EN 1991-1-5 Thermal Actions
Milan Holický and Jana Marková, Czech Technical University in Prague
DAV 2003-11, Conversion of ENV 1991-2-5 (23 NDP)

- General
- Classification of actions
- Design situations
- Representation of actions
- Temperature changes in buildings
- Temperature changes in bridges
- Temperature changes in industrial chimneys, pipelines, etc.
- Annexes
  - A – Isotherm of national temperatures (normative)
  - B – Temperature differences in bridges decks (normative)
  - C – Coefficients of linear expansions (informative)
  - D – Temperature effects in buildings (informative)

PPT file include 24 basic slides and additional (informative) slides.
Background documents

Collapse of the terminal E2 in Paris
Scheme of the collapse

Progressive weakening partly due to cracking during cycles of differential thermal movements between concrete shell and curved steel member.
Bridge in transient design situation
Basic principles and rules

- temperature changes are considered as variable and indirect actions
- characteristic values have probability of being exceeded 0.02 by annual extremes (return period of 50 years)
- the maximum and minimum shade air temperature measured by thermometers in a “Stevenson Screen” by the National Meteorological Service of each Member State
- thermal actions shall be considered for both persistent and transient design situations
- in special cases temperature changes in accidental design situations should be also verified
An example: map of maximum temperatures in CR

Maximum shade air temperatures of being exceeded by annual extremes with the probability of 0,02.

\[ T_{\text{min}} = 32,1 \, ^\circ\text{C} \]
\[ T_{\text{max}} = 40,0 \, ^\circ\text{C} \]
\[ \text{mean } \mu_T = 37,4 \, ^\circ\text{C} \]
Temperature changes in buildings

Thermal actions on buildings shall be considered when ultimate or serviceability limit states may be affected.

Effect of thermal actions may be influenced by nearby buildings, the use of different materials, structural shape and detailing. Three basic components are usually considered:

- a uniform component $\Delta T_u$

  $$\Delta T_u = T - T_0$$

- temperature difference $\Delta T_M$

- temperature differences of different structural parts $\Delta T_p$
# Inner temperatures in buildings

<table>
<thead>
<tr>
<th>Season</th>
<th>Temperature $T_{in}$ in °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>summer</td>
<td>$T_1$ (20 °C)</td>
</tr>
<tr>
<td>winter</td>
<td>$T_2$ (25 °C)</td>
</tr>
</tbody>
</table>

Recommended inner temperatures in the Czech National Annex:
- summer 25 °C
- winter 20 °C
# Outer temperatures $T_{\text{out}}$

<table>
<thead>
<tr>
<th>Season</th>
<th>Relative absorptivity</th>
<th>Temperature $T_{\text{out}}$ in °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5 bright light surface</td>
<td>$T_{\text{max}} + T_3$</td>
</tr>
<tr>
<td>summer</td>
<td>0.7 light coloured surface</td>
<td>$T_{\text{max}} + T_4$</td>
</tr>
<tr>
<td></td>
<td>0.9 dark surface</td>
<td>$T_{\text{max}} + T_5$</td>
</tr>
<tr>
<td>winter</td>
<td></td>
<td>$T_{\min}$</td>
</tr>
</tbody>
</table>

---

**Recommended values:**

<table>
<thead>
<tr>
<th></th>
<th>N, E, N-E</th>
<th>S, W, S-W and H</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_3$</td>
<td>0 °C</td>
<td>18 °C</td>
</tr>
<tr>
<td>$T_4$</td>
<td>2 °C</td>
<td>30 °C</td>
</tr>
<tr>
<td>$T_5$</td>
<td>4 °C</td>
<td>42 °C</td>
</tr>
</tbody>
</table>
Uniform design temperatures in a building

An thermally unprotected steel structure

- ČSN 73 1401: $\Delta T_N = 60 \, ^\circ\text{C}$  
  $T_{e,\text{min}} = -30 \, ^\circ\text{C}$  
  $T_{e,\text{max}} = 30 \, ^\circ\text{C}$

  $\Delta T_{Nd} = 60 \times 1,2 = 72 \, ^\circ\text{C}$

- ČSN P ENV 1991-2-5: $\Delta T_N = 61 \, ^\circ\text{C}$  
  $T_{e,\text{min}} = -24 \, ^\circ\text{C}$  
  $T_{e,\text{max}} = 37 \, ^\circ\text{C}$

  $\Delta T_{Nd} = 61 \times 1,4 = 85 \, ^\circ\text{C}$

- ČSN EN 1991-1-5: in Prague for dark surface and North-East

  $\Delta T_N = 76 \, ^\circ\text{C}$  
  $T_{e,\text{min}} = -32 \, ^\circ\text{C}$  
  $T_{e,\text{max}} = 40 + T_5 = 44 \, ^\circ\text{C}$

