Design
for Fire and Robustness

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Jean-François DEMONCEAU
## List of Lessons at Seminar

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<td>JMD</td>
</tr>
<tr>
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<td>JMD</td>
</tr>
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</table>
Timber structures

František Wald
Czech Technical University in Prague
Objectives of the lecture

- Burning of timber
- Basic design methods
  - Fire load and structural material
  - Charring model
- Timber structures in fire
  - Massive structures – traditional, high fire resistance, predictable based on thermal response only
  - Timber in wall and floor assemblies - challenges
Outline of the lecture

- Introduction
- Wood behaviour in fire
- Bases of design
  - Material properties
  - Charring rate
  - Charring model
  - Reduced cross-section method
  - Reduced properties method
- Worked example
- Connections
- Conclusion
- Fire test
- Summary
History

Wood in fire

Bases of design
Material properties

Charring
Models

Reduced cross-section
Reduced properties

Worked example
Connections

Conclusion
Fire test

Notes
History

Wood in fire

History

- Wood is flammable and combustible
- Fire the cause of damages in municipalities and towns
- The first directive in the 14th century, in Czech mainly in Prague
- "Imperial royal patent for extinguishing a fire" (1755) - prohibition of wooden houses in cities
- "Fire order of Joseph II." (1785) - distances
- Highest court decree from 1816 - prohibition of wooden buildings everywhere
- 1821 the first fire departments in Prague
- The end of the 19th century - as structural material dominate reinforced concrete, steel, masonry technology

Bases of design
Material properties
Charring
Models
Reduced cross-section
Reduced properties
Worked example
Connections
Conclusion
Fire test
Notes
History

- Wood is flammable and combustible
- Fire - the cause of damages municipalities and towns

14th c. Czech mainly Prague first fire directives
1755 "Imperial-royal patent for extinguishing a fire" the prohibition of wooden houses in cities
1785 Fire order of Joseph II. - fire distances
1816 Highest court decree about prohibition of wooden buildings everywhere
1821 the first Fire departments in Prague

Since 19th century
- As structural material dominate reinforced concrete, steel, masonry technology
Today

- Requirements local, e.g. in Germany

Tab. 2.1.1: General Building Code requirements (Muster-Bauordnung MBO)

<table>
<thead>
<tr>
<th>Building class</th>
<th>Level of highest floor (Number of Storeys)</th>
<th>Number of Use Units</th>
<th>Expanse of one use unit</th>
<th>Fire resistance requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Free standing buildings</td>
<td>( \leq 7 \text{ m}^1 (3) )</td>
<td>( \leq 2 )</td>
<td>No limit</td>
<td>None</td>
</tr>
<tr>
<td>2 Free standing buildings for agriculture and forestry use</td>
<td>( \leq 7 \text{ m}^1 (3) )</td>
<td>( \leq 2 )</td>
<td>( \leq 400 \text{ m}^2 )</td>
<td>Fire retardend R30 / EI30</td>
</tr>
<tr>
<td>3 Other Buildings of low height</td>
<td>( \leq 7 \text{ m}^1 (3) )</td>
<td>No limit</td>
<td>No limit</td>
<td>Fire retardend R30 / EI30</td>
</tr>
<tr>
<td>4 Buildings with medium height</td>
<td>( \leq 13 \text{ m}^1 (5) )</td>
<td>No limit</td>
<td>( \leq 400 \text{ m}^2 )</td>
<td>High fire retardend R60 / EI60^2</td>
</tr>
</tbody>
</table>

1 medium distance between ground area surface and level of the highest floor
2 in addition structures shall be encased for 60 minutes according to EN 13501-2/EN 14135 with non-combustible material (K60)
Today

- Requirements local, e.g. in Switzerland

Tab. 2.2.1: General Building Code requirements (living-, office-, school buildings)

<table>
<thead>
<tr>
<th>Building class</th>
<th>Number of Storeys</th>
<th>Number of Use Units</th>
<th>Expanse of one use unit</th>
<th>Fire resistance requirements$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>two storey buildings and highest storey of all type of buildings</td>
<td>$\leq 2$</td>
<td>No limit</td>
<td>$\leq600 / \leq1200$</td>
</tr>
<tr>
<td>2</td>
<td>two storey buildings; including attic</td>
<td>$\leq 2$</td>
<td>No limit</td>
<td>$&gt;600 / &gt;1200$</td>
</tr>
<tr>
<td>3</td>
<td>Buildings with four storeys</td>
<td>$\leq 4$</td>
<td>No limit</td>
<td>No limit</td>
</tr>
<tr>
<td>4</td>
<td>Buildings with six storeys</td>
<td>$\leq 6$</td>
<td>No limit</td>
<td>No limit</td>
</tr>
</tbody>
</table>

