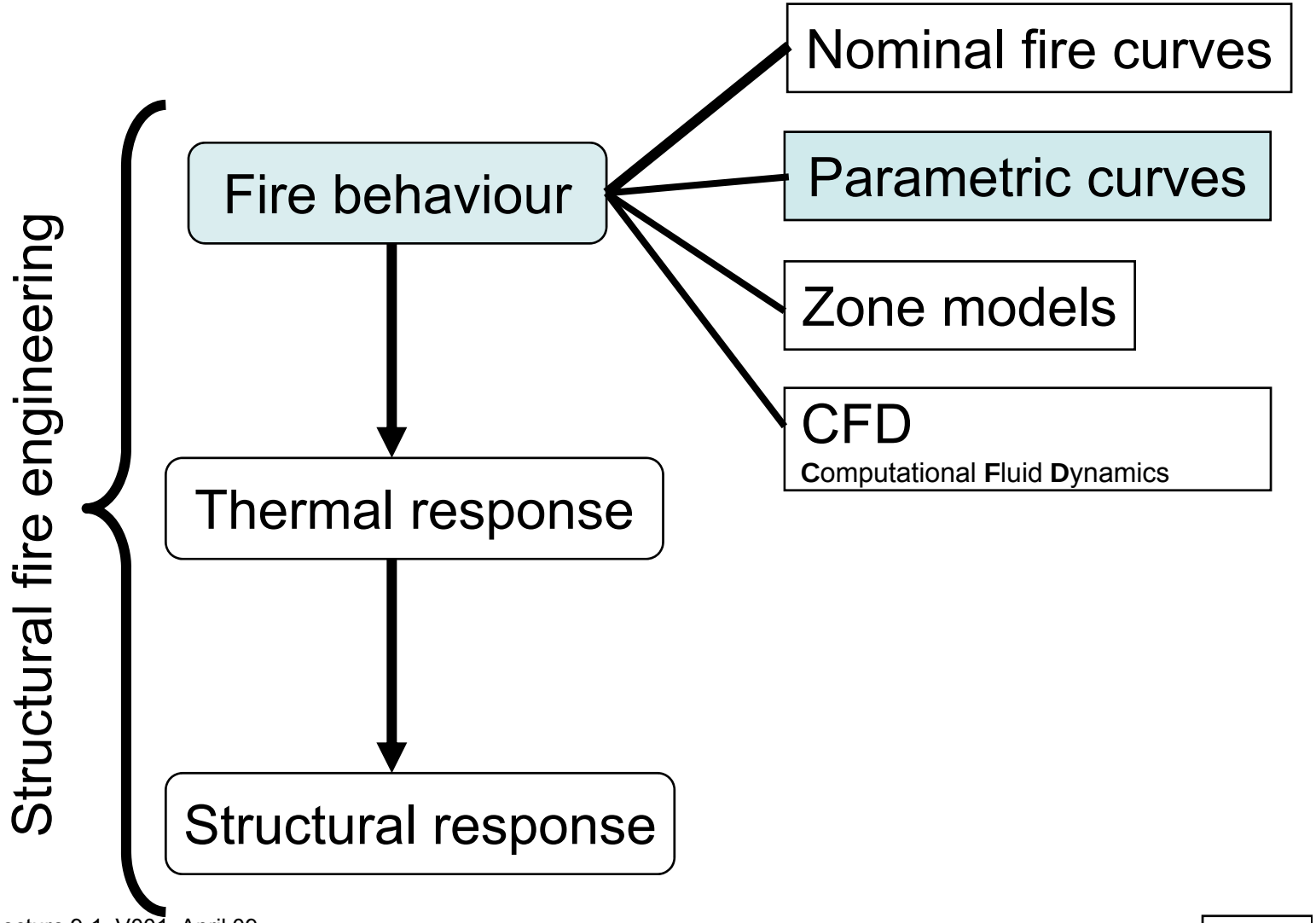
- The temperature depends on time only



Pros and Cons

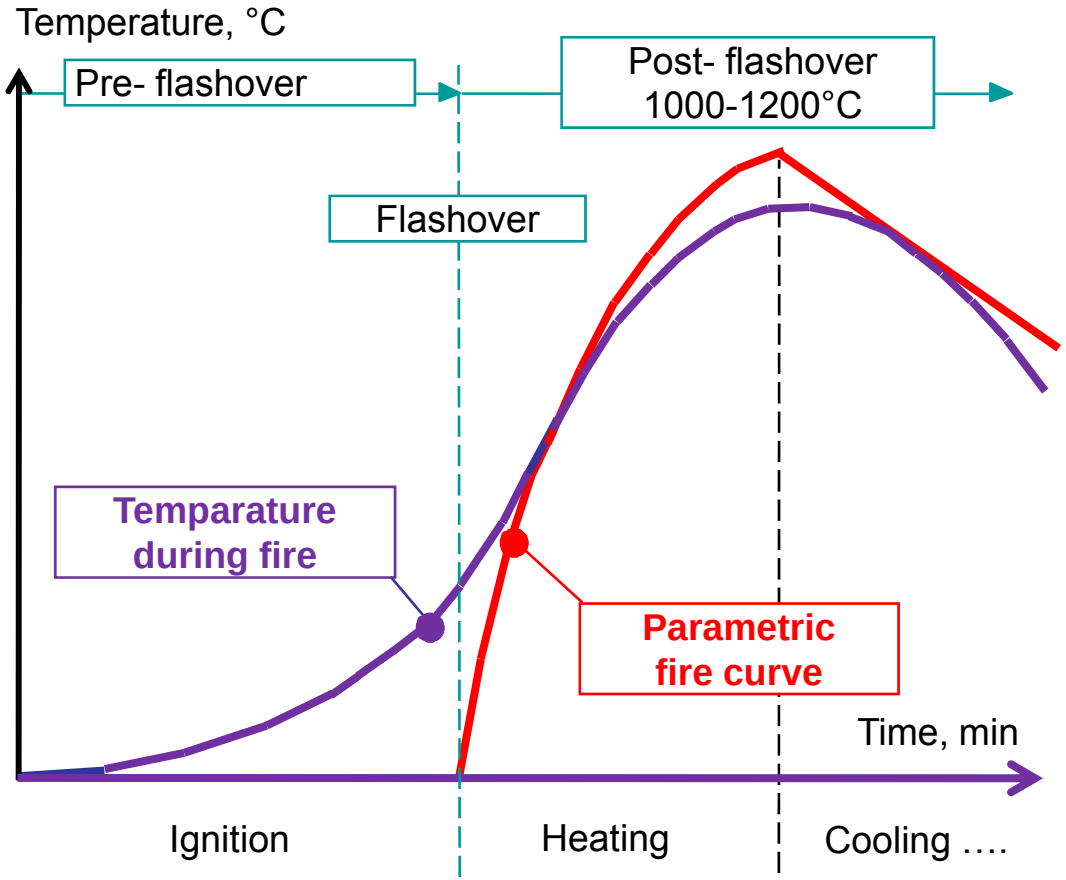
- Has limitations
  - Not based on real fire data
  - Test repeatability difficult
  - No cooling phase
  - Uniform heating
  - Uses gas temperature “not fair”
- But
  - Widely used
  - Can be useful for crudely comparing products

Fire behaviour



Parametric fire curve

The curve contains both phases of the fire **heating and cooling.**



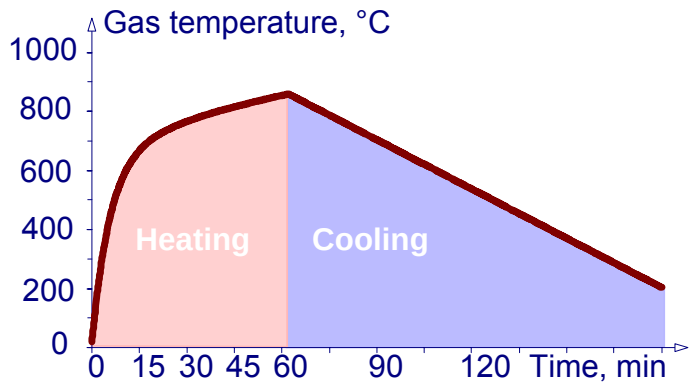
Assumptions in parametric fire curve

- No heat built-up in pre-flashover phase of fire
- Temperature uniform in the compartment
- Uniform heat transfer coefficient in compartment boundaries
- All combustion takes place in the compartment

Limits of parametric fire curve

The calculation is in Annex A of EN 1991-1-2

- The size of the compartment is limited to 500 m^2
- The openings are in the walls only (no openings in the roof)
- Maximal height of the compartment 4 m
- The fire load density $q_{t,d}$ from 50 to 1000 MJ/m^2 (about 3,5 kg to 70 kg of timber / m^2)
- Cellulosic type of fire load



Structure of parametric fire curve

Input data

Fire load density $q_{t,d}$ for calculation of t_{tmax}

Number and size of the openings

Geometry of the fire compartment

$$O = \frac{A_v \sqrt{h}}{A_t} \quad \left[m^{1/2}\right]$$

Thermal properties of boundary of enclosure

$$b = \sqrt{\rho\, c\, \lambda} \quad \left[J/m^2 s^{1/2} K\right]$$

Time modification factor $\Gamma = \dfrac{\left(\dfrac{O}{O_{ref}}\right)^2}{\left(\dfrac{b}{b_{ref}}\right)^2}$

Fictive time in hours $t^* = \Gamma t$

Burining and cooling part of curve

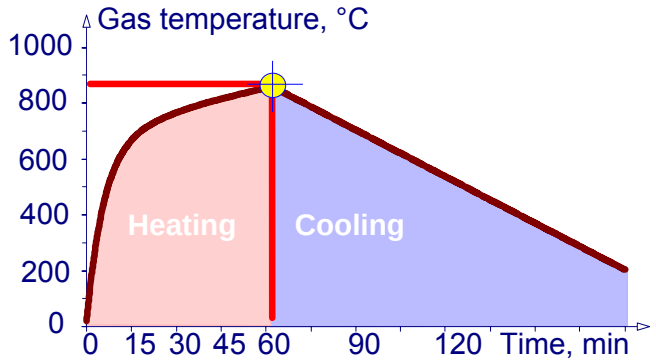
Two parts of the parametric fire curve

The curve in the burning phase

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

The curve in the cooling phase (depends on t^*_{max}, e.g.)

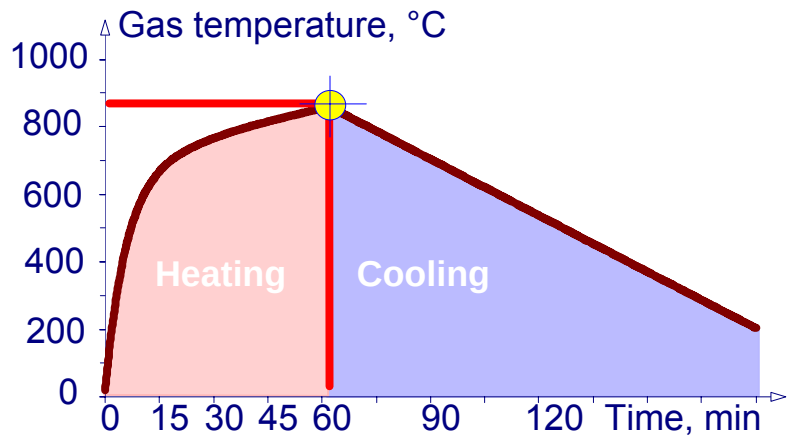
$$\theta_{g,t} = \theta_{max} - 250\left(t^* - t^*_{max}\,x\right)$$



The maximal gas temperature

- Fire driven by ventilation
  - $t_{max} = 0{,}2\ 10^{-3}\ q_{t,d} / O$
  - $t^*_{max} = t_{max}\ \Gamma$

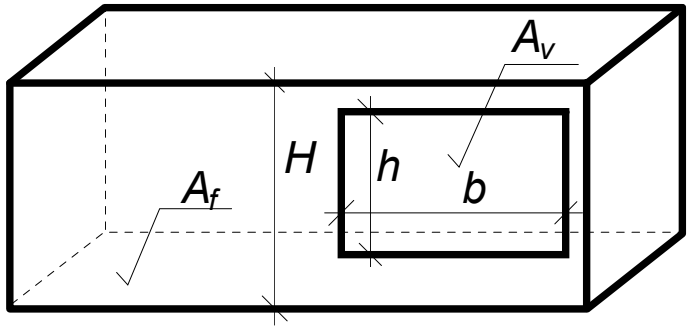
- Fire driven by fire load
  - $t_{max} = t_{lim} = 25$ min (fast fire or 20 min and 15 min slow fire)
  - $t^*_{max} = t_{max}\ \Gamma_{lim}$



