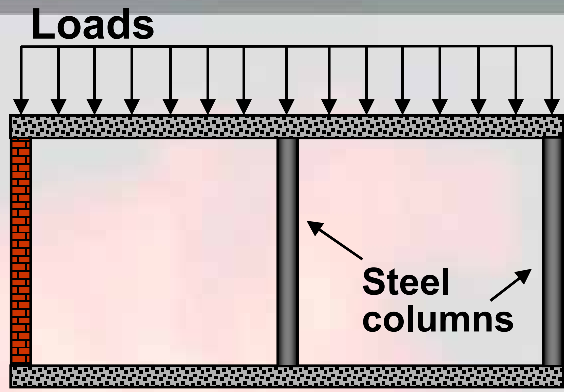
DIFISEK

Part 3: Mechanical response

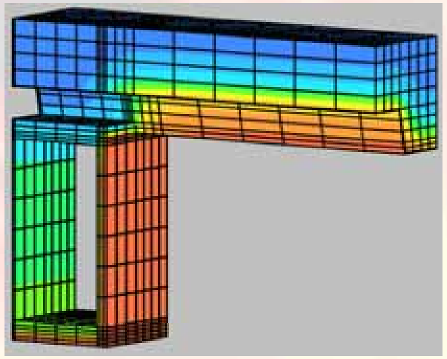
Resistance to fire - Chain of events

1: Ignition

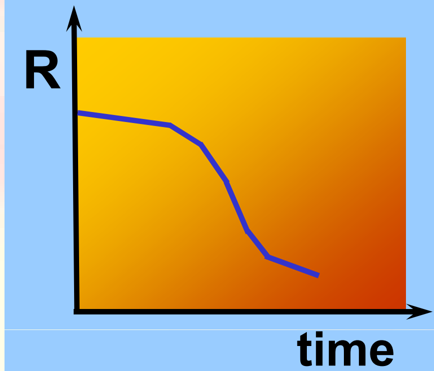
2: Thermal action



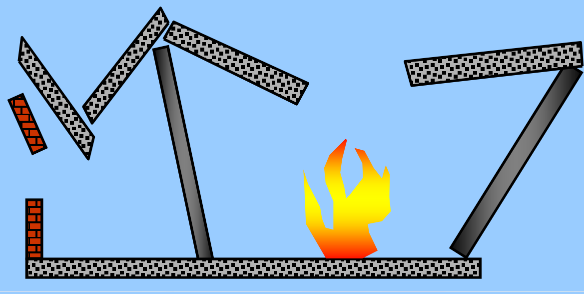
3: Mechanical actions



4: Thermal response



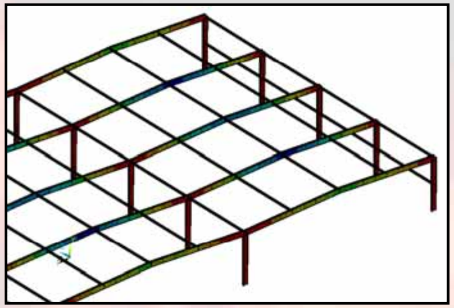
5: Mechanical response



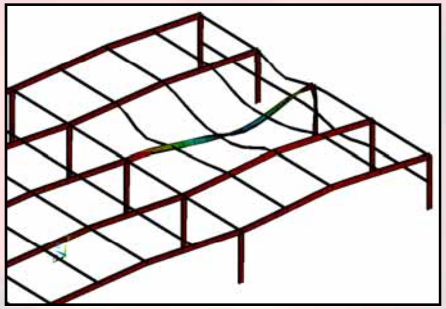
6: Possible collapse

How structures react to fire

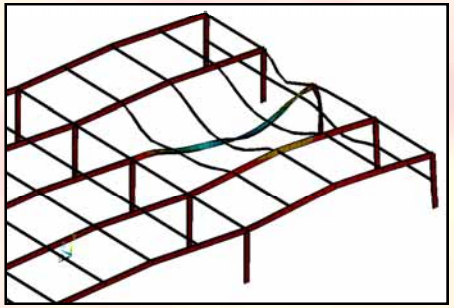
- Temperature rise ➔ thermal expansion + loss of both stiffness and resistance ➔ additional deformation ⇒ eventual collapse



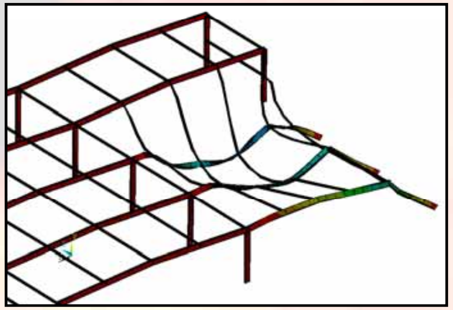
t = 0 θ = 20°C



16 min θ = 620°C



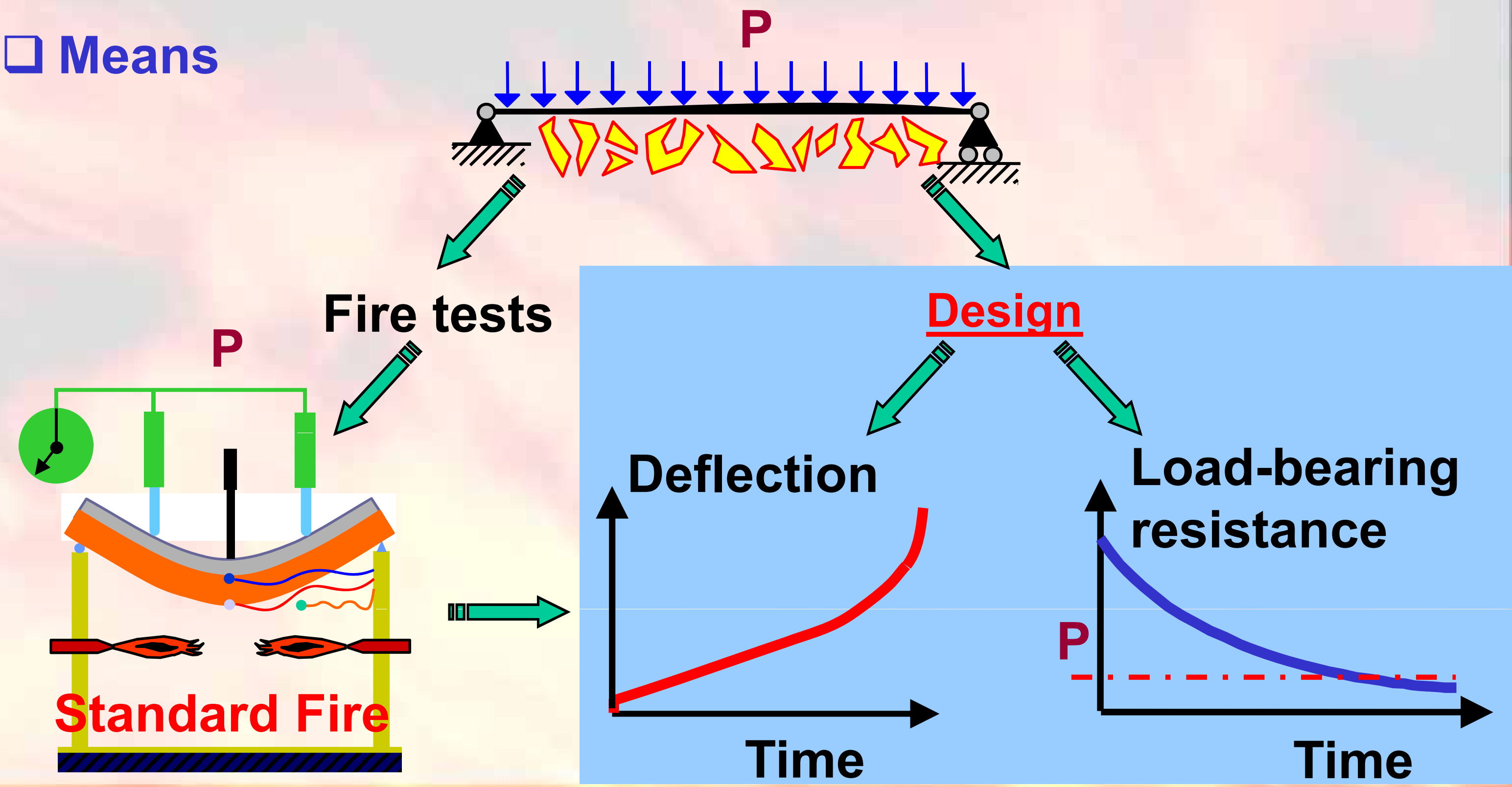
22 min θ = 720°C



31 min θ = 850°C

Assessment of mechanical response of structures in fire

- **Purpose**
  - to describe **structural behaviour** under any type of fire condition
- **Means**