$^1$ Timber frame structure with effective, non-combustible fire-protection linings

$^2$ Euroclass according EN 13501-1 (A – non combustible, D – combustible) of complete structure

$^3$ Reduction of fire resistance time (~30 min) or combustible surfaces, if sprinklers are used
Fire of Globe theatre in Prague
Fire
of Globe theatre in Prague

• Built in 1999
  – After London and Neuss third unique theater space Elizabethan era

• Fire 12 Nov. 2005
• Fire reported 2:50
• The intervention of firemen 3:02
• Burned to 45 min
• Inappropriately close Maroldova panorama
Intervention of firefighters
European Erasmus Mundus Master Course Sustainable Constructions under Natural Hazards and Catastrophic Events

Introduction
Wood in fire
Bases of design
Material properties

Charring Models
Reduced cross-section
Reduced properties

Worked example
Connections

Fire test
Notes

Notes

To fireman attack

Příklady

ze zahraničí

se stejnou stavebníkulturou

jako v ČR

Buid 1995 replo12 Nov 2005
European Erasmus Mundus Master Course
Sustainable Constructions under Natural Hazards and Catastrophic Events

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Příklady

ze zahraničí

se stejnou stavebníkulturou

jako v ČR
After fire

Melted street lights and dried tries outside the theater
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Příklady ze zahraničí se stejnou stavební kulturou jako v ČR

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Cardington fire tests on timber building
Cardington fire tests on timber building

6th floors building
Detail plan of wall construction

Application in the Wälludden project.
Three fire tests

• Fire compartment
• Fire on timber stairs
• Spread of fire at the window
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Požární úsek po požáru R 60
Timber stairs fire test
View of four- and five-storey blocks in the Wälludden development
Timber thermal conductivity

![Timber thermal conductivity graph]

**Thermal conductivity, W/mK**

- **Aluminium, 3xxx, 6xxx**
- **Aluminium, 5xxx, 7xxx**
- **Steel**
- **Concrete, max**
- **Concrete, min**
- **Timber and char layer**

**Temperature, °C**

- 0
- 200
- 400
- 600
- 800
- 1000
- 1200
Wood behaviour in fire

- **Pyrolysis**
  - Thermal degradation of wood producing combustible gases and accompanied by a loss in mass
  - starting from 250°C about

![Diagram showing char layer and residual cross-section with dimensions]
Residual cross section

- Char layer protects the residual cross section from high temperatures

Residual cross section
- cold
- load-bearing

Source: proHolz, Austria
Charring

“Modern manmade intumescent materials applied to steel structural elements are in essence an attempt to replicate what timber does naturally.”

From Smith I, Frangi A, Overview of design issues for tall timber buildings, Structural Engineering International, SEI 2/2008
Charring rate $\beta$

- Ratio (mm/min)
  between charring depth $d_{\text{char}}$ and fire time $t$

$$\beta = \frac{d_{\text{char}}}{t}$$

$$\beta = \frac{50\text{mm}}{63\text{min}} = 0.8\text{mm/min}$$
Charring rate

Depends on

- Fire exposure
  - Constant value for ISO-fire exposure
- Wood species
  - Spruce: ≈ 0.7 mm/min

- Small influence of
  - Moisture content
  - Density of wood

Charring rate

![Graph showing charring depth vs. fire time]

- Charring rate depends on fire exposure and wood species.
- Spruce wood has a charring rate of approximately 0.7 mm/min.
- Other factors like moisture content and density also play a role.

Mean value from fire tests: 0.7 mm/min.
Timber density $\rho$ and the charring rate (RC)

![Graph showing the relationship between timber density $\rho$ and the charring rate (RC)].

- **Timber density $\rho$**
- **Charring and the charring rate (RC)**

**Diagram:**

- RC (%) vs. min^{-1}
- \( \rho \) kgm^{-3}

- Points on the graph indicate the relationship between timber density and charring rate.

**Notes:**

- Timber density $\rho$ and the charring rate (RC) relationship.
- The graph illustrates how timber density affects the rate of charring under fire conditions.
- Understanding this relationship is crucial for designing sustainable constructions under natural hazards and catastrophic events.