Opening factor

Influence of openings

$$O = \frac{\sum A_v \sqrt{h}}{A_t} \quad \left[m^{1/2}\right]$$



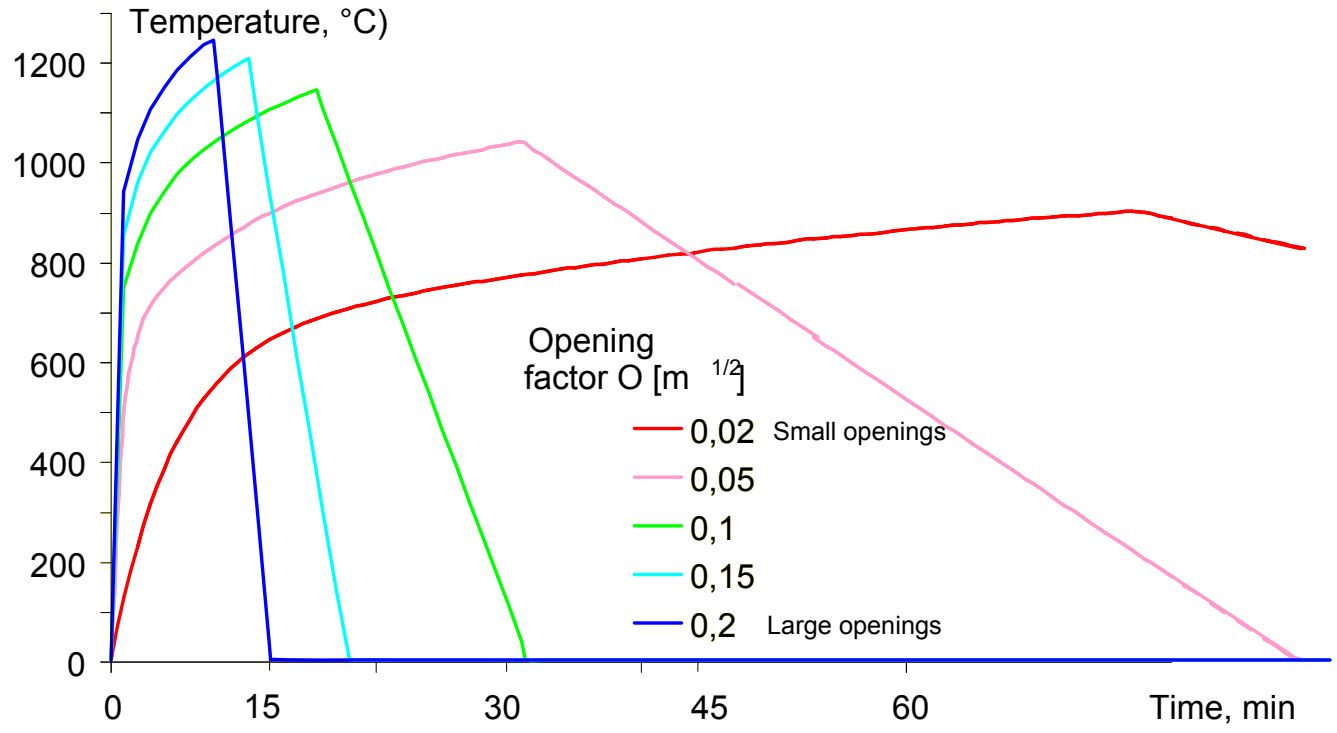
A_v area of opening

h height of opening

A_t total surface area of the enclosure (walls, ceiling and floor, including the openings)

Influence of opening factor

- Small openings - longer and colder fires
- Large openings - faster and hotter fires



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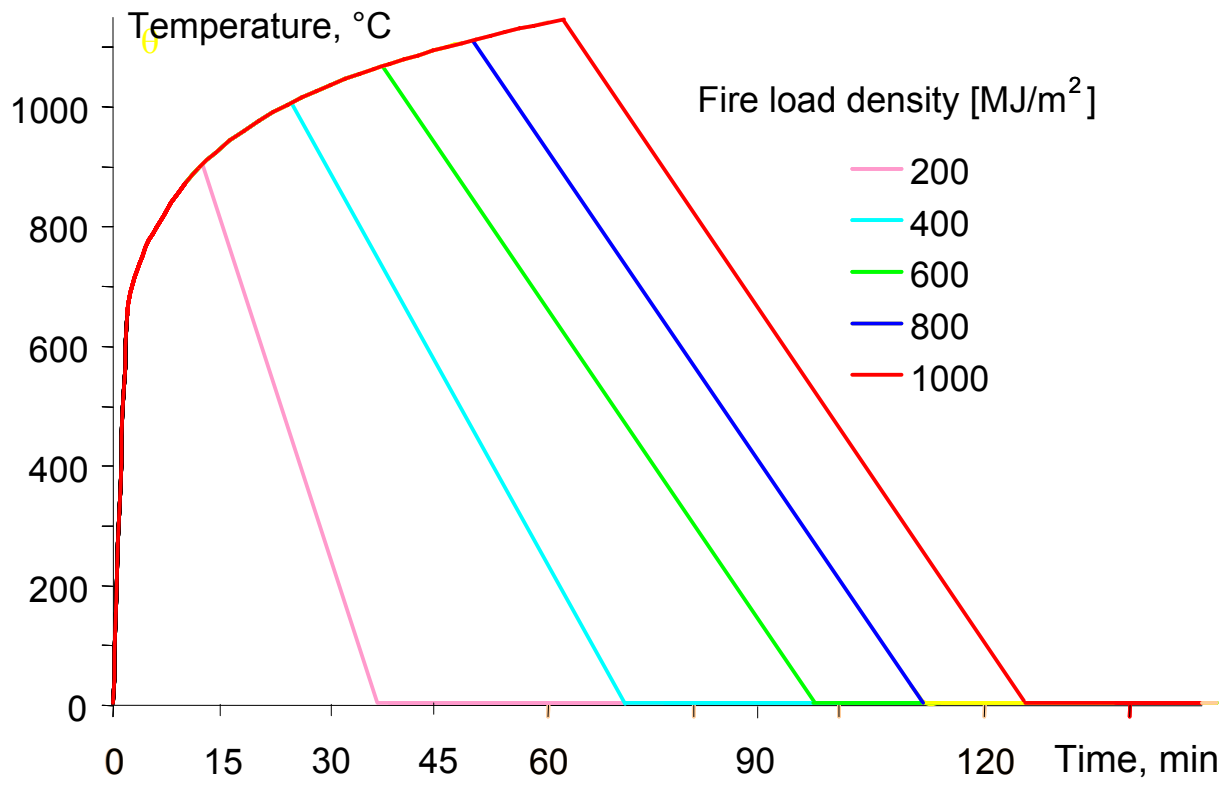
Influence of fire load density

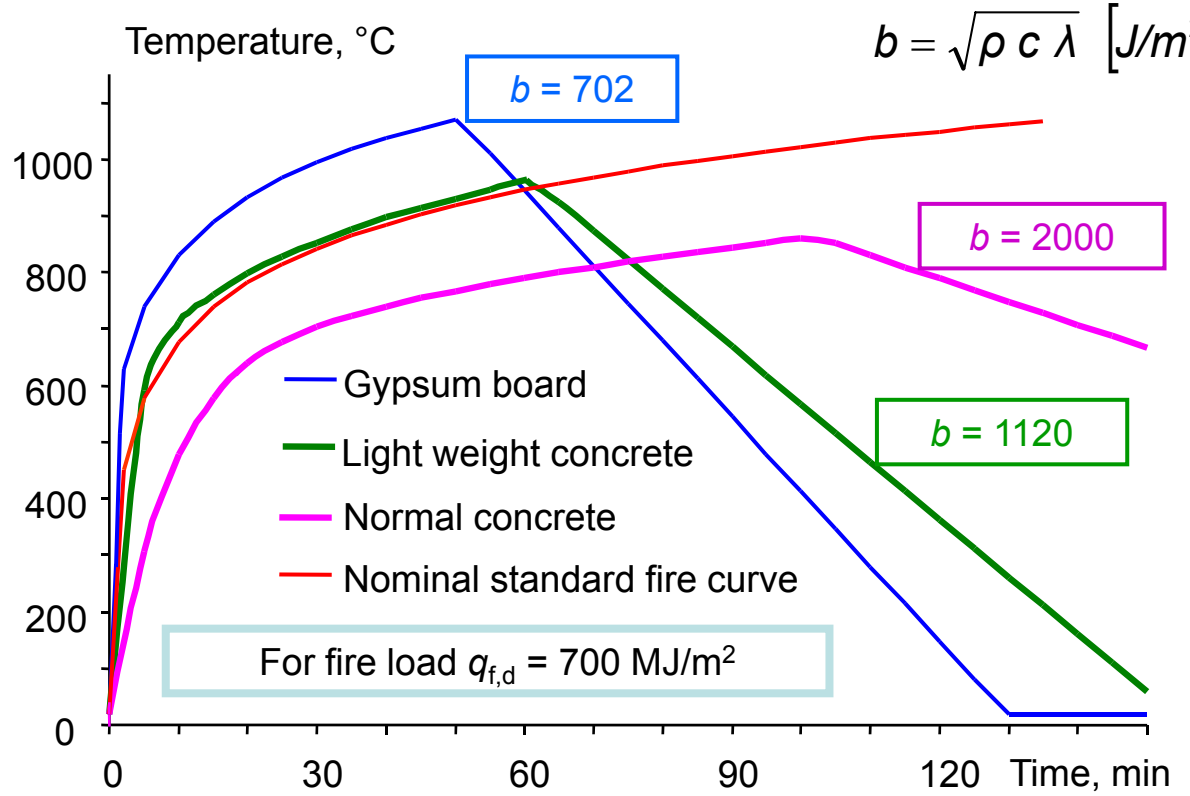
- Low fire load - shorter and coulder fires
- High fire load - longer and wormer fires



Influence of boundary of enclosure

- Heavy walls - higher cooling – lower temp.
- Isolated walls – lower cooling - higher temp.

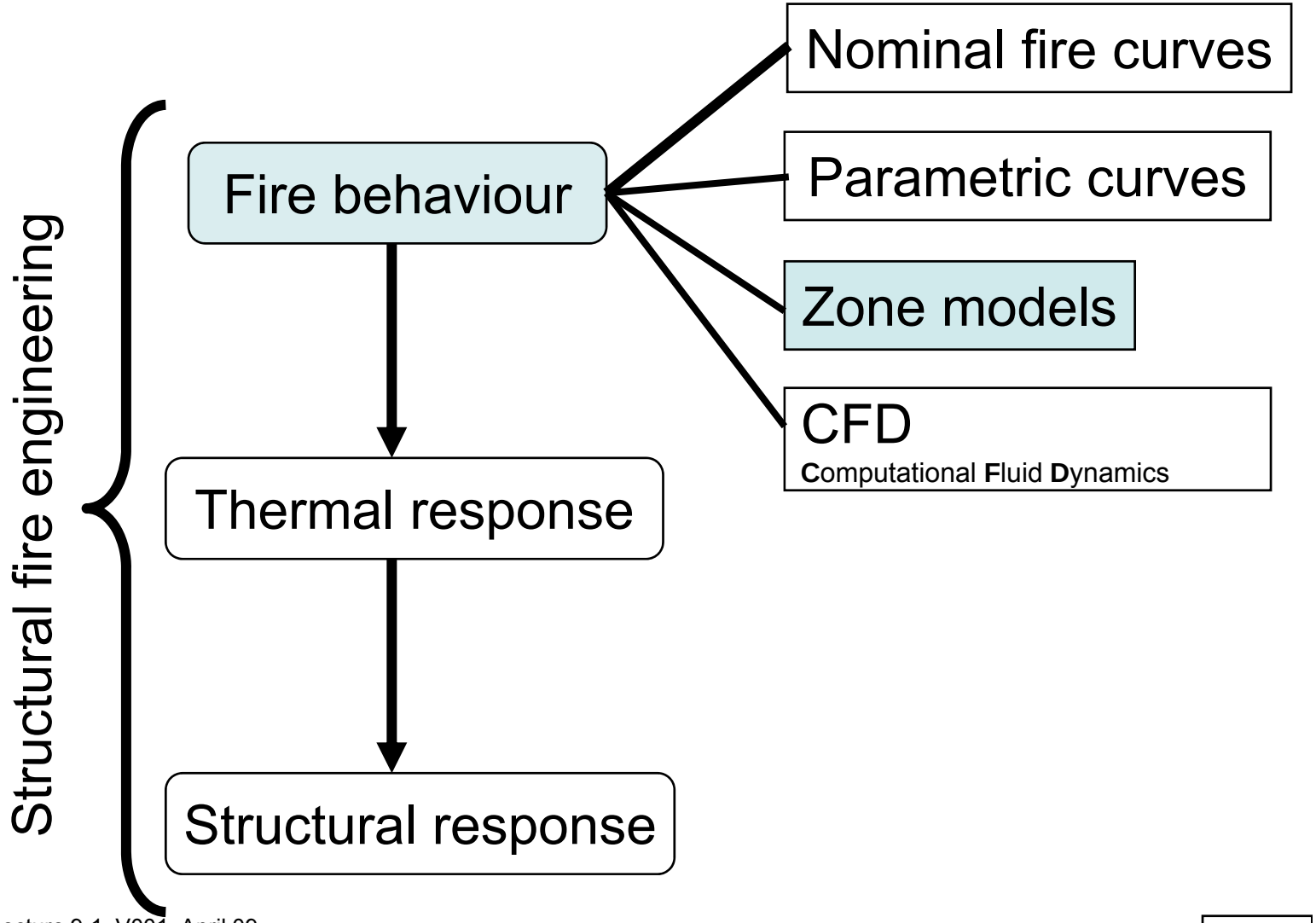
$$b = \sqrt{\rho\, c\, \lambda} \quad \left[J/m^2 s^{1/2} K\right]$$



