APPENDICES

Appendix 1: Properties of materials used in the numerical simulations

The material properties used in this research are to be in accordance with those given in the Eurocodes.

A.1 Mechanical properties of materials at normal temperatures

A.1.1 Mechanical properties of structural steel at normal temperatures

The stress-strain diagram of structural steel applied in the simulations is elastic-perfectly plastic as shown in Figure A1.1 where the modulus of elasticity $E_a = 2.1 \times 10^5$ MPa

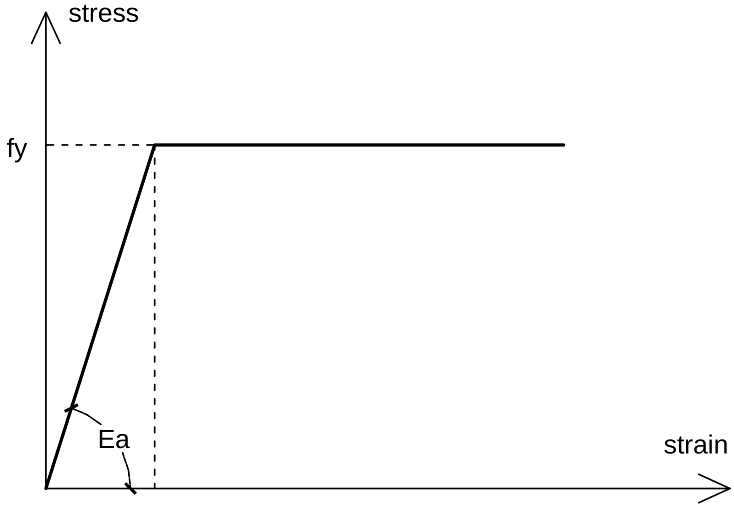


Figure A1.1 Schematic representation of the stress-strain relation of structural steel (for tension and compression)

A.1.2 Mechanical properties of reinforcing steel bar at normal temperatures

The stress-strain diagram of reinforcing steel applied in the simulations is elastic-perfectly plastic where the modulus of elasticity $E_s = 2.0 \times 10^5$ MPa.

A.1.3 Mechanical properties of concrete at normal temperatures

- The tensile strength of concrete is assumed to be negligible. It is taken as zero in simulations.
- The compressive stress-strain relation for structural analysis is non-linear as shown in Figure A1.2

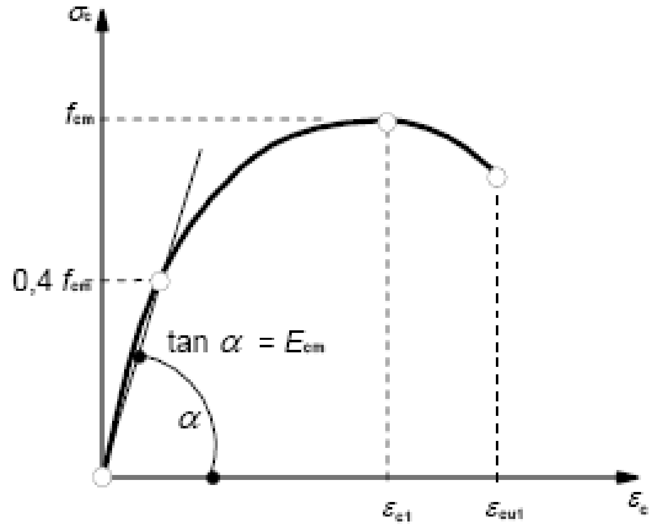


Figure A1.2 Schematic representation of the compressive stress-strain relation of concrete

