9-2. Fire behaviour and thermal response

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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

Prescriptive approach

Design of building
National fire regulations
Fire safety requirements
Fire test of 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
The major steps of the fire design

- **Fire load**
  - Fire design
  - **Fire behaviour**
    - Modelling of the gas temperature in the fire compartment
- **Thermal response**
  - Transfer of heat and development in structure
- **Mechanical load**
  - **Structural response**
    - Design of structure at elevated temperature

**Eurocodes**

- EN 1991-1-2
- EN 1991-1-x
- EN 199x-1-2
Fire behaviour

Nominal fire curves
Parametric fire curves
Advanced fire models
Software support
Assessment 1
Thermal response
Unprotected steel
Protected steel
Software support
Assessment 2
Fire tests in Cardington
Conclusions
Notes

Structural fire engineering

- Nominal fire curves
- Parametric curves
- Zone models
- CFD
  Computational Fluid Dynamics

Fire behaviour

Thermal response

Structural response

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Nominal fire curves

The simplest fire modelling

![Diagram showing temperature and time during a fire event]
Nominal fire curves

Nominal standard curve

\[ \theta_g = 20 + 345 \log_{10}(8t + 1) \]

Nominal external curve

\[ \theta_g = 20 + 660 \left( 1 - 0.687 e^{-0.32t} - 0.313 e^{-0.38t} \right) \]

Nominal hydrocarbon curve

\[ \theta_g = 20 + 1080 \left( 1 - 0.325 e^{-0.167t} - 0.675 e^{-2.5t} \right) \]
Nominal standard fire curve

- The temperature depends on time only

![Diagram showing Nominal standard fire curve, Nominal hydrocarbon curve, and Nominal external fire curve.](image)
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

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Nominal fire curves
Parametric curves
Zone models
CFD
Computational Fluid Dynamics

Structural fire engineering

Fire behaviour

Thermal response

Structural response

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

- **Pre-flashover**
- **Post-flashover 1000-1200°C**
- **Flashover**

- **Temperature during fire**
- **Parametric fire curve**

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

- The size of the compartment is limited to 500 m²
- 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/m² (about 3.5 kg to 70 kg of timber / m²)
- Cellulosic type of fire load
Structure of parametric fire curve

Input data

Fire load density

\[ q_{t,d} \] for calculation of \( t_{\text{max}} \)

Number and size of the openings

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

Geometry of the fire compartment

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

Thermal properties of boundary of enclosure

\[ \Gamma = \left( \frac{O}{O_{\text{ref}}} \right)^2 \left( \frac{b}{b_{\text{ref}}} \right)^2 \]

Time modification factor

Fictive time in hours \( t^* = \Gamma t \)
Burning 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 \( t_{\text{max}}^* \), e.g.)

\[ \theta_{g,t} = \theta_{\text{max}} - 250 \left( t^* - t_{\text{max}}^* \right) \]

Gas temperature, °C

0 15 30 45 60 90 120 Time, min

0 200 400 600 800 1000

Heating Cooling

Notes
The maximal gas temperature

- Fire driven by ventilation
  - $t_{\text{max}} = 0.2 \times 10^{-3} \frac{q_{\text{t,d}}}{O}$
  - $t^{*}_{\text{max}} = t_{\text{max}} \Gamma$

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

Influence of openings

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

- \( A_v \): 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
Influence of fire load density

- Low fire load - shorter and coulder fires
- High fire load - longer and warmer fires
**Influence of boundary of enclosure**

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

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

**Temperature, °C**

- Gypsum board
- Light weight concrete
- Normal concrete
- Nominal standard fire curve

For fire load \( q_{f,d} = 700 \text{ MJ/m}^2 \)
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

Objectives
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Nominal fire curves
Parametric fire curves
Advanced fire models
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Structural fire engineering

Fire behaviour

Thermal response

Structural response

Nominal fire curves
Parametric curves
Zone models
CFD
Computational Fluid Dynamics
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

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Structural fire engineering

- Nominal fire curves
- Parametric curves
- Zone models
- CFD (Computational Fluid Dynamics)

Fire behaviour
Thermal response
Structural response

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CFD Modelling

- **Computational Fluid Dynamics**
- 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 developed 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

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Thermal response

Fire behaviour

Test data
(based on Standard fire curve)

Simple heat transfer models
(step by step procedure)

Advanced heat transfer models
(Finite Element Methods)

Structural response

Structural fire engineering
Principles of step by step procedure for the fire unprotected steel element