Basic features related to assessment of mechanical response of steel structures in fire

- **Mechanical loadings under fire situation**
  - **specific load combination**
- **Mechanical properties of relevant materials at elevated temperatures**
  - **stiffness and resistance varying with temperatures**
- **Assessment methods for structural analysis in fire**
  - **different approaches**
  - **application domain**
- **Specific consideration in fire design of steel and composite structures**
  - **connections, joints, etc**

Mechanical loading – combination according to Eurocode (ČSN EN 1990 and ČSN EN 1991-1-2)

$$\sum_{j \geq 1} G_{k,j} + (\Psi_{1,1} \text{ or } \Psi_{2,1})\, Q_{k,1} + \sum_{i \geq 2} \Psi_{2,i}\, Q_{k,i}$$

$G_{k,j}$: characteristic values of permanent actions

$Q_{k,1}$: characteristic leading variable action

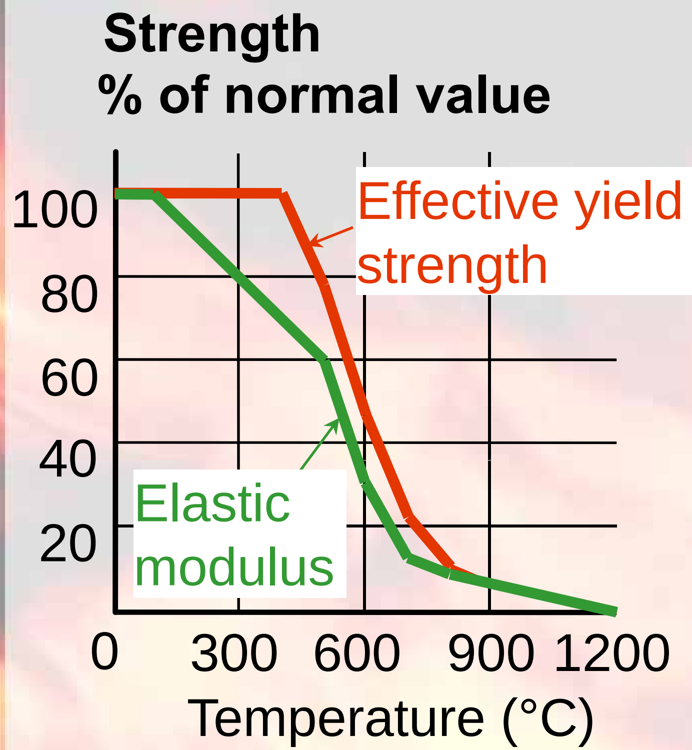
$Q_{k,i}$: characteristic values of accompanying variable actions

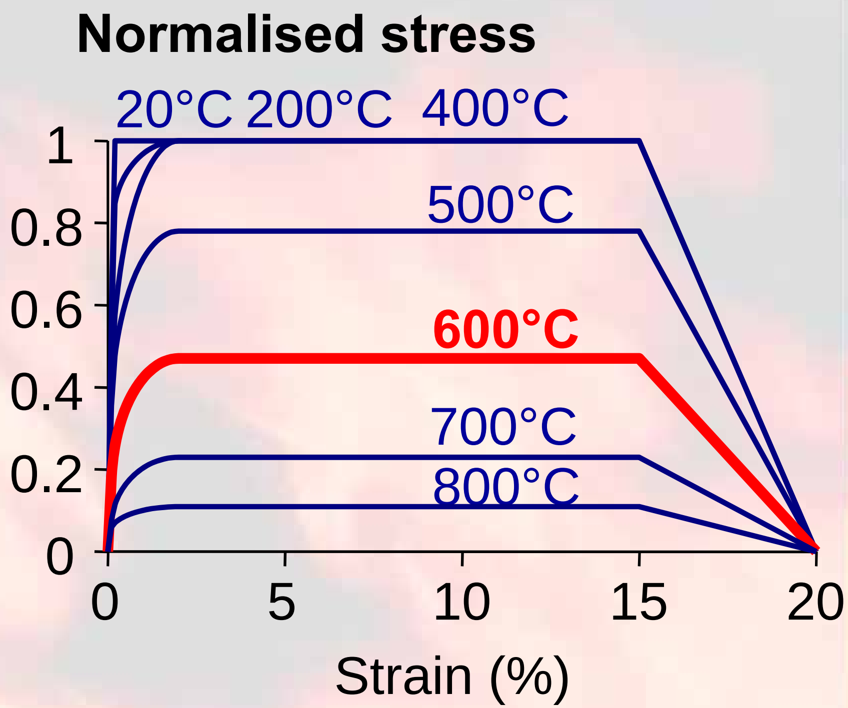
$\psi_{1,1}$: factor for frequent value of a leading variable action

$\psi_{2,i}$: factor for quasi-permanent values of accompaning variable actions

➔ Load level: $\eta_{fi,t}$ (see presentation of WP1)

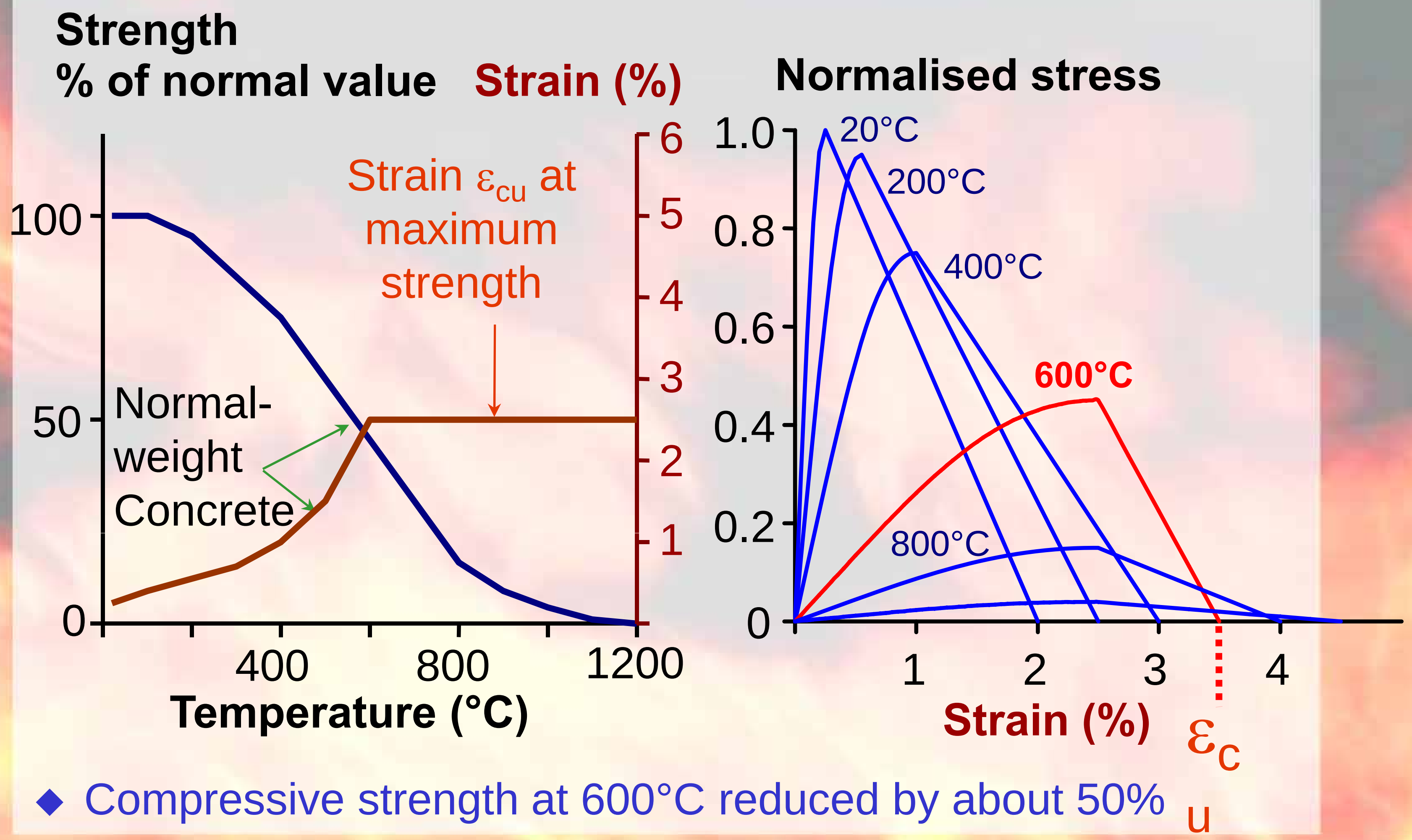
Mechanical properties of structural steel at elevated temperatures (ČSN EN 1993-1-2)





