3 Fire behaviour of concrete structures

What members require closer fire engineering consideration when designing concrete structures?

Fire behaviour of concrete structures

SIA 262: Table 16

Fire resistance class	Minimum cover of reinforcement [mm]	Minimum member dimensions [mm]					
		Columns	Walls	Slabs	Mushroom slabs	Flat slabs	T-beam web width
R 30	20	150	120	60	150	150	100
R 60	20	200	140	80	150	200	150
R 90	30	240	170	100	150	200	200
R 120	30	280	220	120	150	200	300
R 180	40	360	300	150	200	200	400

Fire behaviour of concrete structures

What members require closer fire engineering consideration when designing concrete structures?

Introduction

Fire in warehouse, Gent (1974)

- Dimensions of warehouse 50 m x 50 m in plan
- Shear failure of the façade mullions after 120 min due to thermal expansion of the beams.

Fire in underground car parking, Gretzenbach (2004)

- Burning car as trigger to collapse
- Collapse due to various drivers

Introduction

Fire in underground car parking, Rotterdam (2007)

- Five cars burned out completely.
- Parts of the slab collapsed during and after the fire

Fire in warehouse, near Milano (2018)

- Premature failure of a beam’s web due to extensive spalling

Introduction

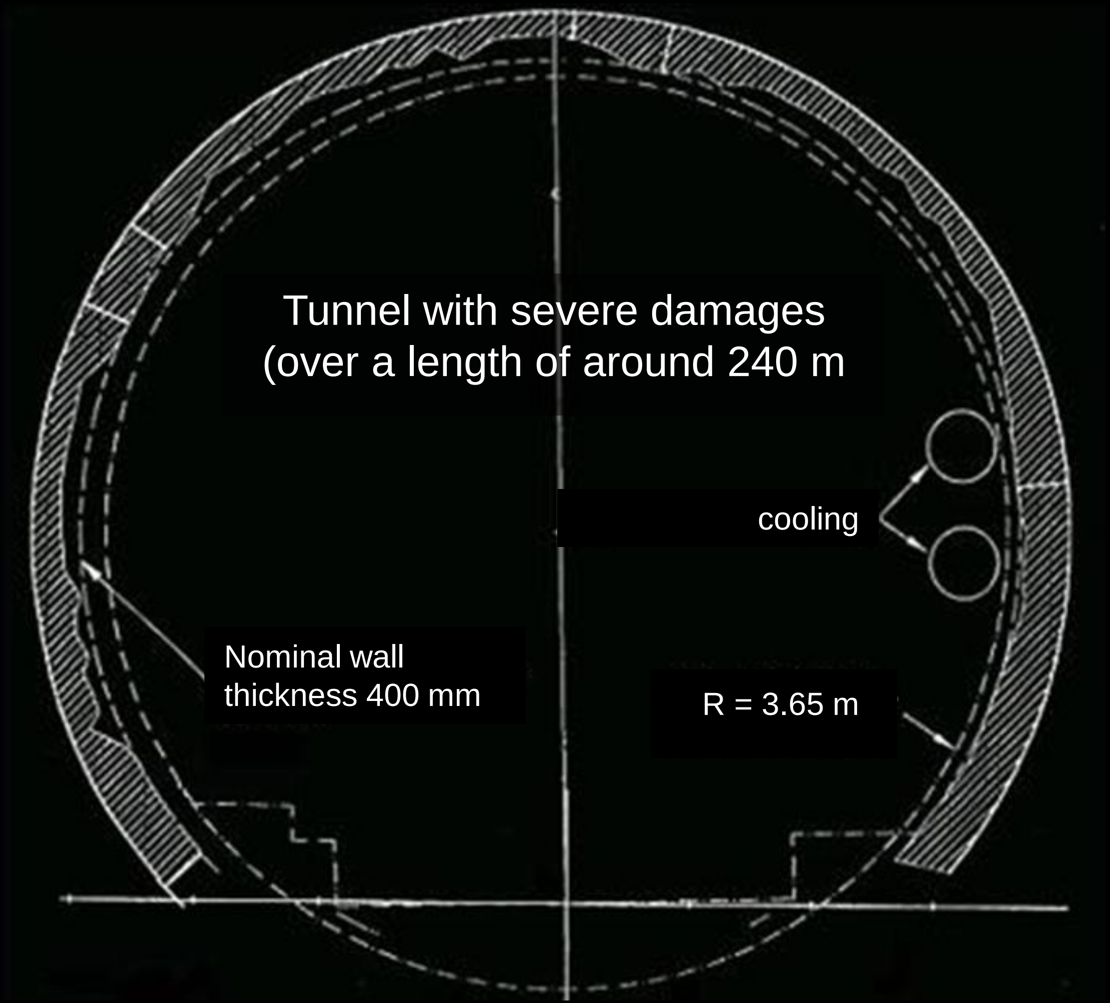
Fire in St. Gotthard tunnel (2001)

- Opened 1980
- Length = 16.9 km
- Damages repaired after fire (tunnel in operation today)

- Suspended ceiling with severe damages over a length of around 230 m

Introduction

Fire in Eurotunnel (Ärmelkanal) (1996)



- Opened 1994
- Length = 50.45 km
- Damages repaired after fire (tunnel in operation today)

Introduction

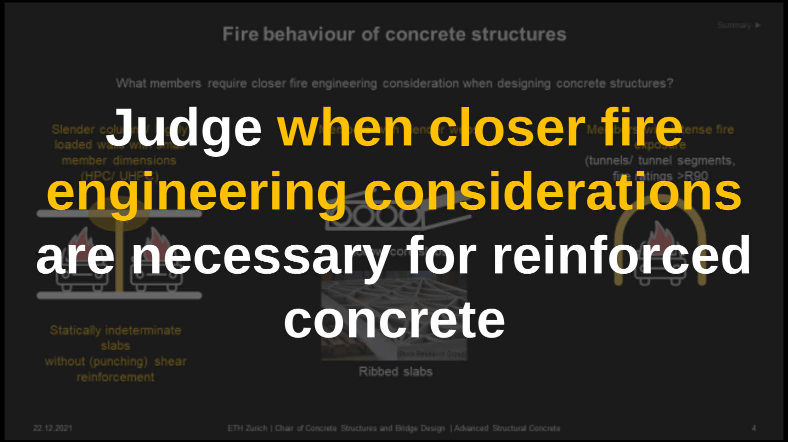
Fire in seven-storey car park (Liverpool Echo Arena, 31.12.2017)

- Dimensions: 70 m x 60 m
- Precast beams and ribbed slabs
- Approx. 1400 cars destroyed

Concrete structures generally exhibit an advantageous behaviour in fire conditions because:

- Concrete is heated comparably slowly (low thermal conductivity, high specific heat) and, therefore, protects the reinforcement from heating
- Concrete cross-sections are comparably massive
- Concrete is non-combustible

Learning objectives



Judge **when closer fire engineering considerations** are necessary for reinforced concrete

Describe the **material behaviour** under fire conditions

Describe the **structural** behaviour under fire conditions

Identify the **most suitable verification method(s)** for the fire design

Apply **simplified design methods** and understand their relation to design methods at ambient temperature

Understand the need for design verifications related to **explosive spalling** and use the appropriate measure to deal with it

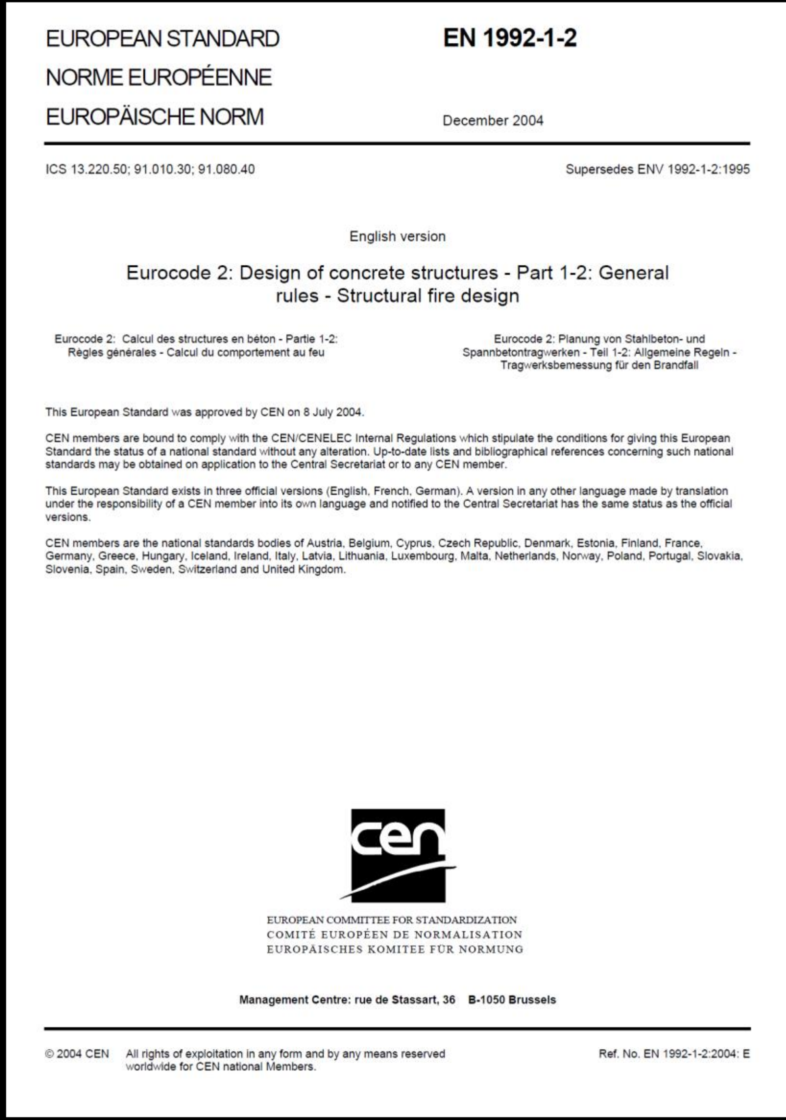
Standardisation - Overview

- The design provisions given in SIA 260-262 on the fire behaviour of concrete structures are limited to basic information.
  - SIA 261:2014 defines basic principles of thermal and mechanical actions and the fire protection concept.
  - SIA 262:2013 (Corrigenda 2017) mainly provides basic rules for structural analysis. Table 16 may be used for very simple member verification.

- For further information and calculation principles, reference is made to the European standards SN EN 1991-1-2 and SN EN 1992-1-2.

- SN EN 1992-1-2 allows two different approaches for design:
  - Design based on prescriptive rules (thermal actions given by nominal fire curves)
  - Design based on performance-based specifications (physically based thermal actions)

- The European structural standards are currently under revision. It is planned to establish the revised EN 1992-1-2 in approx. 2028.



EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1992-1-2

December 2004

ICS 13.220.50; 91.010.30; 91.080.40

Supersedes ENV 1992-1-2:1995

English version

Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design

Eurocode 2: Calcul des structures en béton - Partie 1-2: Règles générales - Calcul du comportement au feu

Eurocode 2: Planung von Stahlbeton- und Spannbetontragwerken - Teil 1-2: Allgemeine Regeln - Tragwerksbemessung für den Brandfall

This European Standard was approved by CEN on 8 July 2004.

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EUROPEAN COMMITTEE FOR STANDARDIZATION
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EUROPÄISCHES KOMITEE FÜR NORMUNG

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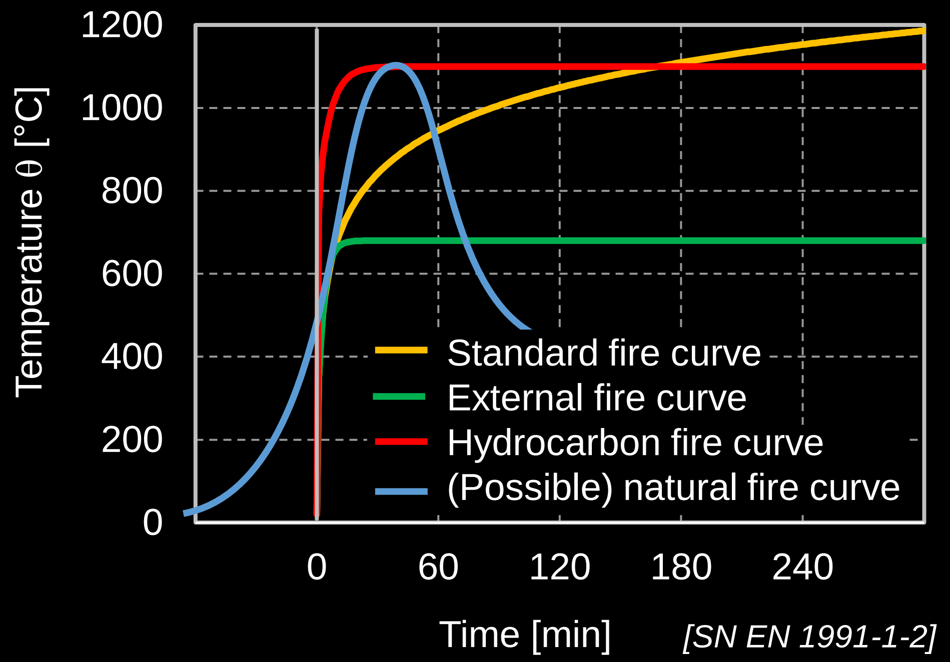
Ref. No. EN 1992-1-2:2004: E

Actions under fire conditions

Fire = accidental design situation (SIA 260/261):

$$\rightarrow E_{d,fi} = E\{G_k, P_k, A_d, \psi_{2i} Q_{ki}, X_d, a_d\} = E\{\underbrace{G_k, P_k,}_{\text{Permanent action incl. P}} \quad \underbrace{A_d,}_{\text{Design value of accidental action}} \quad \underbrace{\psi_{2i} Q_{ki},}_{\text{Variable action: quasi-permanent value}} \quad \underbrace{X_d, a_d}_{\text{Design value of construction material or ground property and geometrical properties}}\}$$

- bridges: no variable actions to be considered
- reinforced concrete buildings: variable actions of ≈ 70% of characteristic action to be considered ($\eta_{fi} = E_{d,fi}/E_d \approx 0.7$)



[SN EN 1991-1-2]

The effects of a fire event are usually taken into account with nominal temperature-time curves:

- Buildings: Fire resistance classification according to the standard temperature-time curve (ETK = Einheitstemperaturzeitkurve, typical designations: "Standard fire curve", "ISO 834").
- Fire load in reinforced concrete buildings only depends on the amount of available combustible material within fire compartments of concern (→ uncertainty)
- Tabulated design data, simplified design methods and design provisions for explosive spalling: only valid for the Standard fire curve
- Tunnels: Hydrocarbon curve / project-specific curves

Learning objectives

Judge **when closer fire engineering considerations** are necessary for reinforced concrete

Describe the **material behaviour** under fire conditions

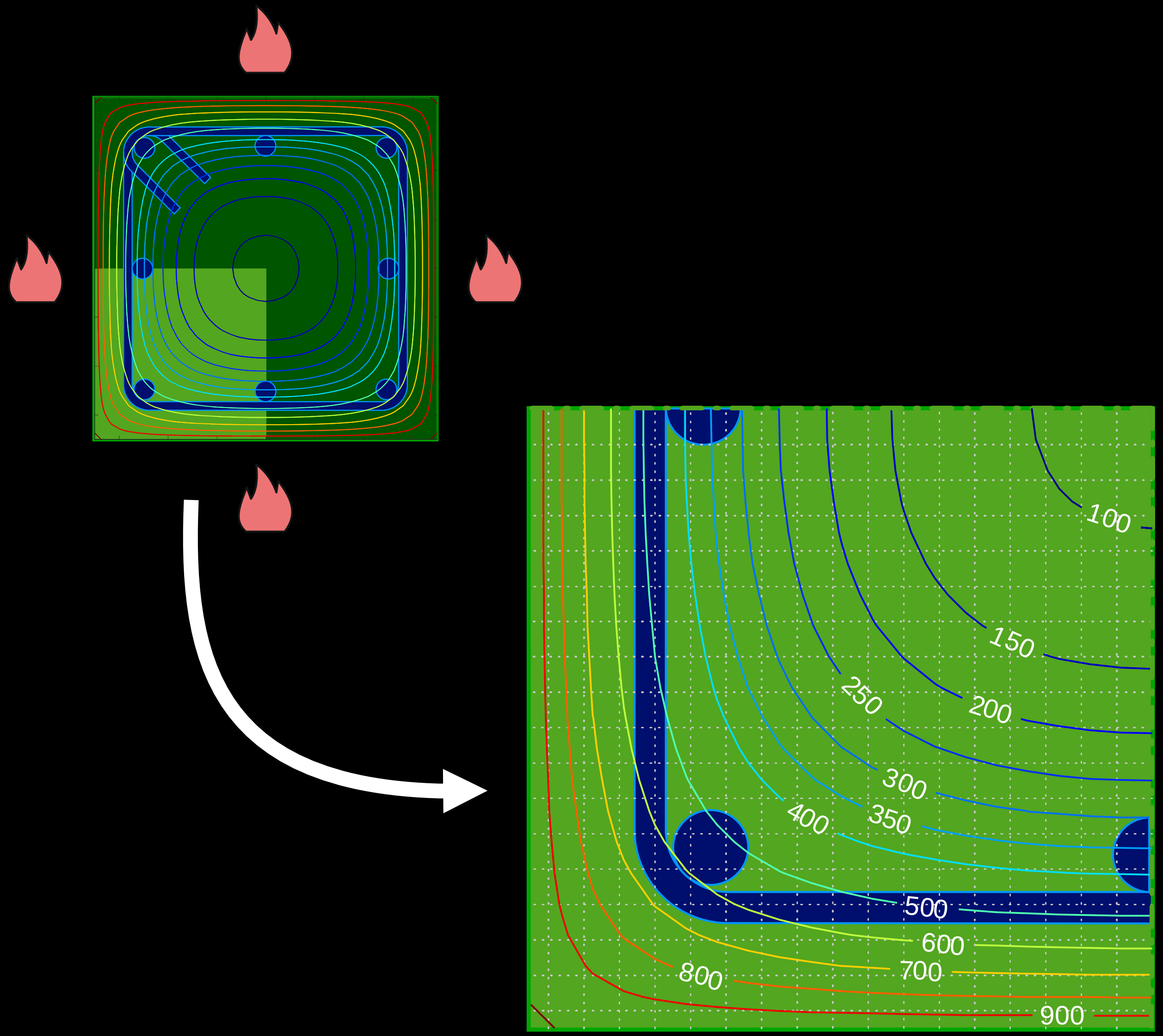
Describe the **structural behaviour** under fire conditions

Identify the **most suitable verification method(s)** for the fire design

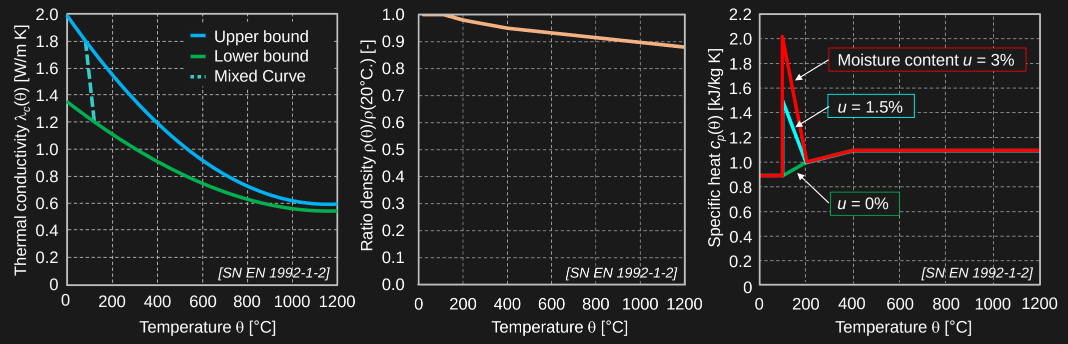
Apply **simplified design methods** and understand their relation to design methods at ambient temperature

Understand the need for design verifications related to **explosive spalling** and use the appropriate measure to deal with it

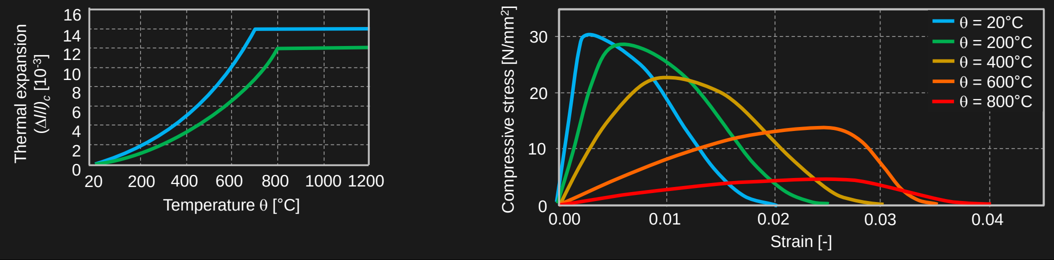
Material behaviour under fire conditions



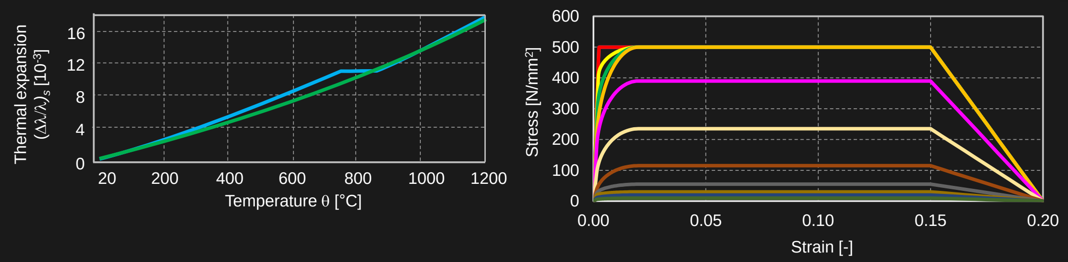
Thermal material behaviour



Mechanical concrete behaviour



Mechanical reinforcement behaviour



Material behaviour under fire conditions

Thermal behaviour of concrete

- Based on temperature-time curves $\theta_g(t)$, the thermal actions on members are calculated as heat flux.
- In a thermal analysis, the transient heat transfer in solids may be determined using Fourier's law:

$$\frac{\partial\theta}{\partial t} = \frac{\lambda}{\rho \cdot c_p} \cdot \left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2} \right),$$

where

θ Temperature [K]
t Time [s]
λ Thermal conductivity [m^2/s]
ρ Material density [kg/m^3]
c_p Specific heat [J/(kgK)]
x, y, z Coordinates [m]

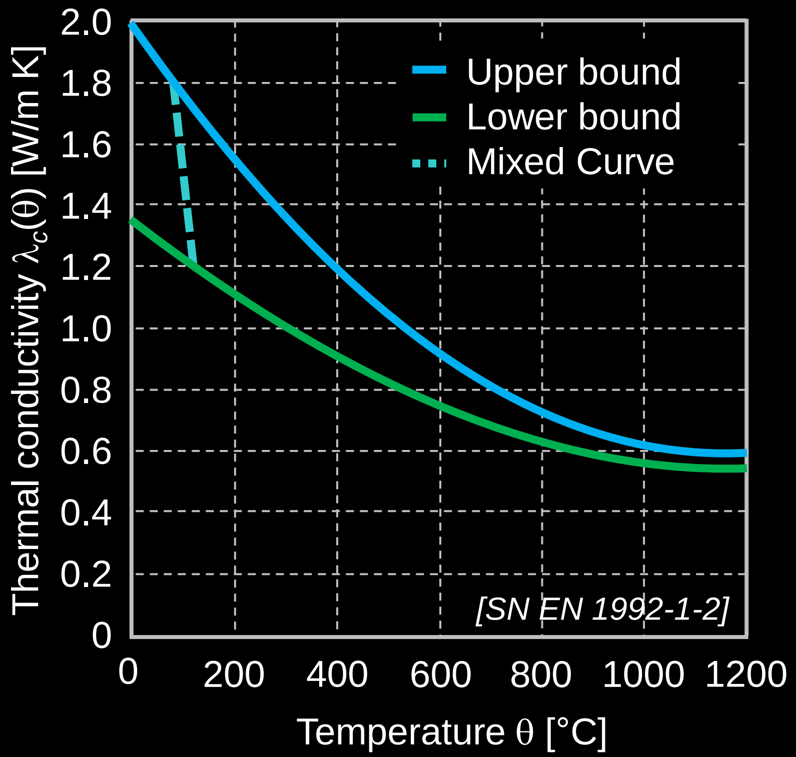
Assumption:
The material properties λ, ρ and c_p depend only on the temperature, i.e. it is assumed that the solid consists of an isotropic material (this assumption is valid for reinforcing bar diameters < 50 mm).

