Fire Design of Aluminium Structures

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Objectives of the lecture

- Summary of structural aluminium and steel design at ambient temperature
- Properties of structural aluminium
- Particularities of aluminium fire design
Outline of the lecture

- Introduction
- Thermal properties
- Mechanical properties
- Transfer of heat
  - Unprotected elements
  - Protected elements
- Elemental analyses
  - Classification of sections
  - Columns
  - Beams
  - Critical temperature
- Summary
  - Worked example
Structural aluminium/steel behaviour?

**Ambient temperature**

- Stress-strain diagram
  - No yield stress
  - Modulus of elasticity 1/3 of steel
  - Lower ductility
- Different production of sections
  - Majority wrought aluminium
  - Buckling curves more favourable
- Heat affected zones HAZ
  - Reduction of material properties
Structural aluminium/steel design?

Ambient temperature

- Different procedures
  - HAZ for resistance
  - HAZ for stability
  - Lugs for stiffening
  - Material model
Structural aluminium/steel design?

Ambient temperature

- Standards different structure
- EN 1999 Design of Aluminium Structures:
  - EN 1999-1-1 General structural rules
  - EN 1999-1-2 Structural fire design
  - EN 1999-1-3 Structures susceptible to fatigue
  - EN 1999-1-4 Cold-formed structural sheeting.
  - EN 1999-1-5 Shell structures
Relative thermal elongation

- As a function of the temperature

\[ \frac{\Delta l}{l} \] vs. \( \theta_{al} \) °C

Graph showing the relative thermal elongation as a function of temperature.
Relative thermal elongation

- Mathematical model

\[
\text{for } 0.0^\circ \text{C} < \theta_{al} \leq 500.0^\circ \text{C}
\]

\[
\frac{\Delta l}{l} = 0.1 \cdot 10^{-7} \theta_{al}^2 + 2.25 \cdot 10^{-6} \theta_{al} - 4.5 \cdot 10^{-4}
\]

where

\[
l \rightarrow \text{is the length at } 20.0^\circ \text{C}
\]

\[
\Delta l \rightarrow \text{is the temperature induced elongation}
\]
Specific heat of aluminium

- As a function of the temperature

![Graph showing specific heat of aluminium as a function of temperature.](image-url)
Specific heat of aluminium

- Mathematical model

\[ c_{al} = 0.41 \cdot \theta_{al} + 903 \cdot (J/kg^\circ C) \]

\[ \text{for } 0^\circ C < \theta_{al} < 500^\circ C \]

![Graph showing specific heat of aluminium vs temperature](image-url)
Thermal conductivity of aluminium alloy $\lambda_{al}$

- The thermal conductivity for $0 \, ^\circ C < \theta_{al} < 500 \, ^\circ C$

![Graph showing thermal conductivity vs. temperature](image-url)

- Series 1000, 3000 to 6000
- Series 12000, 4000, 5000 to 7000
Thermal conductivity

- Mathematical model
  - a) for alloys in 3xxx and 6xxx series:
    \[ \lambda_{al} = 0.07 \cdot \theta_{al} + 190 \, (W/m \cdot K) \]
  - b) for alloys in 5xxx and 7xxx series:
    \[ \lambda_{al} = 0.1 \cdot \theta_{al} + 140 \, (W/m \cdot K) \]
Mechanical properties of aluminium alloys

- At 20 °C should be taken as those given in EN 1999-1-1 for normal temperature design
- For up to 2 hours thermal exposure period
- 0.2% proof strength at elevated temperature

\[ f_{o,\theta} = k_{o,\theta} \cdot f_o \]

where

- \( f_{o,\theta} \) is 0.2 proof strength at elevated temperature
- \( f_o \) is 0.2 proof strength at room temperature according to EN 1999-1-1
0,2 % proof strength at elevated temperature

- 0,2% proof strength ratios $k_{o,\theta}$
  - Two tables
  - Lower limits

<table>
<thead>
<tr>
<th>Aluminium alloy temperature °C</th>
<th>20</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>550</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower limit values</td>
<td>1,00</td>
<td>0,90</td>
<td>0,75</td>
<td>0,50</td>
<td>0,23</td>
<td>0,11</td>
<td>0,06</td>
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</table>
0,2 \% proof strength at elevated temperature