Zone Models

- More sophisticated energy balance models
- Assume uniform temperatures in each zone
- Normally computer based
- Several commercial codes available eg. Ozone, CFast
- Similar drawbacks and benefits to parametric curves

Fire behaviour

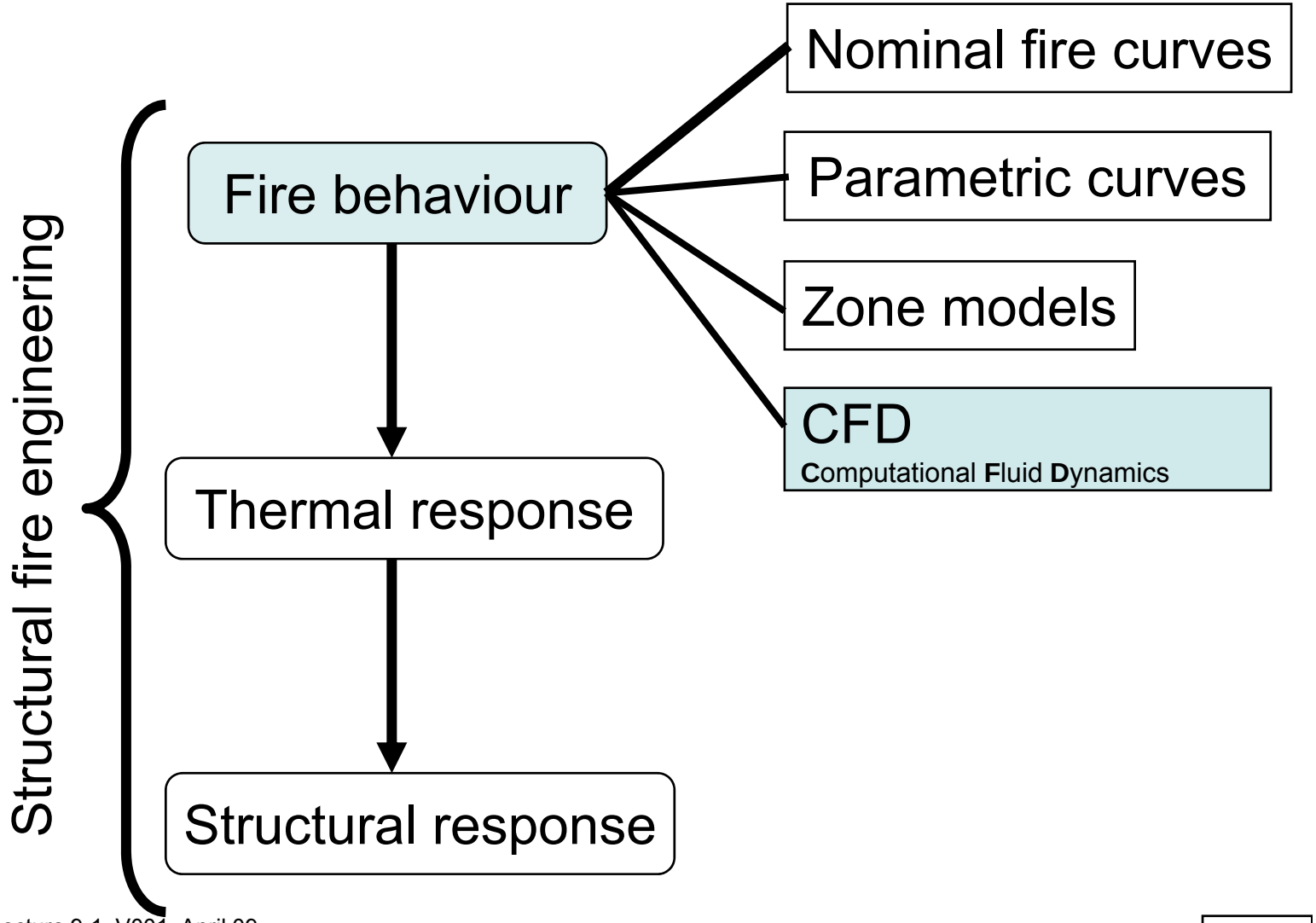


Zone Models

- Based on partial differential equations:
  - Mass balance
- the air (oxygen) entering the fire compartment is used for burning of the fuel, the amount of the incoming air and the gases created as result of the burning is equal to the amount of gas escaping through the openings
  - Energy balance
- the energy released from the burning is used to heat the gas in the fire compartment, the walls, floor and ceiling, some energy is „lost“ as the gas exits the compartment through the openings

- Two zone model
- One zone model

Fire behaviour

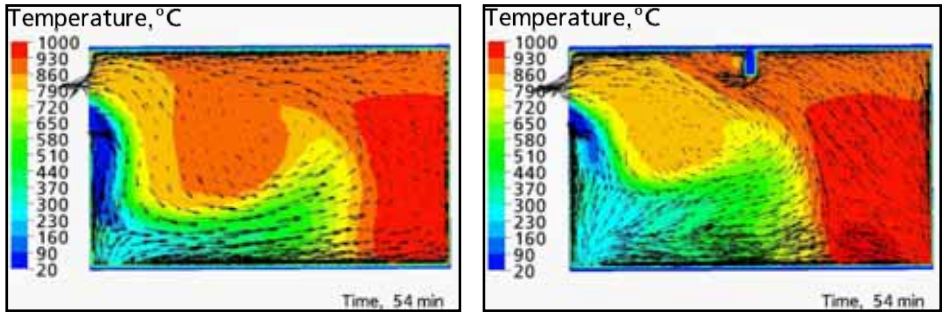


CFD Modelling

- **C**omputational **F**luid **D**ynamics
- Can predict huge range of phenomena
- Difficult to use
  due to many uncertainties in input variables
- Still more a research method

Example of CFD simulation

the influence of the ceiling surface on the temperature development during the seventh Cardington large fire test



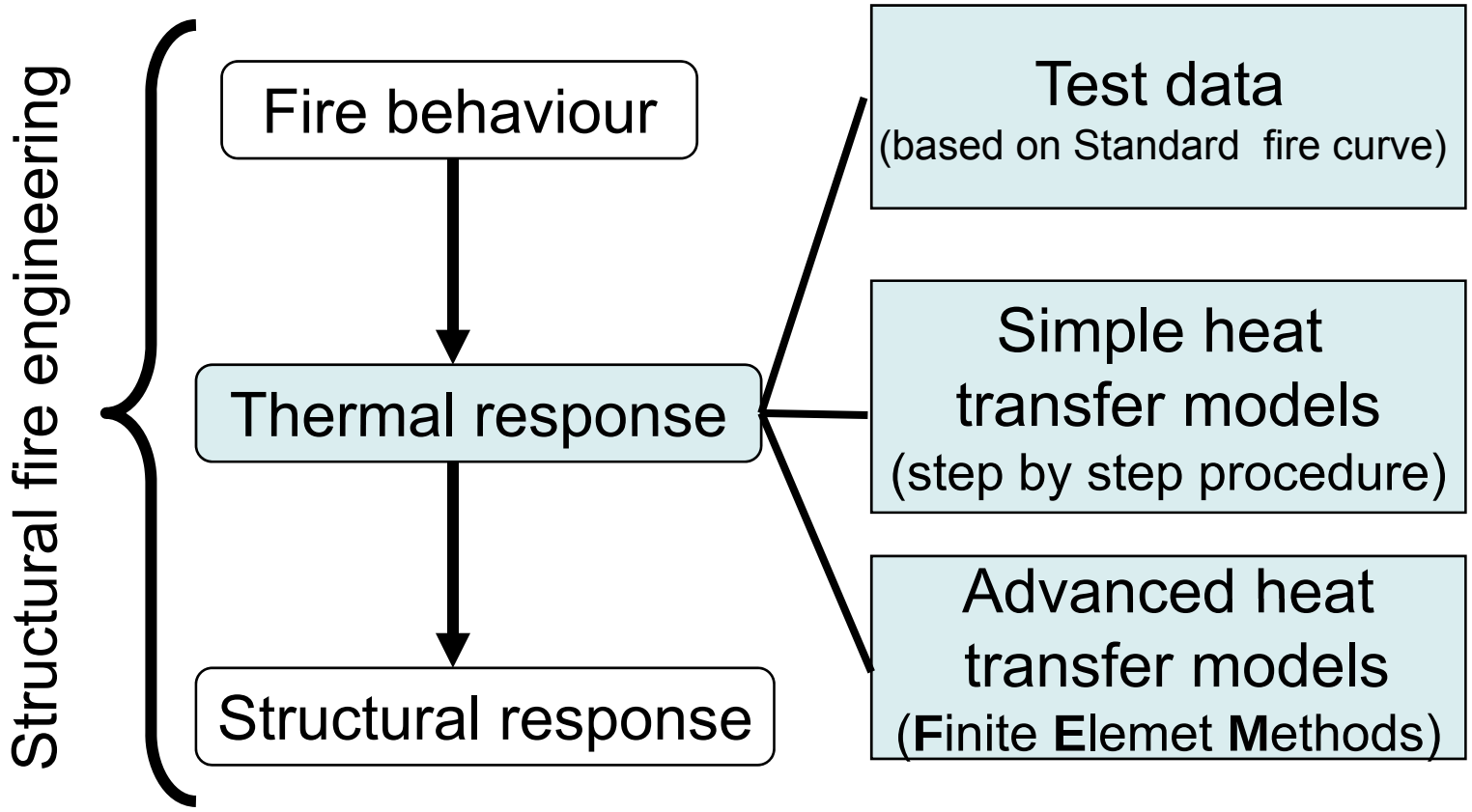
Software support

- The simple tools are developped for
  - Parametric fire curves
    - eg. DIFISEK-EN 1991-1-2 Annex A
  - Zone models
    - eg. Ozone programme
- The description of tools advantages are summarised in
    - DIFISEK+ database

Formative assessment question 1

- Are there some advantages of nominal fire curves?
- What are the advantages of parametric fire curves?
- What determine the maximal temperature of the parametric fire curve?
- How is simulated cooling by parametric fire curve?
- Describe the principles of zone models?