**Additional Content:**

- Introduction
- Wood in fire
- Bases of design
- Material properties
- Charring models
- Reduced cross-section properties
- Worked example
- Connections
- Conclusion
- Fire test

**References:**

- European Erasmus Mundus Master Course
- Sustainable Constructions under Natural Hazards and Catastrophic Events
Bases of design

- Fire resistance of timber structural elements of sufficiently large cross-section can be calculated on the basis of predictable charring rate
  - Heavy timber structure
    - Charring
  - Light timber/timber based structures
    - Fire protection
- The boundary between the charred timber and carbonized timber is assumed at 300 °C
Eurocode 5

- Eurocode 5 (EN 1995) provides rules for the design of timber structures.
  - EN 1995-1-2 is the Fire Part of Eurocode 5

- The two other parts of Eurocode 5 are:
  - EN 1995-1-1 Common rules and rules for buildings
  - EN 1995-2 Bridges
Basic strategies

- Use of massive cross-sections
- Increase of cross sections by charring depth
- Protection of the timber elements with non combustible materials
Material properties

- **Mechanical**
  - Simplified methods for the reduction of the strength and stiffness parameters
  - For advanced calculation methods, a non-linear relationship between strain and compressive stress
Design strength in fire

The fire resistance lower reliability of materials, than at ambient temperatures

The design value on 20% fractale

Not 5% fractale as at ambient temperature

\[ f_{d,\text{fi}} = k_{\text{mod,fi}} \frac{f_{20}}{\gamma_{M,\text{fi}}} \]

\[ f_{20} = k_{\text{fi}} f_k \]

\( k_{\text{mod,fi}} \) modification factor based on design procedure (elevated temperature and moisture)

\( \gamma_{M,\text{fi}} \) partial factor = 1,0
Design strength in fire

\[ f_{20} = k_{fi} f_k \]

**Table 2.1 — Values of \( k_{fi} \)**

<table>
<thead>
<tr>
<th>Material Description</th>
<th>( k_{fi} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid timber</td>
<td>1.25</td>
</tr>
<tr>
<td>Glued-laminated timber</td>
<td>1.15</td>
</tr>
<tr>
<td>Wood-based panels</td>
<td>1.15</td>
</tr>
<tr>
<td>LVL</td>
<td>1.1</td>
</tr>
<tr>
<td>Connections with fasteners in shear with side members of wood and wood-based panels</td>
<td>1.15</td>
</tr>
<tr>
<td>Connections with fasteners in shear with side members of steel</td>
<td>1.05</td>
</tr>
<tr>
<td>Connections with axially loaded fasteners</td>
<td>1.05</td>
</tr>
</tbody>
</table>
Material properties

- Mechanical
  - For advanced calculation methods

Reduction factor for strength parallel to grain of softwood
Material properties

- **Mechanical**
  - For advanced calculation methods

Effect of temperature on modulus of elasticity parallel to grain of softwood
Material properties

- **Thermal**

Temperature-thermal conductivity relationship for wood and the char layer
Material properties

- **Thermal**

Temperature-specific heat relationship for wood and the char layer
Charring depth

- The distance between the outer surface of the original member and the position of the char-line
Charring depth

- Under the standard fire exposure
- An approximate linear relationship
- From numerous fire tests on wood and wood-based materials

\[ d_{\text{char},0} = \beta_0 \ t \]

where

- \( \beta_0 \) is the one-dimensional design charring rate under the standard fire exposure
- \( t \) is the time of fire exposure in mins
## Typical charring rates $\beta_0$

according to EN 1995-1-2:2005

<table>
<thead>
<tr>
<th>Material</th>
<th>Charring description</th>
<th>$\beta_0$ (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwood and beech</td>
<td>Glued laminated timber with a characteristic density of $\geq 290 \text{ kg/m}^3$</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Solid timber with a characteristic density of $\geq 290 \text{ kg/m}^3$</td>
<td>0.65</td>
</tr>
<tr>
<td>Hardwood</td>
<td>Solid or glued laminated hardwood with a characteristic density of $\geq 290 \text{ kg/m}^3$</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Solid or glued laminated hardwood with a characteristic density of $\geq 450 \text{ kg/m}^3$</td>
<td>0.50</td>
</tr>
</tbody>
</table>
Effect of corner roundings and fissures

- The notional charring rate $\beta_n$
- Equivalent residual cross-section

Effect of corner roundings and fissures

- The notional charring rate $\beta_n$
- Equivalent residual cross-section

Border of effective cross-section
Border of residual cross-section
Unaffected part of section
Initial surface of member

Effect of corner roundings and fissures

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The notional charring rate $\beta_n$

<table>
<thead>
<tr>
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<th>$\beta_n$</th>
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<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Solid timber with a characteristic density of $\geq 290$ kg/m$^3$</td>
<td>0.65</td>
<td>0.80</td>
</tr>
<tr>
<td>Hardwood</td>
<td>Solid or glued laminated hardwood with a characteristic density of 290 kg/m$^3$</td>
<td>0.65</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Solid or glued laminated hardwood with a characteristic density of $\geq 450$ kg/m$^3$</td>
<td>0.50</td>
<td>0.55</td>
</tr>
</tbody>
</table>

according to EN 1995-1-2
Charring model

• for unprotected surfaces
Charring model

For initially protected surfaces:

- **Different charring phases**
  
  \[ t_{ch} \] is time of start of charring
  
  \[ t_f \] is failure time of cladding (fall off)

- **For wood-based panels and gypsum plasterboards (type A or H)**
  
  \[ t_{ch} = t_f \]

- **For gypsum plasterboards (type F)**
  
  \[ t_{ch} < t_f \]
Charring model

For initially protected surfaces

- For wood-based panels and gypsum plasterboards type A or H: \( t_{ch} = t_f \)

\[
\text{Charring depth} \\
d_{\text{char},0} \\
\text{or} \\
d_{\text{char},n} \\
[\text{mm}]
\]

\[
\begin{align*}
0 & 10 & 20 & 30 & 40 \\
0 & t_{ch} = t_f
\end{align*}
\]

Time \( t \)
Charring model

For initially protected surfaces

- For wood-based panels and gypsum plasterboards type A or H: $t_{ch} = t_f$
Charring model

For initially protected surfaces

• For gypsum plasterboards type F: \( t_{ch} < t_f \)
Charring model

For initially protected surfaces

- For gypsum plasterboards type F: \( t_{ch} < t_f \)
Charring model

For initially protected surfaces

- For gypsum plasterboards type F: \( t_{ch} < t_f \)
Time of start of charring (failure times of panels)

- For wood-based panels
  \[ t_{ch} = \frac{h_p}{\beta_0} \]

- For gypsum plasterboards type A, H or F (one layer)
  \[ t_{ch} = 2.8 \ h_p - 14 \]

- where \( h_p \) is the thickness of the panel, in mm
Failure modes of protective boards

- Thermal degradation (mechanical failure) of the boards
- Pull-out failure of fasteners due to excessive charring of timber member

![Diagram of steel channels for fixing panels in the ceiling]

- 1 Timber member
- 2 Steel channel
- 3 Panel
- 4 Fastener for fixing of steel channel to timber member
- 5 Fastener for fixing of panel to steel channel
- 6 Char layer

Steel channels for fixing panels in the ceiling
Fixing of fire protective panels to beams or columns

- Fixing of fire protective panels to beams or columns

- Charring

- Models

- Reduced cross-section

- Reduced properties

- Worked example

- Connections

- Conclusion

- Fire test

Notes
Failure modes of protective boards

Wood-based panels: $t_{ch} = t_f$

Gypsum plasterboards type A or H: $t_{ch} = t_f$

Gypsum plasterboards type F
- No generic failure times given in EN 1995-1-2
- To be determined by testing (prEN 13381-7)
Verification methods for load-bearing function

- Analysis of
  - Entire structure (global analysis)
  - Sub-assemblies (e.g. frames)
  - Members (e.g. walls, floors, columns, beams)

\[ E_{d,fi} \leq R_{d,fi} \]
Mechanical loading

- As simplification for residential, social, commercial and administration areas:

\[ E_{d,fi} = 0.6 \ E_d \]
Simple analytical models

- Reduced cross-section method
  - $k_{\text{mod,fi}} = 1$
  - Reduced cross section
- The reduced properties method
  - $k_{\text{mod,fi}} < 1$
  - Reduced material properties
Reduced cross-section method

Border of effective cross-section

Border of residual cross-section

Initial surface of member

Unaffected part of section

$d_{char}$

$d_0$

$def$
Reduced cross-section method

\[ d_{ef} = d_{\text{char},n} + k_0 \cdot d_0 \]

with

\[ d_0 = 7 \text{ mm}, \]

\( d_{\text{char},n} \) charring depth

unprotected surfaces

\[ k_0 = \frac{t}{20} \]

\( t \) time of standard fire exposure \( t < 20 \text{ mins} \)

\[ k_0 = 1.0 \]

for longer fire exposure durations
Reduced properties method

- For rectangular cross-sections of softwood
- Exposed to fire on three or four sides and round cross-sections exposed to fire along their whole perimeter.
- The residual cross-section
- A modification factor $k_{\text{mod,fi}}$ replace the modification factor for normal temperature design $k_{\text{mod}}$ given in EN 1995-1-1: 2005
Modification factor $k_{\text{mod,fi}}$

\[ f_{i,d} = k_{\text{mod,fi}} k_{fi} \frac{f_k}{\gamma_{M,fi}} \]

where $k_{\text{mod,fi}}$ is the modification factor for fire, which takes into account the influence of temperature and humidity; $\gamma_{M,fi}$ is the partial factor for timber in fire, $f_k$ is the characteristic strength at ambient temperature,

For solid timbers $k_{fi} = 1.25$.
For glued-laminated timber and wood-based panels, $k_{fi} = 1.15$.
For for connections with fasteners in shear with side members of steel and for connections with axially loaded fasteners of wood and wood-based panels, $k_{fi} = 1.05$. 