  $\Delta T_{Nd} = 76 \times 1,5 = 114 \, ^\circ\text{C}$
An example of a fixed member

\[ \Delta T_{Nd} = (44 - 10) \times 1.5 = 51 \, ^\circ C \]

\[ q \, [kN/m] \]

---

<table>
<thead>
<tr>
<th>Material</th>
<th>Linear expansion ( \alpha_T \times 10^{-6} \times ^\circ C^{-1} )</th>
<th>Strain ( \varepsilon_T \times 10^{-3} )</th>
<th>Young modulus ( E ) MPa</th>
<th>Stress ( \sigma_T ) MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>10</td>
<td>0.51</td>
<td>30 000</td>
<td>15</td>
</tr>
<tr>
<td>Steel</td>
<td>12</td>
<td>0.61</td>
<td>200 000</td>
<td>122</td>
</tr>
</tbody>
</table>
A uniform temperature component

- National maps of isotherms $T_{\text{max}}, T_{\text{min}}$
- Effective temperatures in bridges – graphical tools

Maximum and minimum effective temperatures $T$

\[
\Delta T_{N,\text{con}} = T_0 - T_{e,\text{min}}
\]
\[
\Delta T_{N,\text{exp}} = T_{e,\text{max}} - T_0
\]

The total range $\Delta T_N = T_{e,\text{max}} - T_{e,\text{min}}$

A frame under a uniform component and different support conditions
Annex D: temperatures in buildings

Temperatures

\[ T(x) = T_{\text{in}} - \frac{R(x)}{R_{\text{tot}}} (T_{\text{in}} - T_{\text{out}}) \]

Thermal resistance [m²K/W]

\[ R_{\text{tot}} = R_{\text{in}} + \sum_i \frac{h_i}{\lambda_i} + R_{\text{out}} \]

\[ R(x) = R_{\text{in}} + \sum_i \frac{h_i}{\lambda_i} \]

where \( \lambda [\text{W/(mK)}] \) is thermal conductivity
Three layers wall - graphical method
### Three layers wall – EXCEL sheet

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>W/m²/°C</th>
<th>W/m/°C</th>
<th>m</th>
<th>°C</th>
<th>Resistance</th>
<th>Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Surface</td>
<td>9</td>
<td>0,111</td>
<td>0,111</td>
<td>18,075</td>
<td>0,081</td>
<td>16,668</td>
</tr>
<tr>
<td>1</td>
<td>Gypsum</td>
<td>0,025</td>
<td>0,013</td>
<td>0,013</td>
<td>16,668</td>
<td>0,081</td>
<td>16,668</td>
</tr>
<tr>
<td>2</td>
<td>Insulation</td>
<td>1,5</td>
<td>0,05</td>
<td>0,05</td>
<td>-17,979</td>
<td>2,000</td>
<td>-17,979</td>
</tr>
<tr>
<td>3</td>
<td>Brick</td>
<td>0,16</td>
<td>0,067</td>
<td>0,067</td>
<td>-19,134</td>
<td>0,050</td>
<td>-19,134</td>
</tr>
<tr>
<td>4</td>
<td>Outside</td>
<td>20</td>
<td>0,183</td>
<td>0,183</td>
<td>-20,000</td>
<td>0,050</td>
<td>-20,000</td>
</tr>
</tbody>
</table>

The total resistance of wall $R_{tot} = 2,309$

### Graph

- $x$: temp
- $y$: Graph

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Temperature changes in bridges

Three types of bridge superstructures are considered

1. Steel deck
   - steel box girder
   - steel truss or plate girder

2. Composite deck

3. Concrete deck
   - concrete slab
   - concrete beam
   - concrete box girder

Basic temperature components

- a uniform component
- vertical temperature differences
- horizontal temperature differences

approach 1 - linear
approach 2 - non-linear
Uniform effective temperatures

Type 1 \( T_{e,\text{max}} = T_{\text{max}} + 16^\circ \text{C} \)
Type 2 \( T_{e,\text{max}} = T_{\text{max}} + 4.5^\circ \text{C} \)
Type 3 \( T_{e,\text{max}} = T_{\text{max}} + 1.5^\circ \text{C} \)

\[
\begin{align*}
\text{for } 30^\circ \text{C} & \leq T_{\text{max}} \leq 50^\circ \text{C} & T_{e,\text{min}} &= T_{\text{min}} - 3^\circ \text{C} \\
\text{for } -50^\circ \text{C} & \leq T_{\text{min}} \leq 0^\circ \text{C} & T_{e,\text{min}} &= T_{\text{min}} + 4.5^\circ \text{C} \quad T_{e,\text{min}} &= T_{\text{min}} + 8^\circ \text{C}
\end{align*}
\]
**Approach 1: linear vertical differences**