- 0,2\% proof strength ratios $k_{0,\theta}$
- Two tables for different alloys and tempers
0,2 % proof strength at elevated temperature

- 0,2 % proof strength ratios $k_{o,\theta}$
- Two tables for different alloys and tempers

\[
\frac{E_{al,\theta}}{E_{al}} \quad k_{o,\theta}
\]

\[
\begin{array}{cccccc}
\theta_{al} / ^{\circ}C & 5005-O & 5083-O & 5454-O & 5052-H34 & 5083-H12 & 5005-H14 & 5454-H34 \\
50 & 1.0 & 0.9 & 0.7 & 0.5 & 0.3 & 0.1 & 0.0 \\
100 & 0.9 & 0.8 & 0.7 & 0.5 & 0.3 & 0.1 & 0.0 \\
200 & 0.8 & 0.7 & 0.6 & 0.4 & 0.2 & 0.0 & 0.0 \\
300 & 0.7 & 0.6 & 0.5 & 0.3 & 0.1 & 0.0 & 0.0 \\
400 & 0.6 & 0.5 & 0.4 & 0.2 & 0.0 & 0.0 & 0.0 \\
500 & 0.5 & 0.4 & 0.3 & 0.1 & 0.0 & 0.0 & 0.0 \\
\end{array}
\]
Exposure period

0,2 proof strength $f_{o,\theta}$ N/mm$^2$

- 160 °C
- 200 °C
- 250 °C
- 300 °C

Time of exposure log min

prEN 1999-1-2: 2004
Modulus of elasticity $E_{al, \theta}$

- Ratio $E = E_{al, \theta}/E_{al}$ for aluminium alloys at elevated temperature $\theta_{al}$ °C

<table>
<thead>
<tr>
<th>Aluminium alloy temperature, $\theta$ (°C)</th>
<th>Modulus of elasticity, $E_{al, \theta}$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>70 000</td>
</tr>
<tr>
<td>50</td>
<td>69 300</td>
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<tr>
<td>100</td>
<td>67 900</td>
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<td>250</td>
<td>54 600</td>
</tr>
<tr>
<td>300</td>
<td>47 600</td>
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<tr>
<td>350</td>
<td>37 800</td>
</tr>
<tr>
<td>400</td>
<td>28 000</td>
</tr>
<tr>
<td>550</td>
<td>0</td>
</tr>
</tbody>
</table>
Modulus of elasticity $E_{al,\theta}$

- Ratio $E = E_{al,\theta}/E_{al}$ for aluminium alloys at elevated temperature $\theta_{al}$ °C
Assessment 1

- What thermal exposure is expected for aluminium alloys during fire?
- When starts at elevated temperature the reduction of 0.2% proof strength?
Unprotected aluminium temperature development

- Simple analytical model
- Step by step procedure (the lumped mass method)

\[ \Delta \theta_{al}(t) = k_{sh} \frac{1}{c_{al} \rho_{al}} \frac{A_m}{V} \dot{h}_{net}\Delta t \]

**where**

- \( k_{sh} \) is the correction factor for the shadow effect from 4.2.3.1 (2)
- \( A_m/V \) is the section factor for unprotected aluminium members \((m^{-1})\)
- \( \dot{h}_{net} \) is the design value of the net heat flux per unit area, see EN 1991-1-2

\( \Delta t \) should not be taken as more than 5 s

\( A_m/V \) the section factor should not be taken as less than 10 \( m^{-1} \)
Section factor for unprotected aluminium members

- Open section exposed to fire on all sides:
  \[ \frac{A_m}{V} = \frac{\text{perimeter}}{\text{cross-section area}} \]

- Tube exposed to fire on all sides:
  \[ \frac{A_m}{V} = \frac{1}{t} \]
Section factor for unprotected aluminium members

- Open section exposed to fire on three sides:
  \[ A_m \approx \frac{A_m}{V} = \frac{\text{surface exposed to fire}}{\text{cross-section area}} \]

- Hollow section (or welded box section of uniform thickness) exposed to fire on all sides:
  \[ A_m \approx \frac{1}{t} \]

- I section flange exposed to fire on three sides:
  \[ A_m \approx \frac{A_m}{V} = \frac{b + 2t_f}{bt_f} \]

- Box section exposed to fire on all sides:
  \[ A_m \approx \frac{2b+h}{V} \]

Summary

- Transfer of heat
  - Unprotected
  - Protected

Elemental analyses
- Classification
- Beams
- Columns
- Critical temp.