The relation between σ_c and ε_c shown in Figure A1.2 (compressive stress and shortening strain shown as absolute values) for short term uniaxial loading is described by the expression:

$$\frac{\sigma_C}{f_{cm}} = \frac{k\eta - \eta^2}{1 + (k-2)\eta} \quad \text{where:}$$

f_{cm} is the mean value of concrete cylinder compressive strength (MPa)

$$\eta = \frac{\varepsilon_c}{\varepsilon_{c1}}$$

ε_{c1} is the strain at peak stress $\varepsilon_{c1} = 0,7\, f_{cm}^{0,31} \times 10^{-3} \quad \leq \quad 2,8 \times 10^{-3}$

$$k = 1.05 E_{cm} \times |\varepsilon_{c1}| / f_{cm}$$

$$E_{cm} \quad = \quad 1,05 \times 22\,000 \left(\frac{f_{cm}}{10} \right)^{0,3}$$

The nominal ultimate strain ε_{cu1} is described by the expression:

$$\varepsilon_{cu1} \quad = \quad 3,5 \times 10^{-3} \qquad \text{if} \quad f_{cm} \leq 50$$

$$\varepsilon_{cu1} \quad = \quad \left(2,8 + 27 \left(\frac{98 - f_{cm}}{100} \right)^4 \right) \times 10^{-3} \quad \text{if} \quad f_{cm} > 50$$

with f_{cm} in MPa

A.2 Thermal and physical properties of materials

Thermal properties which are necessary to calculate the heat transfer and temperature distributions in structures are the thermal conductivity λ and the specific heat c . Physical property which is needed in structural analysis is thermal elongation.

A.2.1 Thermal and physical properties of structural steel

Specific heat

The specific heat of steel c_a valid for all structural and reinforcing steel qualities is determined from the following:

$c_a = 425 + 7.73\times10^{-1}\theta_a - 1.69\times10^{-3}\theta_a^2 + 2.22\times10^{-6}\theta_a^3$ [J/kgK] for $20°C < \theta_a \le 600°C$

$c_a = 666 - \dfrac{13002}{\theta_a - 738}$ [J/kgK] for $600°C < \theta_a \le 735°C$

$c_a = 545 - \dfrac{17820}{\theta_a - 731}$ [J/kgK] for $735°C < \theta_a \le 900°C$

$c_a = 650$ [J/kgK] for $900°C < \theta_a \le 1200°C$

where θ_a is the steel temperature

Thermal conductivity

The thermal conductivity of steel λ_a valid for all structural and reinforcing steel qualities is determined from the following:

$\lambda_a = 54 - 3.33\times10^{-2}\theta_a$ [W/mK] for $20°C < \theta_a \le 800°C$

$\lambda_a = 27.3$ [W/mK] for $800°C < \theta_a \le 1200°C$

where θ_a is the steel temperature

Thermal elongation

The related thermal elongation of steel $\Delta l / l$ valid for all structural and reinforcing steel qualities is determined from the following:

$\Delta l / l$ = -2.416 10-4 + 1.2 10-5 θ + 0.4 10-8 θ² for $20°C < \theta_a \le 750°C$

$\Delta l / l$ = 11 10-3 for $750°C < \theta_a \le 860°C$

$\Delta l / l$ = -6.2 10-3 + 2 10-5 θ for $860°C < \theta_a \le 1200°C$

where:

l is the length at 20°C of the steel member

Δl is the temperature induced elongation of the steel member

θ_a is the steel temperature

A.2.2 Thermal and physical properties of reinforcing steel

Thermal and physical properties of reinforcing steel are the same as those of structural steel

A.2.3 Thermal and physical properties of concrete

Specific heat

The specific heat c_c of normal weight dry, siliceous or calcareous concrete may be determined from the following:

$c_c = 900$	[J/kgK]	for $20°C \leq \theta_c \leq 100°C$
$c_c = 900 + (\theta_c - 100)$	[J/kgK]	for $100°C < \theta_c \leq 200°C$
$c_c = 1000 + (\theta_c - 200)/2$	[J/kgK]	for $200°C < \theta_c \leq 400°C$
$c_c = 1100$	[J/kgK]	for $400°C < \theta_c \leq 1200°C$

where θ_c is the concrete temperature (°C)

Thermal conductivity

The thermal conductivity of normal weight concrete may be determined between lower and upper limit values.