Material behaviour under fire conditions

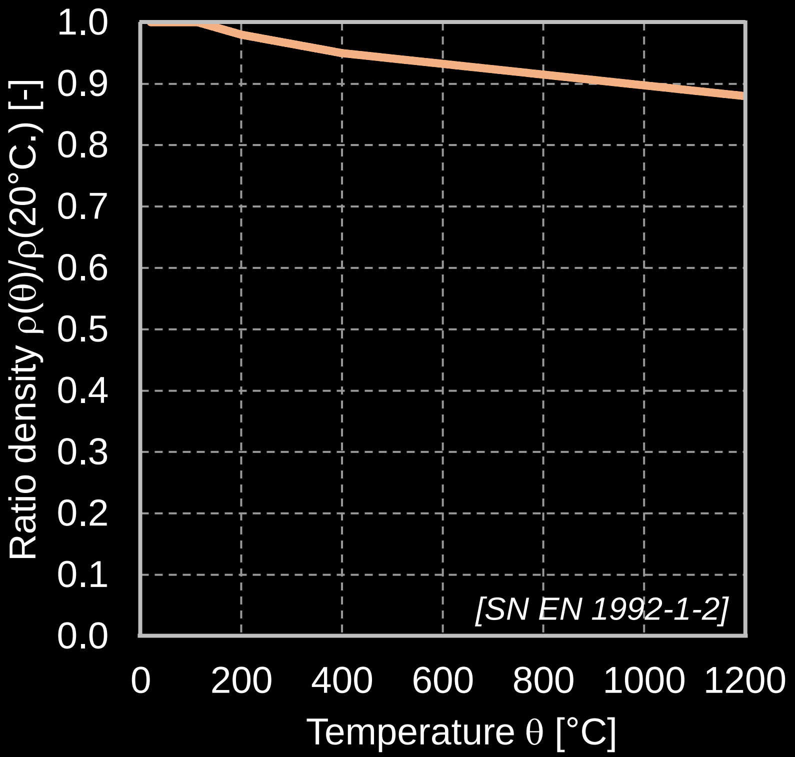
Thermal behaviour of concrete

- The thermal material laws from SN EN 1992-1-2 are based on experiments.
- SN EN 1992-1-2 presents material laws for siliceous and calcareous aggregates.

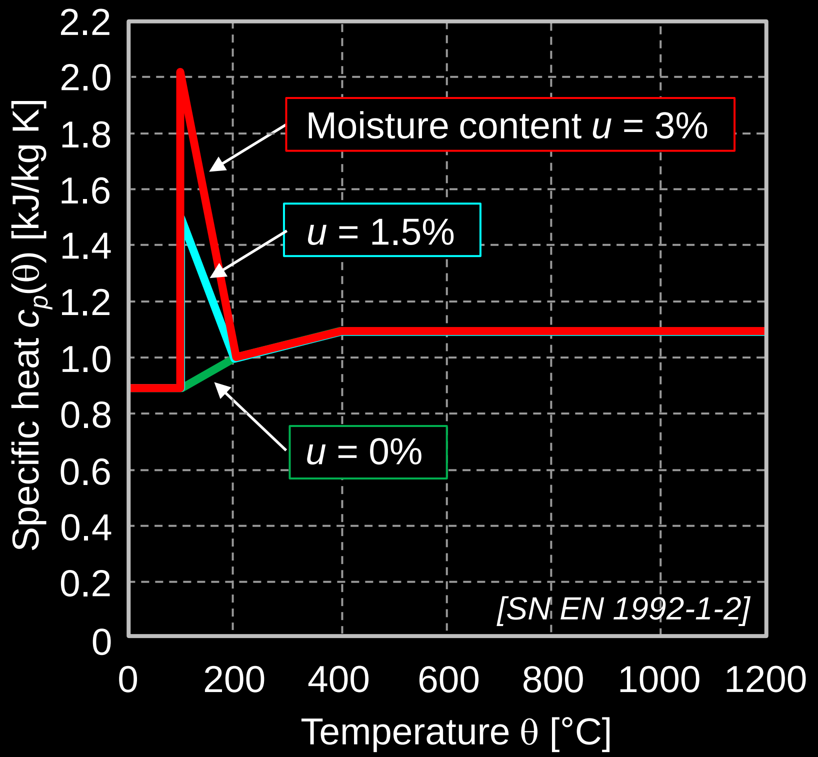
Thermal conductivity $\lambda_c(\theta)$



Ratio density $\rho(\theta)/\rho(20°C.)$



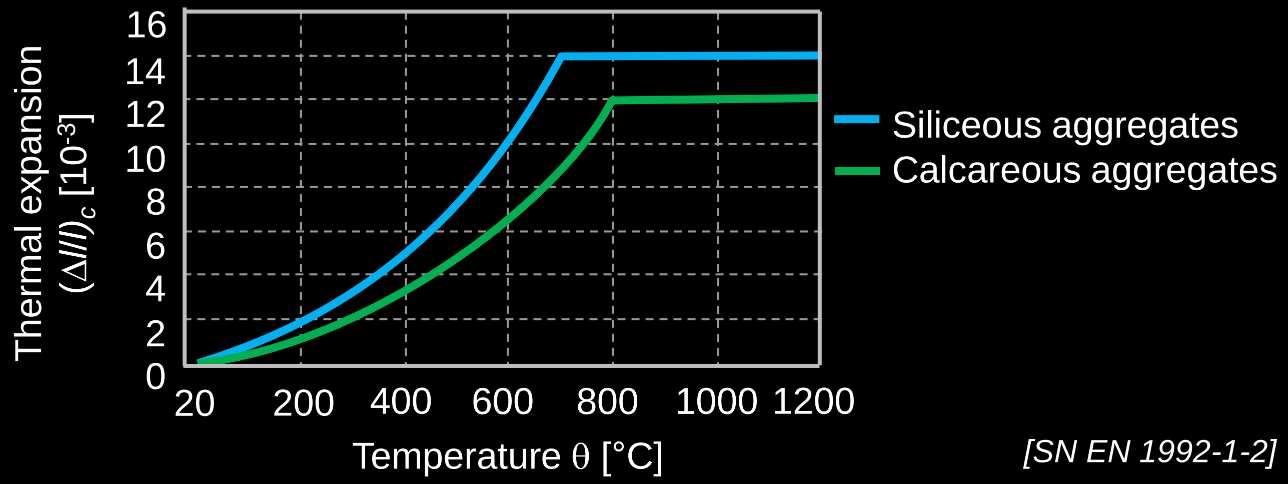
Specific heat $c_p(\theta)$



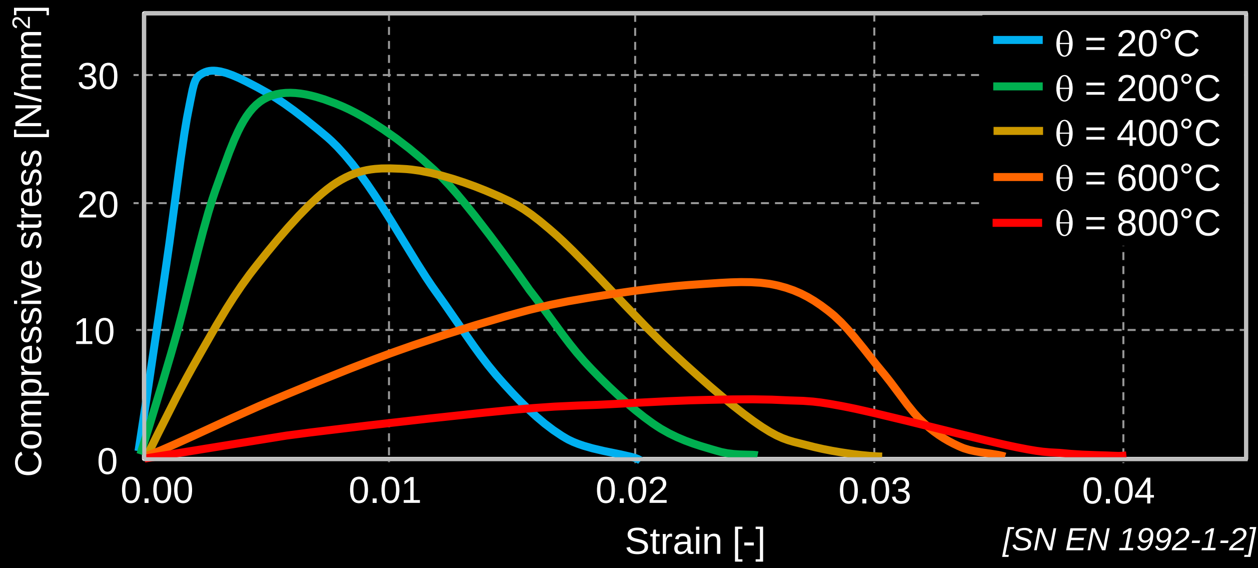
Material behaviour under fire conditions

Mechanical behaviour of concrete

- Concrete expands with increasing temperature.
- Compressive strength and modulus of elasticity of the concrete decrease at high temperatures.
- The tensile strength of the concrete also decreases (more than compressive strength).
- The decrease of strength and stiffness is highly sensitive to the type of aggregate used. SN EN 1992-1-2 gives curves for concrete with siliceous and calcareous aggregates and three curves for high-strength concrete.
- Although the descending branch (and especially the ultimate strain) of the constitutive relationships provided in SN EN 1992-1-1 and SN EN 1992-1-2 do not correspond, the results obtained within a standard sectional analysis are generally consistent.



[SN EN 1992-1-2]

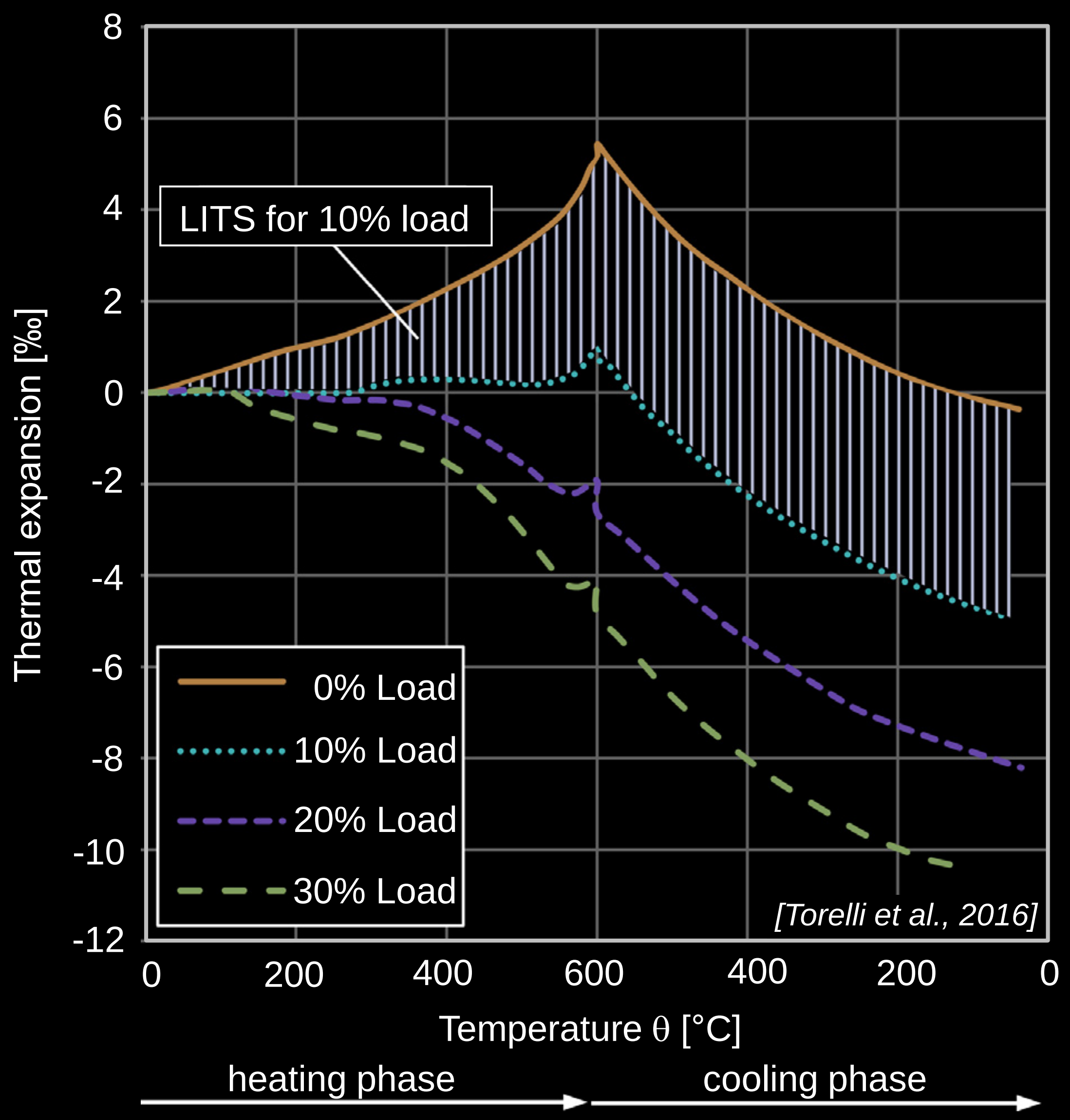


[SN EN 1992-1-2]

Material behaviour under fire conditions

Mechanical behaviour of concrete

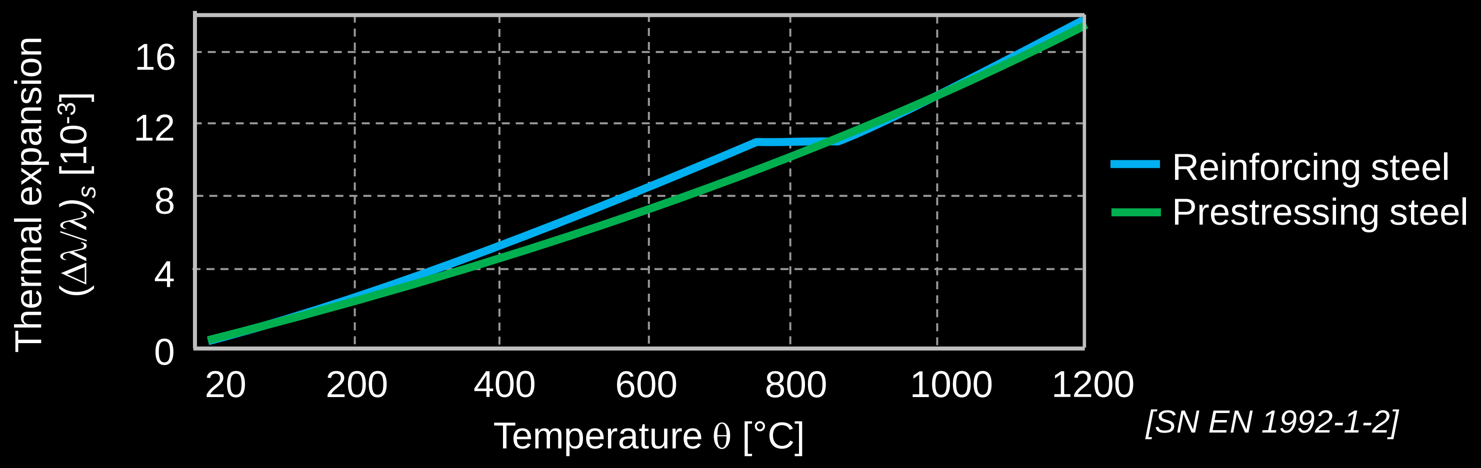
- The load history significantly influences the material strength and stiffness (heating at constant load results in higher $f_{cd,\theta}$ than load increase at constant temperature).
- This effect is mainly due to the load induced thermal strains (= LITS).
- LITS occur under load in the first heating phase and are largely irreversible.
- LITS up to about 400°C are attributed to chemical reactions and microstructural changes in the cement matrix (e.g. dehydration, drying out and rearrangement of water molecules in the cement matrix).
- At higher temperatures, mainly the thermal incompatibility of the cement matrix and aggregates is assumed to generate LITS.
- The material law given in SN EN 1992-1-2 implicitly includes effects from creep strain and transient state strain developed during heating.



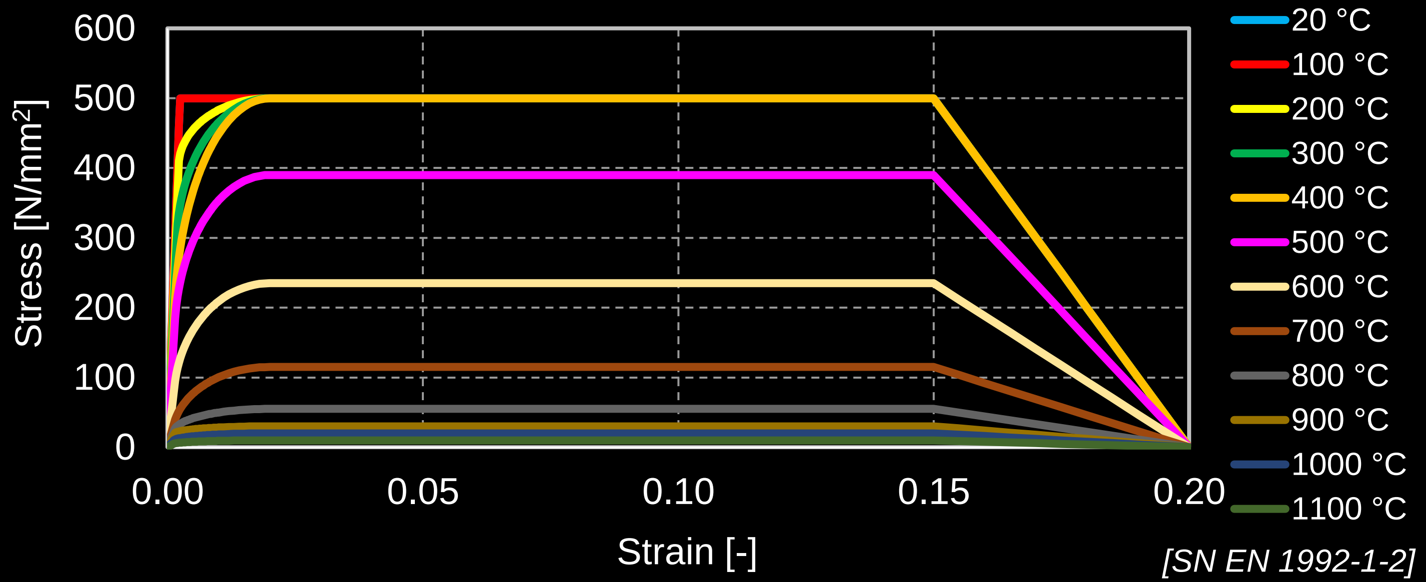
Material behaviour under fire conditions

Mechanical behaviour of reinforcing and prestressing steel

- Steel expands as the temperature rises.
- The strength and modulus of elasticity of reinforcing and prestressing steel decrease at high temperatures.
- SN EN 1992-1-2 gives curves for "hot rolled" (with distinct yield plateau at ambient temperature) and "cold worked" reinforcing steel (shown: hot rolled reinforcing steel).
- SN EN 1992-1-2 gives two classes for reinforcing steel (class N and class X). Generally (also in Switzerland), class N should be used.
- SN EN 1992-1-2 gives two classes for prestressing steel (class A and class B). In Switzerland, class A should be used.