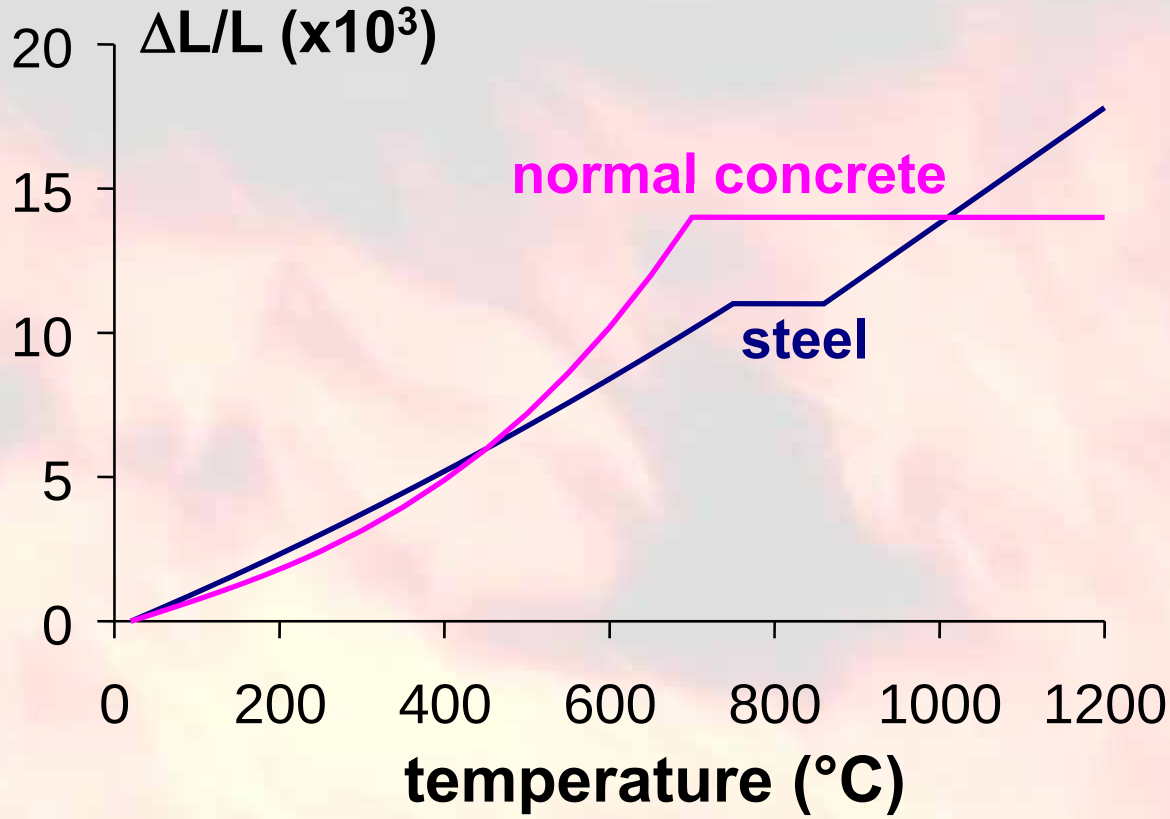
- Elastic modulus at 600°C reduced by about 70%
- Yield strength at 600°C reduced by over 50%

Mechanical properties of concrete at elevated temperatures (ČSN EN 1994-1-2)



- Compressive strength at 600°C reduced by about 50%

Thermal expansion of steel and concrete (ČSN EN 1993-1-2 and ČSN EN 1994-1-2)



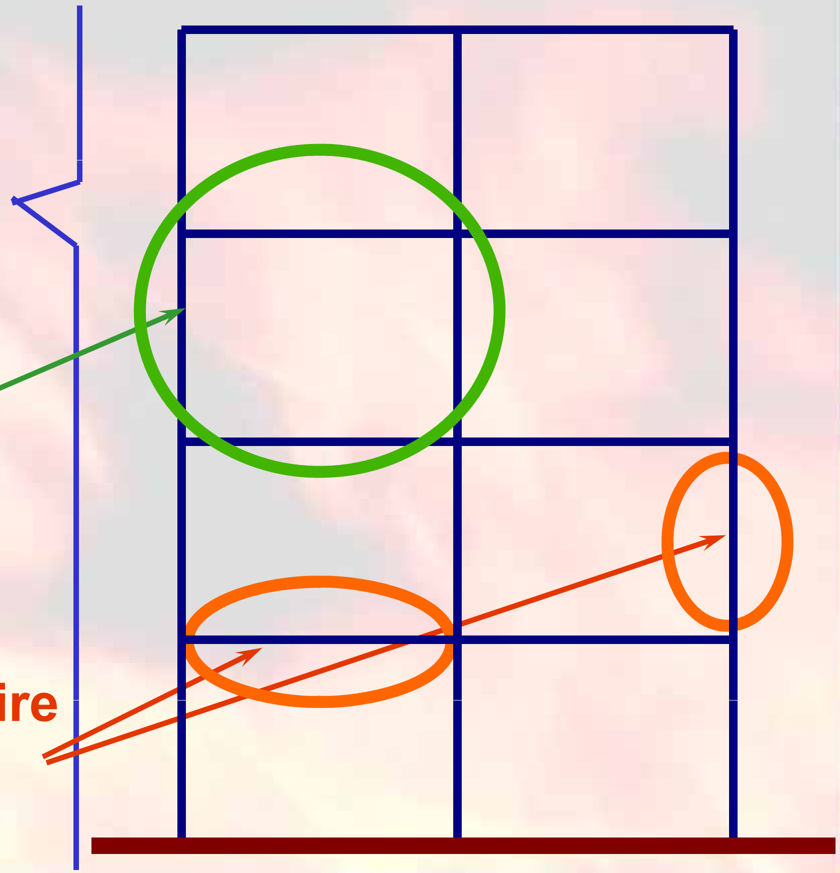
Different design approaches for mechanical response of structure in fire

- Three different approaches according to Eurocodes

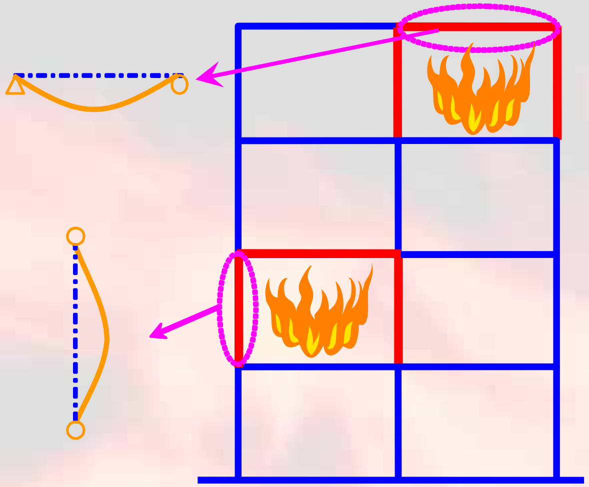
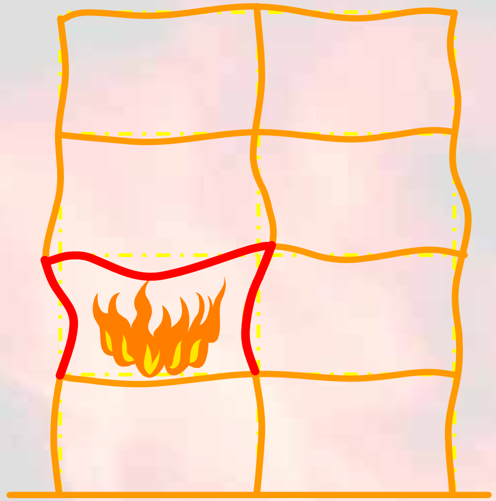
global structural analysis

analysis of parts of the structure

member analysis (mainly when verifying standard fire resistance requirements)



Different design approaches for mechanical response of structure in fire

Member analysis	Global structural analysis
	
➢ independent structural element analysis ➢ simple to apply ➢ generally for nominal fire condition	➢ interaction effects between different parts of the structure ➢ role of compartment ➢ global stability

Three types of design methods for assessing mechannical response of structures in fire