The upper limit is given by:

$$\lambda_c = 2 - 0.2451 . \frac{\theta_c}{100} + 0.0107 \left(\frac{\theta_c}{100}\right)^2 \quad \text{[W/mK]} \quad \text{for } 20°C \leq \theta_c \leq 1200°C$$

The lower limit is given by:

$$\lambda_c = 1.36 - 0.136 . \frac{\theta_c}{100} + 0.0057 \left(\frac{\theta_c}{100}\right)^2 \quad \text{[W/mK]} \quad \text{for } 20°C \leq \theta_c \leq 1200°C$$

where θ_c is the concrete temperature (°C)

Both limits are shown in Figure A1.3. The upper limit has been derived from tests of steel-concrete composite structural elements (EN 1994-1-2). Therefore, in this research the upper limit is used.

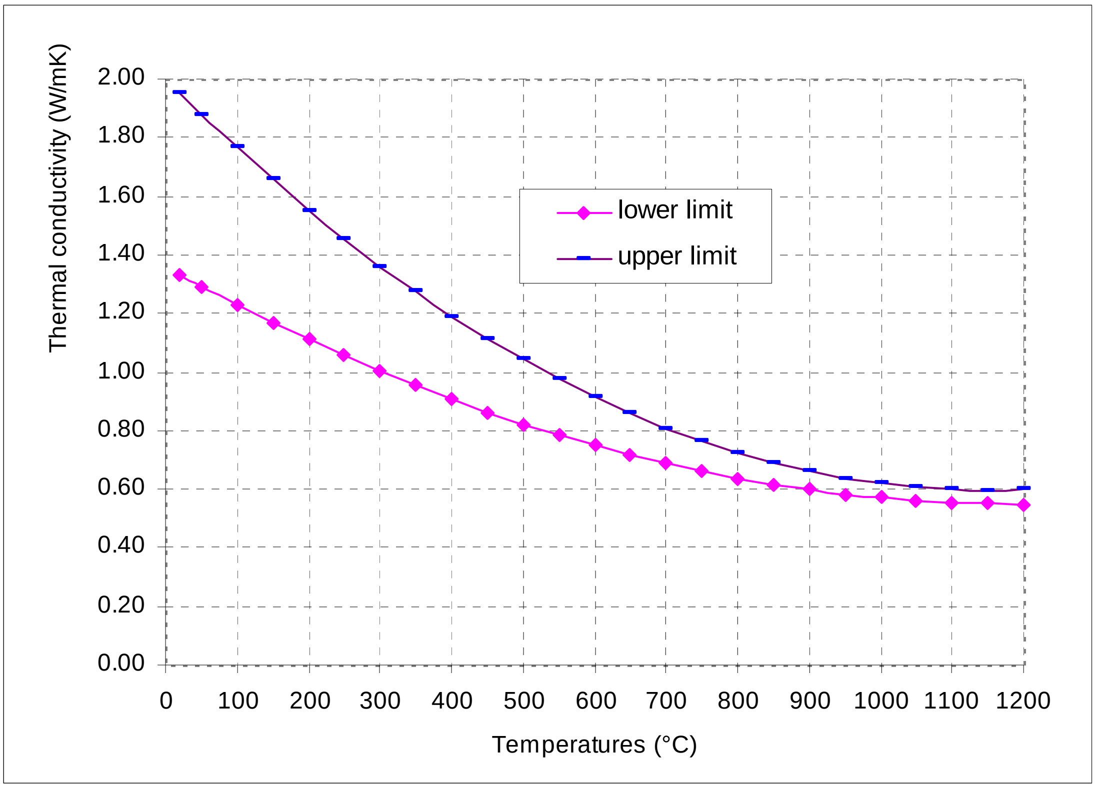


Figure A1.3 Thermal conductivity of concrete according to EN 1992-1-2

Thermal elongation

The related thermal elongation $\Delta l / l$ of normal weight, siliceous concrete is determined from the following:

$$\Delta l / l = -1.8 \times 10^{-4} + 9 \times 10^{-6} \theta_c + 2.3 \times 10^{-11} \times \theta_c^3 \qquad \text{for } 20°C < \theta_c \leq 700°C$$

$$\Delta l / l = 14 \times 10^{-3} \qquad \text{for } 700°C < \theta_c \leq 1200°C$$

where:

l is the length at 20°C of the concrete member

Δl is the temperature induced elongation of the concrete member

θ_c is the concrete temperature

A.3 Mechanical properties of materials at elevated temperatures

A.3.1 Mechanical properties of structural steel at elevated temperatures

The stress-strain relationship given in Figure A1.4 and Table A1.1 is defined by three parameters:

- the slope of the linear elastic range $E_{a,\theta}$
- the proportional limit $f_{ap,\theta}$
- the maximum stress level $f_{ay,\theta}$

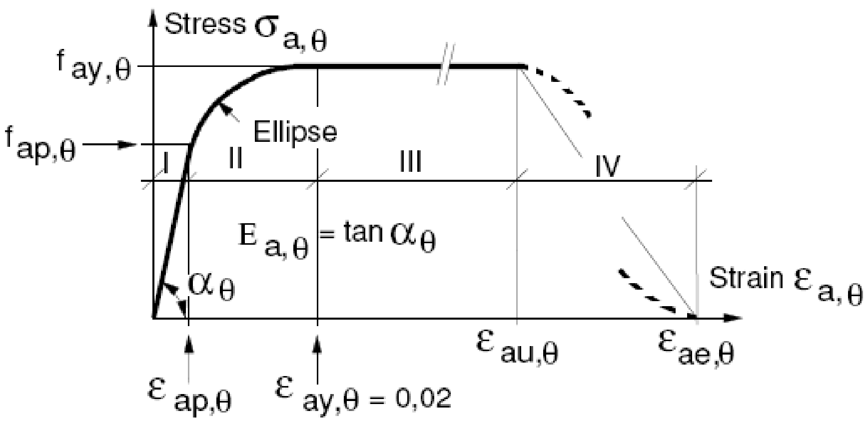


Figure A1.4 Mathematical model for stress-strain relationships of structural steel at elevated temperatures

Strain Range	**Stress σ**	**Tangent modulus**
I / elastic $\varepsilon \le \varepsilon_{ap,\theta}$	$E_{a,\theta}\ \varepsilon_{a,\theta}$	$E_{a,\theta}$
II / transit elliptical $\varepsilon_{ap,\theta} \le \varepsilon$ $\varepsilon \le \varepsilon_{ay,\theta}$	$(f_{ap,\theta} - c) + \frac{b}{a}\ \sqrt{a^2 - (\varepsilon_{ay,\theta} - \varepsilon_{a,\theta})^2}$ with $a^2 = (\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta})(\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta} + c / E_{a,\theta})$ $b^2 = E_{a,\theta}\ (\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta})c + c^2$ $c = \frac{(f_{ay,\theta} - f_{ap,\theta})^2}{E_{a,\theta}(\varepsilon_{ay,\theta} - \varepsilon_{ap,\theta}) - 2(f_{ay,\theta} - f_{ap,\theta})}$	$\frac{b(\varepsilon_{ay,\theta} - \varepsilon_{a,\theta})}{a\sqrt{a^2 - (\varepsilon_{ay,\theta} - \varepsilon_{a,\theta})^2}}$
III / plastic $\varepsilon_{ay,\theta} \le \varepsilon$ $\varepsilon \le \varepsilon_{au,\theta}$	$f_{ay,\theta}$	0

Table A1.1 Relation between the various parameters of the mathematical model of Figure A1.4