Modification factor $k_{\text{mod,fi}}$

\[
E_{\text{fi,d}} = k_{\text{mod,fi}} \cdot k_{\text{fi}} \cdot \frac{E_{k,05}}{\gamma_{M,\text{fi}}}
\]

\[
E_{\text{fi,d}} = k_{\text{mod,fi}} \cdot \frac{E_{\text{mean}}}{\gamma_{M,\text{fi}}}
\]

$E_{k,05}$ is the characteristic modulus of elasticity at ambient temperature for 5% fractile, and $E_{\text{mean}}$ is the average modulus of elasticity at ambient temperature. $k_{\text{fi}}$ is the coefficient for transferring the model from characteristic value to average value.
Modification factor $k_{\text{mod,fi}}$

The modification factor for fire $k_{\text{mod,fi}}$ may be determined in the following way:

- for bending strength:
  \[ k_{\text{mod,fi}} = 1.0 - \frac{1}{200} \frac{p}{A_r} \]

- for compression strength:
  \[ k_{\text{mod,fi}} = 1.0 - \frac{1}{125} \frac{p}{A_r} \]

- for tension strength and modulus of elasticity:
  \[ k_{\text{mod,fi}} = 1.0 - \frac{1}{330} \frac{p}{A_r} \]

where
- $p$ is the perimeter of the fire exposed residual cross-section,
- $A_r$ is the area of the residual cross-section.
Worked example
Solid timber beam

The design beam is made of soft solid timber of cross-section 180 x 220 mm.

The required fire resistance is 60 mins.

The beam span is 5.0 m.

The total mechanical load for the ultimate limit state design at normal temperature is

\[ g_d + q_d = 6.5 \text{ kN/m}. \]

The ratio of the characteristic variable load to the characteristic permanent load is \( Q_{k,1}/G_k = 1.0. \)
Worked example
Solid timber beam

The bending moment at normal temperature is:

\[ M_{\text{Ed}} = \frac{(g_d + q_d) \ell^2}{8} = \frac{6.5 \times 5^2}{8} = 20.31 \text{ kNm} \]

The ratio of the variable load to the permanent load:

\[ \xi = \frac{Q_{k,1}}{G_k} = 1.0 \]

The reduction factor for fire design is:

\[ \eta_{fi} = \frac{\gamma_{G_A} + \psi_{1,1} \xi}{\gamma_G + \gamma_{Q,1} \xi} = \frac{(1.0 + 0.2 \times 1.0)}{(1.35 + 1.5 \times 1.0)} = 0.42 \]

The design bending moment at fire situation is:

\[ M_{\text{fi,d}} = \eta_{\text{fi}} M_d = 0.42 \times 20.31 = 8.53 \text{ kNm} \]
Using reduced properties method

- The coefficient for the 20 % fractile of strength is \( k_{fi} = 1.25 \) (from Tab. 2.1 of EN 1995-1-2: 2005)
- Partial safety factor for the material at fire situation \( \gamma_{m,fi} = 1.0 \)
- The design notional charring rate under the standard fire exposure for solid timber \( \beta_n = 0.8 \) mm/min (from see Table 3.1 of EN 1995-1-2: 2005).
- The charring depth is:
  \[
  d_{\text{char}} = \beta_n t = 0.8 \times 60 = 48 \text{ mm}
  \]
Residual cross-section

- The residual width is:
  \[ b_r = b - 2d_{\text{char}} = 180 - 2 \times 48 = 84 \text{ mm} \]

- The residual height is:
  \[ h_r = h - d_{\text{char}} = 220 - 48 = 172 \text{ mm} \]

The elastic modulus for the residual cross-section exposed to fire by three sides is:

\[
W_r = \frac{b_r \times h_r^2}{6} = \frac{84 \times 172^2}{6} = 414 \times 10^3 \text{ mm}^3
\]

- The area of the residual cross-section is

\[ A_r = b_r h_r = 0.084 \times 0.172 = 1.4 \times 10^{-2} \text{ m}^2 \]

- Perimeter of the fire exposed residual cross-section:

\[ p = b_r + 2h_r = 0.084 + 2 \times 0.172 = 0.428 \text{ m} \]
Bending normal stress