Thermal response



Principles of step by step procedure

for the fire unprotected steel element

- One-dimensional heat transfer
- Equilibrium of **increase of temperature** of structural element and **heat received on surface** of the element in time period Δt

Increase of en element temperature

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

The heat received on surface

where

V volume of the element [m^3] per unit length

A_m surface area of the element [m^2] per unit length

c_a specific heat of steel [simplified c_a = 650 J/kgK]

ρ_a density of steel [ρ_a = 7850 kg/m^3]

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

Δt time period [Δt_{max} = 5 s]

Step by step procedure

for the fire unprotected steel element in EN 1993-1-2

Assuming uniform temperature distribution over the cross-section, the **temperature increase** in time period Δt is

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

where A_m / V is the section factor [m^{-1}]

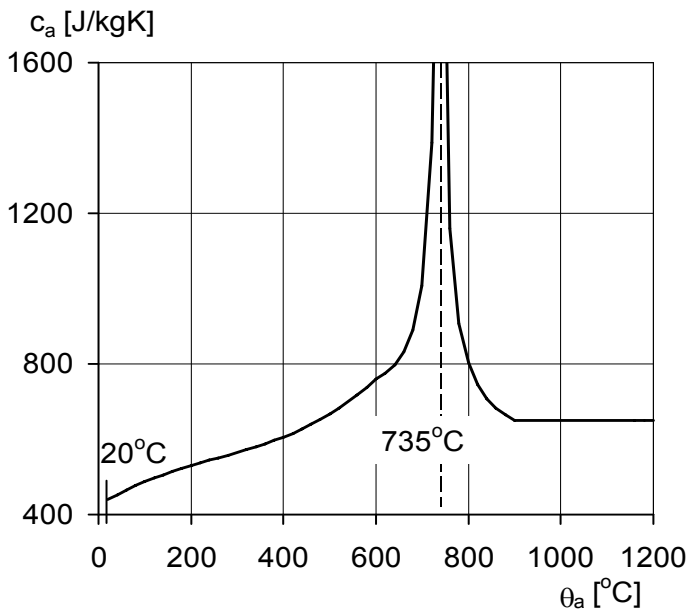
- cannot be used for A_m / V smaller than 10 m^{-1}
- when A_m / V is larger than about 200 m^{-1}, the computation gives $\theta_{a,t} \simeq \theta_{g,t}$
- the time period Δt should not be longer than 5 s

The temperature increase depends on the section factor A_m / V

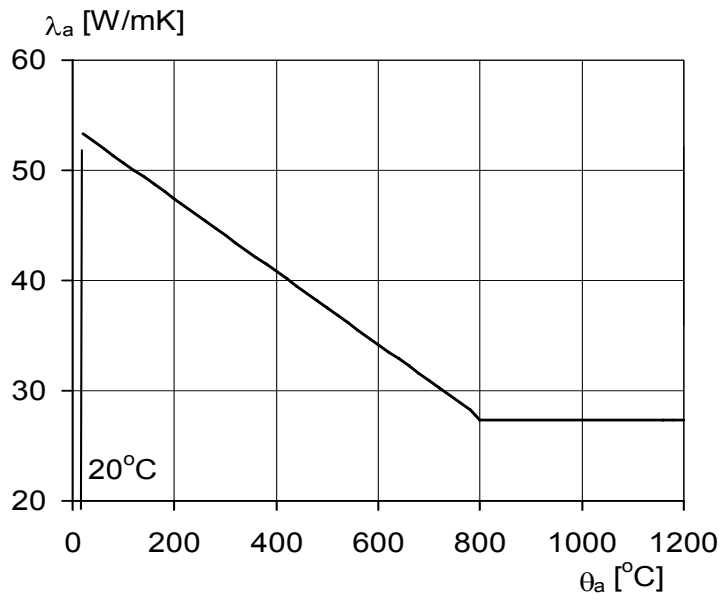
Thermal properties

of carbon steel at elevated temperatures

Specific heat

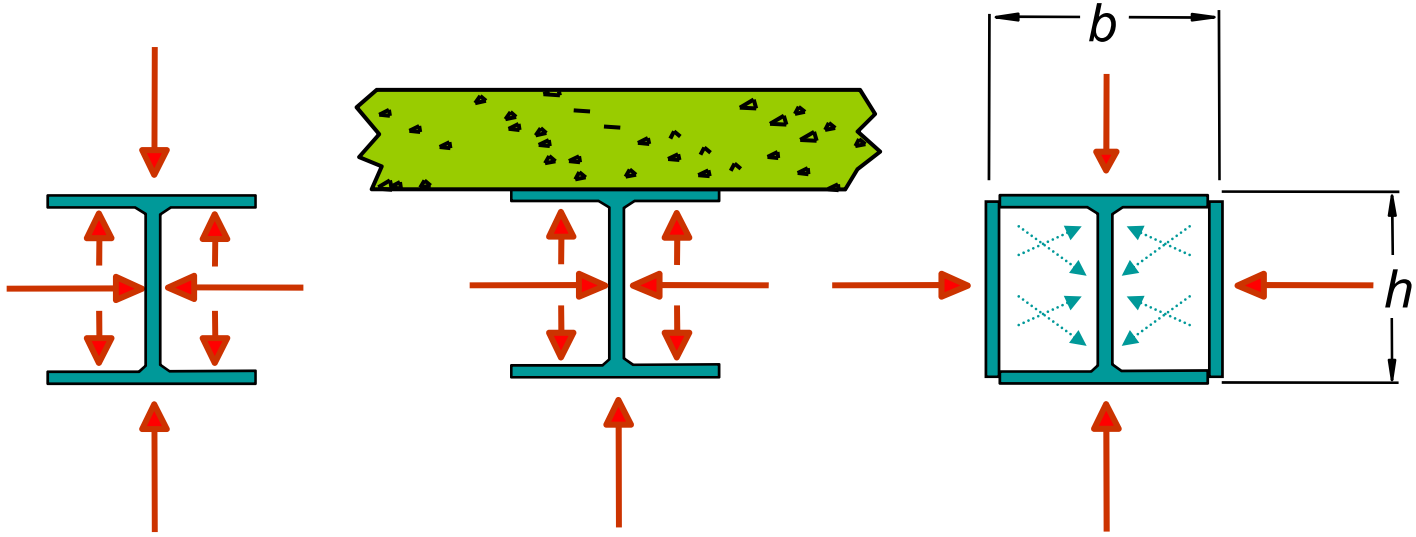


Thermal conductivity

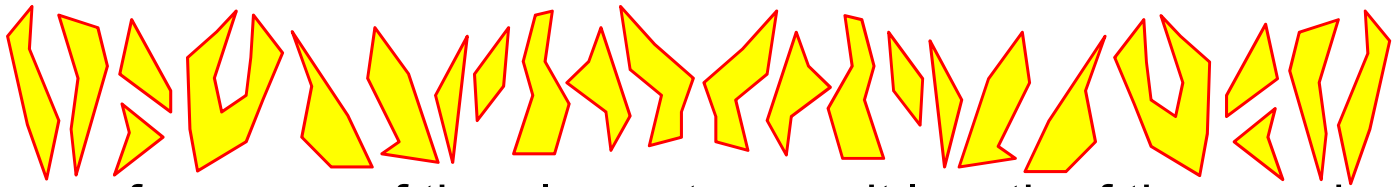


Section factor A_m/V

for the fire unprotected steel element



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



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

Shadow effect

For nominal standard fire curve

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

is applied for the total heat flux

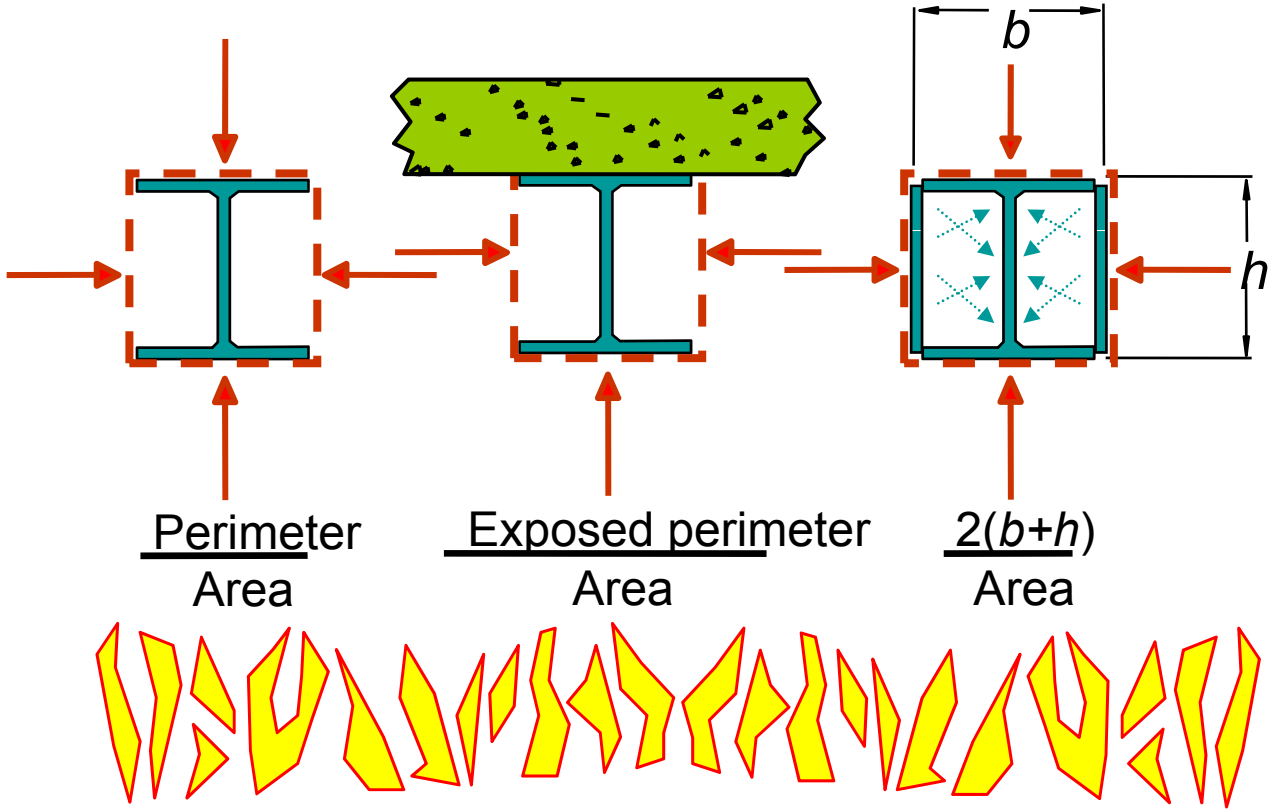
- k_{sh} = 1 for hollow sections of convex shape
- k_{sh} = 0,9 $(A_m/V)_b / (A_m/V)$ for I sections
- k_{sh} = $(A_m/V)_b / (A_m/V)$ for other sections

For I sections may be simplified

$$\Delta\theta_{a,t} = k_{sh} \frac{A_m / V}{c_a \ \rho_a} h_{net,d} \ \Delta t = 0{,}9 \frac{(A_m / V)_b}{A_m / V} \frac{A_m / V}{c_a \ \rho_a} h_{net,d} \ \Delta t$$

Section factor $(A_m/V)_b$

for shadow effect, unprotected steel element



The box value of the the surface area of the element per unit length of the member
devided by the volume of the member per unit length.

Heat flux

The net heat flux h_{net} is given as sum of effect of

convection and
radiation

The design value is given by

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

where

$h_{net,c}$ is effect off **convection**, heat flux from convection [W/m^2]

$h_{net,r}$ is effect off **radiation**, heat flux from radiation [W/m^2]

Convective heat flux

The convective heat flux [W/m^2] is given by

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

where

α_{c} is heat transfer coefficient

- α_{c} = 25 W/m^{2}K for standard curve
- α_{c} = 35 W/m^{2}K for parametric curve
- α_{c} = 50 W/m^{2}K for hydrocarbon curve
- α_{c} = 35 W/m^{2}K for zone models and localized fires

θ_{g} is gas temperature in proximity of the element [°C]

θ_{m} is surface temperature of the element [°C]

Radiative heat flux

The radiative heat flux [W/m^2] 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

ϕ is configuration factor, usually ϕ = 1,0

ε_{res} is resulting emissivity, see next page

θ_{r} is radiating temperature [°C]
can be taken equal to the gas temperature θ_{g}

θ_{m} is surface temperature of steel element [°C]

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

Resulting emissivity

The emissivity is changing during the fire, is influenced by amount of carbon particles and dust in the smoke, and the colour and temperature of the surface.
The value has significant effect on accuracy of the solution

$$\varepsilon_{res} = \varepsilon_f \ \varepsilon_m$$

where

ε_f is **emissivity of fire**, usually ε_f = 1,0

ε_m is **emisivity of material surface** for

- **carbon steel element** ε_m = **0,7**
- stainless steel element ε_m = 0,4
- aluminum alloys not painted ε_m = 0,3
- aluminum alloys painted ε_m = 0,7