Steel Temperature θ_a[°C]	$k_{E,\theta} = \frac{E_{a,\theta}}{E_a}$	$k_{p,\theta} = \frac{f_{ap,\theta}}{f_{ay}}$	$k_{y,\theta} = \frac{f_{ay,\theta}}{f_{ay}}$	$k_{u,\theta} = \frac{f_{au,\theta}}{f_{ay}}$
20	1,00	1,00	1,00	1,25
100	1,00	1,00	1,00	1,25
200	0,90	0,807	1,00	1,25
300	0,80	0,613	1,00	1,25
400	0,70	0,420	1,00	
500	0,60	0,360	0,78	
600	0,31	0,180	0,47	
700	0,13	0,075	0,23	
800	0,09	0,050	0,11	
900	0,0675	0,0375	0,06	
1000	0,0450	0,0250	0,04	
1100	0,0225	0,0125	0,02	
1200	0	0	0	

Table A1.2 Reduction factors k_θ for stress-strain relationships of structural steel at elevated temperatures

Alternatively for temperatures below 400°C, the stress-strain relationships specified in Table A1.1 are extended by the strain hardening option given in Table A1.2, provided local instability is prevented and the ratio $f_{au,\theta} / f_{ay}$ is limited to 1.25 (Figure A1.5)