Notes

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### Section factor for unprotected aluminium members

<table>
<thead>
<tr>
<th>Angle (or any open section of uniform thickness) exposed to fire on all sides:</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \frac{A_m}{V} = \frac{2}{t} ]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I section with box reinforcement exposed to fire on all sides:</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \frac{A_m}{V} = \frac{2b+h}{\text{cross-section area}} ]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flat bar exposed to fire on all sides:</th>
</tr>
</thead>
</table>
| \[ \frac{A_m}{V} = \frac{2b+2t}{bt} \]  
If \( t \ll b \): \( \frac{A_m}{V} \approx \frac{2}{t} \) |

<table>
<thead>
<tr>
<th>Flat bar exposed to fire on three sides:</th>
</tr>
</thead>
</table>
| \[ \frac{A_m}{V} = \frac{b+2t}{bt} \]  
If \( t \ll b \): \( \frac{A_m}{V} \approx \frac{1}{t} \) |
Grooves with gap in the surface

- The calculation of the exposed surface area
- Grooves with gap in the surface less than 20 mm should not be included in the exposed surface area.
- Grooves with gap in the surface > 20 mm, the area of the groove should be included in the area of the exposed area
Surface emissivity $\varepsilon_m$

- The values of $\dot{h}_{\text{net,d}}$ should be obtained from EN 1991-1-2 using

\[
\varepsilon_m = 0.3 \text{ for clean uncovered surfaces} \\
\varepsilon_m = 0.7 \text{ for painted and covered (e.g. sooted) surfaces}
\]
Surface emissivity $\varepsilon_m$

Element temperature, °C

Section factor $A m/ V = 25$

Time, min

$\varepsilon_m = 0.3$

$\varepsilon_m = 0.7$
Aluminium element insulated by fire protection material

For a uniform temperature distribution in a cross-section, the temperature increase

\[ \Delta \theta_{al}(t) = \frac{\lambda_p}{c_{al} \rho_{al}} \frac{A_p}{V} \left( 1 \right) \left( \theta(t) - \theta_{al(t)} \right) \Delta t - \left( e^{\phi/10} - 1 \right) \Delta \theta(t) \]

but \( \Delta \theta_{al(t)} \geq 0 \)

in which:

\[ \phi = \frac{c_p \rho_p d_p}{c_{al} \rho_{al}} \frac{A_p}{V} \]

where

\[ \frac{A_p}{V} \] is the section factor for aluminium members insulated by fire protection material \((m^{-1})\)

\( \theta(t) \) is the ambient gas temperature at time \( t \) \(^{\circ}C\)

\( \theta_{al(t)} \) is the aluminium temperature at time \( t \) \(^{\circ}C\)

\( \Delta \theta(t) \) is the increase of the ambient temperature during the time interval \( \Delta t \) \(^{\circ}C\)
Section factor $A_p/V$
for insulated members

<table>
<thead>
<tr>
<th>Sketch</th>
<th>Description</th>
<th>Section factor ($A_p/V$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Contour encasement" /></td>
<td>Contour encasement of uniform thickness, exposed to fire on four sides.</td>
<td>$\frac{\text{aluminium perimeter}}{\text{aluminium cross - section area}}$</td>
</tr>
<tr>
<td><img src="image2" alt="Hollow encasement" /></td>
<td>Hollow encasement of uniform thickness, exposed to fire on four sides.</td>
<td>$\frac{2(b + h)}{\text{aluminium cross - section area}}$</td>
</tr>
</tbody>
</table>
### Section factor $A_p/V$

**for insulated members**

| | Contour encasement of uniform thickness, exposed to fire on three sides. | aluminium perimeter - $b$  
aluminium cross - section area |
<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| | Hollow encasement of uniform thickness, exposed to fire on three sides. | $2h + b$  
aluminium cross - section area |
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td></td>
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</tr>
</tbody>
</table>
Design tools TALAT