[SN EN 1992-1-2]



[SN EN 1992-1-2]

Learning objectives

Judge **when closer fire engineering considerations** are necessary for reinforced concrete

Describe the **material behaviour** under fire conditions

Describe the **structural behaviour** under fire conditions

Select the **most suitable verification method(s)** for the fire design

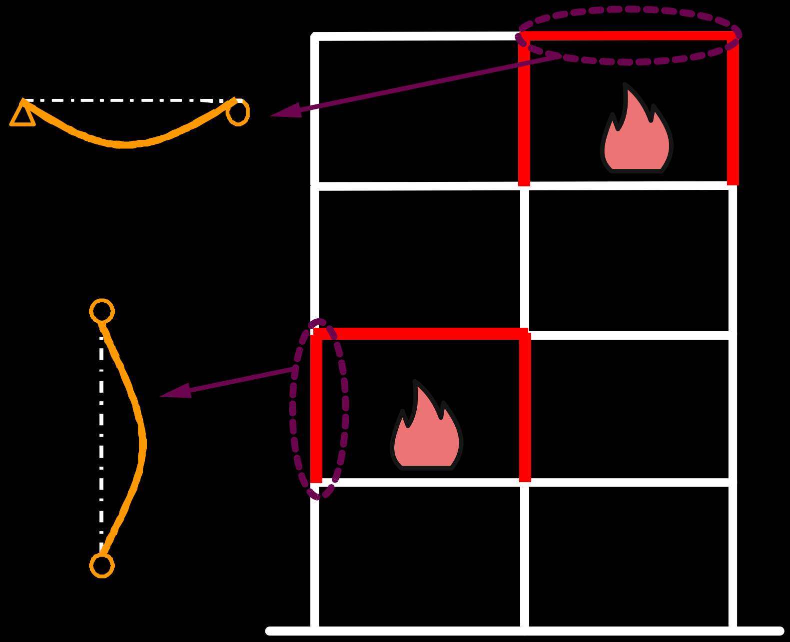
Apply **simplified design methods** and understand their relation to design methods at ambient temperature

Understand the need for design verifications related to **explosive spalling** and use the appropriate measure to deal with it

Structural behaviour under fire conditions

Member analysis

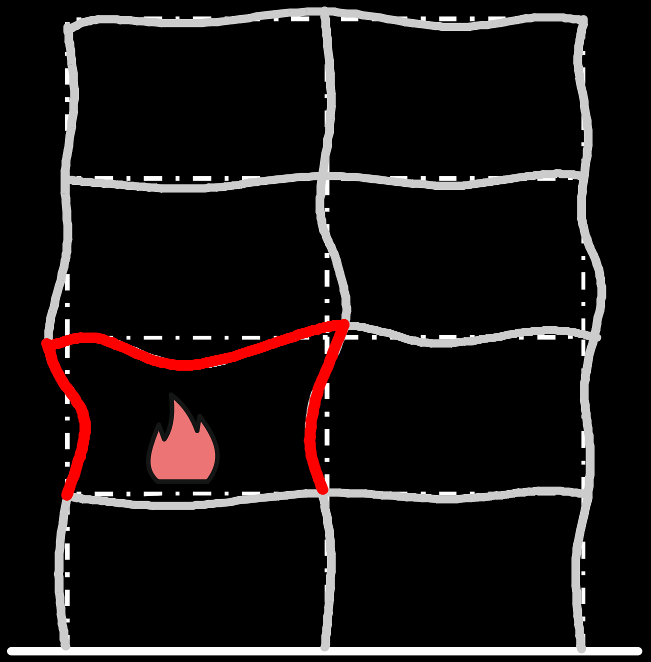
- Member behaviour independent of the structure
- Simple
- Standard analysis for fire design



[ECSC project DIFISEK]

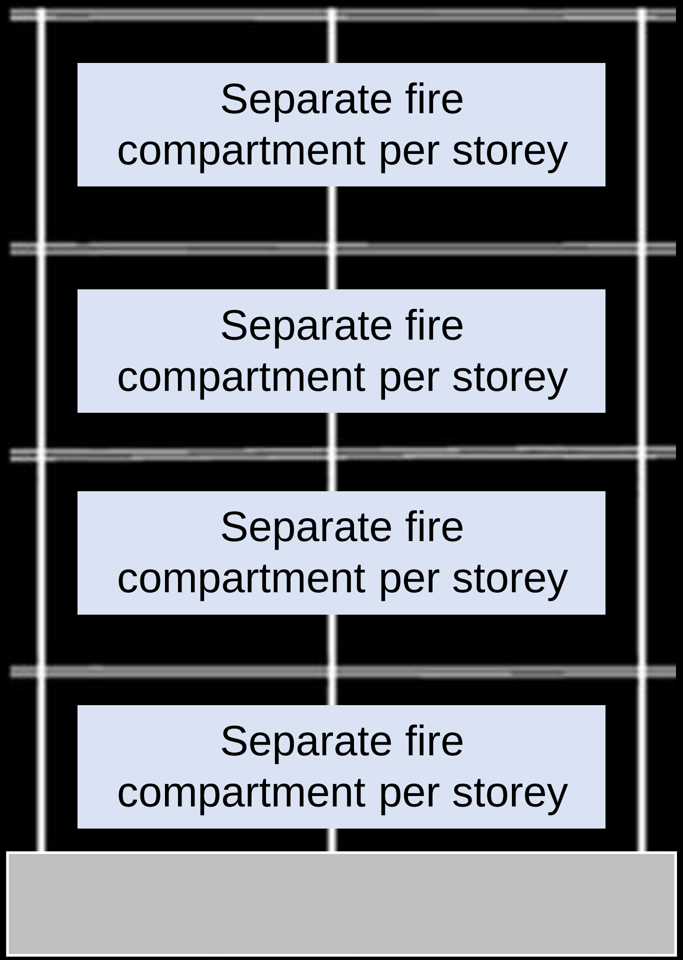
Global structural analysis

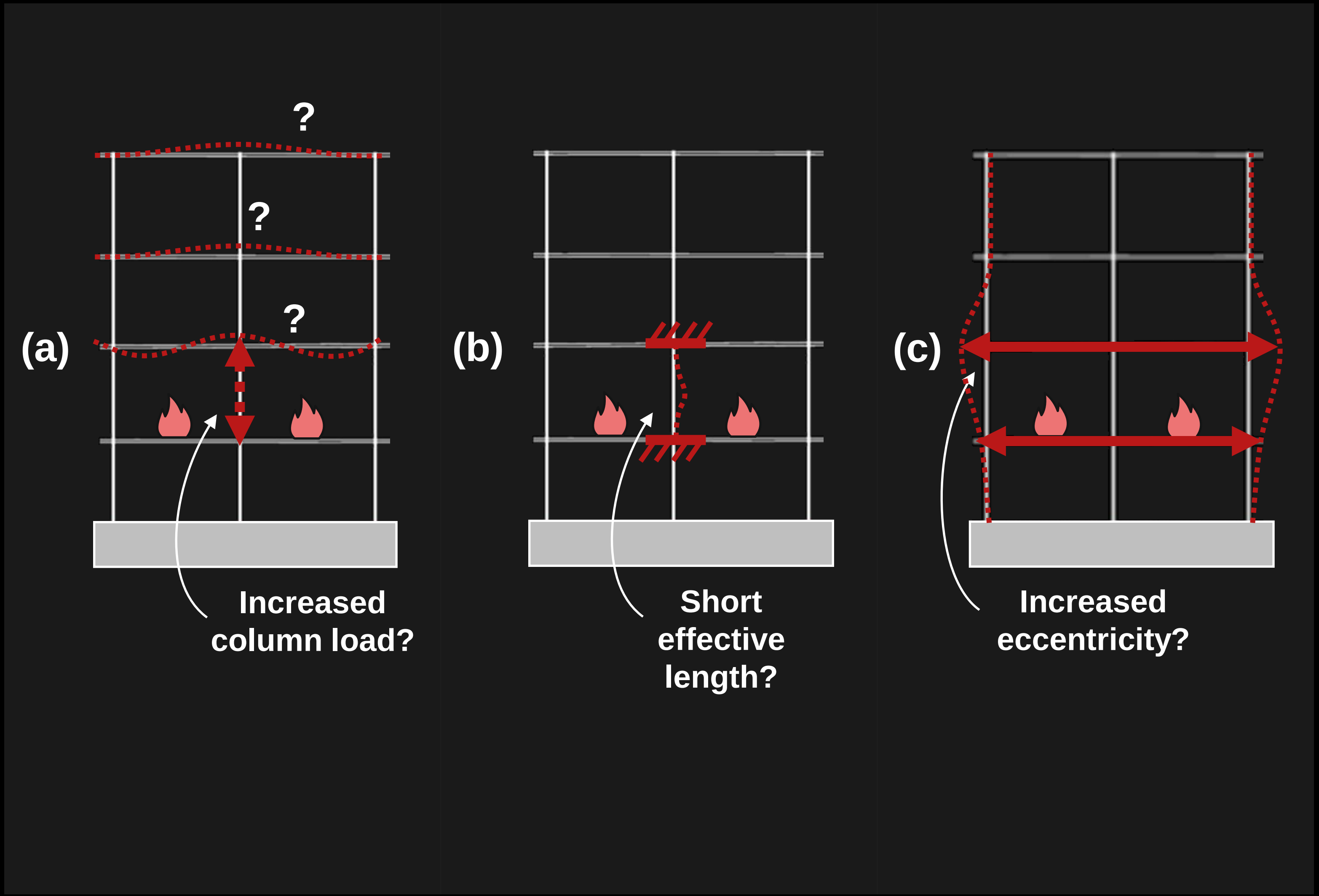
- Interaction between structural members
- Function of concerned compartment / part of the structure
- Global stability



[ECSC project DIFISEK]

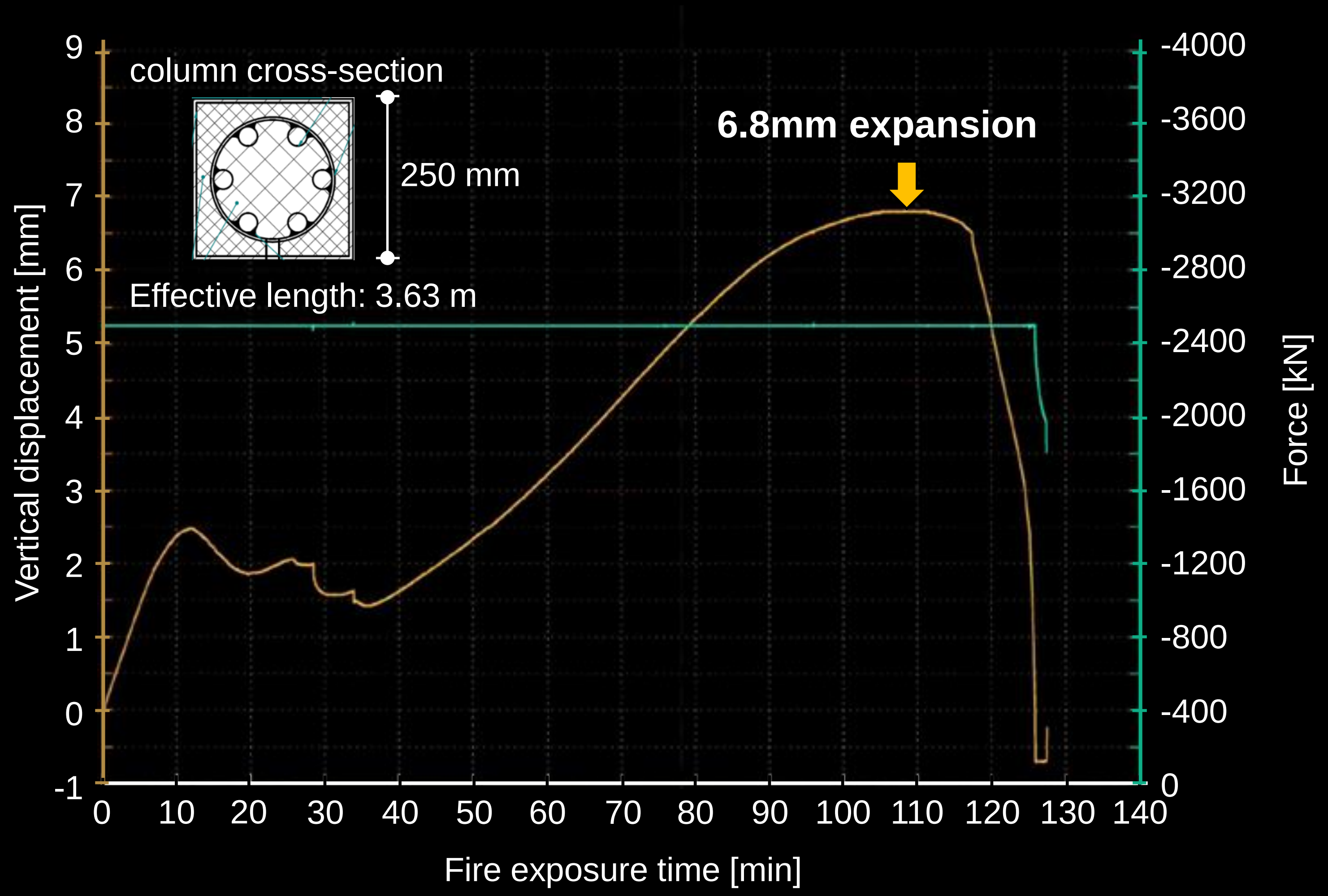
Structural behaviour under fire conditions

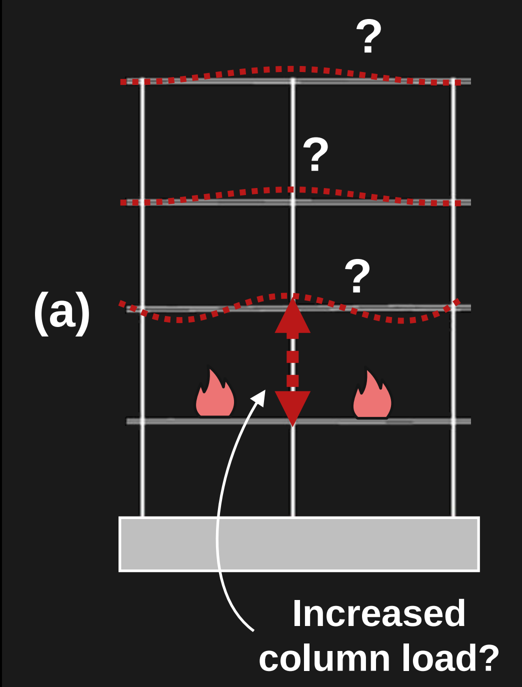




Structural behaviour under fire conditions

Member expansion and restraint action: Column test on composite column by F.J. Aschwanden AG





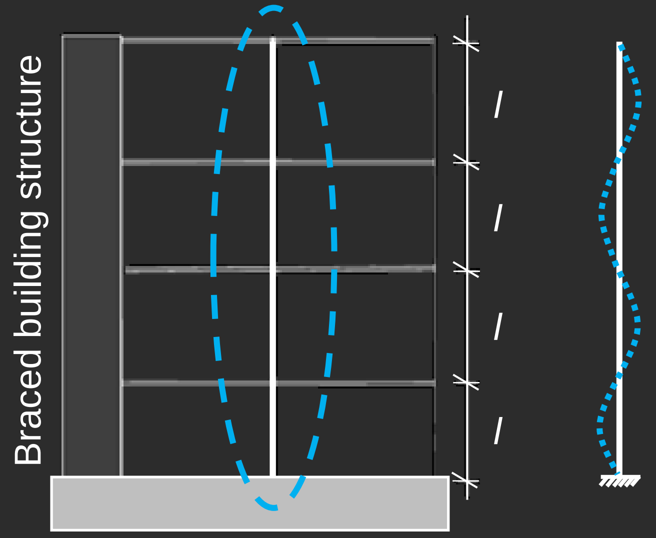
Structural behaviour under fire conditions

Effective length under fire conditions:

SN EN 1992-1-2 5.3.2 (2):

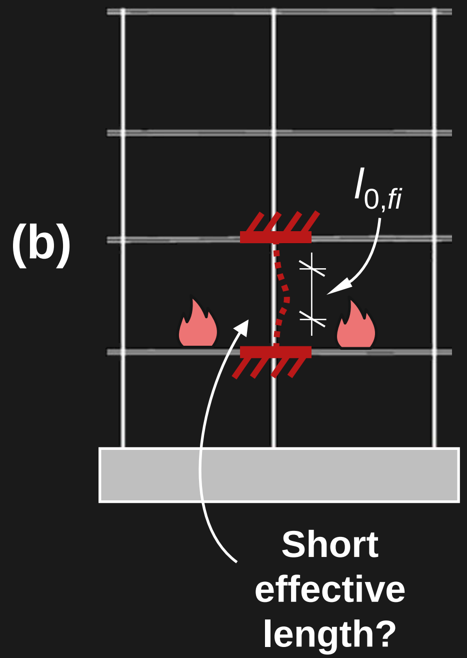
The effective length of a column under fire conditions $l_{0,fi}$ may be assumed to be equal to l_0 at normal temperature in all cases.

For braced building structures where the required Standard fire exposure is higher than 30 minutes, the effective length $l_{0,fi}$ may be taken as 0.5 l for intermediate floors, where l is the actual length of the column (centre to centre).



Deformation at ambient conditions: $l_0 = l$

[Zehfuß, 2015]



Deformation under fire conditions: $l_0 = 0.5l$

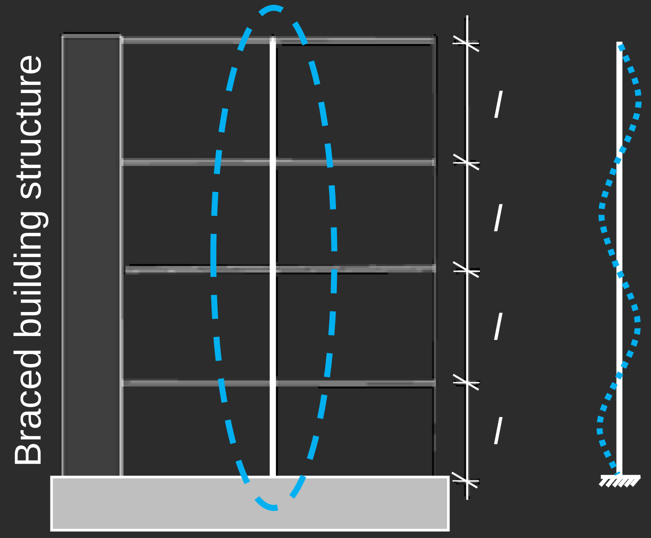
Structural behaviour under fire conditions

Effective length under fire conditions:

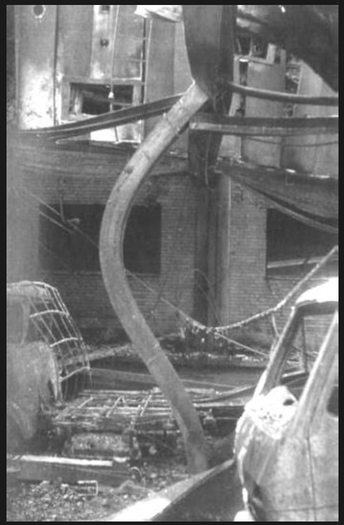
SN EN 1992-1-2 5.3.2 (2):

The effective length of a column under fire conditions $l_{0,fi}$ may be assumed to be equal to l_0 at normal temperature in all cases.

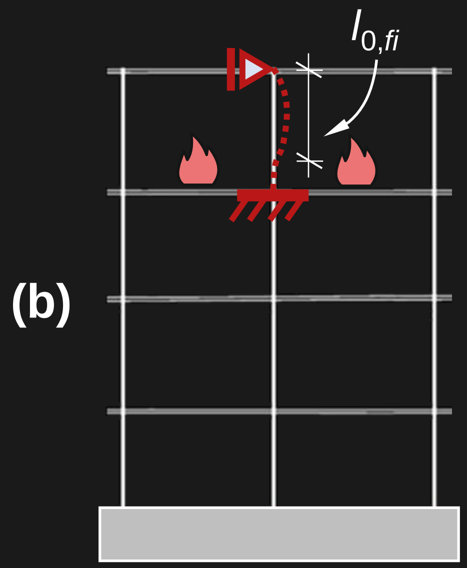
For braced building structures where the required Standard fire exposure is higher than 30 minutes, the effective length $l_{0,fi}$ may be taken $0.5l \leq l_{0,fi} \leq 0.7l$ for the upper floor, where l is the actual length of the column (centre to centre).



Deformation at ambient conditions: $l_0 = l$



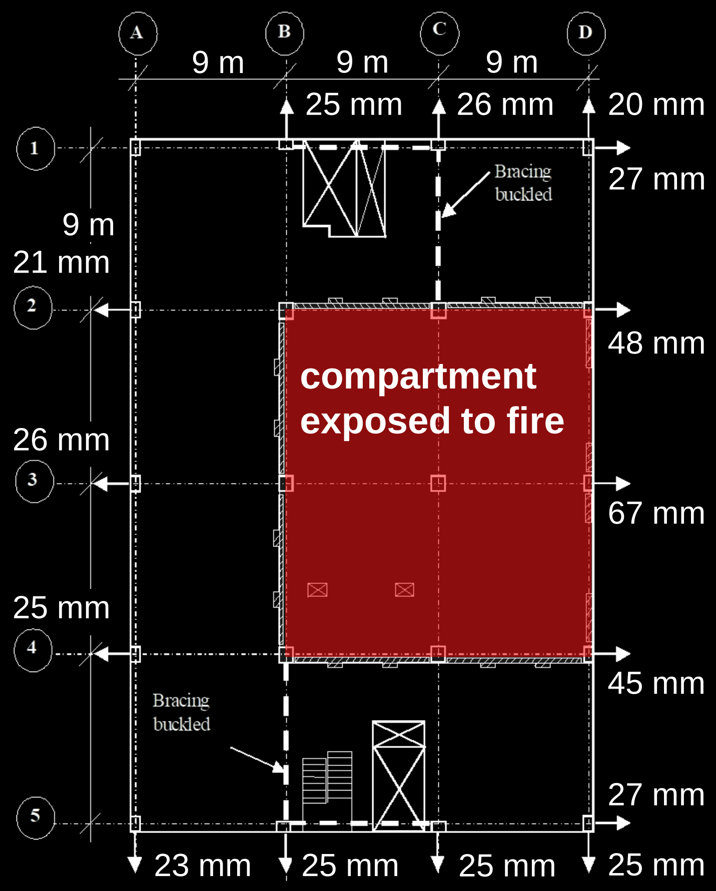
[Zehfuß, 2015]

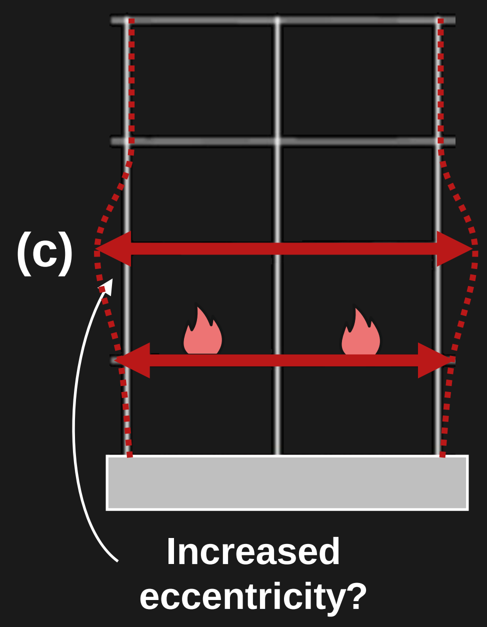


Deformation under fire conditions: $l_0 = 0.7l$

Structural behaviour under fire conditions

Member expansion: Cardington tests, 2001



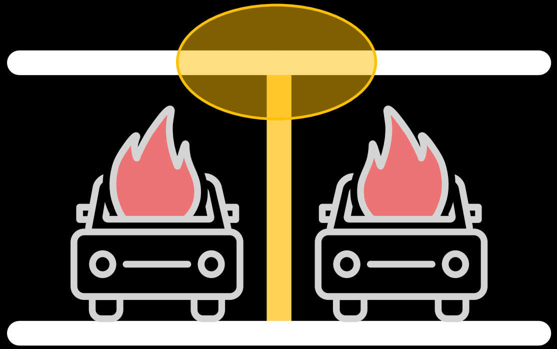


▶ Gent

Structural behaviour under fire conditions

What members require closer fire engineering consideration when designing concrete structures?