The modification factor for fire for the reduced properties method is:

\[ k_{mod,fi} = 1.0 - \frac{1}{200} \frac{p}{A_r} = 1.0 - \frac{1}{200} \frac{42.8 \times 10^{-2}}{1.4 \times 10^{-2}} = 0.85 \]

The design bending strength is:

\[ f_{m,fi,d} = k_{mod,fi} \frac{f_{fi}}{\gamma_{M,fi}} = 0.85 \times 1.25 \frac{22}{1.0} = 23.4 \text{ N/mm}^2 \]

The design bending normal stress is:

\[ \sigma_{m,fi,d} = \frac{M_{fi,d}}{W_r} = \frac{8.53 \times 10^6}{414 \times 10^3} = 20.6 \text{ N/mm}^2 \]

Evaluation by stresses:

\[ \sigma_{m,fi,d} = 20.6 \text{ N/mm}^2 \leq k_{\text{crit}} f_{m,fi,d} = 1.0 \times 23.4 = 23.4 \text{ N/mm}^2 \]

Therefore, the beam is satisfactory for fire resistance rating of 60 mins.

Note: The utilisation factor is \( \sigma_{m,fi,d} / f_{m,fi,d} = 20.6 / 23.4 = 0.88 \)
Using the reduced cross-section method

The beam was further checked using the reduced cross-section method and the results were found to be more conservative compared to the reduced properties method. The reduced cross-section calculation method results are presented below.

The modification factor for fire $k_{\text{mod,fi}} = 1.0$;

The coefficient for the 20 % fractile strength or stiffness property for solid timber $k_{\text{fi}} = 1.25$;

The partial safety factor for fire $\gamma_{\text{m,fi}} = 1.0$
Charring rate

The charring rate under standard fire exposure for solid timber $\beta_n = 0.8 \text{ mm/min}$.

The depth of layer with assumed zero strength and stiffness $d_0 = 7 \text{ mm}$.

$k_0 = 1.0$ (the surface of the beam is not protected and $t \geq 20 \text{ min}$)

The effective charring depth is:

$$d_{ef} = \beta_n \cdot t + k_0 \cdot d_0 = 0.8 \times 60 + 1.0 \times 7 = 55 \text{ mm}$$

The reduced width, see Figure 6.31, is:

$$b_{fi} = b - 2 \cdot d_{ef} = 180 - 2 \times 55 = 70 \text{ mm}$$
Reduced cross section

The reduced width, see Figure 6.31, is:

\[ b_{fi} = b - 2 \cdot d_{ef} = 180 - 2 \times 55 = 70 \text{ mm} \]

The reduced height is:

\[ h_{fi} = h - d_{ef} = 220 - 55 = 165 \text{ mm} \]

The section modulus for the beam with the reduced cross-section exposed is:

\[ W_{fi} = \frac{b_{fi} \cdot h_{fi}^2}{6} = \frac{70 \times 165^2}{6} = 318 \times 10^3 \text{ mm}^3 \]
Design strength

The design strength in fire in bending is:

\[ f_{m,fi,d} = k_{mod,fi} \cdot k_{fi} \cdot \frac{f_{m,k}}{\gamma_{M,fi}} = 1.0 \times 1.25 \times \frac{22}{1.0} = 27.5 \text{ N/mm}^2 \]

The design bending normal stress is:

\[ f_{m,fi,d} = k_{mod,fi} \cdot k_{fi} \cdot \frac{f_{m,k}}{\gamma_{M,fi}} = 1.0 \times 1.25 \times \frac{22}{1.0} = 27.5 \text{ N/mm}^2 < f_{m,fi,d} = 27.5 \text{ N/mm}^2 \]

Therefore, the beam is satisfactory for 60 mins fire resistance.

Note: The utilisation factor is \( \frac{26.8}{27.5} = 0.97 \).

However, 0.97 > 0.88 so the reduced cross-section method is more conservative than the reduced properties method.
Connections

- The fire resistance of connections is influenced by the burn-up of its surface.
Connections

- For connections with side members of wood, for connections with external steel plates, and for axially loaded screws, the simplified rules and the reduced load method may be used.
Connections

- For connections with side members of wood, for connections with external steel plates, and for axially loaded screws, the simplified rules and the reduced load method may be used.
- It also gives the best engineering practice related to the structural detailing of walls and floors.
Only symmetrical three-member connections

Dowel-type fasteners (nails, bolts, dowels, screws) and connectors (split-ring, shear-plate and toothed-plate connectors)
Connections with side members of wood

**Simplified rules** – fire resistance determined by thickness of side members and protective panels, and fastener end/edge distances