- Reference thickness of fire protection
  \[ d_p = k d_{p,\text{ref}} \quad (k \text{ based on material form 0.4 to 1.4}) \]
Assessment 2

- What differences are for step by step procedure of aluminium compare to steel?
- Describe the section factor $A_p/V$ for insulated member by bords?
- What surface emissivity $\varepsilon_m$ is expected for clean uncovered surface?
Structural fire design

- **Simple calculation models**
  \[ E_{fi,d} \leq R_{fi,d,t} \]
  - \( E_{fi,d} \) is the design effect of actions for the fire design situation
  - \( R_{fi,d,t} \) is the design resistance of the aluminium structure or structural member, for the fire design situation

- **Advanced calculation models**
  - The development and distribution of the temperature within structural members (thermal response model);
  - The mechanical behaviour of the structure or of any part of it (mechanical response model).
  - Validation of advanced calculation models
Effect of actions

- For time $t = 0$
- Using combination factors $\psi_{1,1}$ or $\psi_{2,1}$ according to EN1991-1-2

$$E_{f_i,d} = \eta_i E_d$$

Where $E_d$ is the design value of the corresponding force or moment for normal temperature design

- As a simplification the recommended value of $\eta_i = 0.65$ may be used
  (Except areas susceptible to accumulation of goods, including access areas.)
Classification of cross-sections

- Classified as for normal temperature design
- Based on the same relative drop in the 0.2% proof strength and modulus of elasticity

- Actual drop in modulus of elasticity
  - Classification of the section changes
  - Larger capacity value of the section
\[ \varepsilon = \sqrt{250 / f_o} \]

- To introduce different materials
- Plate slenderness

\[ \bar{\lambda}_p = \frac{b}{28,4 \cdot t \cdot \varepsilon \cdot \sqrt{k_\sigma}} = \frac{b}{t \sqrt{\frac{\pi^2}{12 \cdot f_o \cdot (1 - \mu^2)} \sqrt{E} \cdot \varepsilon \cdot \sqrt{k_\sigma}}} = \]

\[ = \frac{b}{t \sqrt{\frac{\pi^2}{12 \cdot f_o \cdot (1 - \mu^2)} \sqrt{E} \cdot \varepsilon \cdot \sqrt{k_\sigma}}} = 0,0620 \frac{b}{t \sqrt{\frac{235E}{f_o} \sqrt{k_\sigma}}} = 0,950 \frac{b}{t \sqrt{\frac{E}{f_o} \sqrt{k_\sigma}}} \]

- \( t \) is plate thickness
- \( b \) is width,
- \( \mu \) is Poisson ratio
- \( E \) is *modulus of elasticity*
- \( f_o \) is 0,2 % proof strength
Reduction of $\varepsilon$ coefficient

- At elevated temperature

\[
\sqrt{\frac{E_\theta}{f_{o,\theta}}} = \sqrt{\frac{k_{E,\theta}}{k_{o,\theta}}} \frac{E}{f_o} = \sqrt{\frac{k_{E,\theta}}{k_{o,\theta}}} \sqrt{\frac{E}{f_o}}
\]

\[
\sqrt{\frac{k_{E,\theta}}{k_{y,\theta}}} \sqrt{\frac{E}{f_y}} \approx 1,00 \sqrt{\frac{E}{f_y}}
\]
Reduction of $\varepsilon$ coefficient for structural steel

![Graph showing the reduction of $\varepsilon$ coefficient for structural steel. The graph plots steel temperature against $\varepsilon$ for different conditions: effective yield strength, proportional limit, and a constant value of 0.85 in EN 1993-1-2.]
Reduction of $\varepsilon$ coefficient for steel