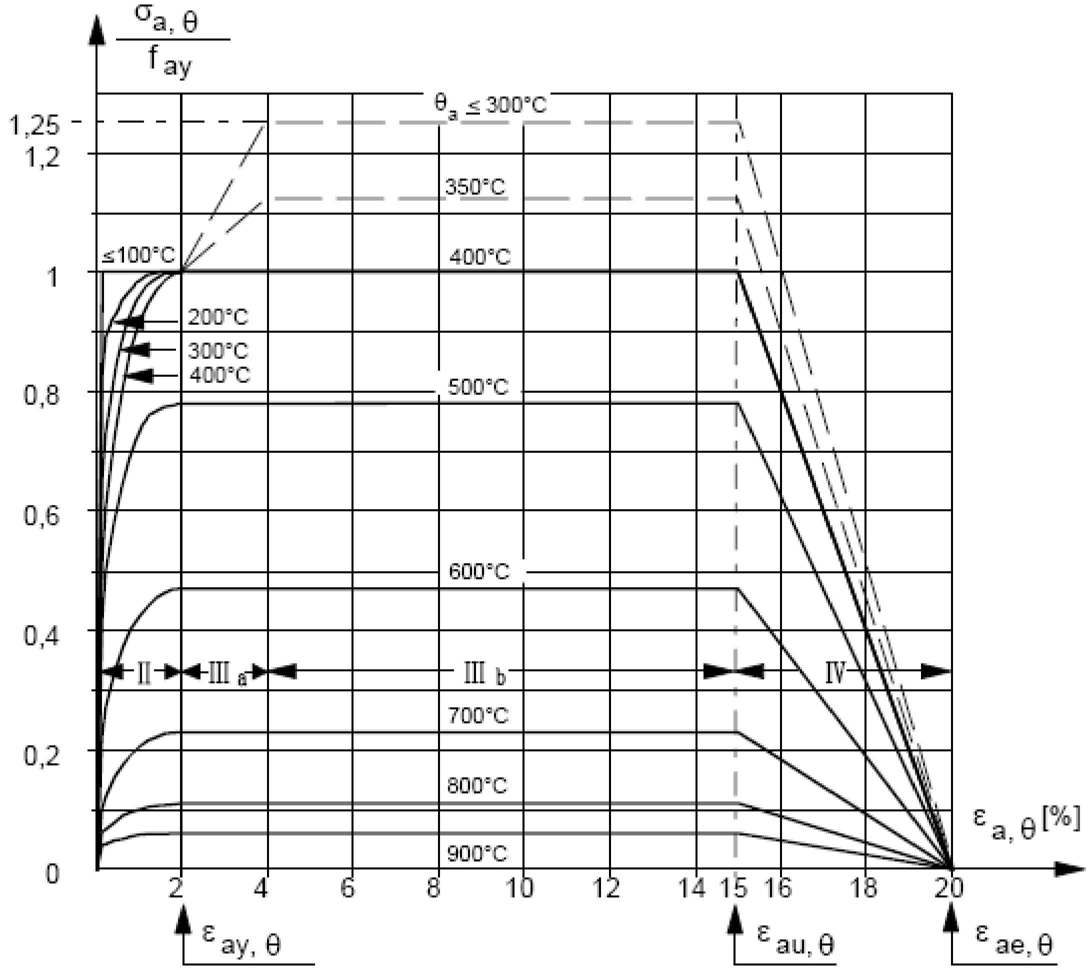


Figure A1.5 Graphical presentation of the stress-strain relationships of structural steel at elevated temperatures, strain-hardening included.

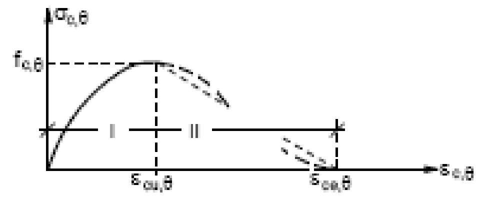
A.3.2 Mechanical properties of reinforcing steel at elevated temperatures

Because the reinforcing steels used in this research are hot rolled, the strength and deformation properties of reinforcing steels are obtained by the same mathematical model as for structural steel except that there is no strain hardening.

A.3.3 Mechanical properties of concrete at elevated temperatures

The stress-strain relationships given in Figure A1.6 are defined by two parameters:

- the compressive strength $f_{c,\theta}$;
- the strain $\varepsilon_{cu,\theta}$ corresponding to $f_{c,\theta}$



RANGE I:

$$\sigma_{c,\theta} = f_{c,\theta} \left[3\left(\frac{\varepsilon_{c,\theta}}{\varepsilon_{cu,\theta}}\right) \bigg/ \left\{ 2 + \left(\frac{\varepsilon_{c,\theta}}{\varepsilon_{cu,\theta}}\right)^3 \right\} \right]$$

$$\left. \begin{array}{l} k_{c,\theta} = \dfrac{f_{c,\theta}}{f_c} \\ \text{and } \varepsilon_{cu,\theta} \end{array} \right\} \text{ to be chosen according to the values of Table 3.3}$$

RANGE II:

For numerical purposes a descending branch should be adopted

Figure A1.6 Mathematical model for stress-strain relationships of concrete under compression at elevated temperatures

Concrete Temperature θ_c [°C]	$k_{c,\theta} = f_{c,\theta}/f_c$		$\varepsilon_{cu,\theta} \cdot 10^3$
	NC	LC	NC
20	1	1	2,5
100	1	1	4,0
200	0,95	1	5,5
300	0,85	1	7,0
400	0,75	0,88	10,0
500	0,60	0,76	15,0
600	0,45	0,64	25,0
700	0,30	0,52	25,0
800	0,15	0,40	25,0
900	0,08	0,28	25,0
1000	0,04	0,16	25,0
1100	0,01	0,04	25,0
1200	0	0	-

Table A1.3 Values for two main parameters of the stress-strain relationships of normal weight concrete (NC) and lightweight concrete (LC) at elevated temperatures

Concrete temperature θ_c [°C]	$\varepsilon_{cu,\theta} \cdot 10^3$ recommended value	$\varepsilon_{ce,\theta} \cdot 10^3$ recommended value
20	2,5	20,0
100	4,0	22,5
200	5,5	25,0
300	7,0	27,5
400	10	30,0
500	15	32,5
600	25	35,0
700	25	37,5
800	25	40,0
900	25	42,5
1000	25	45,0
1100	25	47,5
1200	-	-

Table A1.4 Parameters $\varepsilon_{cu,\theta}$ and $\varepsilon_{ce,\theta}$ defining the recommended range of the descending branch for the stress-strain relationships of concrete at elevated temperatures

The parameters specified in Table A1.3 hold for all siliceous concrete qualities. For calcareous concrete qualities the same parameters may be used. This is normally conservative.