<table>
<thead>
<tr>
<th></th>
<th>( \Delta T_{M,\text{heat}} ) (°C)</th>
<th>( \Delta T_{M,\text{cool}} ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type 1, steel</strong></td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td><strong>Type 2, composite</strong></td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td><strong>Type 3, concrete</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>box girder</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>beam</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>slab</td>
<td>15</td>
<td>8</td>
</tr>
</tbody>
</table>

Thickness of surfacing considered by reduction coefficient \( k_{\text{sur.}} \).
**Approach 2: non-linear vertical difference**

**Type 1 (steel)**

<table>
<thead>
<tr>
<th>Type of Construction</th>
<th>Temperature Difference ($\Delta T$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a) Heating</td>
</tr>
<tr>
<td></td>
<td>$h_1$, $h_2$, $h_3$, $h_4$</td>
</tr>
<tr>
<td>40mm surfacing</td>
<td>$\Delta T_1 = 24^\circ C$</td>
</tr>
<tr>
<td></td>
<td>$h_1 = 0.1m$, $\Delta T_2 = 14^\circ C$</td>
</tr>
<tr>
<td></td>
<td>$h_2 = 0.2m$, $\Delta T_3 = 8^\circ C$</td>
</tr>
<tr>
<td></td>
<td>$h_3 = 0.3m$, $\Delta T_4 = 4^\circ C$</td>
</tr>
</tbody>
</table>

1a. Steel deck on steel box girders

1b. Steel deck on steel truss or plate girders

$h = \text{height}$
## Approach 2: non-linear vertical differences

### Type 2 (composite)

<table>
<thead>
<tr>
<th>Temperature differences</th>
<th>(a) heating</th>
<th>(b) cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td><img src="image4.png" alt="Diagram" /></td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
<tr>
<td><img src="image7.png" alt="Diagram" /></td>
<td><img src="image8.png" alt="Diagram" /></td>
<td><img src="image9.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

### Notes:
- **Normal procedure**
- **Simplified procedure**
- **Surfacing 100 mm**

### Normal procedure
- $h_1 = 0.6h$
- $h_2 = 0.4\ m$

### Simplified procedure
- $\Delta T_1 = 10\ ^\circ C$
- $\Delta T_1 = -10\ ^\circ C$

### Surfacing
- Type 2 Concrete deck on steel box, truss or plate girders
Approach 2: non-linear vertical differences

Type 3
(concrete)

<table>
<thead>
<tr>
<th>Type of Construction</th>
<th>Temperature Difference ($\Delta T$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a) Heating</td>
</tr>
<tr>
<td></td>
<td>$h_1$</td>
</tr>
<tr>
<td>3a. Concrete slab</td>
<td>$h_1$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$h$</th>
<th>$\Delta T_1$</th>
<th>$\Delta T_2$</th>
<th>$\Delta T_3$</th>
<th>$\Delta T_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>$^\circ C$</td>
<td>$^\circ C$</td>
<td>$^\circ C$</td>
<td>$^\circ C$</td>
</tr>
<tr>
<td>$\leq 0.2$</td>
<td>-2.0</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>0.4</td>
<td>-4.5</td>
<td>-1.4</td>
<td>-1.0</td>
<td>-3.5</td>
</tr>
<tr>
<td>0.6</td>
<td>-6.5</td>
<td>-1.8</td>
<td>-1.5</td>
<td>-5.0</td>
</tr>
<tr>
<td>0.8</td>
<td>-7.6</td>
<td>-1.7</td>
<td>-1.5</td>
<td>-6.0</td>
</tr>
<tr>
<td>1.0</td>
<td>-8.0</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-6.3</td>
</tr>
<tr>
<td>$\geq 1.5$</td>
<td>-8.4</td>
<td>-0.5</td>
<td>-1.0</td>
<td>-6.5</td>
</tr>
</tbody>
</table>
Temperature changes in industrial structures

(a) Uniform component

(b) Stepped component

(c) Linear component
Concluding remarks

Temperature effects may be in some cases significant and shall be considered in structural design.

The outer temperatures of a structure depend on absorptivity and orientation of the surface.

A uniform temperature component may be derived using national maps of isotherms.

For bridges the relationship is given for specification of uniform (effective) temperature component.

Two approaches for vertical temperature profile in bridges are given: either linear or non-linear profile should be used.