- One-dimensional heat transfer
- Equilibrium of \textbf{increase of temperature} of structural element and \textbf{heat received on surface} of the element in time period $\Delta t$

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

\textbf{Increase of element temperature}

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 \([\text{simplified } c_a = 650 \ \text{J/kgK}]\)
- $\rho_a$ density of steel \([\rho_a = 7850 \ \text{kg/m}^3]\)
- $h_{\text{net,d}}$ net heat flux received by the surface of the element \([W/m^2]\)
- $\Delta t$ time period \([\Delta t_{\text{max}} = 5 \ \text{s}]\)
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 $\Delta t$ 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 $\theta_{a,t} \approx \theta_{g,t}$
- the time period $\Delta t$ 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

Unprotected steel

Protected steel

Software support

Assessment 2

Fire tests in Cardington

Conclusions
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.
Shadow effect

For nominal standard fire curve

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

is applied for the total heat flux

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

For I sections may be simplified

\[ \Delta \theta_{a,t} = k_{sh} \frac{A_m}{c_a \rho_a} \frac{A_m}{V} h_{net,d} \Delta t = 0,9 \frac{(A_m/V)_b}{A_m/V} \frac{A_m}{c_a \rho_a} \frac{A_m}{V} h_{net,d} \Delta t \]
**Section factor** \((A_m/V)_b\) for shadow effect, unprotected steel element

The box value of 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
Heat flux

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

\begin{align*}
\text{convection} \quad \text{and} \quad \text{radiation}
\end{align*}

The design value is given by

\begin{align*}
h_{\text{net,d}} &= h_{\text{net,c}} + h_{\text{net,r}}
\end{align*}

where

\begin{align*}
h_{\text{net,c}} &\quad \text{is effect of convection, heat flux from convection [W/m}^2] \\
h_{\text{net,r}} &\quad \text{is effect of radiation, heat flux from radiation [W/m}^2]
\end{align*}
The convective heat flux \([W/m^2]\) is given by

\[
h_{net,c} = \alpha_c (\theta_g - \theta_m)
\]

where

- \(\alpha_c\) is heat transfer coefficient
  - \(\alpha_c = 25 \text{ W/m}^2\text{K}\) for standard curve
  - \(\alpha_c = 35 \text{ W/m}^2\text{K}\) for parametric curve
  - \(\alpha_c = 50 \text{ W/m}^2\text{K}\) for hydrocarbon curve
  - \(\alpha_c = 35 \text{ W/m}^2\text{K}\) for zone models and localized fires

- \(\theta_g\) is gas temperature in proximity of the element \([^\circ\text{C}]\)
- \(\theta_m\) is surface temperature of the element \([^\circ\text{C}]\)
Radiative heat flux

The radiative heat flux \([W/m^2]\) is given by

\[
h_{net,r} = \phi \cdot \epsilon_{res} \cdot 5.67 \cdot 10^{-8} \left[ (\theta_r + 273)^4 - (\theta_m + 273)^4 \right]
\]

where

- \(\phi\) is configuration factor, usually \(\phi = 1.0\)
- \(\epsilon_{res}\) is resulting emissivity, see next page
- \(\theta_r\) is radiating temperature \(^\circ C\)
  can be taken equal to the gas temperature \(\theta_g\)
- \(\theta_m\) is surface temperature of steel element \(^\circ C\)

5.67 \cdot 10^{-8} \text{ is Stefan-Boltzmann constant } [W/(m^2K^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

\[ \varepsilon_{\text{res}} = \varepsilon_f \varepsilon_m \]

where

- \( \varepsilon_f \) is emissivity of fire, usually \( \varepsilon_f = 1,0 \)
- \( \varepsilon_m \) is emissivity of material surface for
  - carbon steel element \( \varepsilon_m = 0,7 \)
  - stainless steel element \( \varepsilon_m = 0,4 \)
  - aluminum alloys not painted \( \varepsilon_m = 0,3 \)
  - aluminum alloys painted \( \varepsilon_m = 0,7 \)
Technique of step by step procedure

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

Spreadsheet technique (excel, etc.)