- **Tabulated data**
  - composite structural members
- **Simple calculation models**
  - critical temperature
  - steel and composite structural members

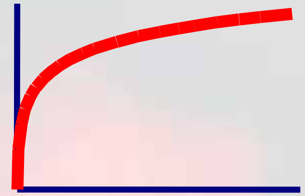
→ ***Classic and traditional application***

- **Advanced calculation models**
  - all types of structures
  - numerical models based on:
    - finite element method
    - finite difference method

→ **Advanced and specific fire design**

Application domain of different design methods under fire situation

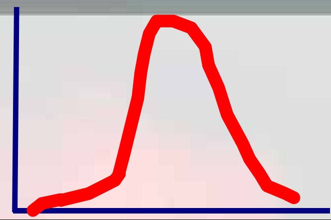
❑Thermal action defined with nominal fires



Type of analysis	Tabulated data	Simple calculation models	Advanced calculation models
Member analysis	Yes ISO-834 standard fire	Yes	Yes
Analysis of a part of the structure	Not applicable	Yes (if available)	Yes
Global structural analysis	Not applicable	Not applicable	Yes

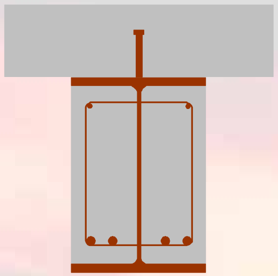
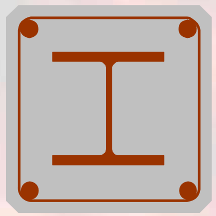
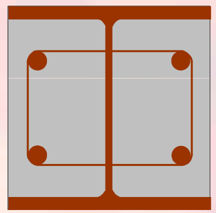
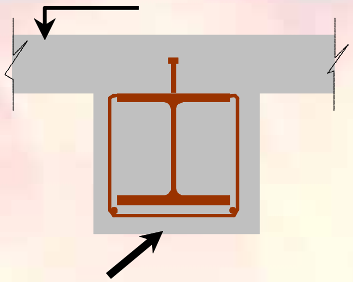
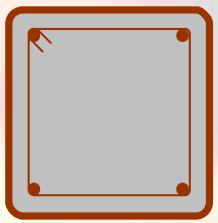
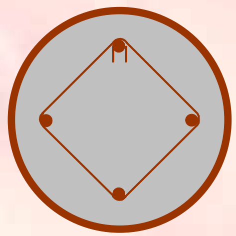
Application domain of different design methods under fire situation

❑Thermal action defined with natural fires

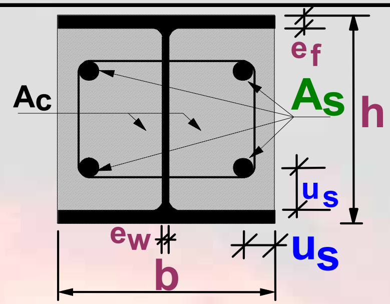


Type of analysis	Tabulated data	Simple calculation models	Advanced calculation models
Member analysis	Not applicable	Yes (if available)	Yes
Analysis of a part of the structure	Not applicable	Not applicable	Yes
Global structural analysis	Not applicable	Not applicable	Yes

Tabulated data (steel and concrete composite members)

Composite beams	Composite columns	
		
		

Tabulated data and relevant parameters (composite columns – ČSN EN 1994-1-2)



		Standard Fire Resistance			
		R30	R60	R90	R120
	Minimum ratio of web to flange thickness e_w/e_f	0,5			
1	Minimum cross-sectional dimensions for load level	$\eta_{fi,t} \leq 0{,}28$			
1.1	minimum dimensions h and b [mm]	160	200	300	400
1.2	minimum axis distance of reinforcing bars u_s [mm]	-	50	50	70
1.3	minimum ratio of reinforcement $A_s/(A_c+A_s)$ in %	-	4	3	4
2	Minimum cross-sectional dimensions for load level	$\eta_{fi,t} \leq 0{,}47$			
2.1	minimum dimensions h and b [mm]	160	300	400	-
2.2	minimum axis distance of reinforcing bars u_s [mm]	-	50	70	-
2.3	minimum ratio of reinforcement $A_s/(A_c+A_s)$ in %	-	4	4	-
3	Minimum cross-sectional dimensions for load level	$\eta_{fi,t} \leq 0{,}66$			
3.1	minimum dimensions h and b [mm]	160	400	-	-
3.2	minimum axis distance of reinforcing bars u_s [mm]	40	70	-	-
3.3	minimum ratio of reinforcement $A_s/(A_c+A_s)$ in %	1	4	-	-

Standard fire rating

Load level

Section dimension

Reinforcing steel

Concrete cover

How to apply tabulated data in fire design (two different situations)

VERIFICATION

R_d of $\theta_{20°C}$

↓

$E_{fi.d}$

↓

$\eta_{fi,t} = E_{fi.d} / R_d$

↓

Section dimension
reinforcing steel
concrete cover

↓

Standard fire rating

PRE-DESIGN

$E_{fi.d}$ and E_d

↓

$\eta_{fi,t} = E_{fi.d} / E_d$

↓

Standard fire rating

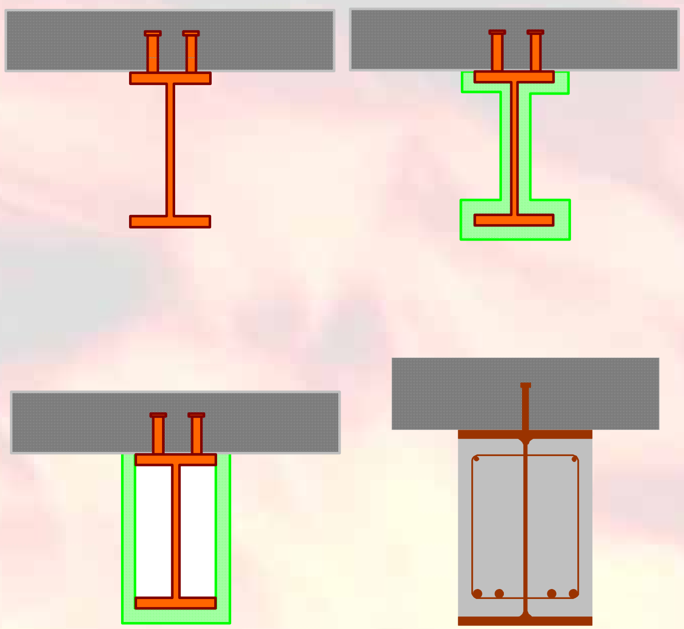
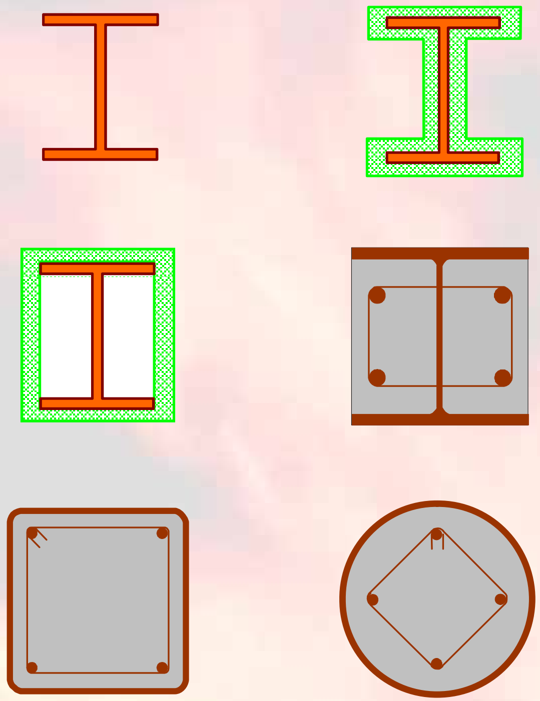
↓