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

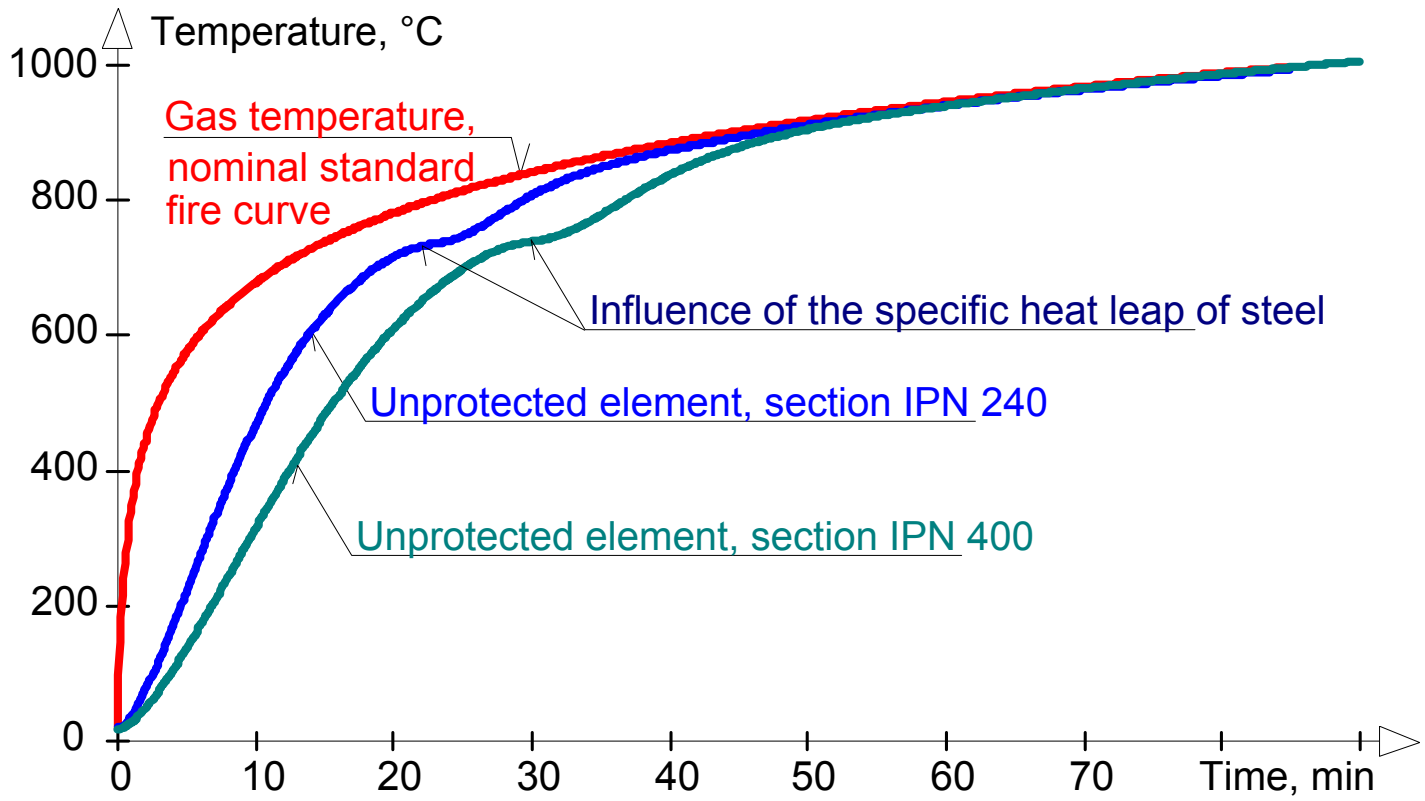
Specific heat of steel

Time

t		t	Θ_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 uprotected steel element heated by nominal standard curve



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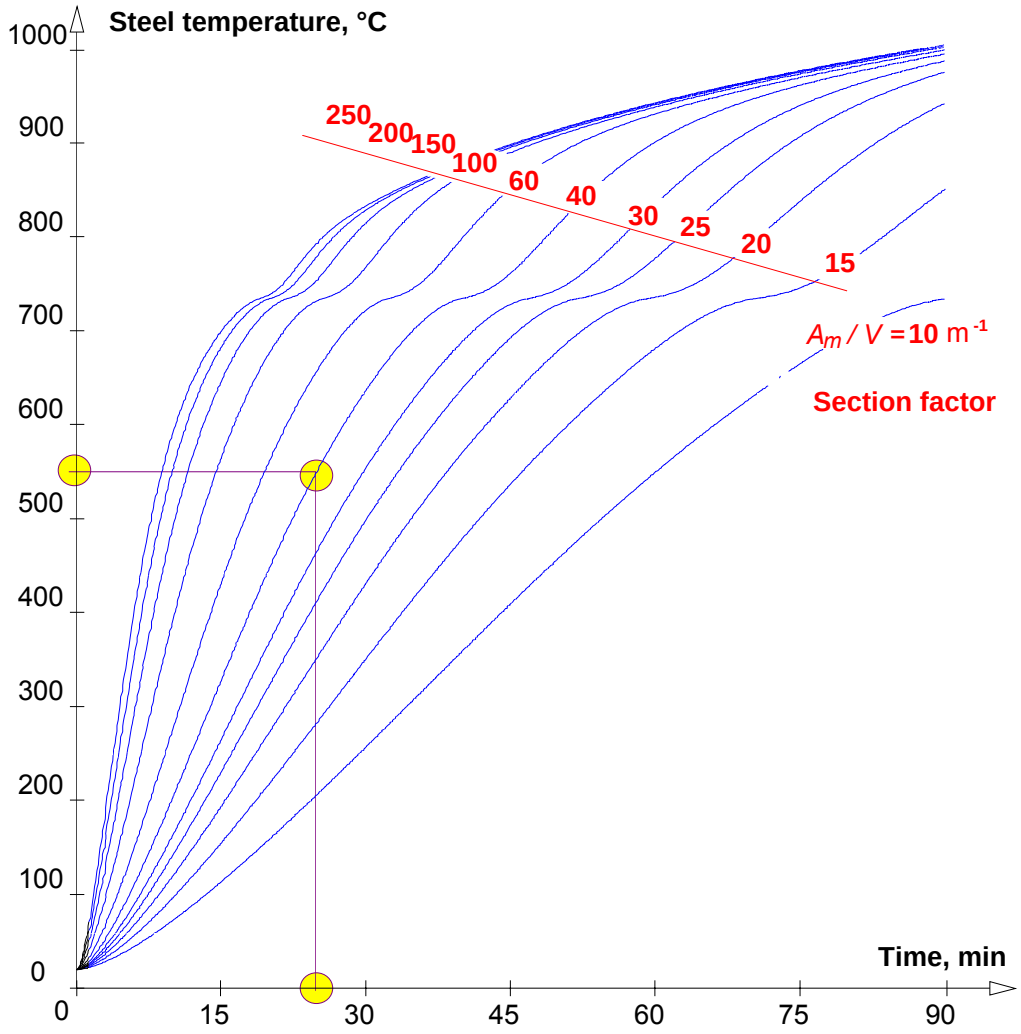
Result of step by step precedure

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

as function of time t

and section factor A_m / V



Principle of step by step procedure

for the fire protected steel element

The surface temperature of fire protection

- the same as the gas temperature $\theta_g - \theta_m << \theta_m - \theta_a$

Heat transfer through the fire protected layer

$$\Delta\theta_a = \frac{K_{ins}}{\rho_a c_a} \cdot \frac{A_m}{V} \cdot \left(\theta_g - \theta_a\right) \cdot \Delta t$$

where

K_{ins} is factor

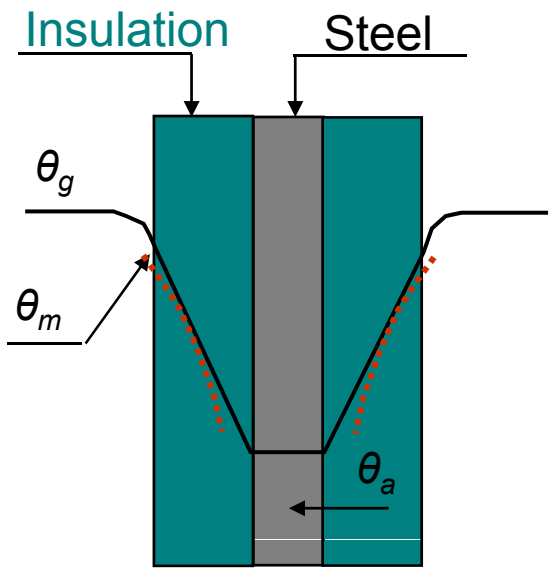
λ_p is thermal conductivity

ρ_p is density

c_p is thermal capacity

d_p is thickness

for light weight fire protection $K_{ins} \approx \lambda_p / d_p$



Temperature gradient is assumed linear

Step by step procedure

for the fire protected steel element in EN 1993-1-2

$$\Delta\theta_{a,t} = \frac{\lambda_p \left(A_p / V\right)}{d_p \, c_a \, \rho_a} \frac{\theta_{g,t} - \theta_{a,t}}{1 + \phi / 3} \Delta t - \left(e^{\phi/10} - 1\right) \Delta\theta_{g,t}$$

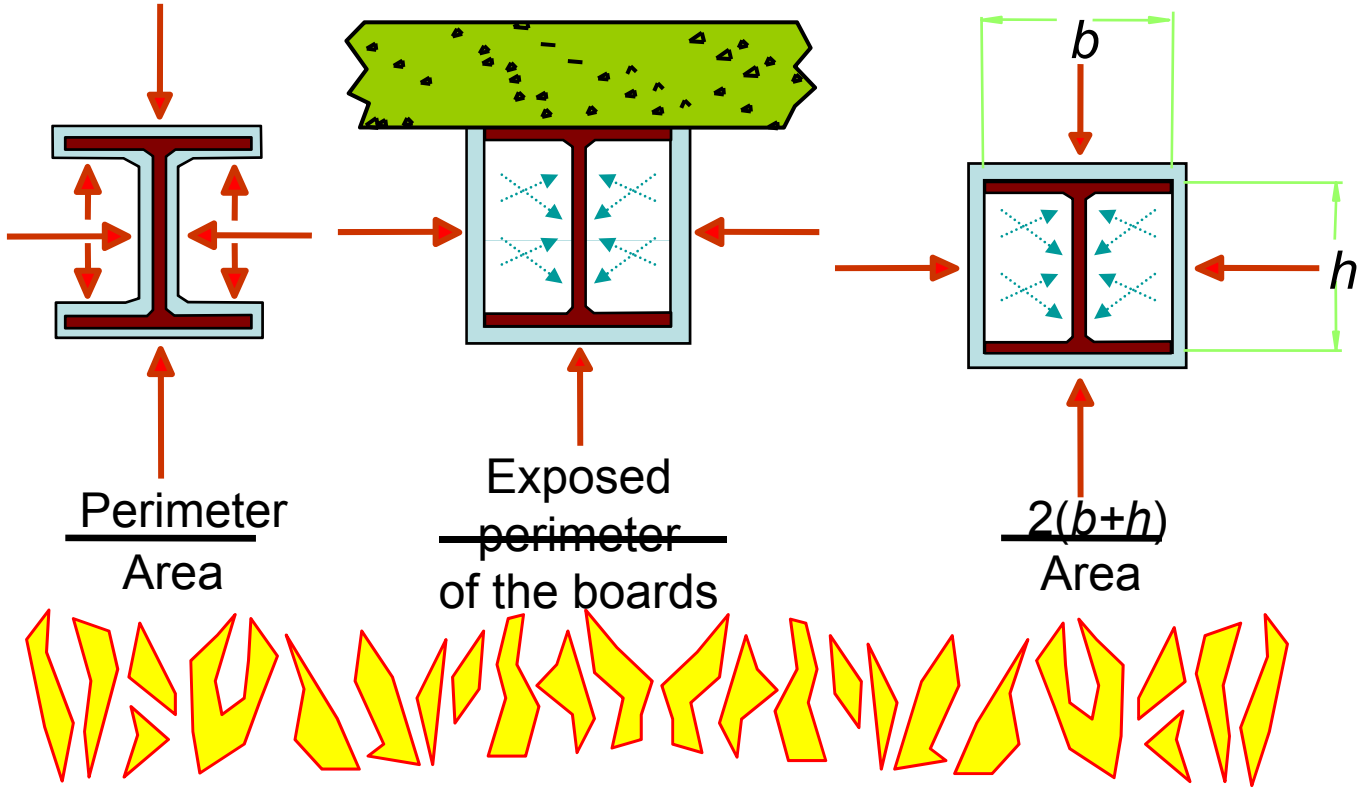
$$\Delta\theta_{a,t} \geq 0$$

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

λ_p	is thermal conductivity of the fire protection [W/m K]
A_p / V	is section factor of fire protected element [m^{-1}]
A_p	is area of fire protection material per unit length of the member [m^2/m];
d_p	is thickness of the fire protection [m]
ρ_p	is density of the fire protection [kg/m^3]
ρ_a	is density of steel [ρ_a = 7850 kg/m^3]
c_p	is thermal capacity of the fire protection [J kg K]
c_a	is thermal capacity of steel
$\Delta\theta_{g,t}$	is temperature increment in time step Δt
Δt	is the time step in seconds, should not be bigger than 30 sec