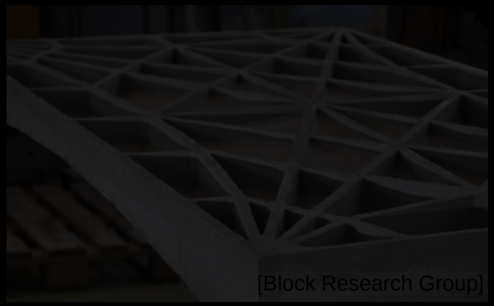
Slender columns/ highly loaded walls with small member dimensions (HPC/ UHPC)



Statically indeterminate slabs
without (punching) shear reinforcement

Members with slender webs

Hollow core slabs

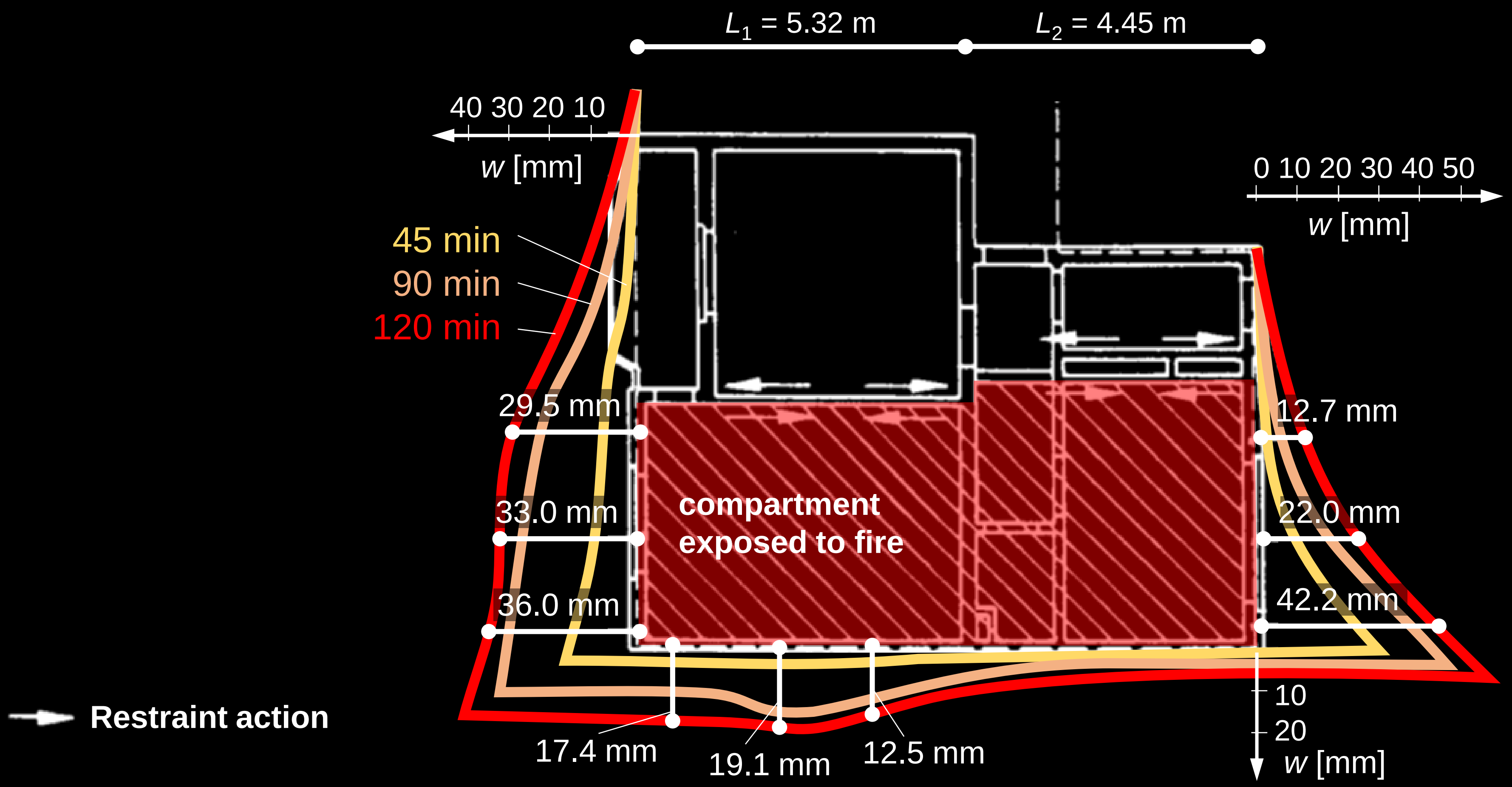


Ribbed slabs

Members with intense fire exposure
(tunnels/ tunnel segments, fire ratings >R90

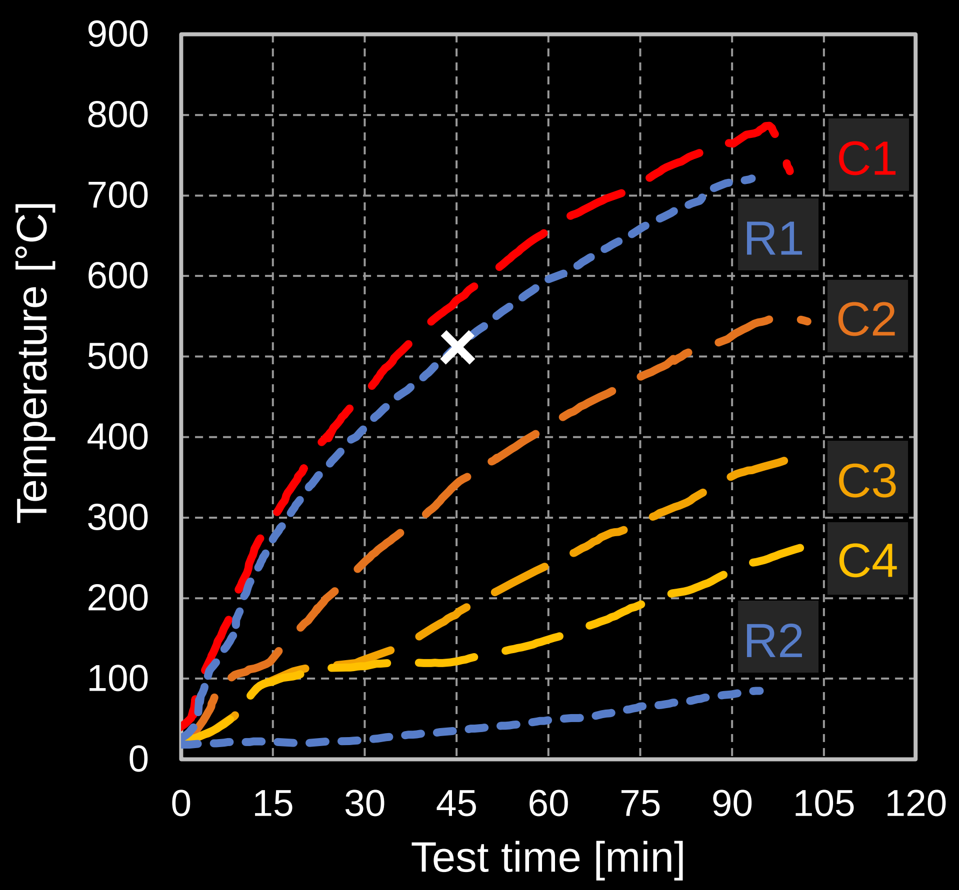
Structural behaviour under fire conditions

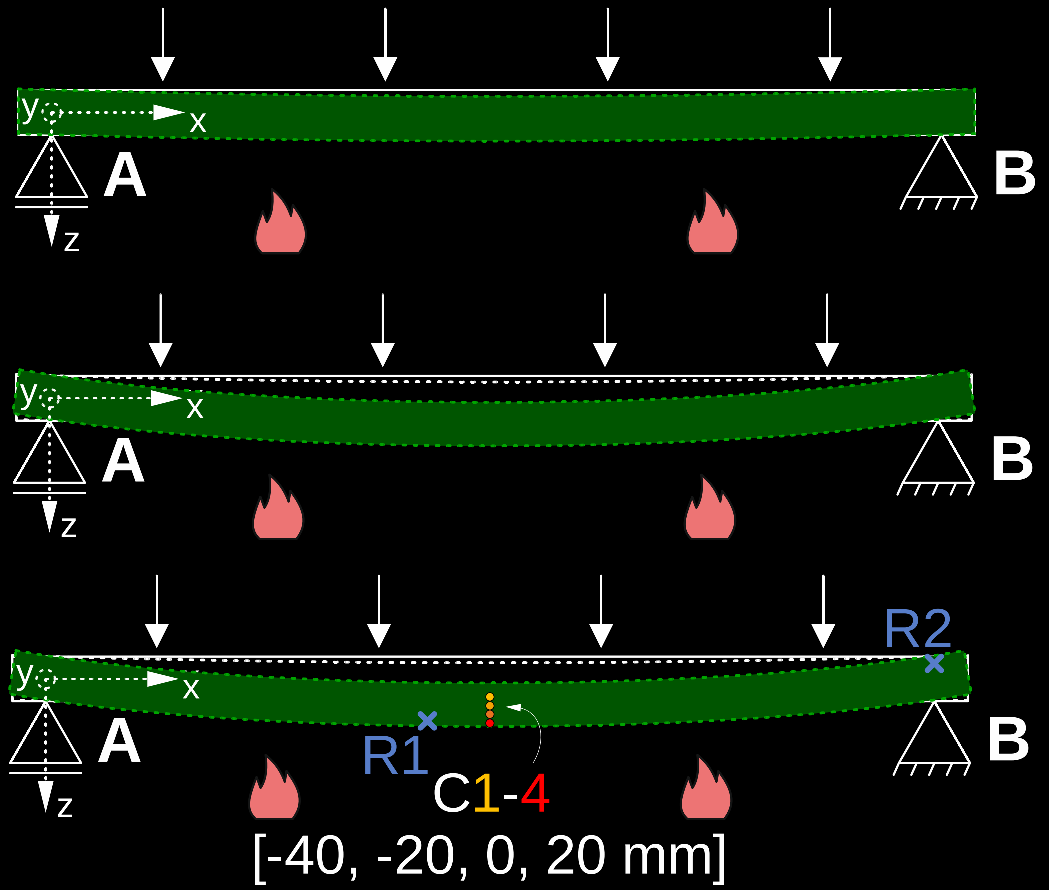
Member expansion and restraint action: Brandversuche Lehrte, 1978



[Bechtold et al., 1978]

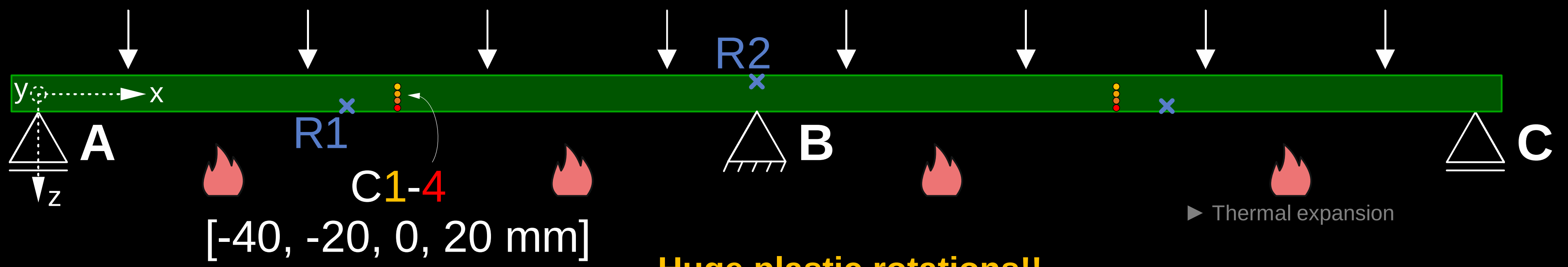
Structural behaviour under fire conditions

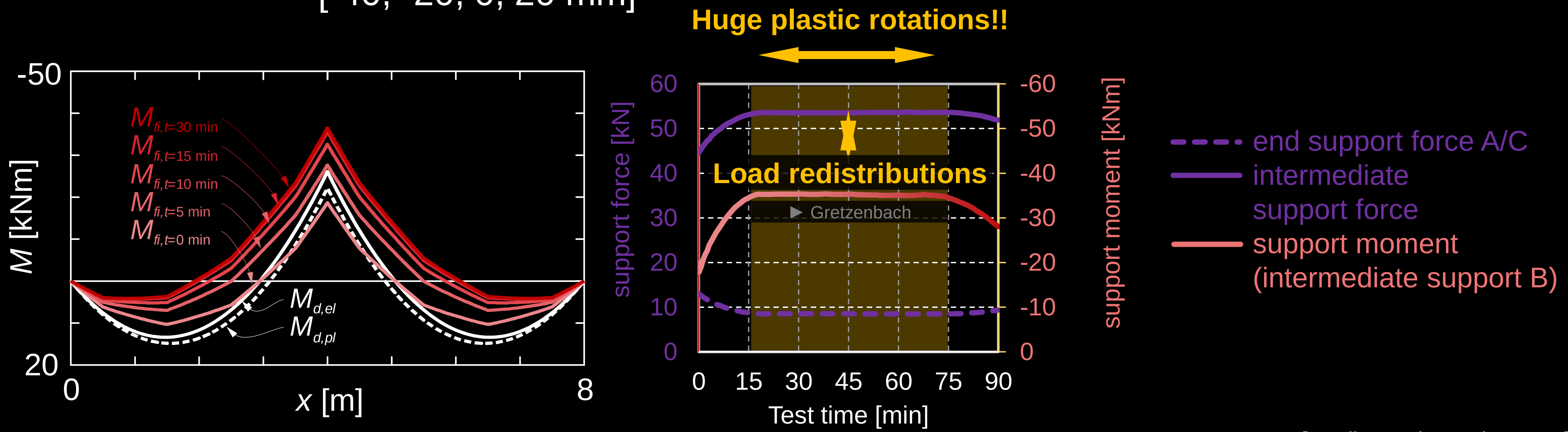




Structural behaviour under fire conditions

Restraint moments: Tests on slender continuous slab strips carried out by Kordina and Wesche, 1979

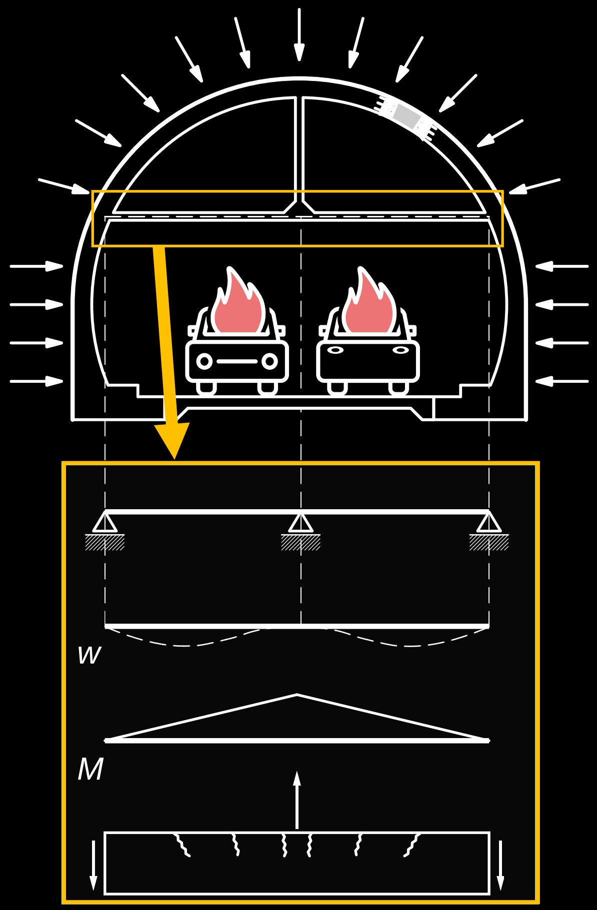




[Kordina und Wesche, 1979]

Structural behaviour under fire conditions

Restraint moments: Tunnels



Suspended ceiling with severe damages over a length of around 230 m

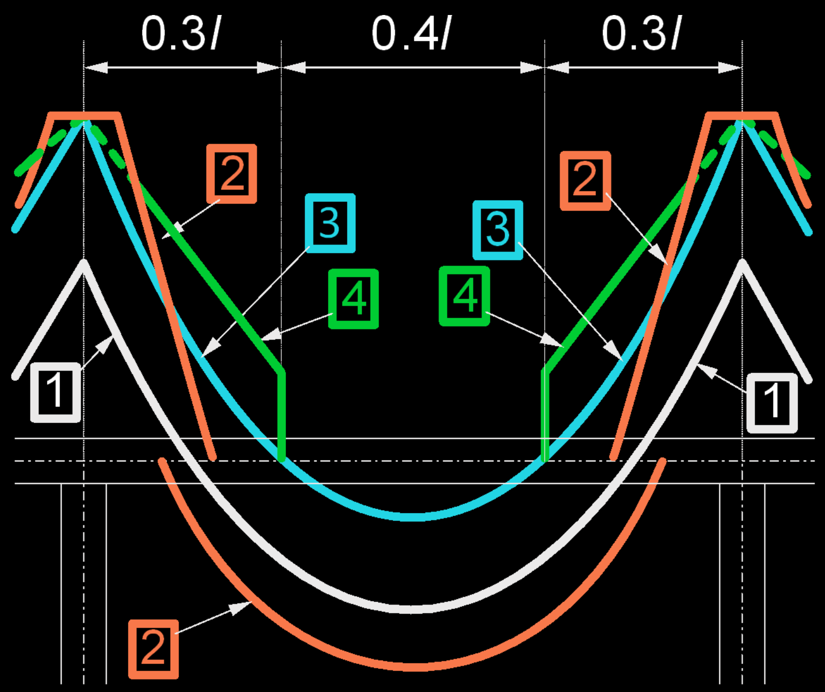
Structural behaviour under fire conditions

Restraint moments: Detailing

Provisions in SN EN 1992-1-2

- For continuous beams or slabs (Figure 5.6, right): increased anchorage length of top reinforcement
- Minimum top reinforcement degree of 0.5% at intermediate supports if:
  - Ductility class A
  - One-way continuous slabs
- For flat slabs: continuous minimum reinforcement over the full span of 20% of the total top reinforcement over intermediate supports required by ambient temperature ULS design in each direction.

‼ Do not use Annex E for moment redistributions



► Kordina & Wesche

(1) Diagram of bending moments for the actions in a fire situation ($E_{d,fi}$) at t = 0
(2) Envelope of required resistance of tensile reinforcement for design at ambient conditions
(3) Diagram of bending moments in fire conditions including restraint moments due to thermal curvature of members
(4) Envelope of requested resistance of tensile reinforcement according to Formula (9.1) in SN EN 1992-1-2

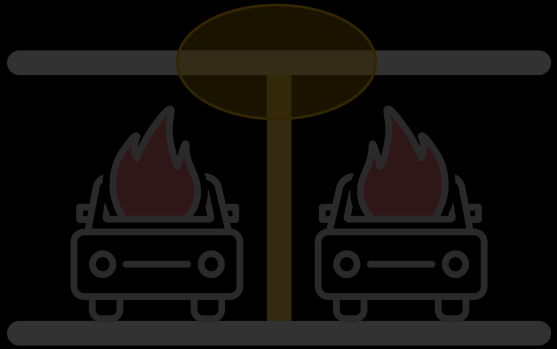
Additional provision in prEN 1992-1-2

- Increased shear loads to be considered if stirrups with more than two legs are used

Structural behaviour under fire conditions

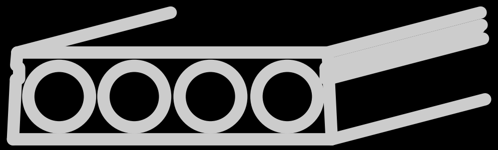
What members require closer fire engineering consideration when designing concrete structures?