Section dimension
reinforcing steel
concrete cover

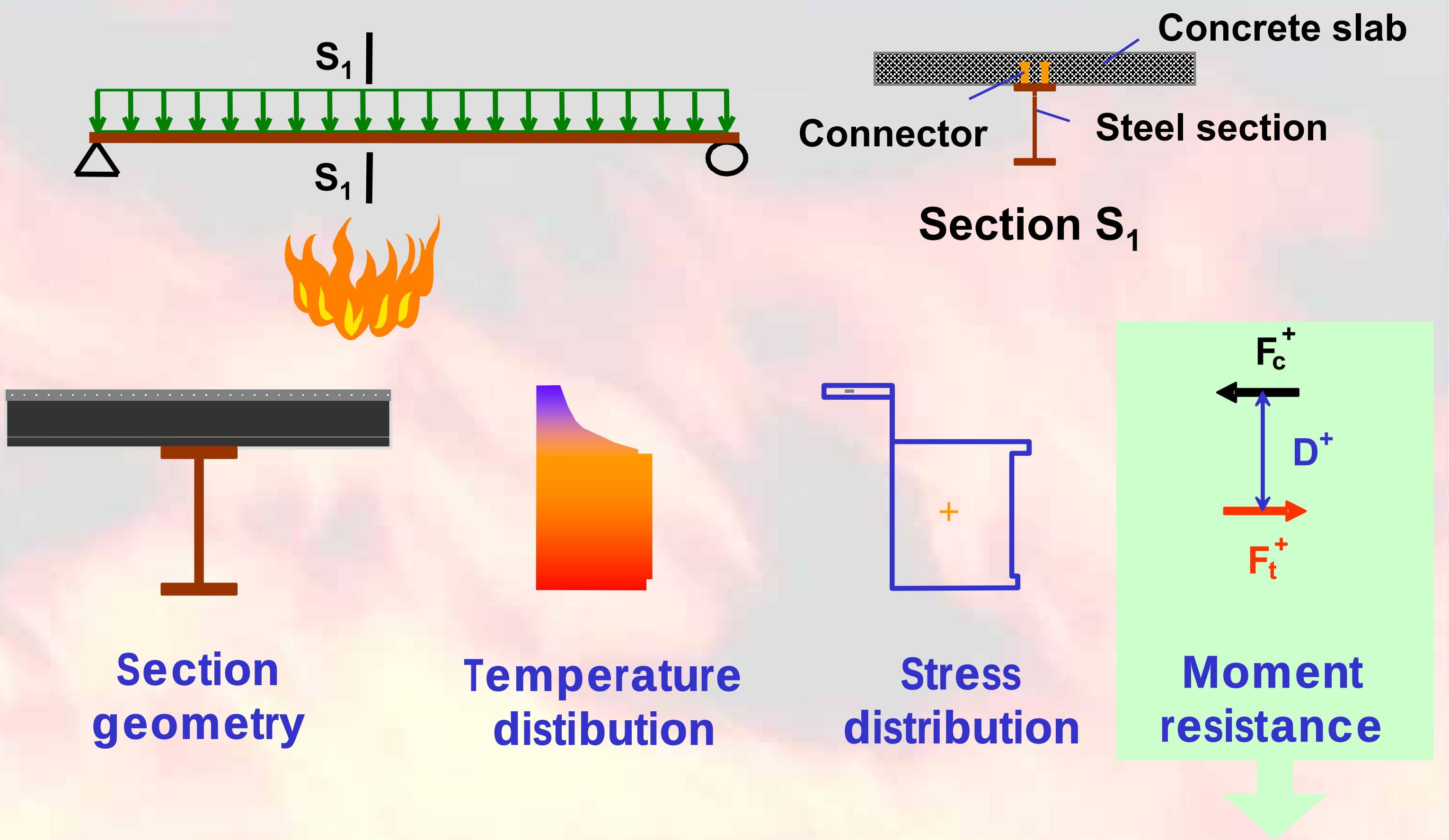
↓

$R_d \geq E_d$

Simple calculation model (steel and composite members)

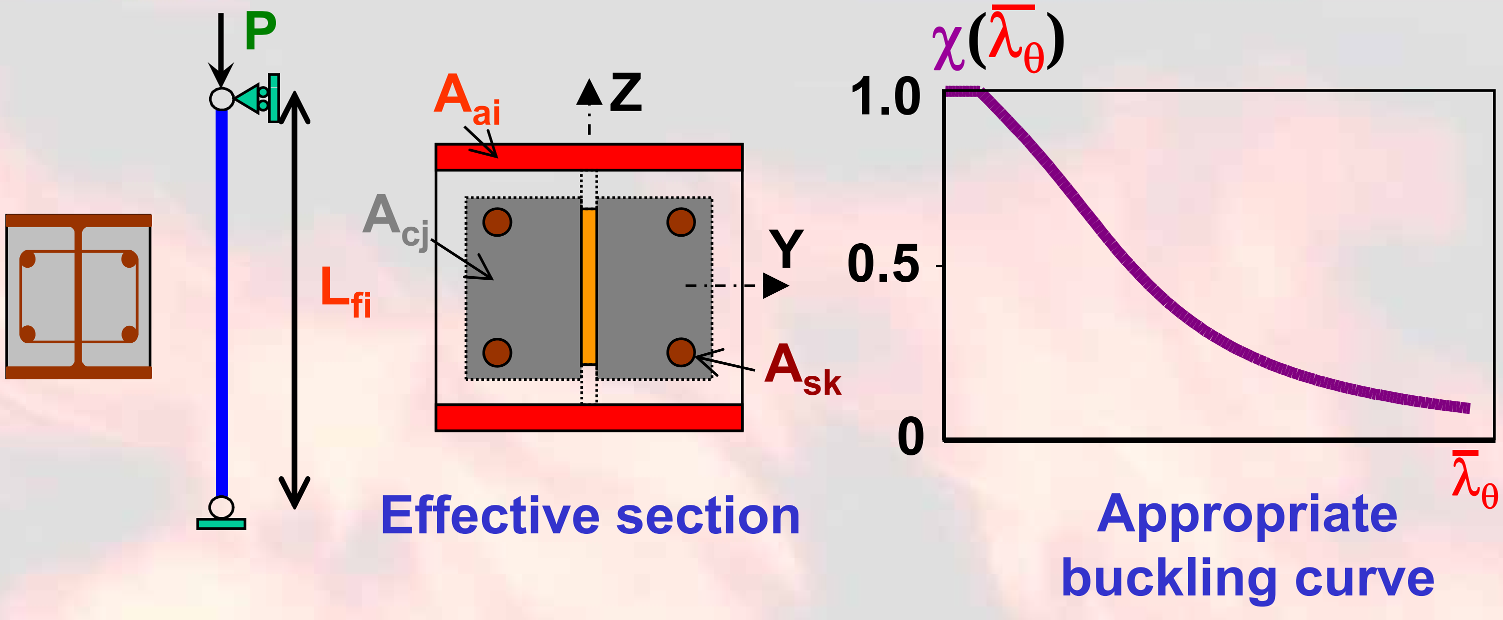
Beams (steel or composite)	Columns
	

Simple calculation model (composite beam) - plastic resistance theory



$$M_{fi,Rd^+} = F_t^+ \times D^+$$

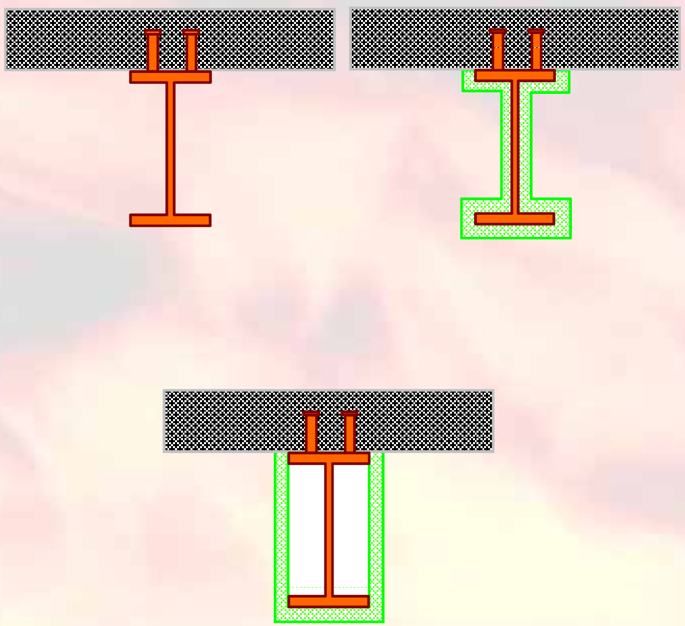
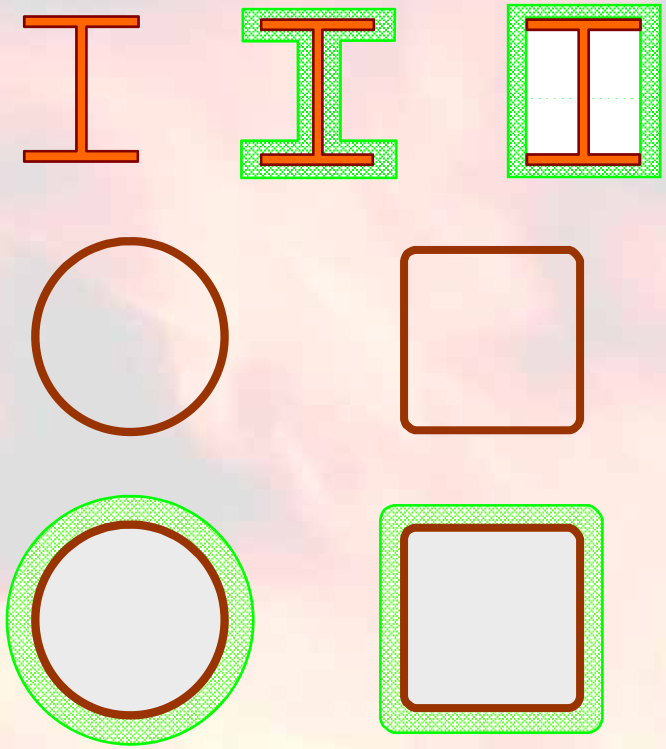
Simple calculation model (composite column) - buckling curve