Gas temperature (according to temperature-time curve)

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Gas temperature (°C)</th>
<th>Components of the heat flux</th>
<th>Specific heat of steel</th>
<th>Temperature of the element at time t</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
<td>20.0</td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>0.083</td>
<td>96.5</td>
<td>1.18</td>
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<tr>
<td>0</td>
<td>10</td>
<td>0.167</td>
<td>147.0</td>
<td>2.00</td>
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<tr>
<td>0</td>
<td>15</td>
<td>0.250</td>
<td>184.6</td>
<td>2.65</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
<td>0.333</td>
<td>214.7</td>
<td>3.18</td>
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<tr>
<td>0</td>
<td>25</td>
<td>0.417</td>
<td>239.7</td>
<td>3.93</td>
</tr>
<tr>
<td>0</td>
<td>30</td>
<td>0.500</td>
<td>261.1</td>
<td>2885</td>
</tr>
</tbody>
</table>
Result of step by step procedure

Temperature of unprotected steel element heated by nominal standard curve

- Gas temperature, nominal standard fire curve
- Influence of the specific heat leap of steel
- Unprotected element, section IPN 240
- Unprotected element, section IPN 400
Result of step by step procedure

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

as function of time $t$

and section factor $A_m / V$

<table>
<thead>
<tr>
<th>Time, min</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel temperature, °C</td>
<td>0</td>
<td>250</td>
<td>200</td>
<td>150</td>
<td>100</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>

$A_m / V = 10 \text{ m}^{-1}$

Section factor
Principle of step by step procedure
for the fire protected steel element

The surface temperature of fire protection - the same as the gas temperature \( \theta_g - \theta_m \ll \theta_m - \theta_a \)

Heat transfer through the fire protected layer

\[
\Delta \theta_a = \frac{K_{\text{ins}}}{\rho_p c_p} \cdot \frac{A_m}{V} \cdot (\theta_g - \theta_a) \cdot \Delta t
\]

where

- \( K_{\text{ins}} \) is factor
- \( \lambda_p \) is thermal conductivity
- \( \rho_p \) is density
- \( c_p \) is thermal capacity
- \( d_p \) is thickness

for light weight fire protection \( K_{\text{ins}} \approx \frac{\lambda_p}{d_p} \)
Step by step procedure
for the fire protected steel element in EN 1993-1-2

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

where \( \phi = \frac{c_p \ \rho_p}{c_a \ \rho_a} d_p \frac{A_p}{V} \)

\( \Delta \theta_{a,t} \geq 0 \)

\( \lambda_p \) 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 [m²/m];
\( d_p \) is thickness of the fire protection [m]
\( \rho_p \) is density of the fire protection [kg/m³]
\( \rho_a \) is density of steel \([\rho_a = 7850 \text{ kg/m}^3]\)
\( c_p \) 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 \( \Delta t \)
\( \Delta t \) 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 divided 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

- Gas temperature
- Nominal standard fire curve
- Thickness of fire protection $d_p = 5$ mm
- 10 mm
- 15 mm

Steel temperature of fire protected element IPN240

Temperature, °C

Time, min
Result of step by step procedure

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

Temperature, °C

Section factor $\frac{A_p}{V \cdot d_p}$ [W K$^{-1}$ m$^{-3}$]

Time, min

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Parametric fire curves
Advanced fire models
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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 difference 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 structures
Three multistorey buildings

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Timber structure

Concrete structure

Steel to concrete composite building finished 1994; plan area 945 m²

Lecture 9-1, V001, April 09
Eight floors composite building

- Objectives
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Lecture 9-1, V001, April 09
Floor plan of composite building

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 Restrained beam test

1\textsuperscript{th} large scale fire experiment on composite frame

Localised fire
Restrained beam test

Temperature of unprotected beam

MAX = 1055 °C

Nominal standard fire curve

Gas temperature
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

4\textsuperscript{th} large scale fire experiment on composite frame

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<td>Assessment 2</td>
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</table>

\textbf{Fire tests in Cardington}

| Conclusions |
| Notes |

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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

Fire tests in Cardington
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 fire curve
- Zone model of fire supported by software brings an effective tool for practical design
- For worked examples consult AccessSteel and DIFISEK+
- The accuracy of prediction of gas and steel temperature is shown 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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**Fire load**

**Fire design**

**Eurocodes**

- EN 1991-1-2
- EN 1991-1-x
- EN 199x-1-2

**Fire behaviour**

- Modelling of the gas temperature in the fire compartment

**Thermal response**

- Transfer of heat and development in structure

**Structural response**

- Design of structure at elevated temperature
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](http://www.access-steel.com) and [www.difisek.eu](http://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.
- The reached accuracy in prediction of element temperature is shown on the prediction of the seventh large scale Cardington fire test.