- Currently for steel

\[ \sqrt{\frac{k_{E,\theta}}{k_{y,\theta}}} \sqrt{\frac{E}{f_y}} \approx 0.85 \sqrt{\frac{E}{f_y}} \]
Reduction of $\varepsilon$ coefficient for aluminium

$$\varepsilon = \alpha_\theta \sqrt{\frac{250}{f_0}}$$

at elevated temperature

$$\alpha_\theta = \sqrt{\frac{k_{E,al,\theta}}{k_{o,\theta}}} \sqrt{\frac{E_{al,\theta}}{E_{al}}} \sqrt{\frac{f_{o,\theta}}{f_o}}$$
Reduction of $\varepsilon$ coefficient for aluminium

$$\varepsilon = \alpha_0 \sqrt{\frac{250}{f_0}}$$
Reduction of $\varepsilon$ coefficient for aluminium

\[ \varepsilon = \alpha_\theta \sqrt{\frac{250}{f_0}} \]

<table>
<thead>
<tr>
<th>Aluminium temperature $^\circ$C</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN AW-6063; O</td>
<td>1.0</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
<td>1.8</td>
<td>2.0</td>
<td>2.2</td>
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<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
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<td>2.6</td>
<td>2.8</td>
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<td>3.2</td>
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<td>EN AW-5154; O</td>
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<td>1.6</td>
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<td>2.0</td>
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<td>2.6</td>
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<tr>
<td>EN AW-6063; H34</td>
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<td>1.4</td>
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<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Tension members

- The design resistance

\[ N_{fi,t,Rd} = \sum A_i k_{o,\theta,i} f_o \gamma_{M,fi} \]

where

- \( A_i \) is an elemental area of the net cross-section with a temperature \( \theta_i \), including a deduction if required to allow for the effect of HAZ softening.

The deduction is based on the reduced thickness of \( \rho_{o,HAZ} \cdot t \)

- \( k_{o,\theta,i} \) is the reduction factor for the effective 0,2 % proof strength at temperature \( \theta_i \).
Beams

The design $M_{fi,t,Rd}$ of a cross-section in class 1, 2, 3 or 4 with a uniform temperature distribution at time $t$

$$M_{fi,t,Rd} = k_{o,\theta} M_{Rd} (\gamma_{Mx}/\gamma_{M,fi})$$

where

$M_{Rd}$ is the moment resistance of the cross-section for normal temperature design. $M_{Rd}$ is either $M_{c,Rd}$ or $M_{u,Rd}$

$\gamma_{Mx}$ is the material coefficient according to EN 1999-1-1. $\gamma_{M1}$ is used in combination with $M_{c,Rd}$ and $\gamma_{M2}$ is used in combination with $M_{u,Rd}$

The design resistance $M_{fi,t,Rd}$ is given by the combination of $M_{Rd}$ and $\gamma_{Mx}$ which gives the lowest capacity.
Columns

The design buckling resistance $N_{b,fi,t,Rd}$ of a compression member at time $t$

$$N_{b,fi,t,Rd} = k_{o,\theta,max} N_{b,Rd} \left( \gamma_{M1}/1.2 \gamma_{M,fi} \right)$$

where

$N_{b,Rd}$ is the buckling resistance for normal temperature design according to EN 1999-1-1

1.2 is a reduction factor of the design resistance due to the temperature dependent creep of aluminium alloys
Buckling length of a column in intermediate storey

Braced frame in which each storey comprises a separate fire compartment with sufficient fire resistance

A: Shear wall or other bracing system
B: Separate fire compartments in each storey
C: Column buckling length
D: Deformation mode in fire
Relative slenderness

- The same relative drop in the 0.2% proof strength and modulus of elasticity.
- If the actual drop in modulus of elasticity is taken into account, a larger capacity value can be obtained.

\[
\bar{\lambda}_{\Theta} = \frac{\bar{\lambda}}{\alpha_{\Theta}} \quad \alpha_{\Theta} = \sqrt{\frac{k_{E,al,\Theta}}{k_{o,\Theta}}} \sqrt{\frac{E_{al,\Theta}}{E_{al}}} \sqrt{\frac{f_{o,\Theta}}{f_{o}}}
\]
Buckling curves

- Buckling classes: A
- 1.2 is a reduction factor of the design resistance due to the heat for fire design.
Buckling resistance at elevated temperature

- Buckling length of rectangular hollow section 60x60x4
The critical temperature of aluminium alloys