Section factor A_p/V

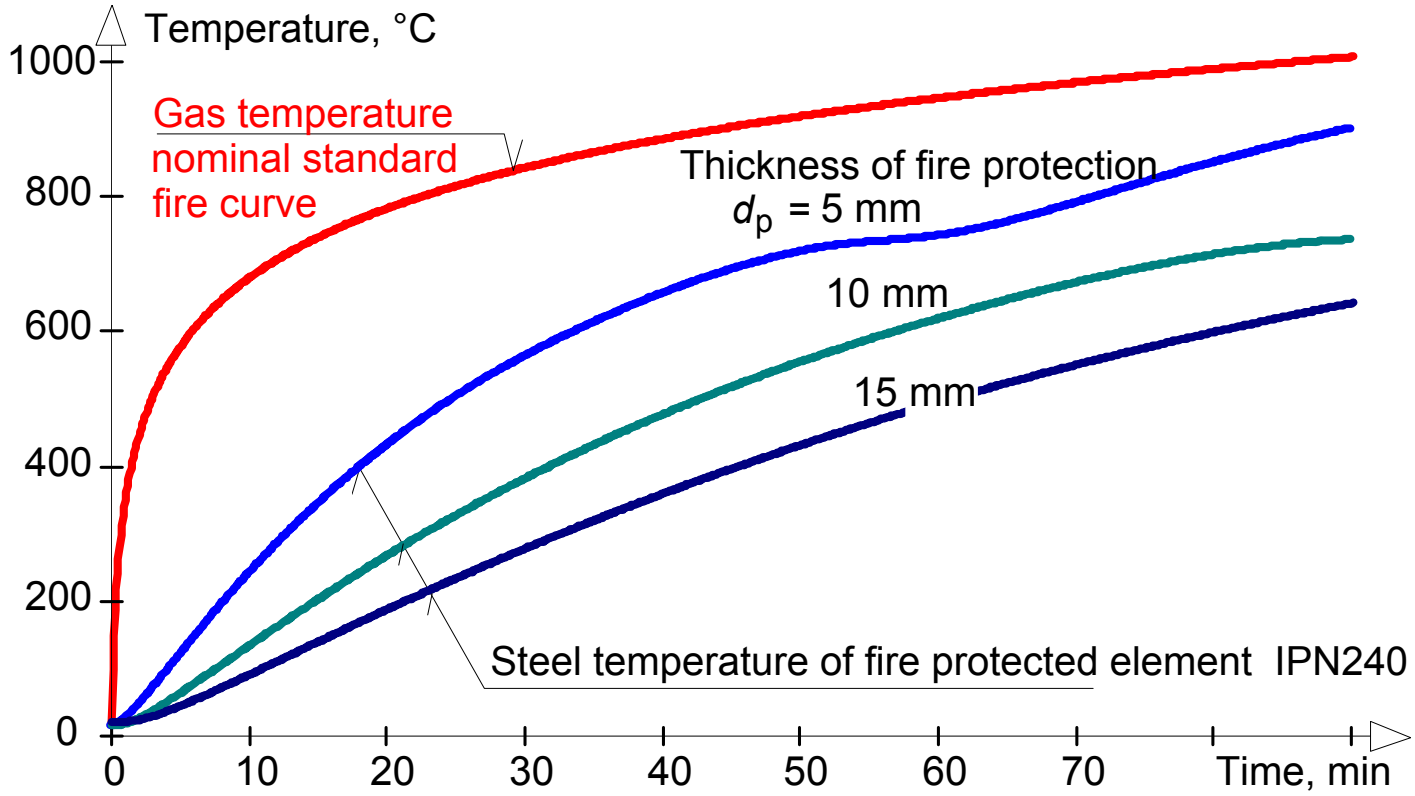
for the fire protected steel element



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

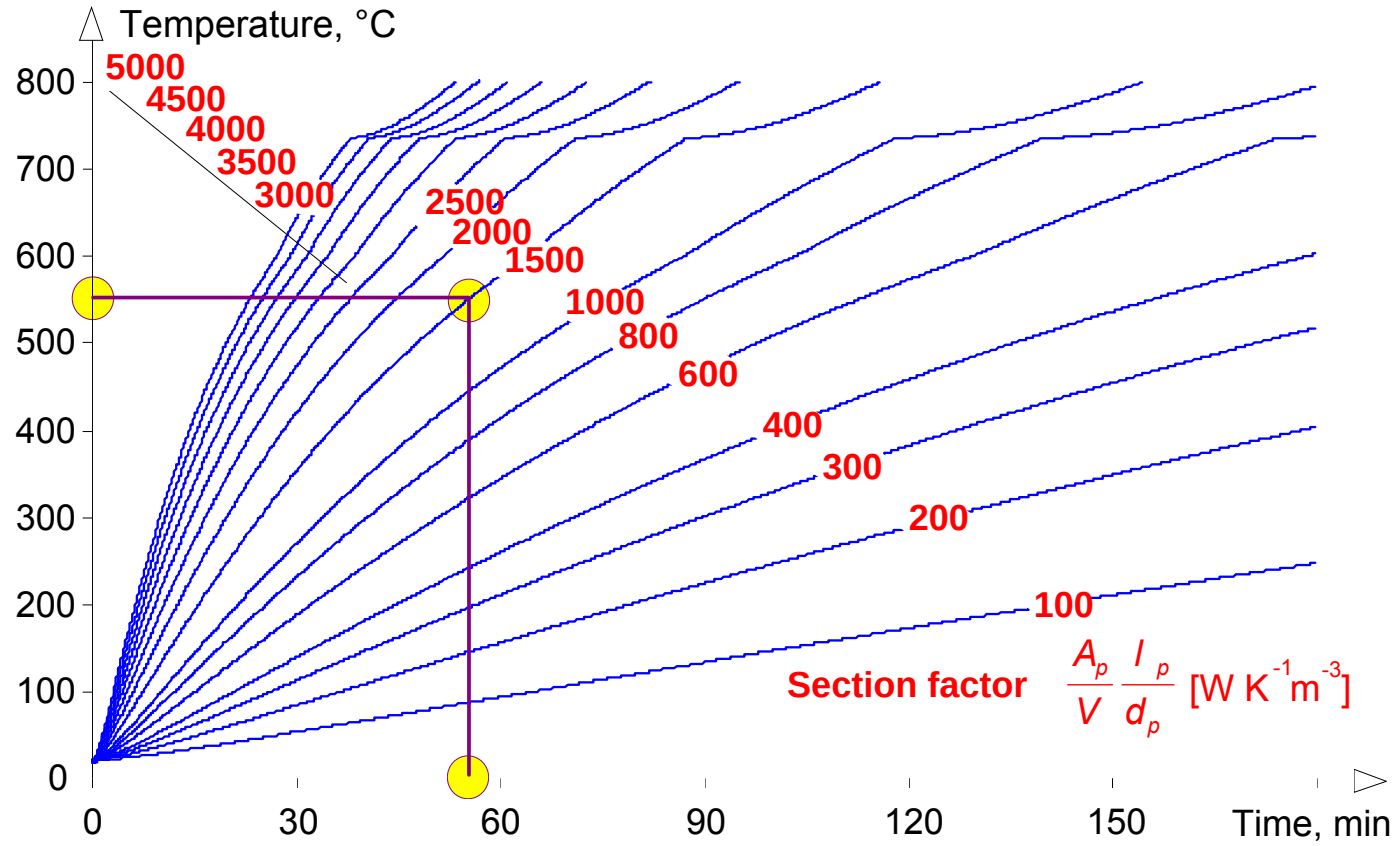
Result of step by step procedure

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



Result of step by step procedure

Temperature of the fire protected steel elements $\theta_{a,t}$ as function of time t and section factor A_p / V



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Software support

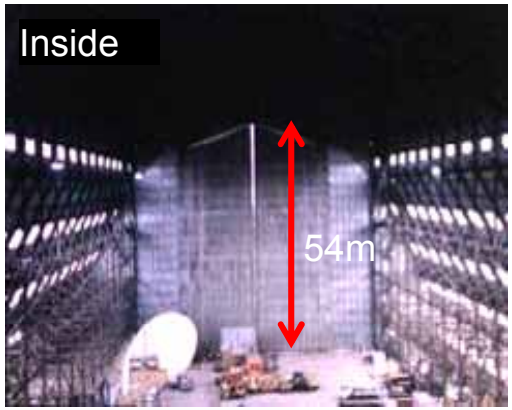
- Heat transfer
  - Step by step procedure
    - Many tools available for free download
      - e.g. Heat transfer in steel structures or DIFISEK
  - FE modelling
      - The description of tools advantages is summarised in DIFISEK+ database
- Temperature distribution
  - FE modelling
    - Commercial packages
      - The description of tools advantages is summarised in DIFISEK+ database
    - Free download tools
      - e.g. for concrete and composite elements ConTemp

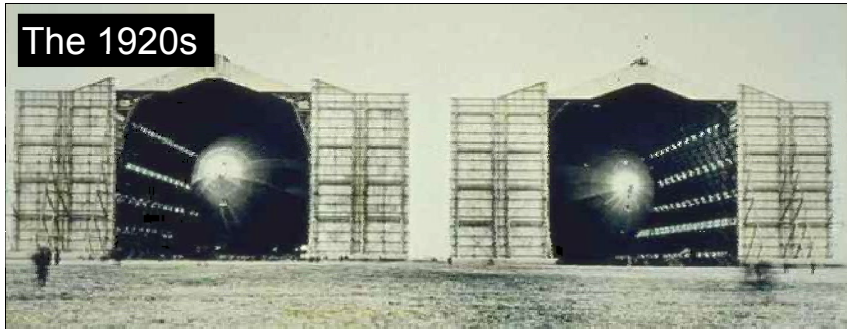
Formative assessment question 2

- What is the principle of step by step procedure of heat transfer for the fire unprotected steel element?
- Describe the major components of heat flux?
- What is influencing the emissivity during the fire?
- What are the principles of step by step procedure of heat transfer for the fire protected steel element?
- What is diference in section factor for the fire protected and unprotected steel elements?

The BRE Cardington laboratory

- The basical findings of European fire research 1980 - 2005
- Fire safety of composite steel to concrete strutures