Load capacity: $N_{fi.Rd} = \chi(\bar{\lambda}_\theta)\, N_{fi.pl.Rd}$

$\chi(\bar{\lambda}_\theta) \Leftarrow$ **strength and rigidity of effective section + column buckling length L_{fi}**

Critical temperature method (only steel members and certain composite beams)

Beams (steel and composite)	Columns
	

Critical temperature method

- According to simple calculation models, for uniformly heated steel members: $R_{fi,d,t} = k_{y,\theta}\, R_{fi,d,0}$
- On the other hand, fire resistance should satisfy:

$$R_{fi,d,t} \geq E_{fi,d} = \frac{E_{fi,d}}{R_{fi,d,0}} R_{fi,d,0} = \mu_0 R_{fi,d,0} \quad \Longrightarrow \quad k_{y,\theta} \geq \mu_0$$

- In particular, when $k_{y,\theta} = \mu_0$ the corresponding temperature is defined as critical temperature θ_{cr}
- In ČSN EN 1993-1-2, a simple formula is given to determine critical temperature θ_{cr}

$$\theta_{cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482$$

How to apply critical temperature method

Action in fire $E_{fi.d}$

↓

Design resistance at 20°C: R_d
or design action at 20°C: E_d

↓

Load level in fire: $\eta_{fi,t} = \dfrac{E_{fi,d}}{R_d}$

↓

Utilisation level: $\mu_0 = \eta_{fi,t} \dfrac{\gamma_{M,fi}}{\gamma_M}$

↓

Critical temperature: θ_{cr}

- **direct method**
- **iterative method**

Why direct and iterative critical temperature method (case of steel column)

- **Short column without instability** → $N_{b,fi,t,Rd} = A\, k_{y,\theta max}\, f_y \dfrac{1}{\gamma_{M,fi}}$

Strength reduction factor $k_{y.\theta.max}$ at $\theta_{a,max}$

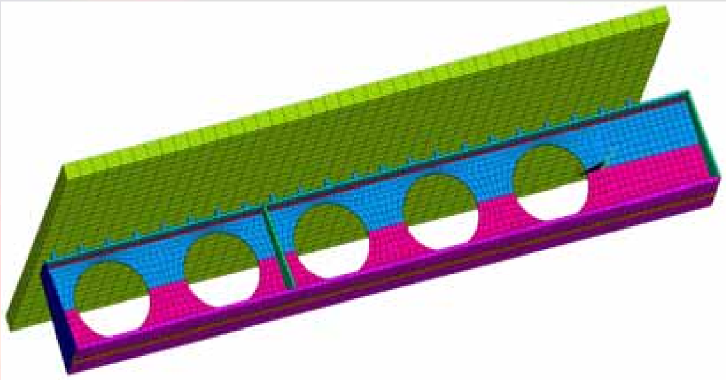
- **Column with risk of buckling** → $N_{b,fi,t,Rd} = \chi(\lambda_\theta) A k_{y,\theta max} f_y \dfrac{1}{\gamma_{M,fi}}$

Reduction factor of buckling $\chi(\lambda_\theta)$ depends on:

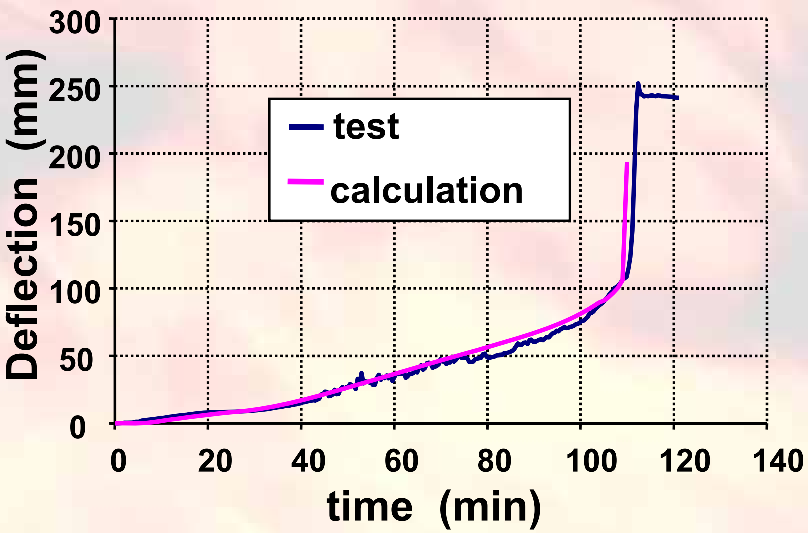
- strength
- **stiffness**

- **As a consequence, simple iterative procedure is needed to find the accurate $\theta_{a,max}$ in case of instability problem**

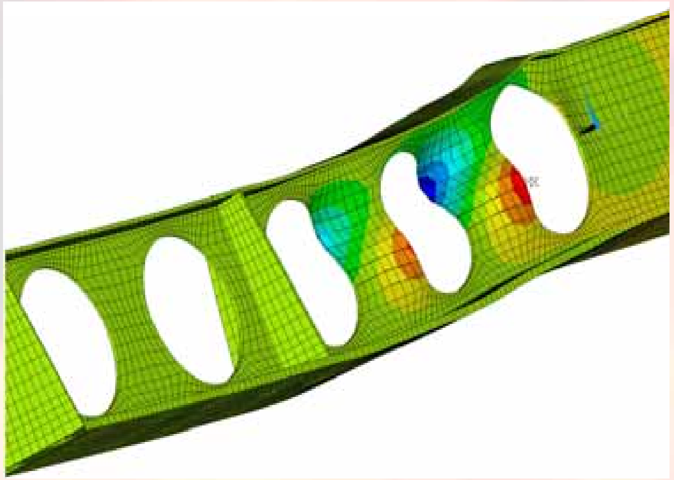
Advanced calculation model for any case (steel and concrete composite cellular beam)



Tested failure mode



Calculation vs test



Simulated failure mode

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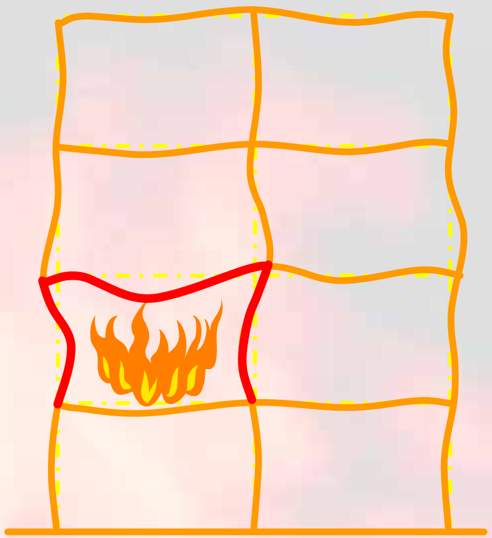
Fire design by global structural analysis

- General rules
  - necessary to use advanced calculation model
  - choice of appropriate structural modeling
  - existing boundary conditions
  - loading conditions
  - appropriate material models
  - restrained condition in relation with unmodeled parts of the structure
  - analysis of results and check on failure criteria
  - review of untreated features in direct analysis (consistency between numerical model and constructional details)