Slender columns/ highly loaded walls with small member dimensions (HPC/ UHPC)

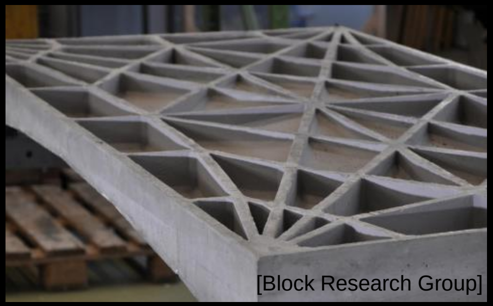


Statically indeterminate slabs
without (punching) shear reinforcement

Members with slender webs



Hollow core slabs

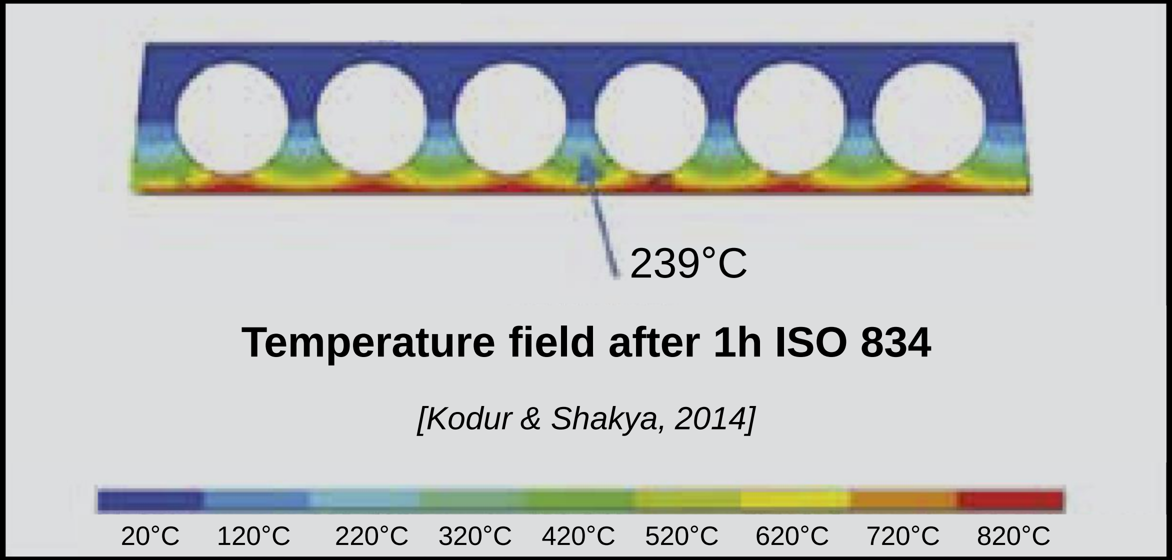


Ribbed slabs

Members with intense fire exposure
(tunnels/ tunnel segments, fire ratings >R90

Structural behaviour under fire conditions

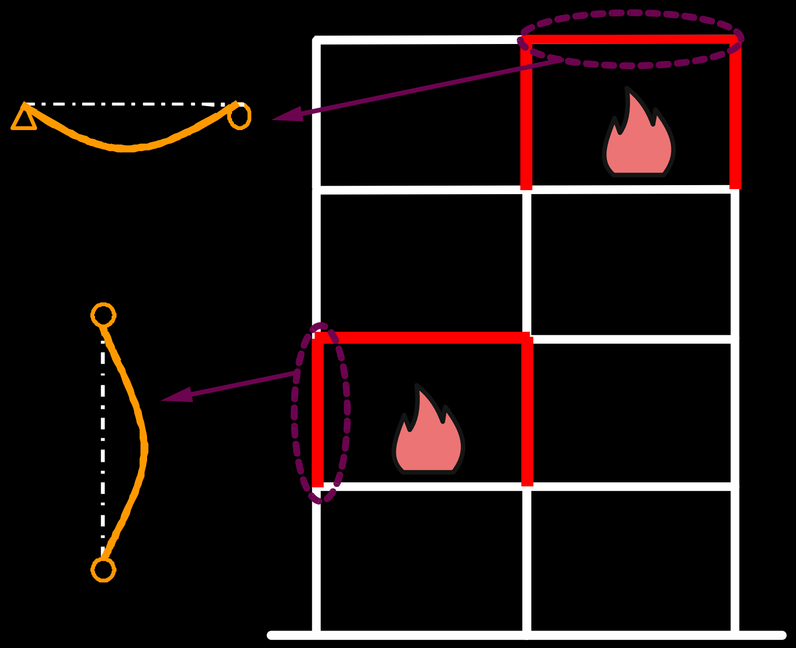
Members with slender webs



Fire in underground parking, Rotterdam (2007)

- Anchorage zones (pretensioning reinforcement), supports, cavities, dapped ends, slender webs, etc. may be critical under fire conditions.
  They require good detailing!

Structural behaviour under fire conditions

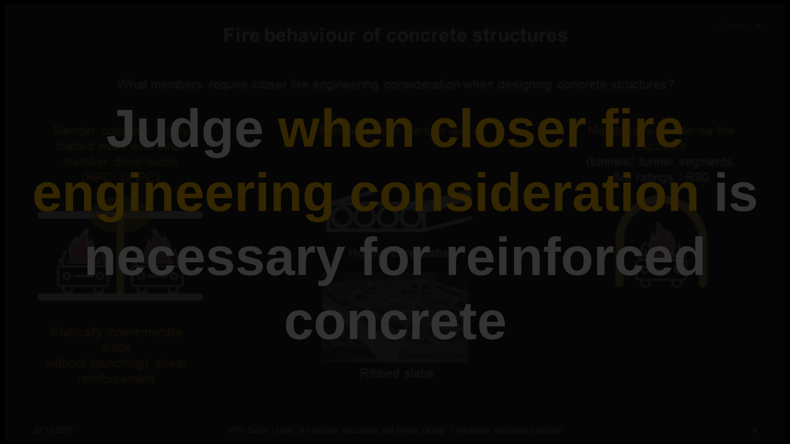


[ECSC project DIFISEK]

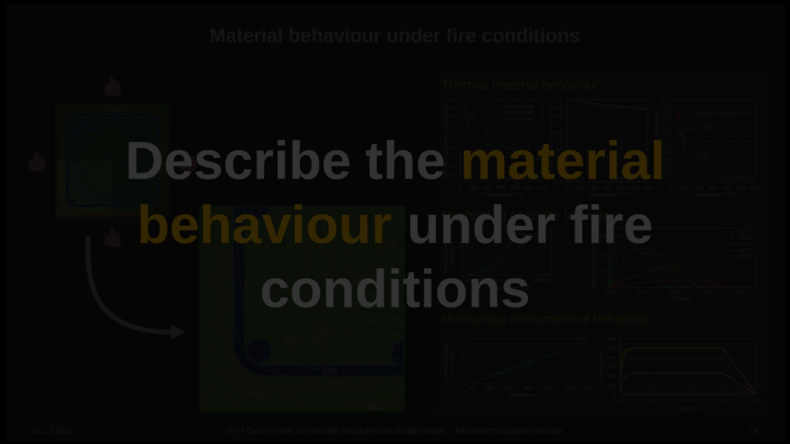
Design recommendations for fire design

- Member analysis with awareness of structural behaviour
- Axially restrained support conditions in the axial direction are usually favourable for beams or slabs (membrane or catenary action) but may, in rare cases, be unfavourable for members where stability failure occurs (such as columns or walls).
- Column design:
  - Definition of N_{Ed} with some reserve in case of stiff boundary conditions
  - No “blind” reduction of the effective length of a column under fire conditions
  - Rough estimation of column eccentricity due to thermal expansion of slab
- Slab / beam design:
  - Use of m_d/m_{Rd} = 1 (ULS design) for slabs without shear/ punching reinforcement.
  - Consideration of detailing rules in SN EN 1992-1-2.

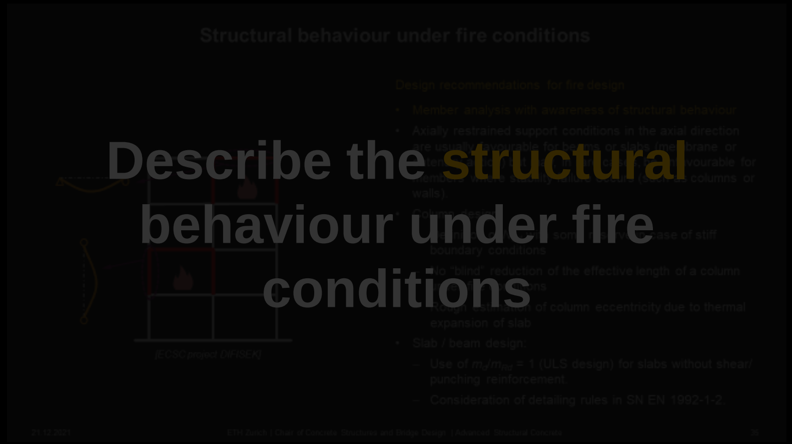
Learning objectives



Judge **when closer fire engineering consideration** is necessary for reinforced concrete



Describe the **material behaviour** under fire conditions



Describe the **structural behaviour** under fire conditions

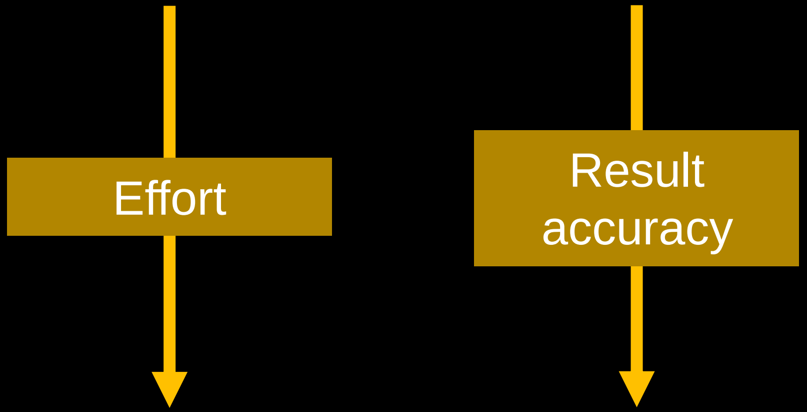
Select the **most suitable verification method(s)** for the fire design

Apply **simplified design methods** and understand their relation to design methods at ambient temperature

Understand the need for design verifications related to **explosive spalling** and use the appropriate measure to deal with it

Design and structural analysis

- Fire is an accidental design situation. Thus, the fire design/ structural analysis is carried out with reduced partial safety factors (see slide 12 for actions).
- Design values of mechanical material properties for the fire situation are equivalent to the characteristic values (used for simplified design methods and advanced design methods) :
  - Concrete: e.g. $f_{c,\theta} = k_c \, f_{ck} \, \gamma_{M,fi}$, with $\gamma_{M,fi} = 1$
  - Reinforcement: e.g. $f_{sy,\theta} = k_s \, f_{sy} \, \gamma_{M,fi}$, with $\gamma_{M,fi} = 1$
- In principle, SN EN 1992-1-2 provides four levels of approximation in design:
  - Level 1: Verification with tabulated design data
  - Level 2: Verification with simplified design methods (cross-sectional resistance)
  - Level 3: Verification by the advanced design methods (FEM)
  - Level 4: Verification by experiments



- The choice of the appropriate method depends on the required information and the required model accuracy.
- The tables and design models from SN EN 1992-1-2 are based on the assumption of the standard fire curve. For other fire curves, advanced design methods should be used.

Design and structural analysis

Verification with tabulated design data according to SIA 262

- Minimum dimensions and concrete covers for different members for all fire resistance classes
- Tabulated design data is based on experiments (and a certain amount of extrapolation)
- Example: Table 16 from SIA 262:

Fire resistance class	Minimum cover of reinforcement [mm]	Minimum member dimensions [mm]					
		Columns	Walls	Slabs	Mushroom slabs	Flat slabs	T-beam web width
R 30	20	150	120	60	150	150	[illegible]
R 60	20	200	140	80	150	200	150
R 90	30	240	170	100	150	200	[illegible]
R 120	30	280	220	120	150	200	[illegible]
R 180	40	360	300	150	200	200	400

NB1: the application of Table 16 for columns is generally limited to R 180 and for columns additionally to slenderness $\lambda \leq 50$ for R 90 and $\lambda \leq 30$ for R 120.

NB2: Table 5.2a (columns) of SN EN 1992-1-2 defining minimum member dimensions and axis distances ($c_{nom} + \varnothing_{stirrups} + \varnothing_{longitudinal}/2$) is more conservative than Table 16 of SIA 262, mainly because it can be used up to l_0 = 6 m.

Design and structural analysis

Verification with tabulated design data according to SN EN 1992-1-2

- Tabulated design data for normal strength columns, walls, beams and slabs defining minimum dimensions and axis distances in Section 5
- Tabulated data based on experiments (and a certain amount of extrapolation)
- Example shown (right): Table 5.5 from SN EN 1992-1-2
- Several tables for verifying columns:
  - Method A: Table 5.2a and Formula 5.7 (see next slide):
    To be used only for $l_{0,fi} = 0.5 l_0$
    Exception: Expertise documents
  - Method B: Application not recommended
  - Annex C: Amendment 2019 may be used.

Table 5.5: Minimum dimensions and axis distances for simply supported beams made with reinforced and prestressed concrete

Standard fire resistance	Minimum dimensions (mm)						
	Possible combinations of a and b_{min} where a is the average axis distance and b_{min} is the width of beam				Web thickness b_w		
					Class WA	Class WB	Class WC
1	2	3	4	5	6	7	8
R 30	b_{min} = 80 a = 25	120 20	160 15*	200 15*	80	80	80
R 60	b_{min} = 120 a = 40	160 35	200 30	300 25	100	80	100
R 90	b_{min} = 150 a = 55	200 45	300 40	400 35	110	100	100
R 120	b_{min} = 200 a = 65	240 60	300 55	500 50	130	120	120
R 180	b_{min} = 240 a = 80	300 70	400 65	600 60	150	150	140
R 240	b_{min} = 280 a = 90	350 80	500 75	700 70	170	170	160
$a_{sd} = a$ + 10mm (see note below)							

For prestressed beams the increase of axis distance according to 5.2(5) should be noted.

a_{sd} is the axis distance to the side of beam for the corner bars (or tendon or wire) of beams with only one layer of reinforcement. For values of b_{min} greater than that given in Column 4 no increase of a_{sd} is required.

* Normally the cover required by EN 1992-1-1 will control.

Design and structural analysis

Verification with tabulated design data according to SN EN 1992-1-2

- For columns, Method A is available in the normative part of SN EN 1992-1-2.
- Method A is very simple, completely empirical but provides (mostly) conservative results for $l_{0,fi} = 0.5 l_0$. The fire resistance duration is calculated as follows (equation 5.7):

$$R = 120\left(\left(R_{\eta fi} + R_a + R_l + R_b + R_n\right)/120\right)^{1.8}$$

- Parameters: Load utilisation ($R_{\eta fi}$), axis distance (R_a), buckling length (R_l), cross-sectional dimension (R_b), number of reinforcing bars placed in the corner of the cross-section (R_n)
- Limits of application:
  - First order of eccentricity $e_1 = M_{0Ed,fi} / N_{0Ed,fi} \leq e_{max} = 0.15\,h$
  - Axis distance 25 mm $\leq a \leq$ 80 mm
  - Equivalent length in case of fire $l_{0,fi} \leq 3$ m
  - Reinforcement $A_s < 0.04\,A_c$
  - Rectangular columns: 200 mm $\leq b' = 2A_c/(b+h)$, circular columns: $\varnothing \leq 450$ mm ($h \leq 1.5b$)

Design and structural analysis

Verification with simplified design methods according to SN EN 1992-1-2 (cross-sectional resistance)

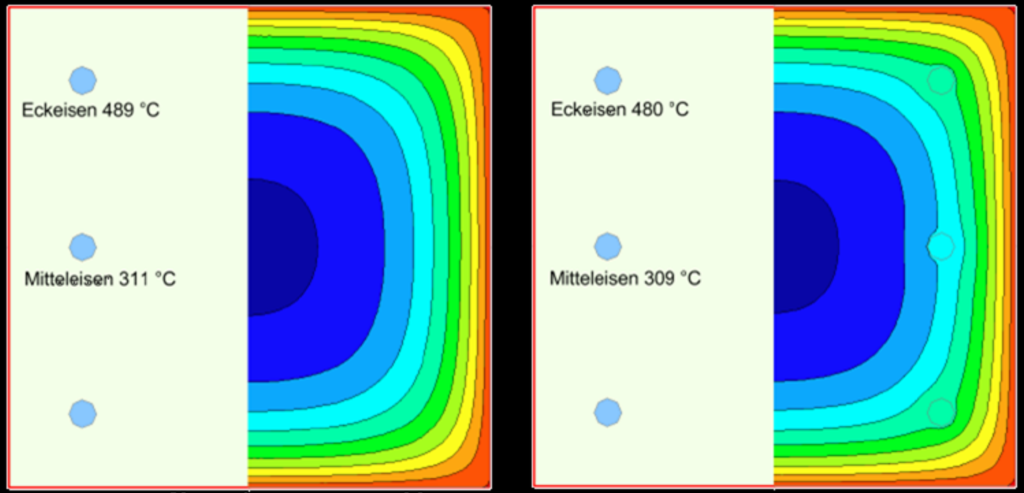
- Existing methods in SN EN 1992-1-2 :
  - Annex B.1 (informative): 500°C Isotherm Method, application not permitted in Switzerland
  - Annex B.2 (informative): Zone Method, application permitted in Switzerland for bending verification
  - Annex B.3 (informative): Method for assessment of a reinforced concrete cross-section exposed to bending moment and axial load by the method based on estimation of curvature), application permitted in Switzerland
  - Annex D (informative): Calculation methods for shear, torsion and anchorage of reinforcement
  - Annex E (informative): Simplified calculation methods for beams and slabs, application not permitted in Switzerland

Bending	Bending and axial load	Shear
Annex B.1 Annex B.2 Annex E	~~Annex B.1~~ ~~Annex B.2~~ Annex B.3 Refined Zone Method (new Annex C)	Annex D (additional information required, see prEN 1992-1-2)

Design and structural analysis

Verification with simplified design methods according to SN EN 1992-1-2 (cross-sectional resistance)

1. Thermal analysis
   a. Annex A (Isotherms) of SN EN 1992-1-2
   b. Simplified design method
   (available in SN EN 1992-1-2:202x)
   c. Advanced design method (FEM)



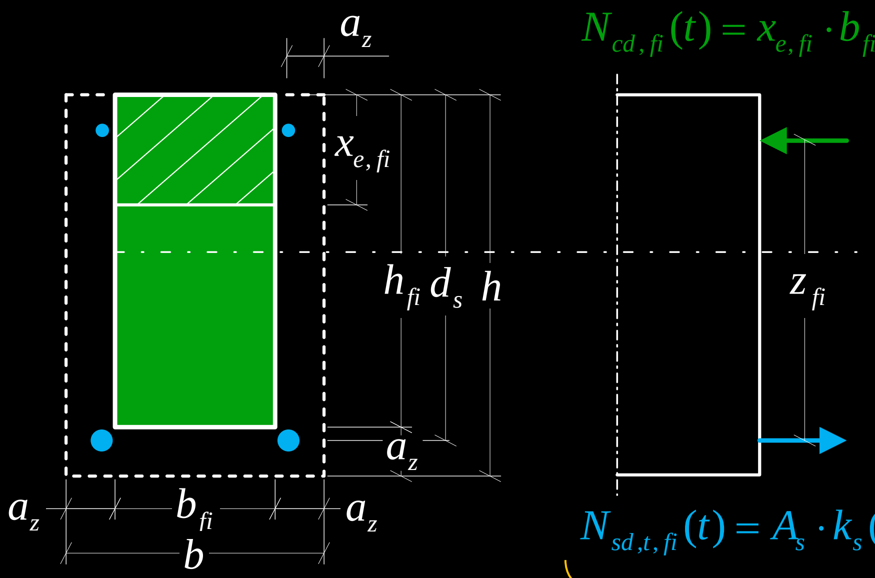
Temperature profile after 90 minutes of fire without consideration of reinforcement

Temperature profile after 90 minutes of fire with consideration of reinforcement *[Infograph]*

2. Mechanical analysis

Principle:

$N_{cd,fi}(t) = x_{e,fi} \cdot b_{fi} \cdot k_c(\theta_{c,M}) \cdot f_{ck}$



$N_{sd,t,fi}(t) = A_s \cdot k_s(\theta_s) \cdot f_{yk}$

$\gamma_{c,fi} = \gamma_{s,fi} = 1$

Verification:

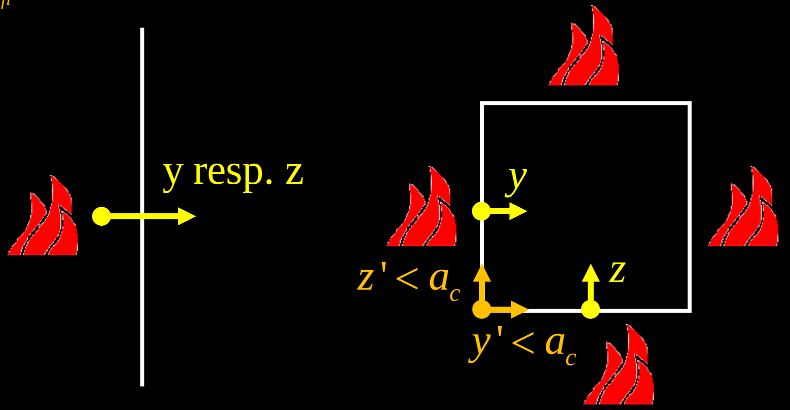
$M_{R,fi,d} = N_{sd,t,fi} \cdot z_{fi} \geq M_{E,fi,d}$

Design and structural analysis

Verification with simplified design methods according to SN EN 1992-1-2 (cross-sectional resistance)

1. Thermal analysis
   b. Simplified design method (available in future in EN 1992-1-2:202x)
   Formulae for temperature profile for checking the load-bearing capacity in the event of fire (function R)

$$\theta_1 = 345°\text{C}\cdot\log\left(\frac{7\left(R_{fi}-720\text{ s}\right)}{60\text{ s}}+1\right)\cdot e^{-y\sqrt{\frac{0.9\cdot k}{R_{fi}}}} \text{ or } 345°\text{C}\cdot\log\left(\frac{7\left(R_{fi}-720\text{ s}\right)}{60\text{ s}}+1\right)\cdot e^{-z\sqrt{\frac{0.9\cdot k}{R_{fi}}}}$$



$t =$ duration of the standard fire (in seconds)

y resp. $z =$ distance from the exposed surface (in m)