Critical temperature °C

Simplified value 170 °C

Degree of utilisation $\mu_0$

Steel
Aluminium

EN AW-5454
EN AW-5086
EN AW-5083
EN AW-6082
EN AW-3003
The critical temperature of aluminium alloys

\[ \theta_{a,cr} = C \ln \left( \frac{1}{A \mu_0^D} - 1 \right) + B \]

- where the degree of utilisation \( \mu_0 = \frac{E_{fi,d}}{R_{fi,d,0}} \) may not be taken less than 0.015
- \( E_{fi,d} \) is the design effect of actions for the fire design situation according to EN 1991-1-2 and
- \( R_{fi,d,0} \) is the corresponding design resistance of the steel member for fire design situation at time \( t \).
- The accuracy of the prediction varies is limited.
- The prediction of critical temperature of steel shows a deviation 3.73%.
# The critical temperature of aluminium alloys

## Constants for calculation of critical temperature of aluminium alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Thermal treatment</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Maximal deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN AW-5052</td>
<td>O</td>
<td>0.9905</td>
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<td>74.88</td>
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<td>0.9885</td>
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<tr>
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</tbody>
</table>
ECCS nomogram for aluminium

Reduction of material

Critical temperature \( \theta_{\text{crit}} \), °C

Section factor \( \frac{l_m}{V} \), m⁻¹

Transfer of heat

Utilisation

Time, min

Critical temperature

(\( \frac{A_p}{V} \)/)(\( \frac{\lambda_p}{d_p} \)) W K⁻¹ m⁻³
Assessment 3

- What advantage may be utilised for classification of aluminium cross-sections?
- How is treated the temperature dependent creep of aluminium alloys for simple modelling of buckling resistance?
- What is the simplified value of critical temperature of aluminium alloys?
Summary

- EN1999-1-2 first standard for fire design of aluminium str.
- Based on steel knowledge
- Lower fire resistance compare to steel
  - The low melting point of aluminum (590 °C až 650 °C)
  - The good emisivity 0,3

![Diagram showing reduction factor and temperature relationship between steel and aluminium.](image)
Worked example – beam column

- Laterally restrained beam
- Load \((g_k + q_k)\) 2 kN/m
- Load reduction factor \(\gamma_F = 1.45\)
- Alloy EN AW-5083 (material class B)
Section classification

Flage in compression not decide

Web in compression – stiffened plate

$\eta$ is taken form diagram 6.4 in EN 1999-1-1

$$\beta = \eta \frac{b}{t} = 0,95 \frac{180}{5} = 34,2 > \beta_3 = 18 \cdot \varepsilon = 18 \cdot 1,51 = 27,1$$

Web and all section Class 4

Web in bending

section asymmetry coefficient $\varepsilon$

varying the stress coefficient $g$

$$\beta = \eta \cdot g \frac{b}{t} = 0,95 \cdot 0,351 \frac{180}{5} = 12,0 < \beta_1 = 13 \cdot \varepsilon = 13 \cdot 1,63 = 21,1$$

Web and all section Class 1
Effective section

Reduction factor for web in compression material buckling class B

\[ \rho_c = \frac{C_1}{b/t} - \frac{C_2}{(b/t)^2} = \frac{29}{180/5} - \frac{198}{(180/5)^2} = 0,894 \]

Effective area

\[ A_{\text{eff}} = A_g - (1 - \rho_c) \cdot 2 \cdot b \cdot t = 3848 - (1 - 0,894) \cdot 2 \cdot 180 \cdot 5 = 3752 \text{ mm}^2 \]

Shift of the center of gravity due to buckling

\[ \Delta z_t = \frac{-(1 - \rho_c) \cdot 2 \cdot b \cdot t \cdot z}{A_{\text{eff}}} = \frac{-(1 - 0,894) \cdot 2 \cdot 180 \cdot 5 \cdot \left(\frac{180}{2} - 83\right)}{3752} = 0,36 \text{ mm} \]
Resistance check

Section bending resistance

Section poor compression resistance

Buckling factor $\chi$

Combination of buckling and pure bending

\[
\left( \frac{N_{Ed}}{\chi \cdot N_{Rd}} \right)^{\psi_c} + \frac{M_{Ed}}{M_{y,Rd}} = \left( \frac{27,9}{0,483 \cdot 375,2} \right)^{0,8} + \frac{15,3}{22,8} = 0,895 < 1,0
\]

kde $\psi_c = \max\left( 0,8; 1,3 \cdot \chi_{\text{min}} \right) = \max\left( 0,8; 1,3 \cdot 0,483 \right) = 0,8$