**Reduced load method** – 'load-carrying capacity vs time' assumed as one-parameter exponential empirical model

![Diagram showing connections with side members of wood]
## Simplified rules

### unprotected connections

Connections designed according to EN 1995-1-1

<table>
<thead>
<tr>
<th>Fastener / connector type</th>
<th>Fire resistance $t_{d,11}$ [min.]</th>
<th>Provisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nails</td>
<td>15</td>
<td>$d \geq 2.8$ mm</td>
</tr>
<tr>
<td>Screws</td>
<td>15</td>
<td>$d \geq 3.5$ mm</td>
</tr>
<tr>
<td>Bolts</td>
<td>15</td>
<td>$t_1 \geq 45$ mm</td>
</tr>
<tr>
<td>Dowels</td>
<td>20</td>
<td>$t_1 \geq 45$ mm</td>
</tr>
<tr>
<td>Connectors (EN 912)</td>
<td>15</td>
<td>$t_1 \geq 45$ mm</td>
</tr>
</tbody>
</table>

$d$ is the diameter of the fastener

$t_1$ is the thickness of the side member
Simplified rules
- unprotected connections

Greater fire resistance (not exceeding 30 min.) by increasing:

- thickness of side members
- width of the side members
- end / edge distance to fasteners

\[ a_{fi} = \beta_n \cdot k_{\text{flux}} \cdot (t_{\text{req}} - t_{d,fi}) \]

- \( \beta_n \) is the notional charring rate
- \( k_{\text{flux}} \) is a coefficient taking into account increased heat flux through the fastener
- \( t_{\text{req}} \) is the required fire resistance
- \( t_{d,fi} \) is the fire resistance of the unprotected connection (previous table)
Simplified rules - protected connections

Wood panelling, wood-based panels or gypsum plasterboard type A or H

\[ t_{ch} \geq t_{req} - 0.5 \cdot t_{d,fi} \]

Gypsum plasterboard type F

\[ t_{ch} \geq t_{req} - 1.2 \cdot t_{d,fi} \]

- *t_{ch}* is the time until start of charring of the protected member: \( t_{ch} = t_{ch} (h_p) \)
- *t_{req}* is the required fire resistance
- *t_{d,fi}* is the fire resistance of the unprotected connection

\[ \text{additional protection using panels} \]
\[ \text{glued-in plugs} \]
\[ \text{fasteners fixing of the additional protection} \]

\[ \text{member providing protection} \]
\[ \text{bolt head} \]
Simplified rules
- protected connections

Fixing of additional protection by nails or screws

- Distance between fasteners:
  - $\leq 100$ mm (along the boards edges)
  - $\leq 300$ mm (for internal fastenings)

- Edge distance of fasteners $\geq a_f$

- Penetration depth of fasteners:
  - $\geq 6 \cdot d$ (wood-based panels or gypsum plasterboard type A or H)
  - $\geq 10 \cdot d$ (gypsum plasterboard type F)
Simplified rules - protected connections

Connections with internal steel plates

width $b_{st}$ of the steel plate (with unprotected edges)

<table>
<thead>
<tr>
<th>Edge Protection</th>
<th>Protection Time</th>
<th>$b_{st}$ Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unprotected edges in general</td>
<td>R30</td>
<td>$b_{st} \geq 200$ mm</td>
</tr>
<tr>
<td>R60</td>
<td>$b_{st} \geq 280$ mm</td>
<td></td>
</tr>
<tr>
<td>Unprotected edges in one or two sides</td>
<td>R30</td>
<td>$b_{st} \geq 120$ mm</td>
</tr>
<tr>
<td>R60</td>
<td>$b_{st} \geq 280$ mm</td>
<td></td>
</tr>
</tbody>
</table>

Steel plates narrower than the timber member are protected if

- Plate thickness $\leq 3$ mm
  - R30: $d_g \geq 30$ mm
  - R60: $d_g \geq 60$ mm
- Joints with glued-in strips or protective wood based boards
  - R30: $d_g$ or $h_p \geq 10$ mm
  - R60: $d_g$ or $h_p \geq 30$ mm
Connections

Reduced load method

‘Load-carrying capacity’ vs Fire resistance

- assumed as one-parameter exponential empirical model
- model parameter $k$ for each connection type and limited to a maximum fire exposure period

\[ F_{V,Rk,fi} = \eta \cdot F_{V,Rk} \]
\[ \eta = e^{-k \cdot t_{d,fi}} \]

Graph showing load ratio vs fire resistance for different connection types:
- Steel-to-timber (dowels, bolts)
- Timber-to-timber (bolts)
- Timber-to-timber (dowels)
Connections