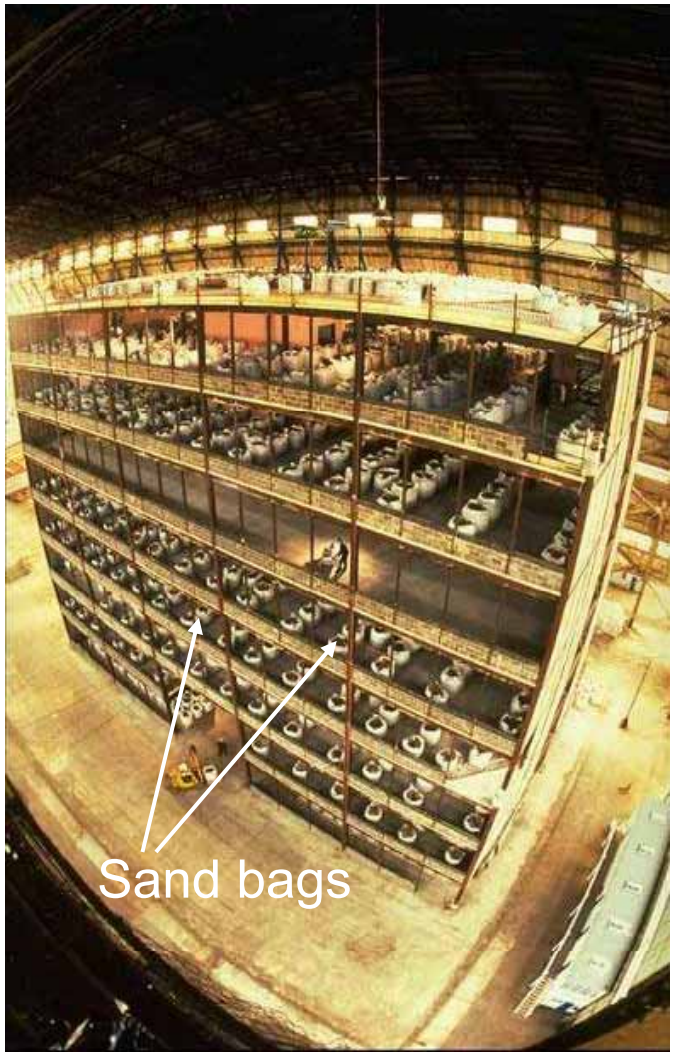
Three multistorey buidings

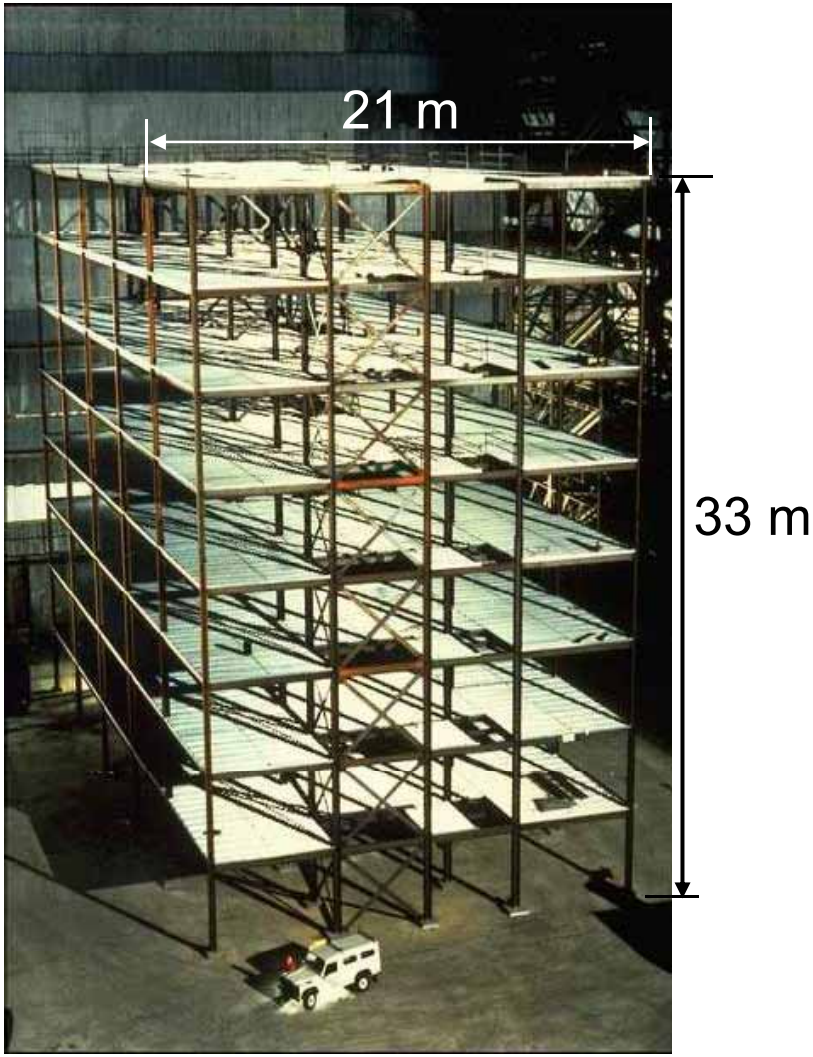
Timber structure

Steel to concrete composite building finished 1994; plan area 945 m^2

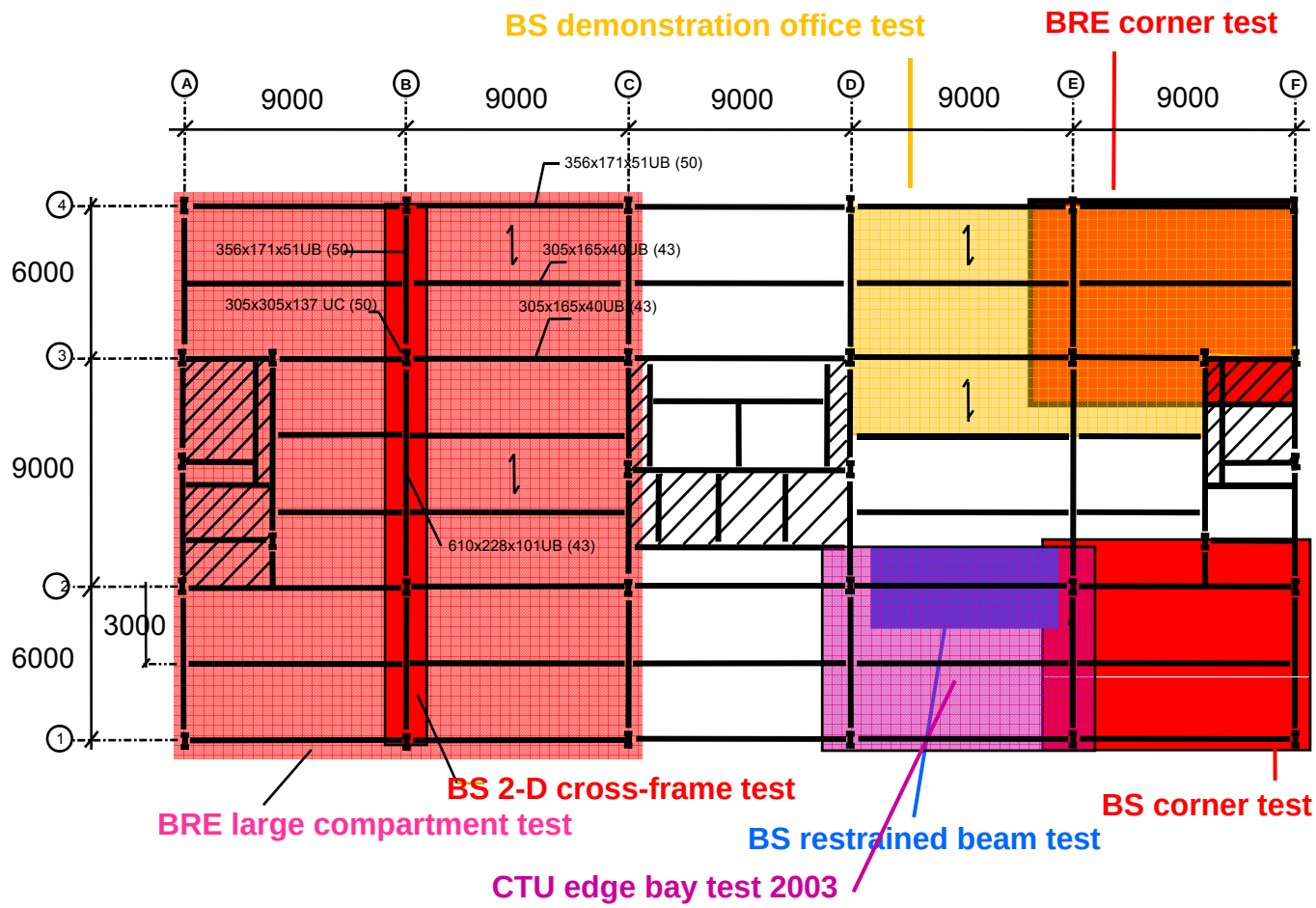
Concrete structure

Eight floors composite building





Floor plan of composite building



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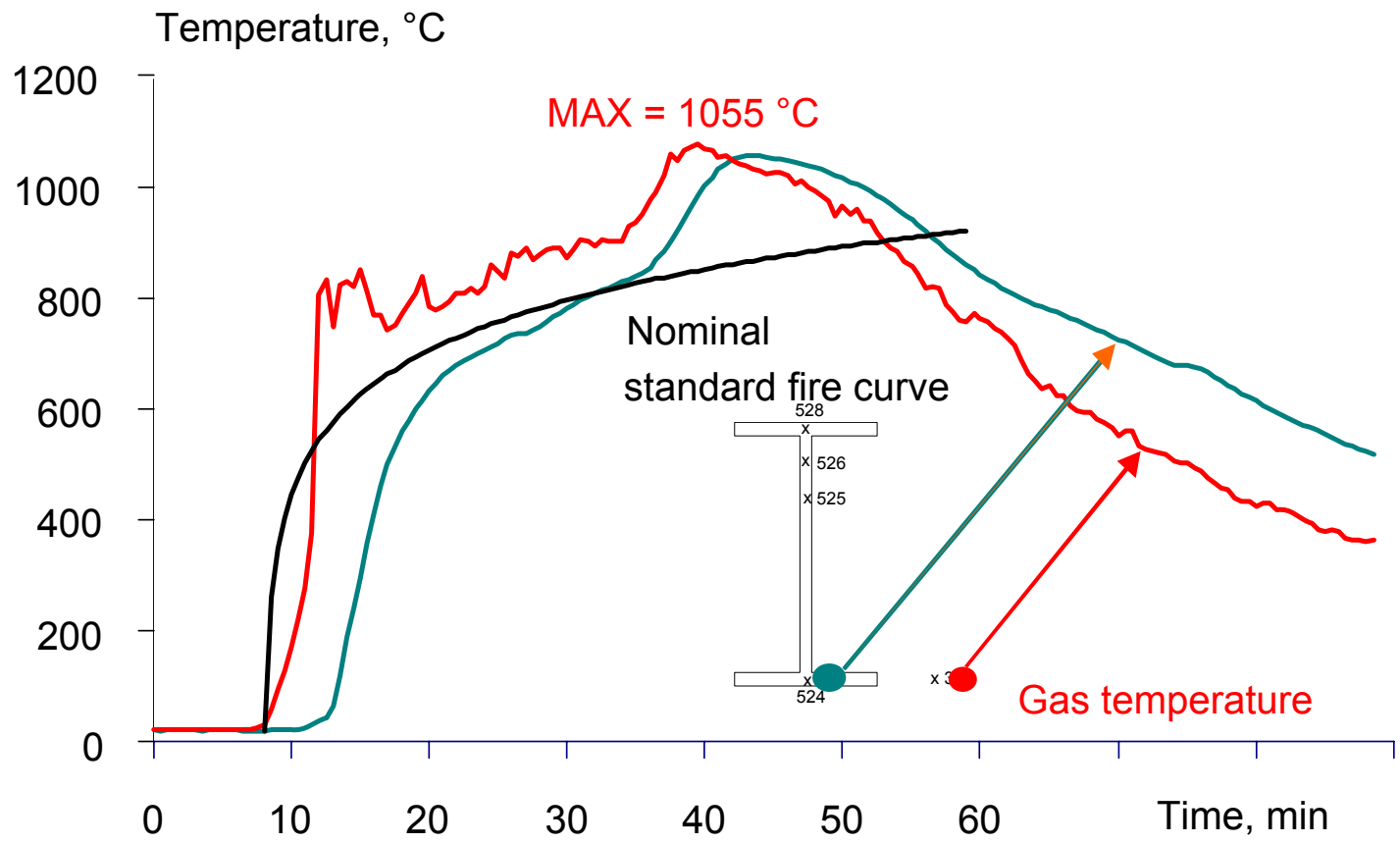
Restrained beam test