$k = \rho\cdot c_p/\lambda = 3.3\cdot 10^6\ \text{s/m}^2$

member exposed on one side: $\theta = \theta_1\left(y \text{ resp. } z, t\right) + 20°\text{C}$

member exposed on two sides: $\theta_2 = \theta_1\left(y \text{ resp. } z, t\right) + \theta_1\left(b - y \text{ resp. } h - z, t\right) + 20°\text{C}$

b and h: member dimensions

member exposed on four sides: $\theta_4 = \theta_2\left(y,t\right) + \theta_2\left(z,t\right) + \frac{\theta_2\left(y,t\right)\cdot\theta_2\left(z,t\right)}{\theta_0\left(0,t\right)} + \left(345°\text{C}\cdot\log\left(\frac{8t}{60\text{ s}}+1\right) - \theta_0\left(0,t\right)\right)\cdot\frac{\left(a_c - y'\right)\cdot\left(a_c - z'\right)}{a_c^2} + 20°\text{C}$

$$a_c = \begin{matrix} 0.04\text{ m for } R_{fi} \le 60\text{ min} \\ 0.10\text{ m for } R_{fi} > 60\text{ min} \end{matrix}$$

Design and structural analysis

Verification with simplified design methods according to SN EN 1992-1-2 (cross-sectional resistance)

2. Mechanical analysis for *beams/ slabs*
   1. Determination of the width of the rim zone a_z (use Figure B.5)
   2. Determination of a reduced width and height of the cross-section by excluding the rim zone a_z
   3. Determination of the reduction of the concrete compression strength
      (use Figure B.5a) with only one zone → θ_M = Temperature in the centre of the cross-section)
   4. Determination of the reduced strength of each reinforcing bar based on its temperature (see next slide).
   5. Determination of the ultimate load-bearing capacity and verification of the fire design assuming a rectangular concrete compression stress block according to EN 1992-1-1:
      – $x_{e,fi} = x_{sb} = 0.8x$
      – $\varepsilon_{cu} = 3.5‰$

Zone Method (steps 1–5)

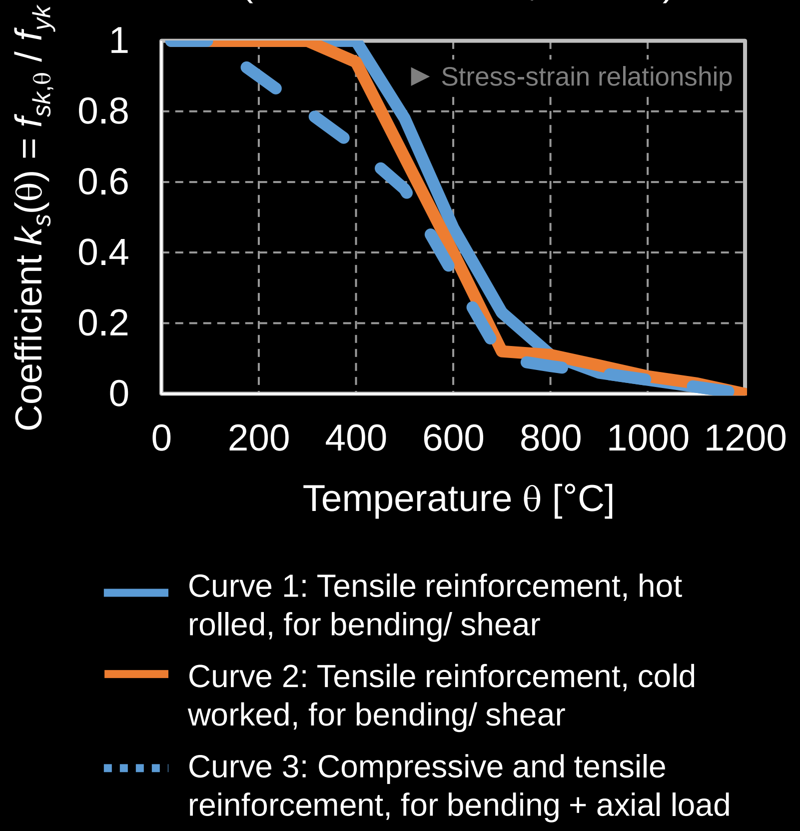
Methodology from Annex E (steps 4–5)

Design and structural analysis

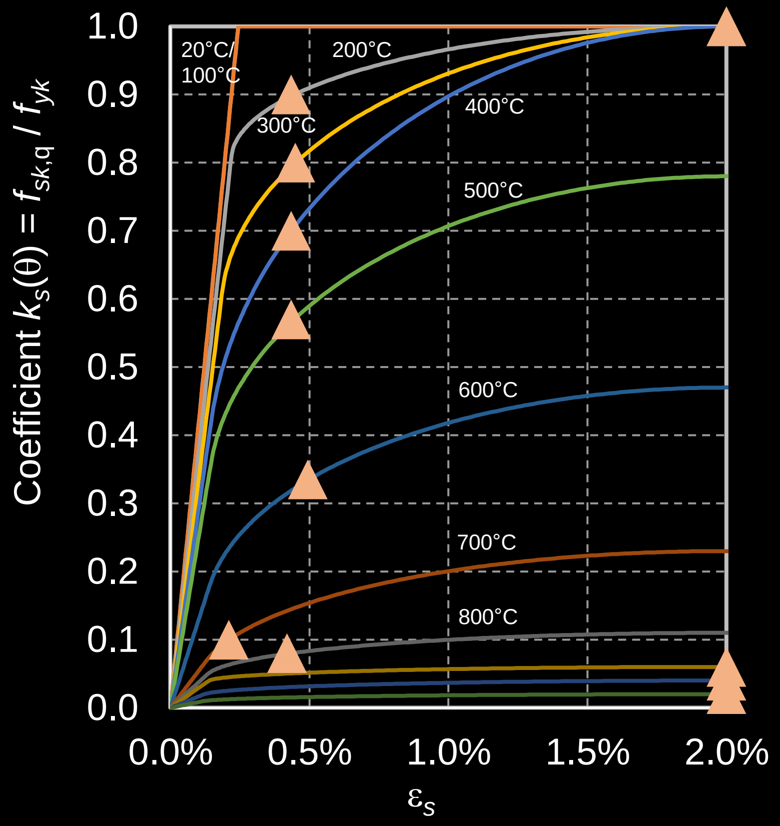
Verification with simplified design methods according to SN EN 1992-1-2 (cross-sectional resistance)

2. Mechanical analysis for *beams / slabs / columns*
   1. …
   2. …
   3. …
   4. Determination of the reduced strength of each reinforcing bar (with SN EN 1992-1-2, 4.2.4.3)
      - Curve 1 and 2 (hot rolled and cold worked reinforcing steel, respectively) to be used for bending and shear
      - Curve 3 approximately represents the average of the general stress-strain relationship (SN EN 1992-1-2, 3.2.3) from ε_s = 0% to ε_s = 2% (yielding), to be used for bending and axial load

Figure 4.2a
(SN EN 1992-1-2, 4.2.4.3)



Stress-strain relationship
(SN EN 1992-1-2, 3.2.3)



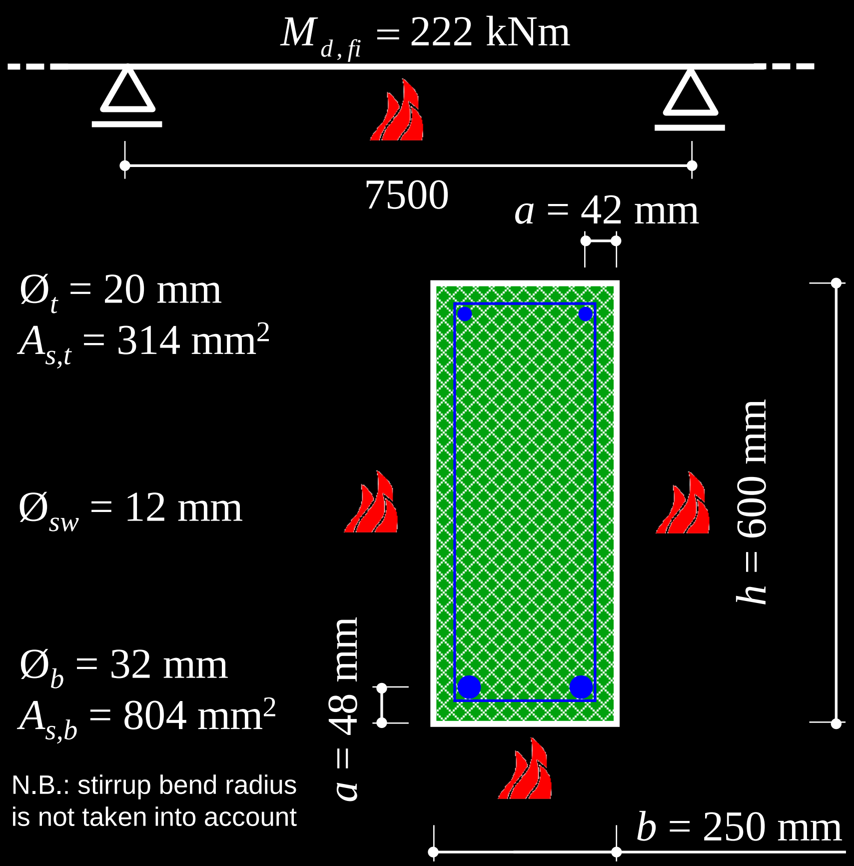
Design and structural analysis

Verification with simplified design methods according to SN EN 1992-1-2 (cross-sectional resistance)

2. Mechanical analysis for *beams/ slabs*

   Example (from Lennon et al., 2007)

   - Cross section dimensions: h = 600 mm, b = 250 mm
   - Span: l = 7500 mm
   - Concrete cover (for stirrups): c_{nom} = 20 mm
   - Concrete strength: f_{ck} = 30 MPa
   - Steel strength: f_{yk} = 500 MPa
   - Standard fire curve



$$T_{sd} = 2 \cdot A_{s,b} \cdot f_{sd} = 699 \text{ kN}, \; x = \frac{T_{sd}}{b \cdot f_{cd}} = 165 \text{ mm}, \; c = 0.8 \cdot x = 132 \text{ mm}$$

$$z = h - 48 \text{ mm} - \frac{c}{2} = 486 \text{ mm}, \; M_{Rd} = T_{sd} \cdot z = 340 \text{ kNm}$$

Design and structural analysis

Verification with simplified design methods according to SN EN 1992-1-2 (cross-sectional resistance)

2. Mechanical analysis for *beams/ slabs*

   Example for R90

– Zone Method

$$a_z = 27.5 \text{ mm}$$

$$k_s(\theta) = 0.61$$

$$b_{fi} = 250 \text{ mm} - 2 \cdot a_z = 195 \text{ mm}$$

$$N_{sd,t,fi} = A_{st} \cdot k_s(\theta) \cdot f_{sk} = 494 \text{ kN}$$

$$x_{fi} = \frac{N_{sd,t,fi}}{0.8 \cdot b_{fi} \cdot k_c(\theta) f_{ck}} = 107 \text{ mm}, \; x_{e,fi} = 0.8 \cdot x_{fi} = 86 \text{ mm}$$

$$z_{fi} = h - a - \frac{x_{e,fi}}{2} = 509 \text{ mm}$$

$$M_{Rd,fi} = N_{sd,t,fi} \cdot z_{fi} = 252 \text{ kNm (FE: } M_{Rd,fi} = 247 \text{ kNm)}$$

$$\varepsilon_{s,t} = \varepsilon_{cu} \cdot \frac{h - a - x_{fi}}{x_{fi}} = 1.5\% < 2\%$$

– Methodology from Annex E

$$k_s(\theta) = 0.61$$

$$N_{sd,t,fi} = A_{st} \cdot k_s(\theta) \cdot f_{sk} = 494 \text{ kN}$$

$$x_{fi} = \frac{N_{sd,t,fi}}{0.8 \cdot b \cdot f_{ck}} = 82 \text{ mm}, \; x_{e,fi} = 0.8 \cdot x_{fi} = 66 \text{ mm}$$

$$z_{fi} = h - a - \frac{x_{e,fi}}{2} = 519 \text{ mm}$$

$$M_{Rd,fi} = N_{sd,t,fi} \cdot z_{fi} = 257 \text{ kNm (FE: } M_{Rd,fi} = 247 \text{ kNm)}$$

$$\varepsilon_{s,t} = \varepsilon_{cu} \cdot \frac{h - a - x_{fi}}{x_{fi}} = 1.99\% < 2\%$$

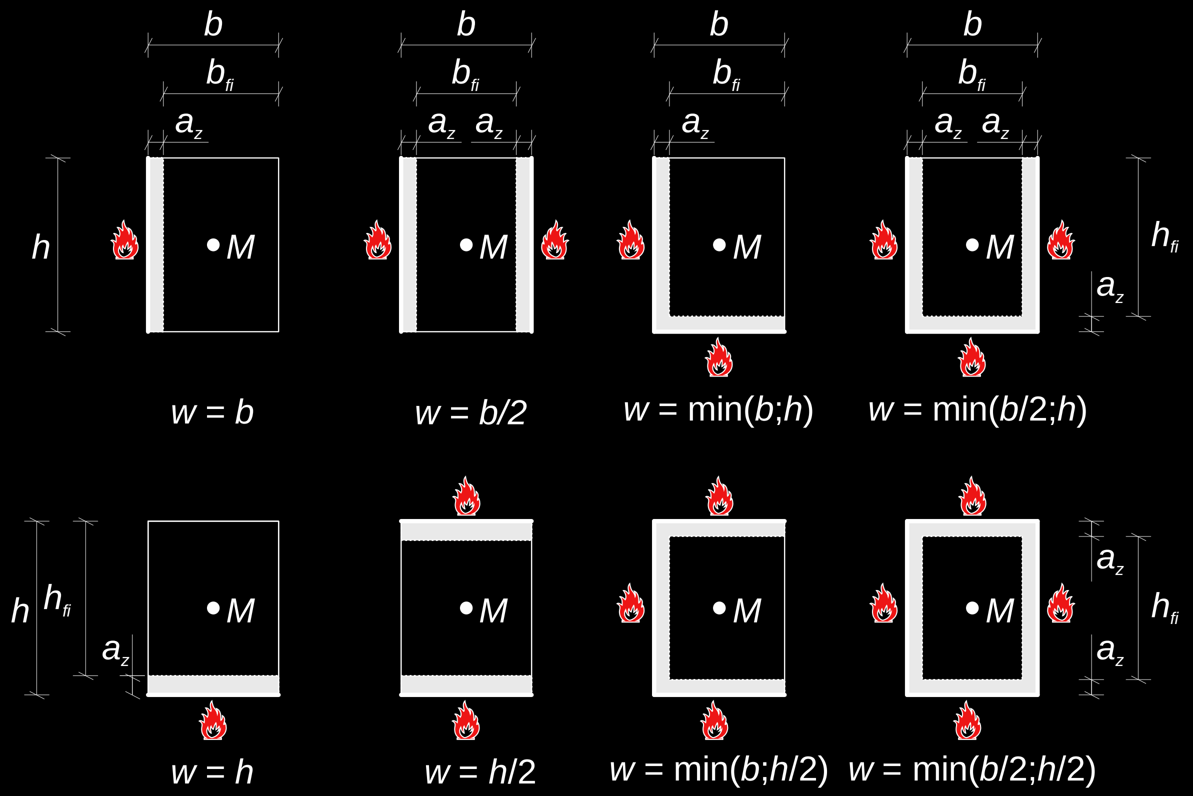
Design and structural analysis

Verification with simplified design methods according to prEN 1992-1-2 (cross-sectional resistance)

2. Mechanical analysis for *columns*
    1. Determination of the width of the rim zone a_z:

$$a_z = \begin{cases} 0.011 \cdot \sqrt{1+\dfrac{R_{fi}-27}{27} \cdot \sqrt{\dfrac{w}{0.0125}}} & \text{for } 0.075 \leq w < 0.20 \\ 0.011 \cdot \sqrt{1+4\dfrac{R_{fi}-27}{27}} & \text{for } w \geq 0.20 \end{cases},$$

       where R_{fi} [min] is the design resistance for the load-bearing criterion in fire situations and w [m] is a reduced cross-section depending on the fire exposure.
    2. Determination of a reduced width and height of the cross-section by excluding the rim zone a_z
    3. Determination of the reduction of the concrete compression strength $k_c(\theta)$ (Section 4 of SN EN 1992-1-2) based on the temperature in the centre of the cross-section (θ_M).



Design and structural analysis

Verification with simplified design methods according to prEN 1992-1-2 (cross-sectional resistance)

2. Mechanical analysis for *columns*

   …

   5. Determination of the ultimate load-bearing capacity and verification of the fire design:

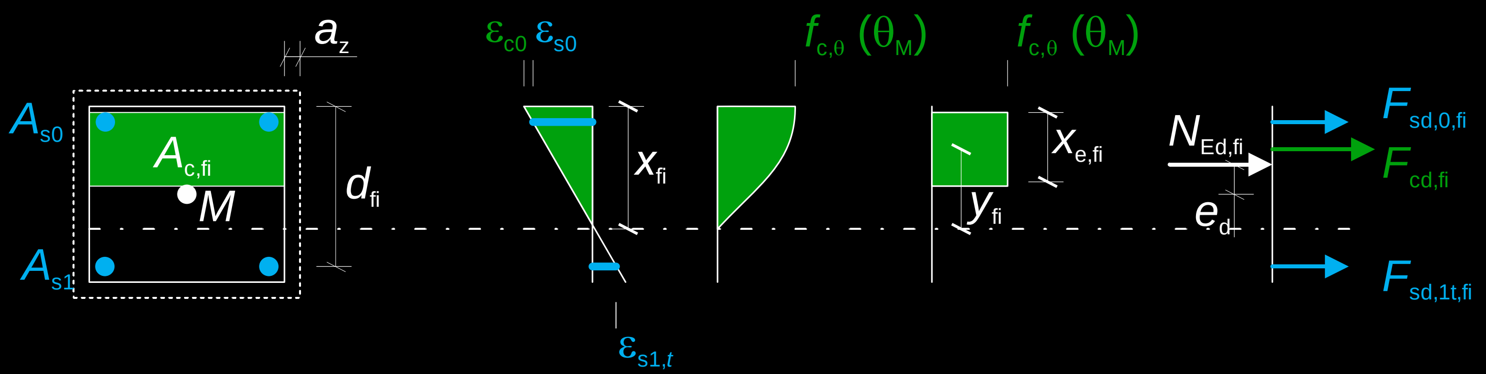
      - compression zone for $0 \le x_{fi} < 3(d_{fi} + a_{fi})$

        $\varepsilon_{c0} \le \varepsilon_{c1,\theta}$ for $x_{fi} < (d_{fi} + a_{fi})$,

        $\varepsilon_{c0} = \varepsilon_{c1,\theta}$ for $(d_{fi} + a_{fi}) \le x_{fi} < 3(d_{fi} + a_{fi})$,

        $$x_{e,fi} = \min\left(0.6\frac{\varepsilon_{c0}}{\varepsilon_{c1,\theta}},\ 0.75 - 0.15\frac{x_{fi}}{d_{fi} + a_{fi}}\right)x_{fi},$$

        $$y_{fi} = \max\left(0.65,\ 0.55 + 0.10\frac{x_{fi}}{d_{fi} + a_{fi}}\right)x_{fi},$$



where:

– ε_{c0} is the maximum compressive strain in the concrete at the edge of the cross-section

– $d_{fi} = d - a_z$ is the reduced depth of a cross-section

– $a_{fi} = a - a_z$ is the reduced axis distance of the reinforcement.

Design and structural analysis

Verification with simplified design methods according to prEN 1992-1-2 (cross-sectional resistance)

2. Mechanical analysis for *columns*

   …

   5. Determination of the ultimate load-bearing capacity and verification of the fire design:

      - resisting reinforcement forces

$$F_{sd,0,fi} = \max\left\{E_{s,fi} A_{s0}\left(\varepsilon_{s0} - 1.35 \cdot 10^{-5}\left(\theta_{sc} - 20°\text{C}\right)\left(1 - a_{fi}/d_{fi}\right)\right); -A_{s0} k_{s,\text{Curve 3}}(\theta)\, f_{yk}\right\}$$

$$F_{sd,1t,fi} = \min\left\{E_{s,fi} A_{s1} \varepsilon_{s1,t}; A_{s1} k_{s,\text{Curve 3}}(\theta)\, f_{yk}\right\} \text{ if } x_{fi} < d_{fi}$$

$$F_{sd,1c,fi} = \max\left\{E_{s,fi} A_{s1} \varepsilon_{s1,c}; -A_{s1} k_{s,\text{Curve 3}}(\theta)\, f_{yk}\right\} \text{ if } x_{fi} > d_{fi}$$

where:

- ε_{s0} and $\varepsilon_{s1,c}$ are the compression strains in the relevant reinforcing layers,
- $\varepsilon_{s1,t}$ is the tension strain in the relevant reinforcing layer,
- A_{s0} and A_{s1} correspond to the steel cross section in the relevant reinforcing layer,
- $\theta_{sc} = \frac{\sum_{i=1}^{i=n_{sc}} \theta_{sc,i}}{n_{sc}}$ (°C) represents the average temperature of all effective reinforcing bars in the compression zone with n_{sc} being the number of effective reinforcing bars in the compression zone.

Design and structural analysis

Verification with simplified design methods according to prEN 1992-1-2 (cross-sectional resistance)

2. Mechanical analysis for *columns*

   …

   5. Determination of the ultimate load-bearing capacity and verification of the fire design:

      - design moment

        $M_{d,fi} = -N_{d,fi} \cdot e_d,$

        where:

        $e_d = e_{0d} + e_{1d} + e_{2d} + e_{thermal}$

        e_{0d}, e_{1d}, and e_{2d} are defined as given in SIA 262. $e_{thermal}$ is defined as:

        $$e_{thermal} = \frac{l_{0,fi}^2}{8} \cdot \max\left\{ \frac{1.2 \cdot 10^{-5} \cdot \max\left(\theta_T - 20°C; 180°C\right)}{d_{fi} + a_{fi} + a_z - y_T}; \frac{1.35 \cdot 10^{-5}\left(\theta_{st} - 20°C\right)}{d_{fi}} \right\}$$

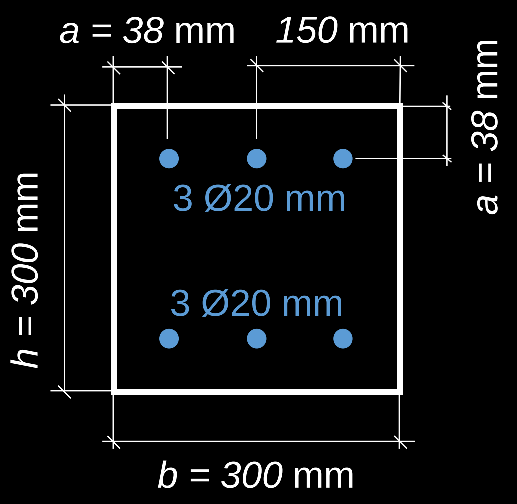
        where:

        – θ_T (°C.) is the concrete temperature in the reference point T. The reference point T is located at $y_T = \min(0.125(d+a), 50\ \text{mm})$ from the edge of the tension side of the cross-section.