Fire design by global structural analysis

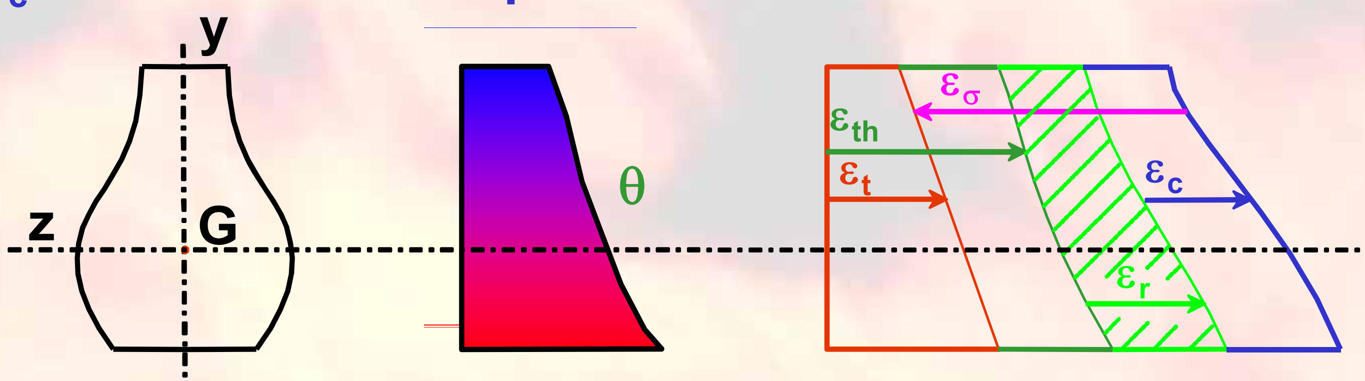
- Application requirement of advanced calculation models
  - requirement on material models
    - strain composition
    - kinematical material model
    - strength during cooling phase
  - step by step iterative solution procedure
  - check of possible failure untreated in direct analysis
    - rupture due to excessive steel elongation
    - cracking and crushing of concrete

Requirement on material model

Strain composition

$$\varepsilon_t = \varepsilon_{th} + (\varepsilon_\sigma + \varepsilon_c) + \varepsilon_r$$

- ε_t: total strain
- ε_t: strain due to thermal elongation
- ε_σ: strain due to stress tensor
- ε_r: strain due to residual stress (<u>if appropriate</u>)
- ε_c: strain due to creep

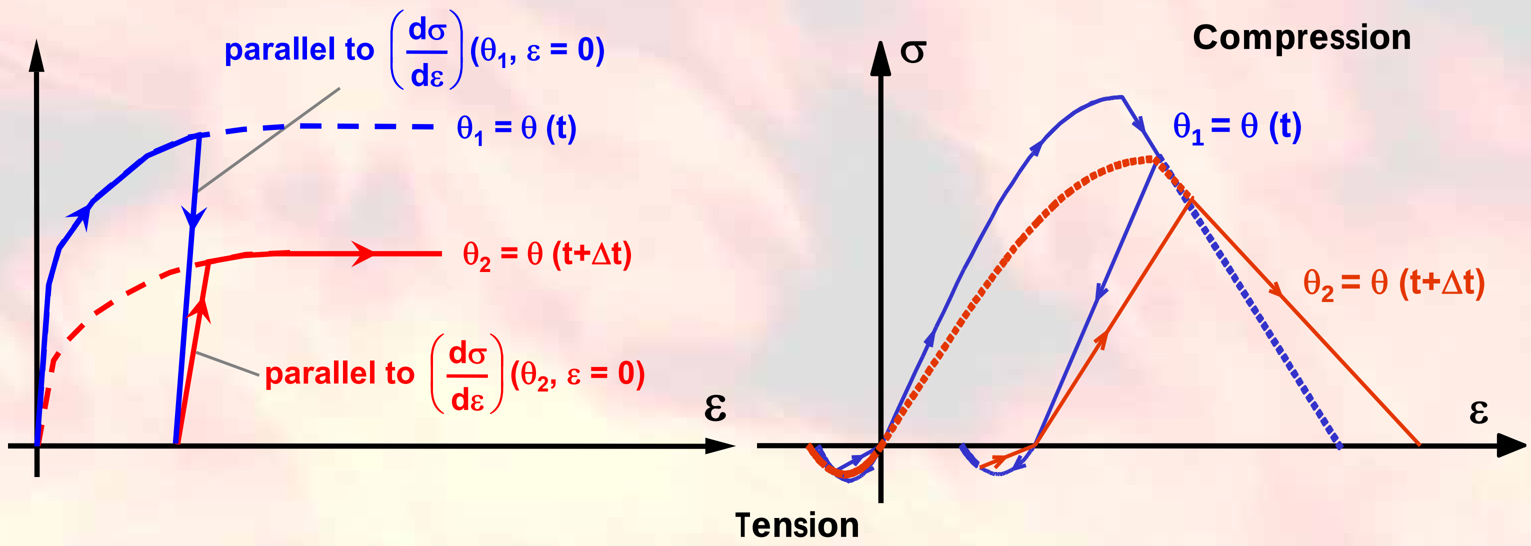


Section | Temperature distribution z = constant | Unitary strain

Requirement on material model

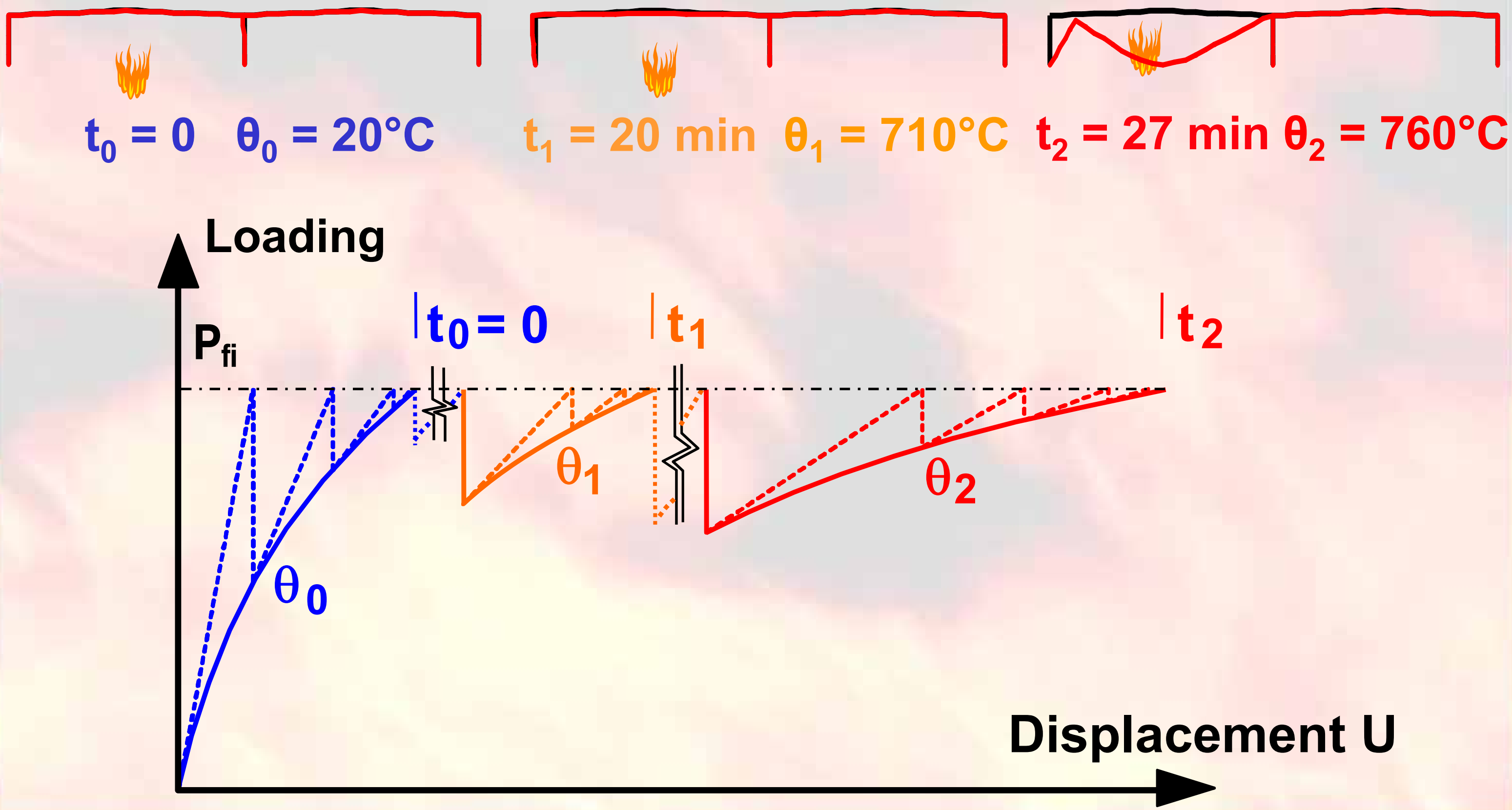
kinematical material model

Steel	Concrete
(isotropic material)	(compression-tension anisotropic material)