For industrial structures uniform, linear and stepped components are considered; technological temperatures in accordance of design specifications.
An example: map of minimum temperatures in CR

Minimum shade air temperatures of being exceeded by annual extremes with the probability of 0.02.

\[ T_{\text{min}} = -35.2 \, ^\circ\text{C} \]
\[ T_{\text{max}} = -28.1 \, ^\circ\text{C} \]

mean \( \mu_T = -31.3 \, ^\circ\text{C} \)
## Linear expansion coefficients

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha_T \times 10^{-6} \times ^\circ C^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium, aluminium alloys</td>
<td>24</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>16</td>
</tr>
<tr>
<td>Structural steel</td>
<td>12</td>
</tr>
<tr>
<td>Concrete (except as specified below)</td>
<td>10</td>
</tr>
<tr>
<td>Concrete with light aggregates</td>
<td>7</td>
</tr>
<tr>
<td>Masonry</td>
<td>6-10</td>
</tr>
<tr>
<td>Timber, along grain</td>
<td>5</td>
</tr>
<tr>
<td>Timber, across grain</td>
<td>30-70</td>
</tr>
</tbody>
</table>
Constituent components of a temperature profile

a) a uniform component $\Delta T_u$
b) a linear component about $z$-$z$, $\Delta T_{My}$ (in the direction of axis $y$)
c) a linear component about $y$-$y$-, $\Delta T_{Mz}$ (in the direction of axis $z$)
d) a non-linear component $\Delta T_E$
Transient design situations

Return periods $R$ for the characteristic values $Q_k$

<table>
<thead>
<tr>
<th>Nominal period $t$</th>
<th>$t \leq 3$ days</th>
<th>$3 \text{ days} &lt; t \leq 3 \text{ months}$</th>
<th>$3 \text{ months} &lt; t \leq 1 \text{ year}$</th>
<th>$t &gt; 1 \text{ year}$</th>
<th>2 years</th>
<th>5 years</th>
<th>10 years</th>
<th>50 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p = 0.5$</td>
<td>$p = 0.2$</td>
<td>$p = 0.1$</td>
<td>$p = 0.02$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$$T_{\text{max},p} = T_{\text{max}} \left\{ k_1 - k_2 \ln \left[ - \ln (1 - p) \right] \right\}$$

$$T_{\text{min},p} = T_{\text{min}} \left\{ k_3 + k_4 \ln \left[ - \ln (1 - p) \right] \right\}$$

The coefficients $k_1$ to $k_4$ are given in EN 1991-1-5.
Reduction coefficients $k$ for different return periods $R$

The characteristic value $Q_k$ for return period $R$

$$Q_{k,R} = k \cdot Q_{k,50}$$

<table>
<thead>
<tr>
<th>Return period $R$</th>
<th>$p$</th>
<th>Reduction coefficient $k$ for $T_{\text{max},R}$</th>
<th>$T_{\text{min},R}$</th>
<th>$S_{n,R}$ snow</th>
<th>$v_{b,R}$ wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 years</td>
<td>0.5</td>
<td>0.8</td>
<td>0.45</td>
<td>0.64</td>
<td>0.77</td>
</tr>
<tr>
<td>5 years</td>
<td>0.2</td>
<td>0.86</td>
<td>0.63</td>
<td>0.75</td>
<td>0.85</td>
</tr>
<tr>
<td>10 years</td>
<td>0.1</td>
<td>0.91</td>
<td>0.74</td>
<td>0.83</td>
<td>0.90</td>
</tr>
<tr>
<td>50 years</td>
<td>0.02</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
**A uniform temperature component**

**ENV 1991-2-5:** -24°C, 37°C; in **EN 1991-1-5**, Prague -32°C, 40°C

**Prestressed concrete bridge**

- **ČSN 73 6203:** $\Delta T_N = 55$ °C
  - $T_{e,\text{min}} = -20$ °C
  - $T_{e,\text{max}} = 35$ °C

- **ČSN P ENV 1991-2-5:** $\Delta T_N = 55$ °C
  - $T_{e,\text{min}} = -16$ °C
  - $T_{e,\text{max}} = 39$ °C

- **ČSN EN 1991-1-5:** $\Delta T_N = 66$ °C
  - $T_{e,\text{min}} = -24$ °C
  - $T_{e,\text{max}} = 42$ °C

**Composite bridge**

- **ČSN 73 6203:** $\Delta T_N = 65$ °C
  - $T_{e,\text{min}} = -25$ °C
  - $T_{e,\text{max}} = 40$ °C