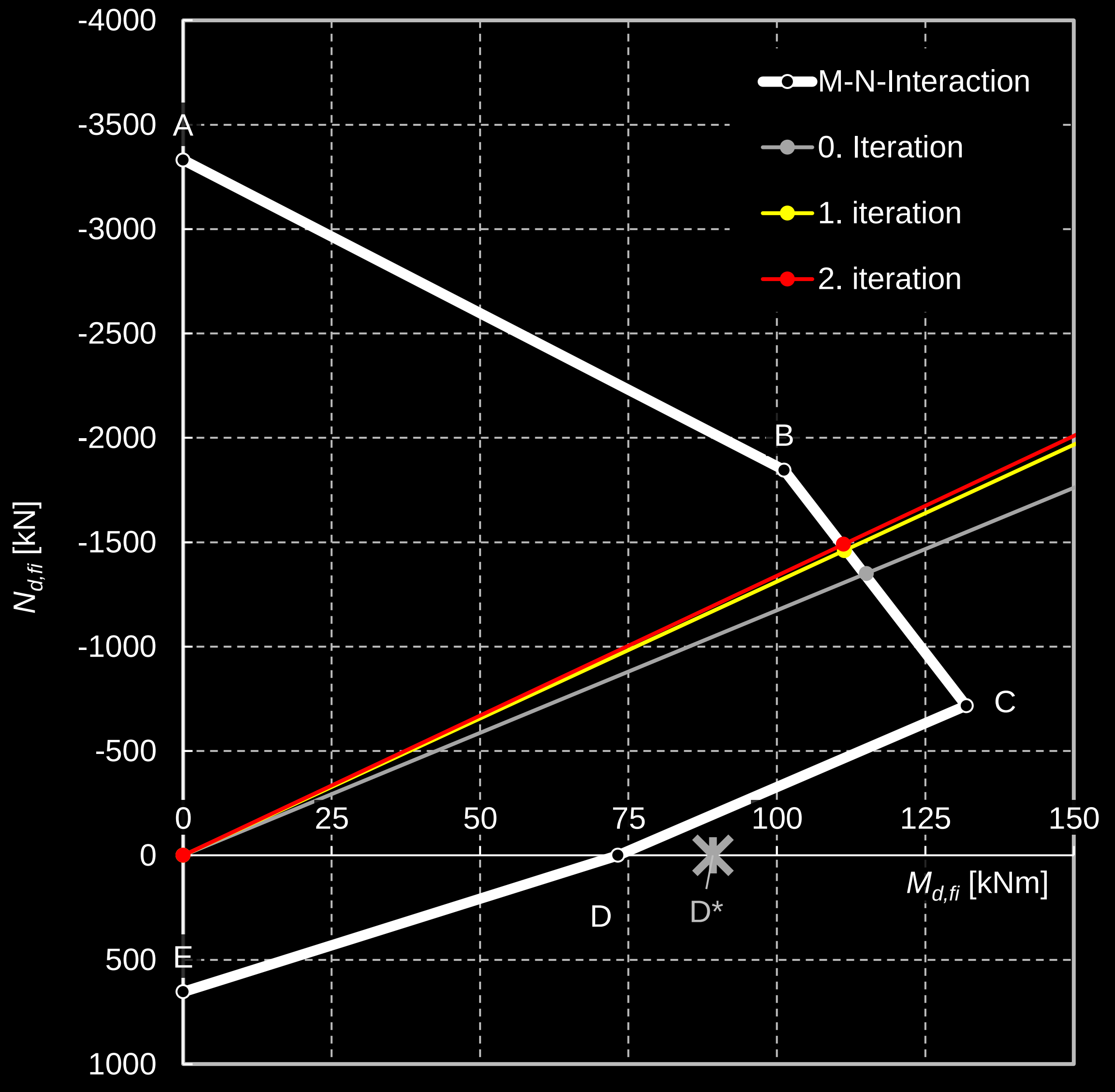
        – $\theta_{st} = \frac{\sum_{i=1}^{i=n_{st}} \theta_{st,i}}{n_{st}}$ (°C) represents the average temperature of all effective reinforcing bars in the tension zone with n_{st} being the number of effective reinforcing bars in the tension zone.

Design and structural analysis

Verification with simplified design methods according to prEN 1992-1-2 (cross-sectional resistance)



Column properties
e_1 = 5 mm
l_{cr} = 3.76 m
$l_{cr,fi}$ = 3.76 m
λ_{fi} = 43.4
Material properties
f_{sk} = 452 MPa
f_c = 42.3 MPa
E_s = 200 GPa



Design and structural analysis

Verification with simplified design methods according to SN EN 1992-1-2 (cross-sectional resistance)

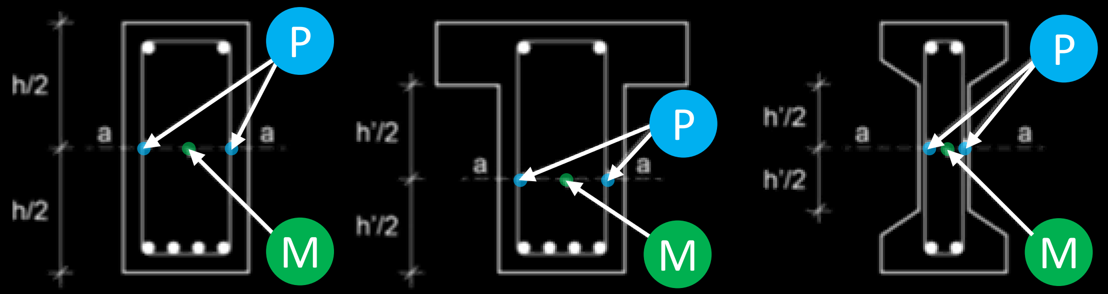
2. Mechanical analysis
   1. Determination of the width of the rim zone a_z
   2. Determination of a reduced width and height of the cross-section by excluding the rim zone a_z
   3. Determination of the reduction of the concrete compression strength (use Figure B.5a) with only one zone → θ_M = Temperature in the centre of the cross-section

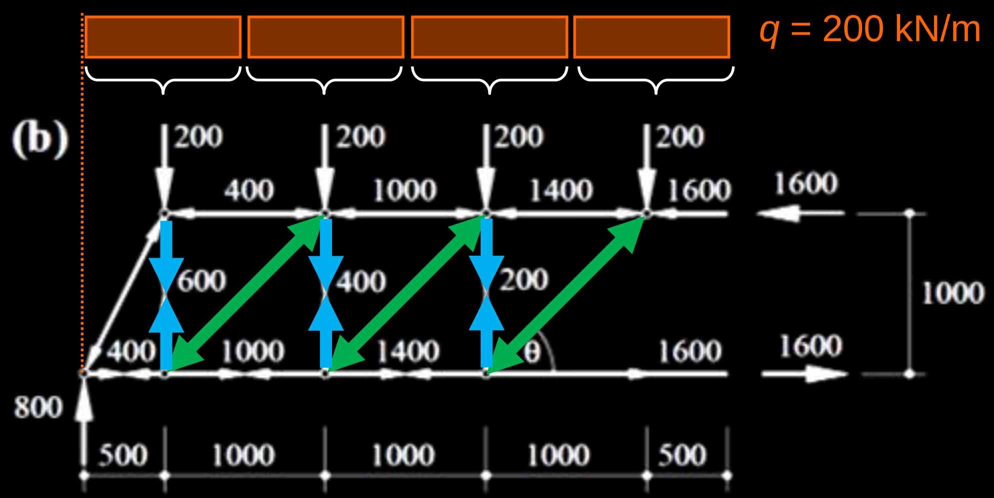
Shear without / with little shear reinforcement

- Verifications may be conducted by using the first three steps of the simplified design method introduced above for bending.
- The design shear strength should be reduced by the factor $k_{ct} = f_{ct,\theta}/f_{ct}$.
- For members with no or little shear reinforcement (e.g. Hollow-Core-Slabs), thermal strains have a negative influence on the resistance for shear loads.

Design and structural analysis

Verification with simplified design methods according to SN EN 1992-1-2 (cross-sectional resistance)





[Marti et al., 1999]

Shear and torsion with shear reinforcement

- Verifications may be conducted by using the simplified design method introduced above for bending.
- The concrete compression strength is reduced relying on the temperature at the reference point M with $f_{c,\theta} = f_{c,\theta}(\theta_M)$.
- The tensile strength of the stirrups is reduced relying on the temperature at the reference point P with $f_{s,\theta} = f_{sy,\theta}(\theta_P)$.
- Increased shear loads to be considered (to account for load redistributions) if stirrups with more than two legs are used
- The same procedure may be applied to verify torsion.

Design and structural analysis

Verification by advanced design methods

Step 1: Thermal analysis
Time-dependent evaluation of temperature field within cross-sections with thermal material properties

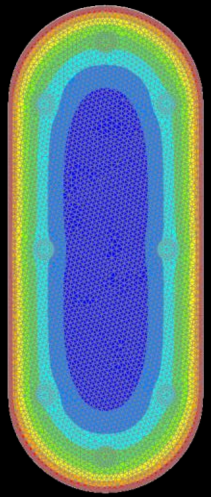
Step 2: Mechanical analysis
Time-dependent evaluation of internal and external actions (restraint!)

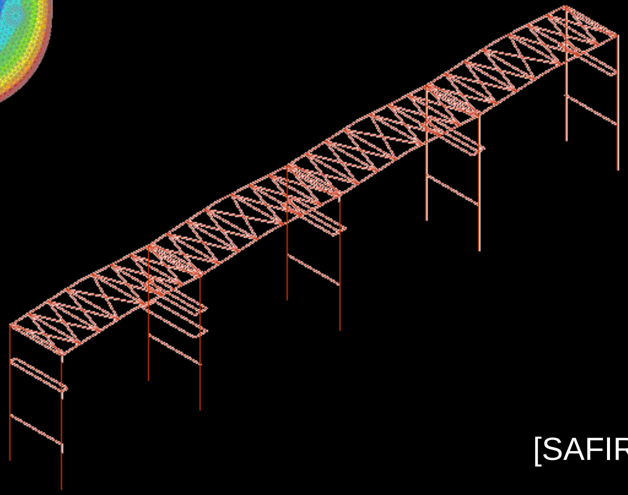
Step 3: Verifications
Verification of load-bearing capacity
$E_{fi,d,t} \leq R_{fi,d,t}$

Verification of fire resistance time
$t_{fi,d} \leq t_{fi,req}$

Verification of critical temperatures
$\theta_d \leq \theta_{cr,d}$

Requirement:
no significant spalling





[SAFIR]

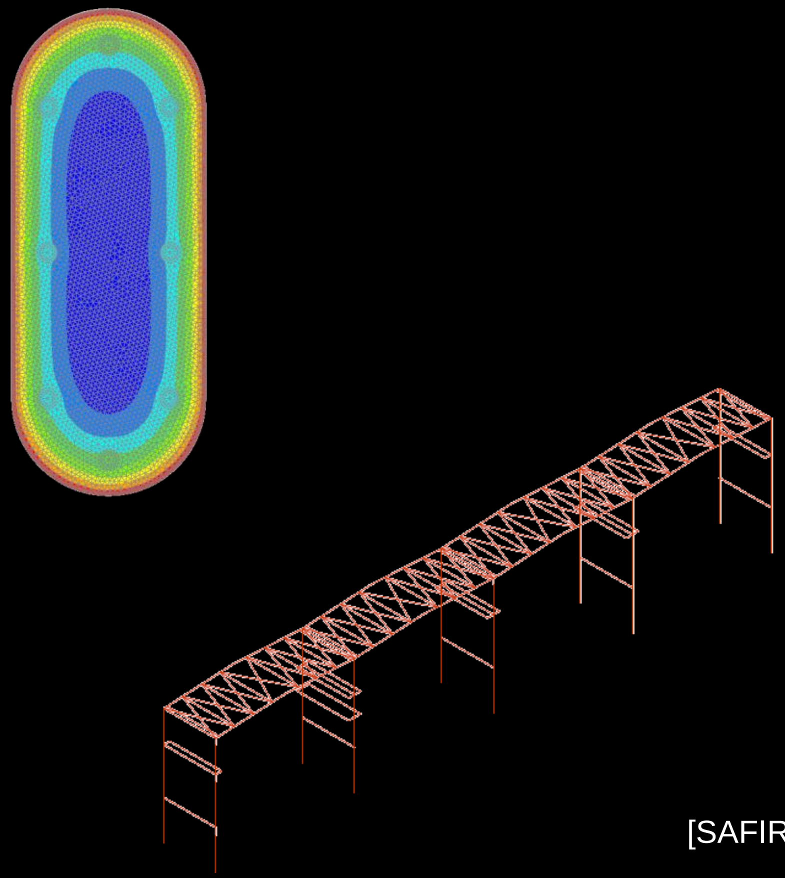
Design and structural analysis

Verification by advanced design methods

- The fire load usually is considerably lower than in tests/ covered by the code with the Standard fire curve.
- Calibration of the used material relationships is unavoidable if part of a structure or entire structures are modelled (especially if internal actions are evaluated for statically indeterminate systems).
- Model uncertainty should be considered, safety concept (partial factors or global safety factor) should be adopted to the design problem.

Conclusion:

A global structural analysis with advanced design methods is highly demanding to designing experts



[SAFIR]

Design and structural analysis

Verification by experiments

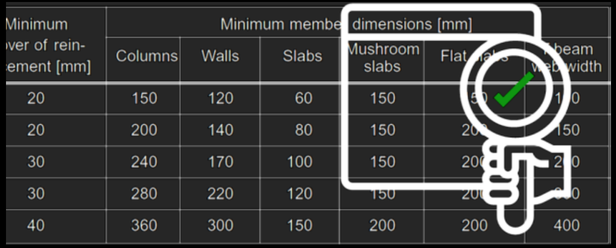
- Fire tests under standard fire exposure by recognised test institutes.

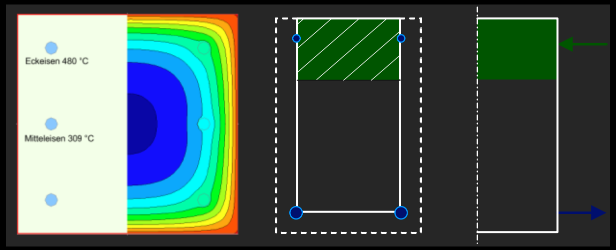
Example: Tests 1:1 under load at the Bundesanstalt für Materialforschung und -prüfung in Berlin

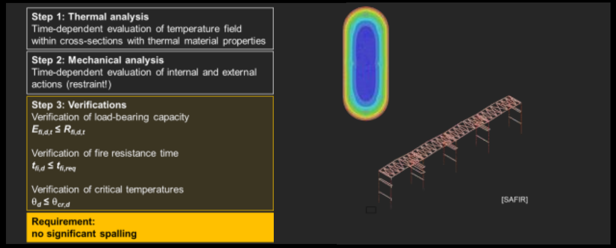
[F.J. Aschwanden AG 2014]

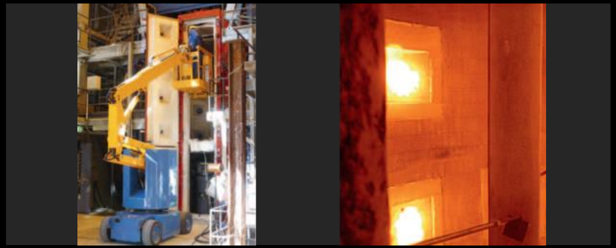
Design and structural analysis

Evaluation of design methods

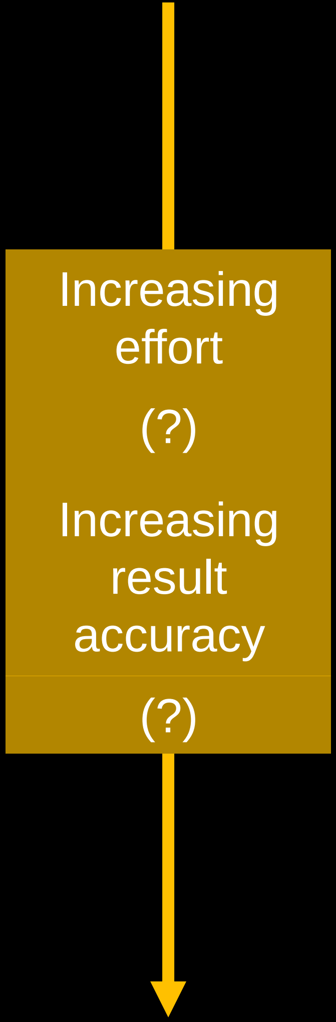








- Level 1: Verification with tabulated design data
  - Covers most design scenarios
  - Quick and easy application
  - Not always more conservative than other design methods
- Level 2: Verification with simplified design methods
  - Deliver structural understanding
  - Easy application
  - (Almost) always conservative than advanced design methods
- Level 3: Verification by the advanced design methods
  - “black box”: numerous thermal and mechanical input parameters ▶
  - useful for fire curves different to Standard fire curve
  - double check with table or simplified design method
- Level 4: Verification by experiments
  - Expensive (only reasonable for example columns)



Learning objectives

Judge **when closer fire engineering consideration** is necessary for reinforced concrete

Describe the **material behaviour** under fire conditions

Describe the **structural behaviour** under fire conditions

Select the **most suitable verification method(s)** for the fire design

Apply **simplified design methods** and understand their relation to design methods at ambient temperature

Understand the need for design verifications related to **explosive spalling** and use the appropriate measure to deal with it

Explosive spalling of concrete

Concretes or members at risk of explosive spalling:

- High strength and ultra high strength concrete
- Very dense concrete (e.g. self compacting concrete)
- Highly stressed members (columns, supports)

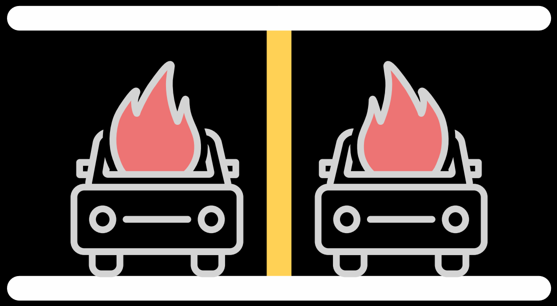
After explosive spalling of the concrete cover, the reinforcement is no longer protected from the effects of temperature. Hence, fire safety must be demonstrated for concretes at risk, taking into account explosive spalling, or preventive measures must be taken.

NB: The great attention that explosive spalling in the event of fire has received in the last 10 years in Switzerland was triggered by extensive damages in tunnel fire events (very extreme fire exposure) and the extremely explosive behaviour of loaded high strength concrete (compressive strength classes >> C50/60) in fire tests.

Explosive spalling of concrete

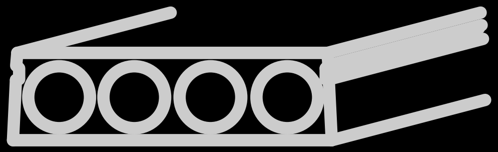
What members require closer fire engineering consideration when designing concrete structures?

Slender columns/ highly loaded walls with small member dimensions (HPC/ UHPC)

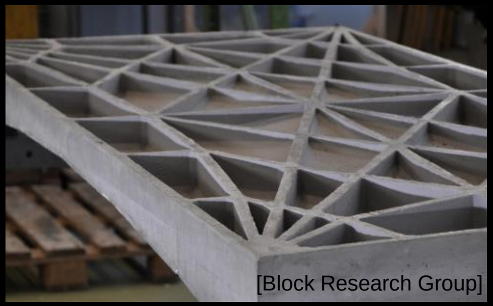


Statically indeterminate slabs
without (punching) shear reinforcement

Members with slender webs (especially when using HPC or UHPC)



Hollow core slabs



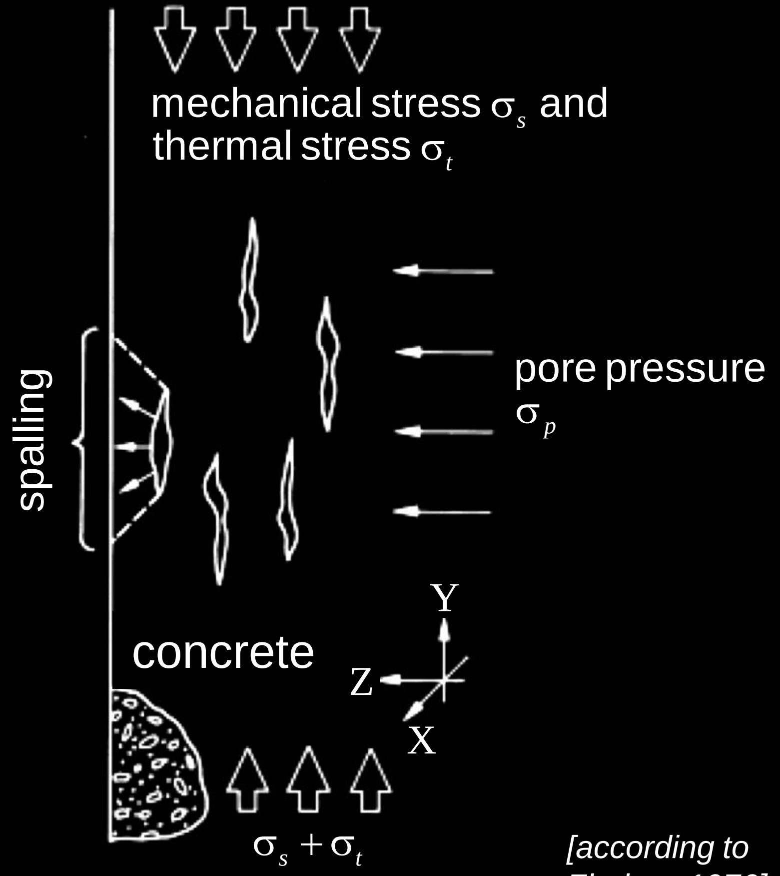
Ribbed slabs

Members with intense fire exposure
(tunnels/ tunnel segments, fire ratings >R90

Explosive spalling of concrete

Approach to explain the phenomenon:

- Temperature increase → Vapour pressure in concrete (water vapour tries to escape) and thermal stresses (restrained expansion, note: reinforced concrete ≠ homogeneous).
- Thermal stress is superimposed to mechanical stress.
- Possible criterion for plausibility:
  Spalling if the resulting stress exceed the tensile strength of concrete (reduced by temperature increase).