1th large scale fire experiment on composite frame

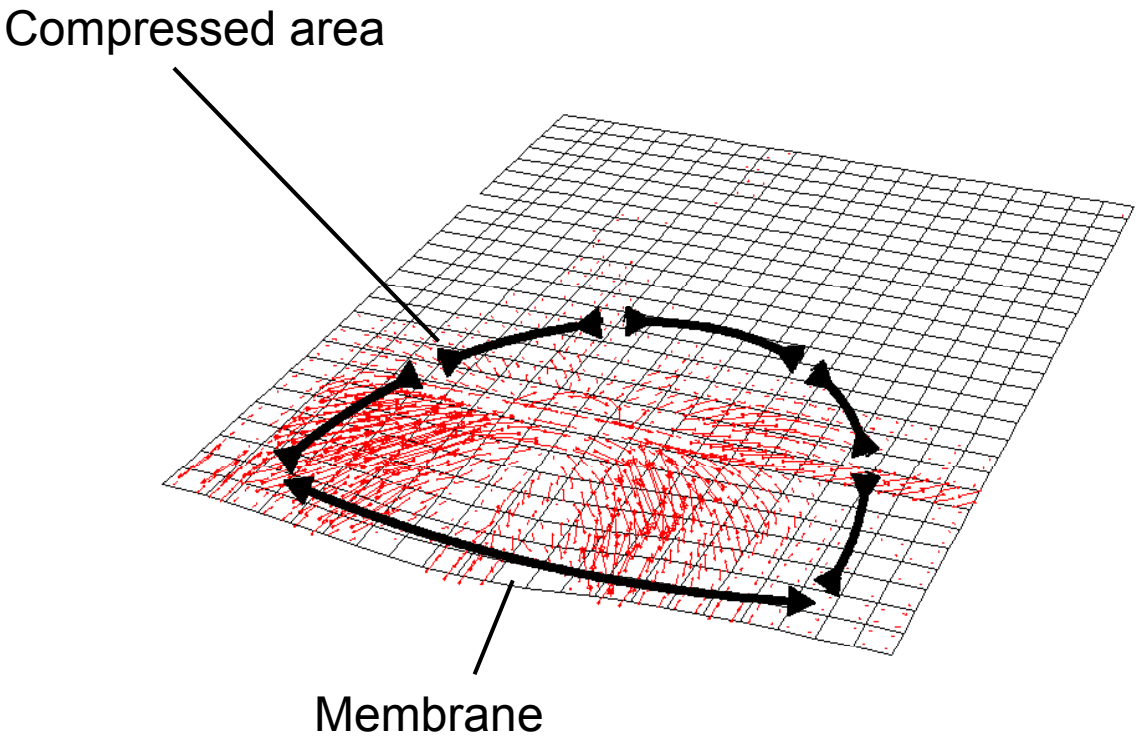
Restrained beam test

Temperature of unprotected beam



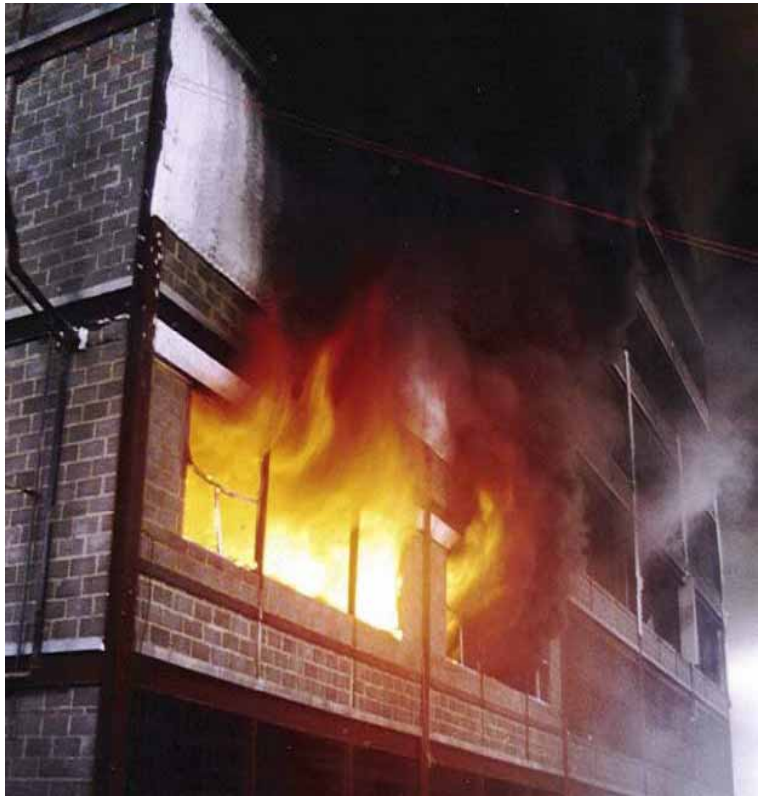
Membrane action of composite slab

One of the developments of the Cardington laboratory was the development of the models of fire safety of partially unprotected columns under the composite slab in steel multistorey buildings.



BRE large compartment test

4th large scale fire experiment on composite frame

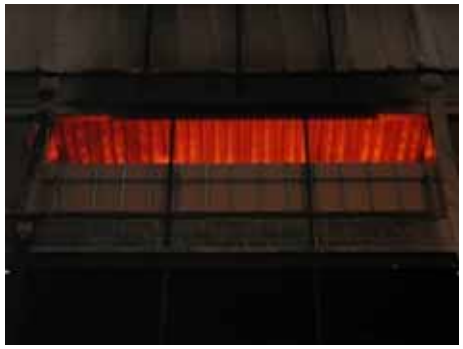


CTU edge bay test

7th large scale fire experiment on composite frame

- Connection temperatures (a widen MS PowerPoint presentation)
- Connection forces and behavior (a widen MS PowerPoint presentation)
- Composite slab






Assessment

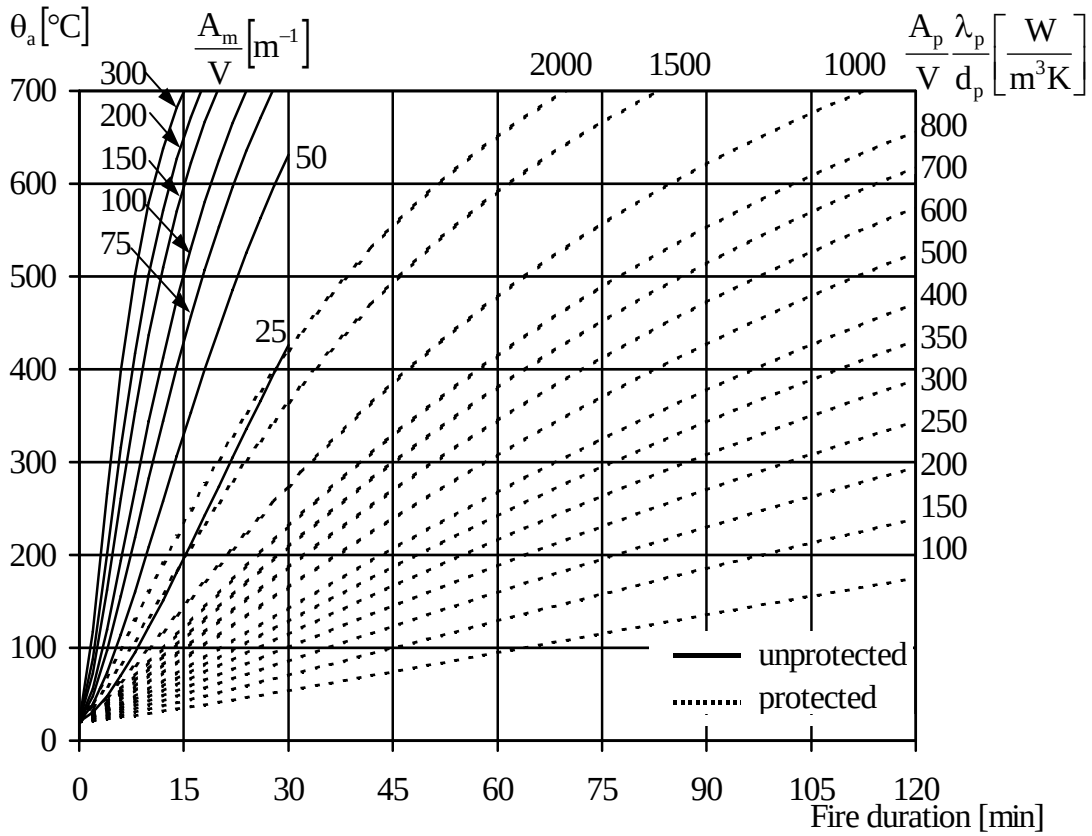
- Describe the basic models of fire.
- What are the major limits of parametric fire curve?
- What is the principle of zone models of fire?
- Describe the models of transfer of heat.
- What is difference of transfer of heat to the fire protected and fire unprotected steel element?
- Which material thermal properties of fire protection are taken into account in evaluation of transfer of heat to the fire protected elements?

Conclusions

- Simpliest model of fire is a nominal firve curve
- Zone model of fire supported by software brings an effective tool for practical design
- For worked examples consult AcceesSteel and DIFISEK+
- The accuracy od prediction of gas and steel temperature is show on a fire test

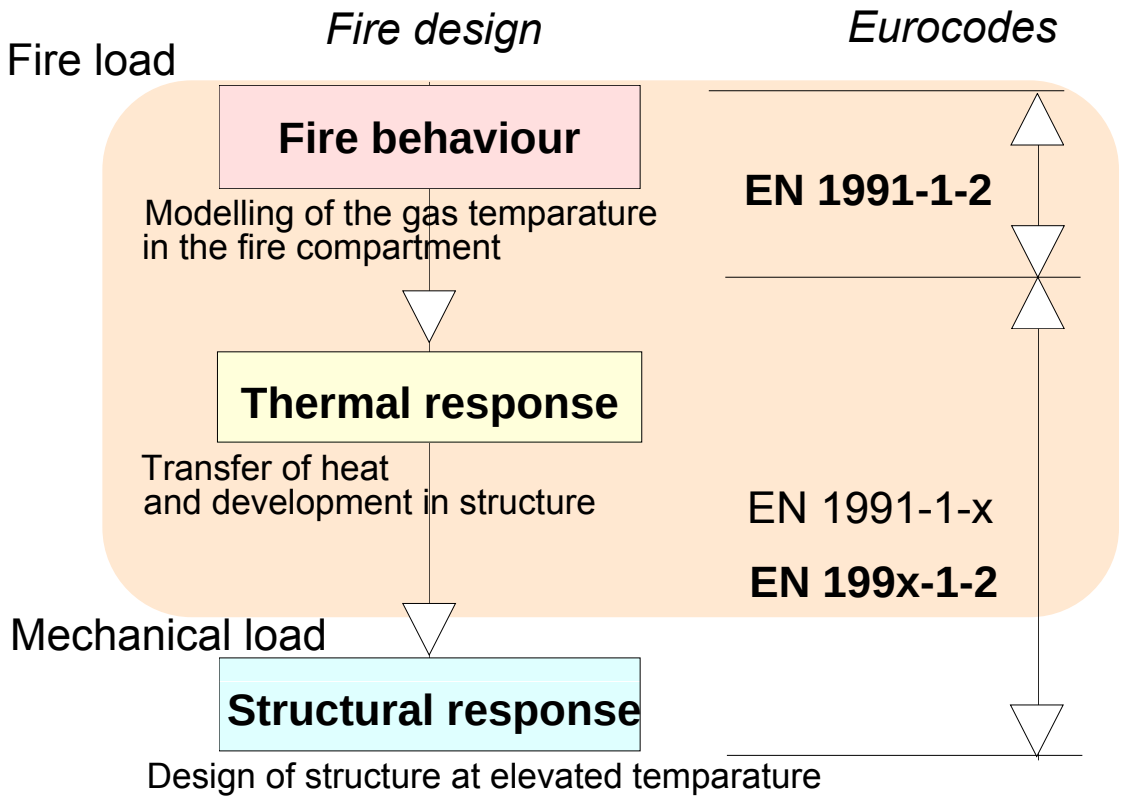
Conclusions

Nomogram prepared based on step by step procedure describes the heating of the fire protected and fire unprotected steel members exposed to nominal standard fire curve.



Conclusions

- The lecture introduced the bases of modelling of the compartment fire and transfer of heat into structure according to the Eurocodes.



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Thank you
for your attention

Notes to users of the lecture

- This session is a basic information about the modeling of fire and transfer of heat to the structure and requires about 60 min lecturing.
- Further readings on the relevant documents from website of www.access-steel.com and www.difisek.eu.
- The use of relevant standards of national standard institutions are strongly recommended.
- Formative questions should be well answered before the summative questions completed within the tutorial session.
- Keywords for the lecture:

  fire design, fire modelling, fire curve, transfer of heat, fire protection, Eurocodes.

Notes to users of the lecture

Worked examples for heat transfer

- The application of the table is in AccessSteel example
  - Fire resistance of a partially encased composite column
- The application of the graph is in AccessSteel example
  - Fire design of an unprotected beam using graphs
- The description of step by step procedure for heat transfer is in AccessSteel examples
  - Fire design of an unprotected IPE section beam exposed to the standard time temperature curve
  - Fire design of a protected HEB section column exposed to the standard temperature time curve

Notes to users of the lecture

Worked examples for fire modelling

- The application of the nominal fire curve is in AccessSteel example
  - Fire design of an unprotected IPE section beam exposed to the standard time temperature curve
- The description of parametric fire curve is in AccessSteel example
  - Parametric fire curve for a fire compartment
- The application of the zone model is in the DIFISEK+ lecture
  - WP4 – Software for fire design, slide 10

Notes for lecturers

- Subject: Fire modelling and transfer of heat to structure.
- Lecture duration: 60 min
- Keywords: fire design, fire modelling, fire curve, transfer of heat, fire protection, Eurocodes.
- Aspects to be discussed: high advantage of utilisation of advanced fire models, the simplicity of heat transfer by step by step procedure and its limits.
- Within the lecturing, the procedure of Eurocode fire design is explained.
- Further reading: relevant documents from website of www.access-steel.com and www.difisek.eu.
- The reached accuracy in prediction of elemenst temperature is shown on the prediction of the seveth large scale Cardington fire test.