- **ČSN P ENV 1991-2-5:** $\Delta T_N = 62$ °C
  - $T_{e,\text{min}} = -20$ °C
  - $T_{e,\text{max}} = 42$ °C

- **ČSN EN 1991-1-5:** $\Delta T_N = 73$ °C
  - $T_{e,\text{min}} = -28$ °C
  - $T_{e,\text{max}} = 45$ °C
An example of temperature profile

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An example of temperature effects-
Čekanice, Czech Republic

Typical section
# Load combinations in accordance EN

**EN**

<table>
<thead>
<tr>
<th>Expr.</th>
<th>Main</th>
<th>$M$ [MNm]</th>
<th>$\sigma_{\text{hor}}$ [MPa]</th>
<th>$\sigma_{\text{dol}}$ [MPa]</th>
<th>$M$ [MNm]</th>
<th>$\sigma_{\text{hor}}$ [MPa]</th>
<th>$\sigma_{\text{dol}}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.10</td>
<td>$Q$</td>
<td>-36,26</td>
<td>1,23</td>
<td>-8,89</td>
<td>34,97</td>
<td>-6,21</td>
<td>3,54</td>
</tr>
<tr>
<td>6.10</td>
<td>$T$</td>
<td>-32,67</td>
<td>0,85</td>
<td>-8,27</td>
<td>34,65</td>
<td>-6,18</td>
<td>3,48</td>
</tr>
<tr>
<td>6.10a</td>
<td>-</td>
<td>-27,88</td>
<td>0,34</td>
<td>-7,44</td>
<td>27,61</td>
<td>-5,44</td>
<td>2,27</td>
</tr>
<tr>
<td>6.10b</td>
<td>$Q$</td>
<td>-28,92</td>
<td>0,45</td>
<td>-7,62</td>
<td>30,6</td>
<td>-5,75</td>
<td>2,78</td>
</tr>
<tr>
<td>6.10b</td>
<td>$T$</td>
<td>-25,32</td>
<td>0,069</td>
<td>-6,99</td>
<td>30,28</td>
<td>-5,72</td>
<td>2,73</td>
</tr>
</tbody>
</table>

**ČSN**

<table>
<thead>
<tr>
<th>$M$ [MNm]</th>
<th>$\sigma_{\text{hor}}$ [MPa]</th>
<th>$\sigma_{\text{dol}}$ [MPa]</th>
<th>$M$ [MNm]</th>
<th>$\sigma_{\text{hor}}$ [MPa]</th>
<th>$\sigma_{\text{dol}}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-32,85</td>
<td>0,32</td>
<td>-8,48</td>
<td>32,93</td>
<td>-5,83</td>
<td>2,99</td>
</tr>
</tbody>
</table>
Alternative load combinations in accordance with EN

Bending moments at mid-span sections T2 and K2 for linear (E) and non-linear (N) temperatures.
Simultaneous temperature components

\[ \Delta T_{M, \text{heat}} \text{ (or } \Delta T_{M, \text{cool}}) + \omega_N \Delta T_{N, \text{exp}} \text{ (or } \Delta T_{M, \text{con}}) \]

\[ \omega_M \Delta T_{M, \text{heat}} \text{ (or } \Delta T_{M, \text{cool}}) + \Delta T_{N, \text{exp}} \text{ (or } \Delta T_{N, \text{con}}) \]

Coefficients:

\[ \omega_M = 0.75 \quad \omega_N = 0.35 \]

- Difference in uniform components of different members
- Differences of temperatures of bridge piers
An example of a fixed member

\[ \Delta T_{N_d} = 76 \times 1.5 = 114 \, ^\circ C \]

\[ q \, [\text{kN/m}] \]

Concrete: \( \alpha_T = 10 \times 10^{-6} \times ^\circ C^{-1} \)
Linear expansion for \( \alpha_T = 10 \times 10^{-6} \times ^\circ C^{-1} \)
Temperature strain \( \varepsilon_T = 10 \times 10^{-6} \times 114 = 1.14 \times 10^{-3} \)
Young modulus for concrete member, \( E \approx 30 000 \, \text{MPa} \)
Stress \( \sigma_T = E \varepsilon_T = 1.14 \times 10^{-3} \times 30 000 = 34 \, \text{MPa} \)

Structural steel: \( \alpha_T = 12 \times 10^{-6} \times ^\circ C^{-1}, \, E \approx 200 000 \, \text{MPa} \)
\( \varepsilon_T = 12 \times 10^{-6} \times 114 = 1.37 \times 10^{-3} \)
\( \sigma_T = E \varepsilon_T = 1.40 \times 10^{-3} \times 200 000 = 274 \, \text{MPa} \)