Reduced load method

Load-carrying capacity after a given fire exposure

\[ F_{V,Rk,fi} = e^{-k \cdot t_{d,fi}} \cdot F_{V,Rk} \]

\[ F_{V,Rd,fi} = e^{-k \cdot t_{d,fi}} \cdot F_{V,Rk} \cdot \frac{k_{fi}}{\gamma_{M,fi}} \]

- \( F_{V,Rk} \) is the characteristic load-carrying capacity at normal temperature
- \( t_{d,fi} \) is the design fire resistance (in minutes)
- \( k_{fi} \) is a factor to convert 5-percentile values to 20-percentile
- \( \gamma_{M,fi} \) is the partial safety factor for timber in fire

### EN 1995-1-1

<table>
<thead>
<tr>
<th>Connection type</th>
<th>( k )</th>
<th>Maximum period of validity for ( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nails and screws</td>
<td>0.08</td>
<td>20 min.</td>
</tr>
<tr>
<td>Bolts wood-to-wood (( d \geq 12 ))</td>
<td>0.055</td>
<td>30 min.</td>
</tr>
<tr>
<td>Bolts wood-to-wood (( d \geq 12 ))</td>
<td>0.085</td>
<td>30 min.</td>
</tr>
<tr>
<td>Dowels wood-to-wood (( d \geq 12 ))</td>
<td>0.04</td>
<td>40 min.</td>
</tr>
<tr>
<td>Dowels steel-to-wood* (( d \geq 12 ))</td>
<td>0.085</td>
<td>30 min.</td>
</tr>
<tr>
<td>Connectors (EN 912)</td>
<td>0.059</td>
<td>30 min.</td>
</tr>
</tbody>
</table>

* requires one bolt for every four dowels
Advanced calculation methods

FE analysis

- **Thermal analysis**
  Effective thermal properties include effects of mass transport, and cracking and surface recession of char-layer (only valid for standard fire exposure)

- **Structural analysis**
  Thermo-mechanical properties include transient effects of combined moisture and elevated temperature and mechano-sorptive creep
Fire separation function

Fire separating function of walls and floors
Conclusions

- Resistance of timber structures during fire can be well predicted
- Timber structures in fire charring
  - Remaining sections not changed its strength and stiffness

- Tests
  - To achieve higher fire resistance
  - If no design procedure available
  - To precise the design procedures
EN 1995-1-2 has filled many gaps in the knowledge of structural timber design in fire

However, some problems are still to be solved, hopefully before the next generation of Eurocodes will be published

Further knowledge in “Fire safety in Timber Buildings”
Technical guideline for Europe SP Report 2010
Formative assessment question

- What are the advantages of prescriptive based approach for fire safety of buildings?
- How is defined section factor?
- What are the advantages of fire engineering?
- Explain major steps of fire engineering?
- How are divided the models of fire?
Fire test at CTU in Prague

- Timber based wall panel

40 min
Fire test at CTU in Prague

- Timber based wall panel

67 min
Fire test at CTU in Prague

- Timber based wall panel

83 min
Fire test at CTU in Prague

- Timber based wall panel
  - Gas temperature
Fire test at CTU in Prague

- Timber based wall panel
  - Temperatures in panel

![Graph showing temperature over time for different tests PH1, PH2, PH3, PH4. The graph plots time in minutes on the x-axis and temperature in degrees Celsius on the y-axis. Each line represents a different test, with PH4 showing a sharp increase around 70 minutes.]
Fire test of timber and **steel fibre reinforced floor**
## List of Lessons at Seminar

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<th>Instructor(s)</th>
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<td><strong>Fire safety</strong></td>
<td>RZ</td>
</tr>
<tr>
<td>2</td>
<td>Fire and mechanical loading</td>
<td>RZ</td>
</tr>
<tr>
<td>3</td>
<td>Thermal response</td>
<td>RZ</td>
</tr>
<tr>
<td>4</td>
<td>Steel structures</td>
<td>RZ</td>
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<td>Definitions of <strong>Design for Robustness</strong></td>
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<td>Global response of structures</td>
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<td>14</td>
<td>Design recommendations</td>
<td>JMD</td>
</tr>
<tr>
<td>15</td>
<td>Alternative load path method</td>
<td>JMD</td>
</tr>
</tbody>
</table>
Thank you for your attention

František WALD

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Notes to users of the lecture

- Text books
Notes to users of the lecture

• Further readings, e.g. Models of separation function of wall and floor assemblies see the lecture 1E6 Timber structures

• Keywords for the lecture: fire design, timber structures, charing rate, elemental design, Eurocodes.
Sources