OK
Serviceability check

Full gross section

Due to lower stessess no local buckling

Web in compression

Simplified

Secant modulus of elasticity for maximal stress

Ramberg-Osgood material model

\[
E_s = \frac{E}{1 + 0.002 \frac{E}{\sigma_{Ed,ser}} \left( \frac{\sigma_{Ed,ser}}{f_0} \right)^n} = \frac{70 \times 10^3}{1 + 0.002 \frac{70 \times 10^3}{55.8} \left( \frac{55.8}{110} \right)^5} = 61 \, 022 \, \text{MPa}
\]

OK
Design et elevated temperature

- Hall of a train station

- Localised fire of newsstand
  - The largest diameter of fire 2 m
  - Fire load 4 640 MJ
  - Medium speed fire development $t_\alpha = 300$ s
  - The fastest rate of heat release $RHR_f = 1250$ kW/m$^2$
**Mechanical actions at fire**

Reduction factor $\eta_{fi}$

For snow loading $\psi_{1,1} = 0,2$

$$\eta_{fi} = \frac{G_k + \psi_{1,1} Q_k}{G_k \gamma_G + Q_k \gamma_Q} = \frac{0,66 + 0,2 \cdot 1,33}{0,66 \cdot 1,35 + 1,33 \cdot 1,5} = 0,321$$

$$M_{fi,Ed} = M_{Ed} \ \eta_{fi} = 15,3 \cdot 0,321 = 4,91 \text{ kNm}$$

$$N_{fi,Ed} = N_{Ed} \ \eta_{fi} = 27,9 \cdot 0,321 = 8,96 \text{ kN}$$
Termal loading during fire


Rate of heat release $Q$

![Graph showing the rate of heat release over time, with a peak at 30 MW after 20 minutes.](image-url)
Thermal heat during fire

Flame height in time \( t \)

Diameter of the fire in time \( t \)

Temperature along the flame axes

Convective part of the rate of heat release \( Q_c \)

![Graph showing flame height over time](chart.png)
Transfer of heat into structure

Step by step procedure

Surface emissivity of the member $\varepsilon_m = 0.3$

Clean aluminium element

Coefficient of heat transfer by convection $\alpha_c = 35 \text{ W/m}^2\text{K}$

Section factor $A_m/V = 130 \text{ m}^{-1}$

Section exposed to three sides
Transfer of heat into structure

Maximal beam temperature 272 °C in 22 min 40 s

Reduction factor for $k_{0,\theta,\text{max}} = 0.596$
Resistance at elevated temperature

Bending resistance

Buckling resistance

Buckling length as at ambient temperature

Interaction as at ambient temperature

\[
\left( \frac{N_{fi,Ed}}{N_{b,fi,t,Rd}} \right)^{\psi_c} + \frac{M_{fi,Ed}}{M_{fi,t,Rd}} = \left( \frac{8.96}{99.0} \right)^{0.8} + \frac{4.91}{14.95} = 0.475 < 1.0
\]
<table>
<thead>
<tr>
<th>Lesson Number</th>
<th>Lesson Title</th>
<th>Instructor(s)</th>
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<tbody>
<tr>
<td>1</td>
<td>Fire safety</td>
<td>RZ</td>
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<tr>
<td>2</td>
<td>Fire and mechanical loading</td>
<td>RZ</td>
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<tr>
<td>3</td>
<td>Thermal response</td>
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<td>Steel structures</td>
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<td>After fire and Historical structures</td>
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<td>15</td>
<td>Alternative load path method</td>
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</table>
Thank you for your attention

František WALD

wald@fsv.cvut.cz
Notes to users of the lecture

- Further readings on the relevant documents from website of www.eaa.net/eaa/education/TALAT

- Keywords for the lecture:
  fire design, aluminium structures, material properties,
Notes to users of the lecture

• Text books
Sources

- Educational programme TALAT
  www.eaa.net/eaa/education/TALAT