[according to Zhukov, 1976]

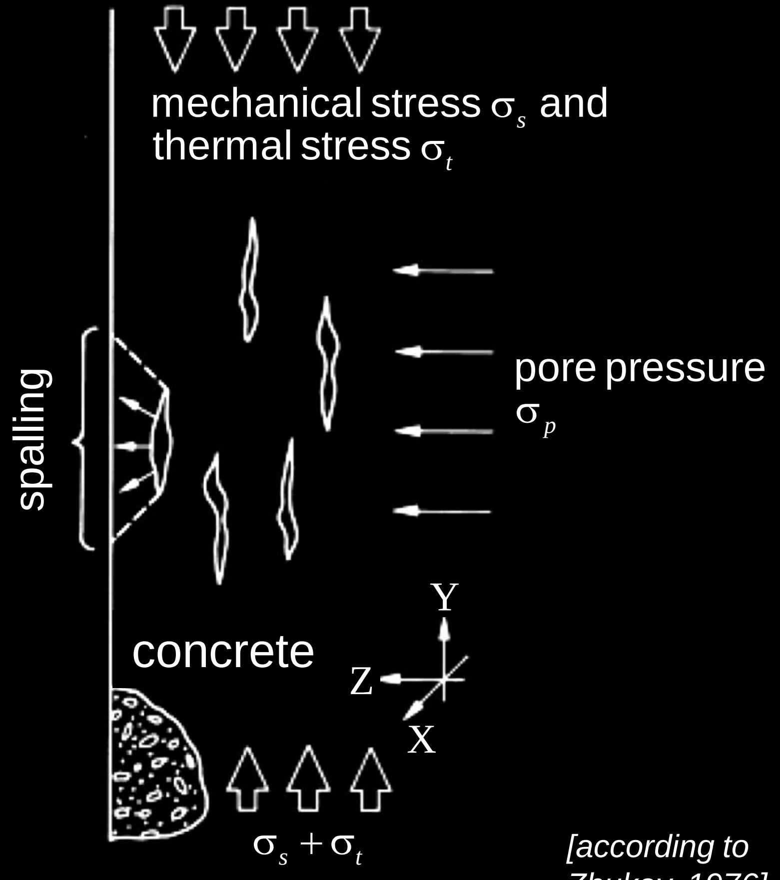
Explosive spalling of concrete

Influencing parameters include:

- Effect of temperature (heating rate)
- Type of aggregates (lightweight, recycled)
- Mechanical stress
- Cracks
- Concrete composition (→ concrete properties)
- Moisture content
- Reinforcement density and arrangement
- …

Current state of knowledge:

Despite progress in research, it is still not possible today to specify generally applicable, reliable quantitative rules for the prediction or the prevention of explosive spalling.



[according to Zhukov, 1976]

Explosive spalling of concrete

Standard provisions identifying the risk of explosive spalling for Standard fire curve

- SN EN 1992-1-2 → purely material-based approach:
  - Moisture content k < 3% for ≤ C50/60
  - ≥ C55/60 to ≤ C80/95: Silica fume content < 6%.
  - Exposure classes X0 and XC1 for 2.5% ≤ k ≤ 3%
  - Verification with tables (for ≤ C50/60)

{ Important, but not exclusive parameters! Rarely known in design phase (← moisture content / silica fume content)

{ Contradiction to the definition of minimum requirements for material (← exposure classes X0 and XC1)

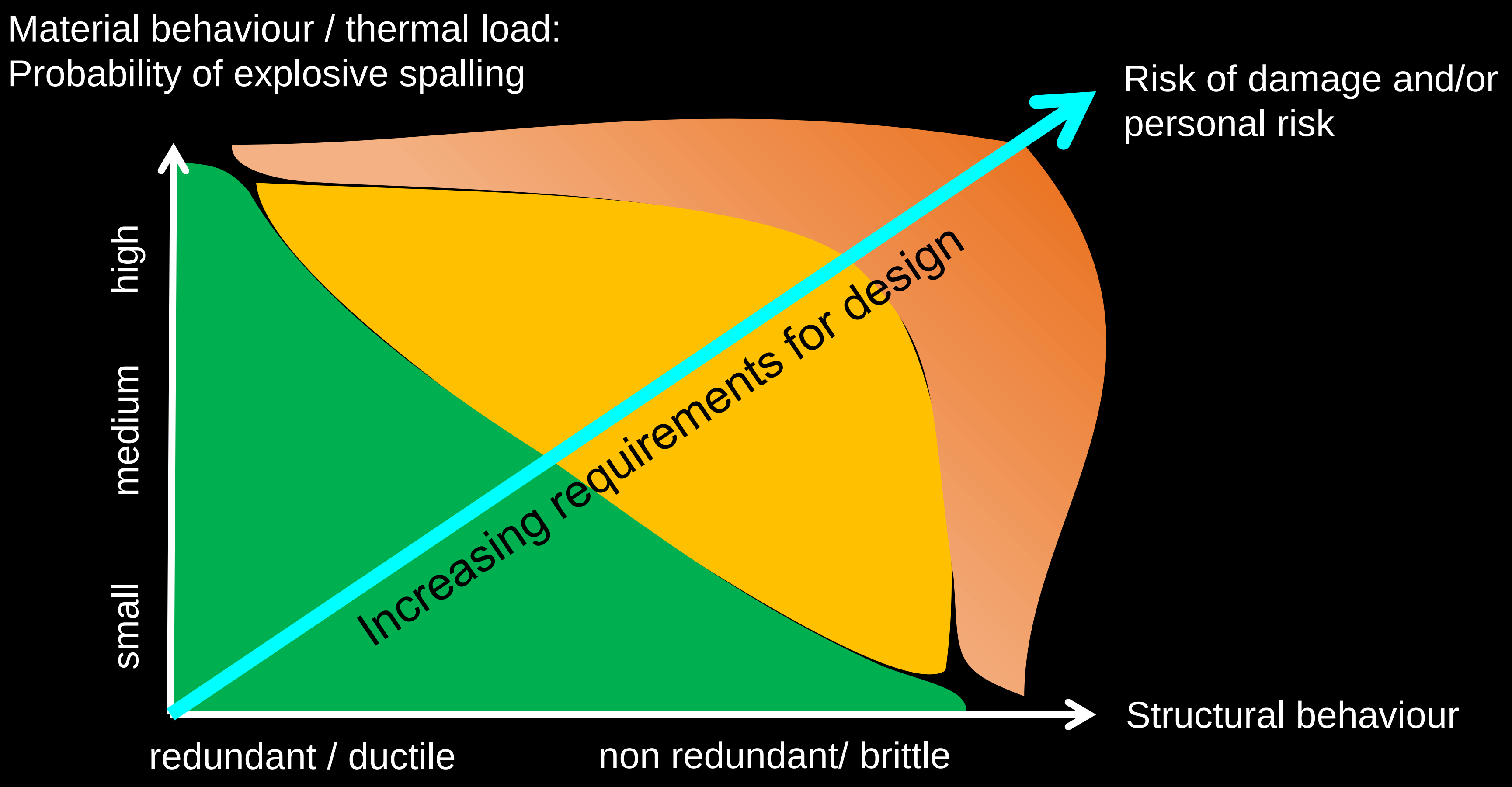
- SIA 262 → implied risk-based approach (explanation see next slide):

<table>
<tr><th></th><th>≤ R 30</th><th>R 60</th><th>R 90</th><th>> R 90</th></tr>
<tr><td>≤C25/30</td><td rowspan="5">No verification</td><td colspan="3" rowspan="2">$f_{cm,28}$ = 45 MPa ▼ No verification</td></tr>
<tr><td>C30/37</td></tr>
<tr><td>C35/45</td><td colspan="3" rowspan="3">Verification required for self-compacting concrete (SCC),
Definition of SCC via flow classes
Exception: redundant / ductile members and robust structures</td></tr>
<tr><td>C40/50</td></tr>
<tr><td>C45/55</td></tr>
<tr><td>C50/60</td><td colspan="4" rowspan="2">Verification required (all consistency classes)
Exception: redundant / ductile members and robust structures</td></tr>
<tr><td>> C50/60</td></tr>
</table>

- Design provisions in SN EN 1992-1-2 and SIA 262 concerning explosive spalling are only valid for the Standard fire curve

Explosive spalling of concrete

Risk-based approach dealing with uncertainties related to material behaviour



Explosive spalling of concrete

Identification of an "explosive spalling issue" according to prEN 1992-1-2:2019

	Tabulated design data	Simplified design methods	Advanced design methods
≤C 60/75	**No verification** unless: • Silica fume content ≥ 6% • Exceptions below apply	**No verification** unless: • Slender columns highly loaded (to be defined) • Slender webs • Silica fume content ≥ 6% • Exceptions below apply	
C 70/85	**Verification required**		
C 80/95			
C 90/105			
C 100/115			

Verification required in any case:

- lightweight aggregate concrete
- buildings in a water saturated environment
- insulating permanent formwork which prevents concrete from drying

Explosive spalling of concrete

Measures: PP fibres

[www.expressbeton.at 2016]

Tests on specimens with PP fibres

UHPC
4 kg/m^3 PP fibres
d = 32 µm
l = 6 mm

UHPC
2 kg/m^3 PP fibres
d = 18 µm
l = 6 mm

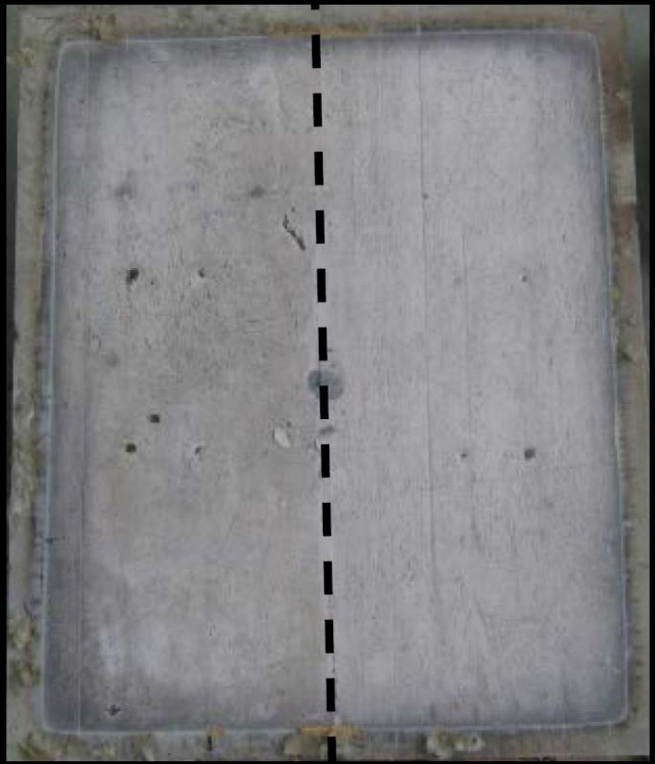
[Klingsch et al., 2013]

Explosive spalling of concrete

Measures: PP fibres

Tests on UHPC concrete slabs with PP fibres: No spalling after 120 min exposure to Standard fire curve

UHPC
2 kg/m^3 PP-Fasern
d = 18 µm
l = 6 mm



UHPC
3 kg/m^3 PP-Fasern
d = 18 µm
l = 6 mm

[Klingsch et al., 2013]

Explosive spalling of concrete

Measures: Fire protection systems

Tests on HPC concrete slabs with coating of thickness d_p: 120 min exposure to Standard fire curve

Continuous spalling after
17 min of fire exposure
d_p = 0 mm

Explosive spalling after
119 min of fire exposure
d_p = 10 mm

No spalling

d_p = 20 mm

[Klingsch et al., 2013]

Explosive spalling of concrete

Measures against explosive spalling of concretes or members at risk

- Use of concrete of strength class < C50/60 (crane/pumped concrete) or $f_{cm,28} \leq 45$ MPa (self-compacting concrete)
- Design of redundant / ductile members and robust structures
  prEN 1992-1-2:2019: Influence on performance (R and/or EI) of severe spalling may be taken into account considering the loss of strength of member(s) either at member or at structure level by a reduced effective cross section omitting a spalled layer of concrete based on experimental evidence.
- Use of members with valid *VKF-Zertifikat* (columns and prestressed ribbed slabs)
- Verification with fire tests to obtain *VKF-Zertifikat*:
  - «direkter Anwendungsbereich»: each test only applies to the member as tested
  - «erweiterter Anwendungsbereich»: several tests, further analyses carried out by experts
    → useful for precast elements with large quantities and varying configurations

  For other fire curves than the Standard fire curve, fire tests are necessary.
- Use of concrete mixes with PP fibres/ use of protective layers.
  The effectiveness of PP fibres in the corresponding concrete mix and of protective layers must be demonstrated by tests (e.g. defining the exact geometry of the PP fibres, uniform distribution of the PP fibres indispensable).

Assessment of existing structures

- Even though the standards SIA 262 and SN EN 1992-1-2 are intended for the design of new structures, they are used for the assessment of existing structures (no standards are available for the assessment of existing structures exposed to fire)
- Thermal properties and reduction factors for mechanical properties given in SN EN 1992-1-2 may be used.
- Tabulated design data as well as simplified and advanced design methods given in SIA 262 and SN EN 1992-1-2 may be used provided the cross-section geometry is retained throughout the fire (no explosive spalling).
- No systematic studies on the susceptibility of existing concrete (with increased concrete strength (*) and reduced moisture content) to explosive spalling are available. Tests on few samples of existing structures indicate that concretes built before 1995 tend to have a low probability of explosive spalling.
- An increased susceptibility of existing concrete to spalling may be approached by a systematic structural analysis defining alternative load paths.

(*) relevant since old concrete, particularly if produced several decades ago with almost 100% clinker cement (CEM I), typically has a much higher compressive strength today than at the time of construction, and, therefore, violates the spalling susceptibility criteria of current guidelines solely depending on the compressive strength.

Assessment of existing structures

Typical procedure:

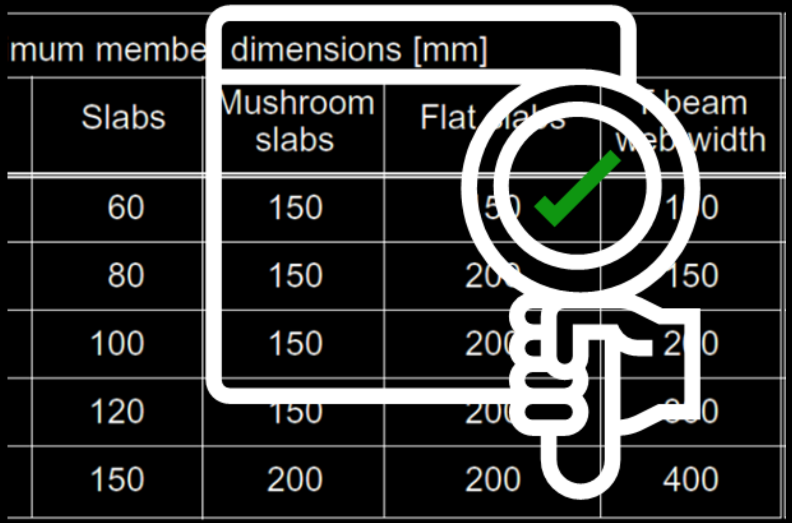
1. Study of plans / analysis of structure
2. Investigation on site
   - Determination / verification of minimum member dimensions
   - Determination / verification of concrete cover / average axis distance per member
   - Estimation of actual concrete strength, e.g. by Schmidt hammer

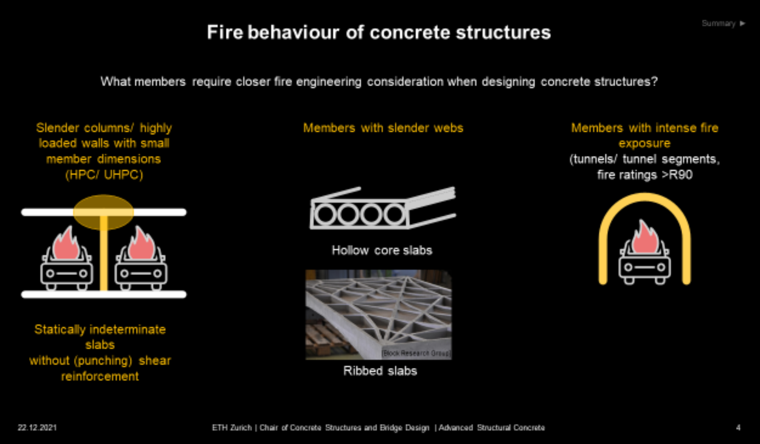
   Possibly more detailed investigation:
   - Concrete strength from samples (useful also to calibrate Schmidt hammer results)
   - Concrete permeability: air-permeability (see Figure) or oxygen permeability
   - Concrete moisture content
3. Determination of fire resistance time
   - Check of cross-sectional dimensions by tabulated design data or analysis with simplified / advanced design methods

   Possibly more detailed investigation:
   - Check of susceptibility to explosive spalling by testing (representative conditions)

[TFB AG]

Summary



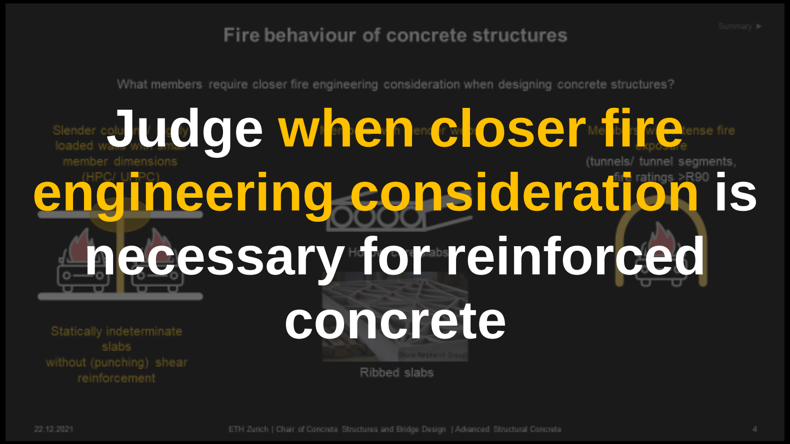


In principle, concrete offers good protection against high temperatures caused by fire.

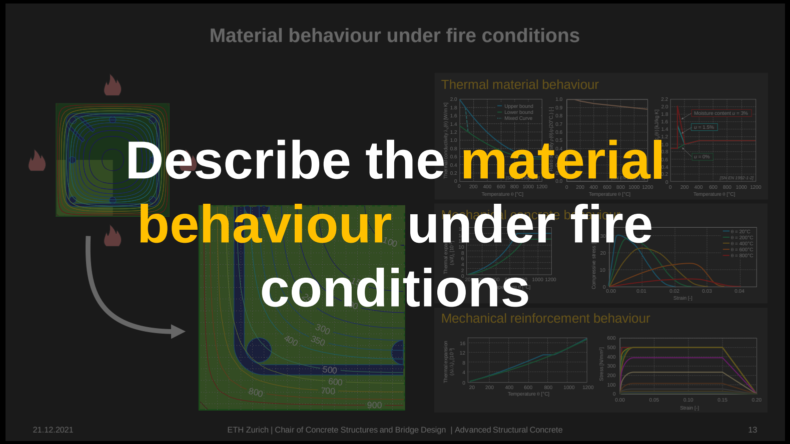
The fire resistance of reinforced concrete structures can in most cases be ensured by conceptual decisions and quick verifications of minimum dimensions using tabulated design data.

Some members require closer fire engineering consideration when designing concrete structures

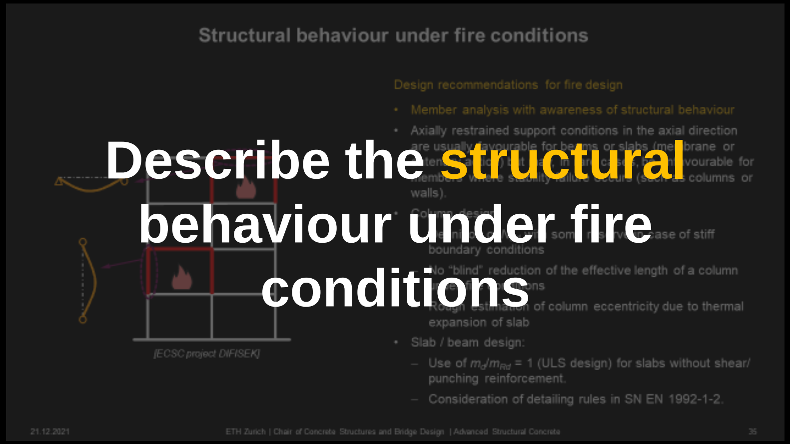
Learning objectives - Summary



Judge when closer fire engineering consideration is necessary for reinforced concrete

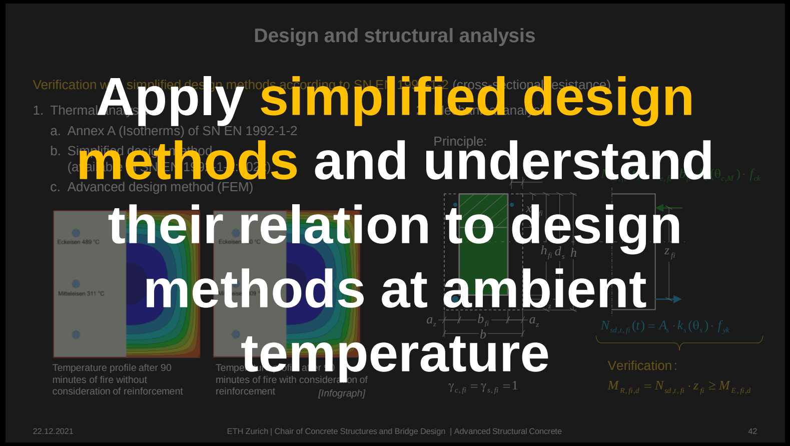


Describe the material behaviour under fire conditions



Describe the structural behaviour under fire conditions

Select the most suitable verification method(s) for the fire design



Apply simplified design methods and understand their relation to design methods at ambient temperature

Understand the need for design verifications related to explosive spalling and use the appropriate measure to deal with it