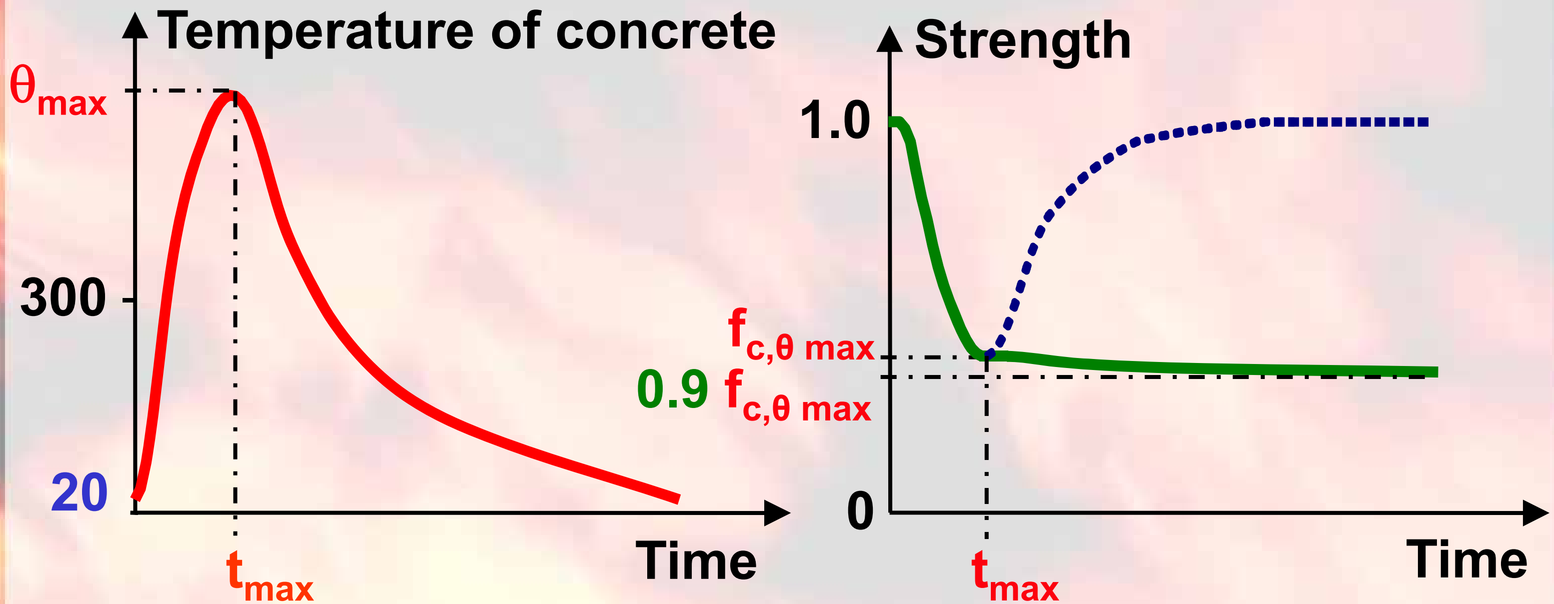
Step by step iterative solution procedure

- Calculation procedure must take account of temperature dependance of both stiffness and strength of the structure



Material strength during cooling phase

- ❑ Steel recovers its initial strength during cooling phase
- ❑ Concrete during cooling phase

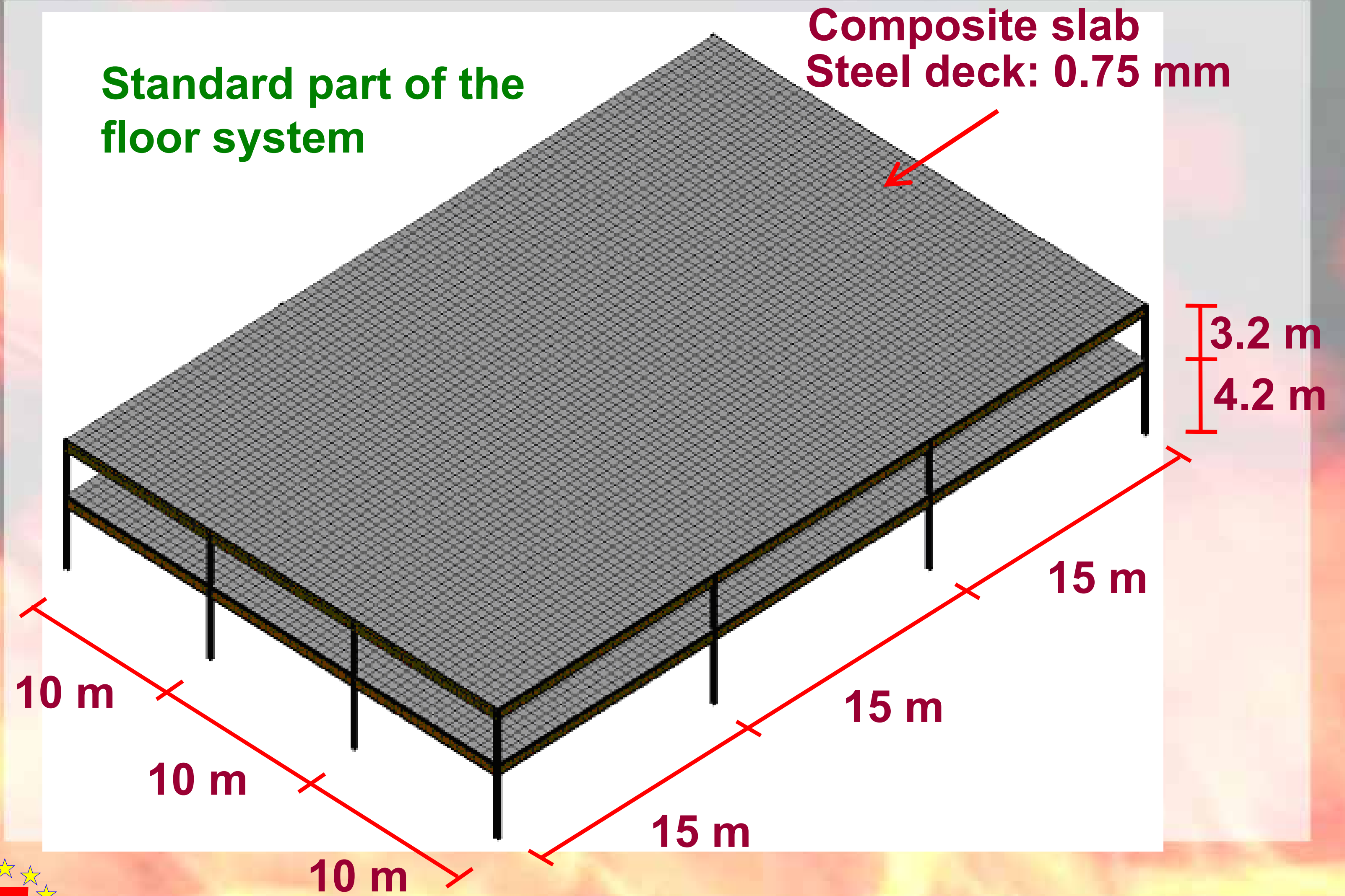


For example if $\theta_{max} \geq 300$ °C

$f_{c,\theta,20°C} = 0.9\ f_{c,\theta\ max}$

Linear interpolation applies to $f_{c,\theta}$ for θ between θ_{max} and 20°C

Global analysis of steel and concrete composite floor under localised fire

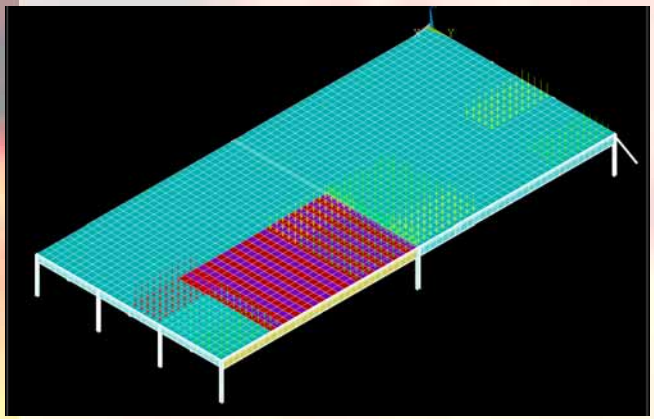


Choice of structural model

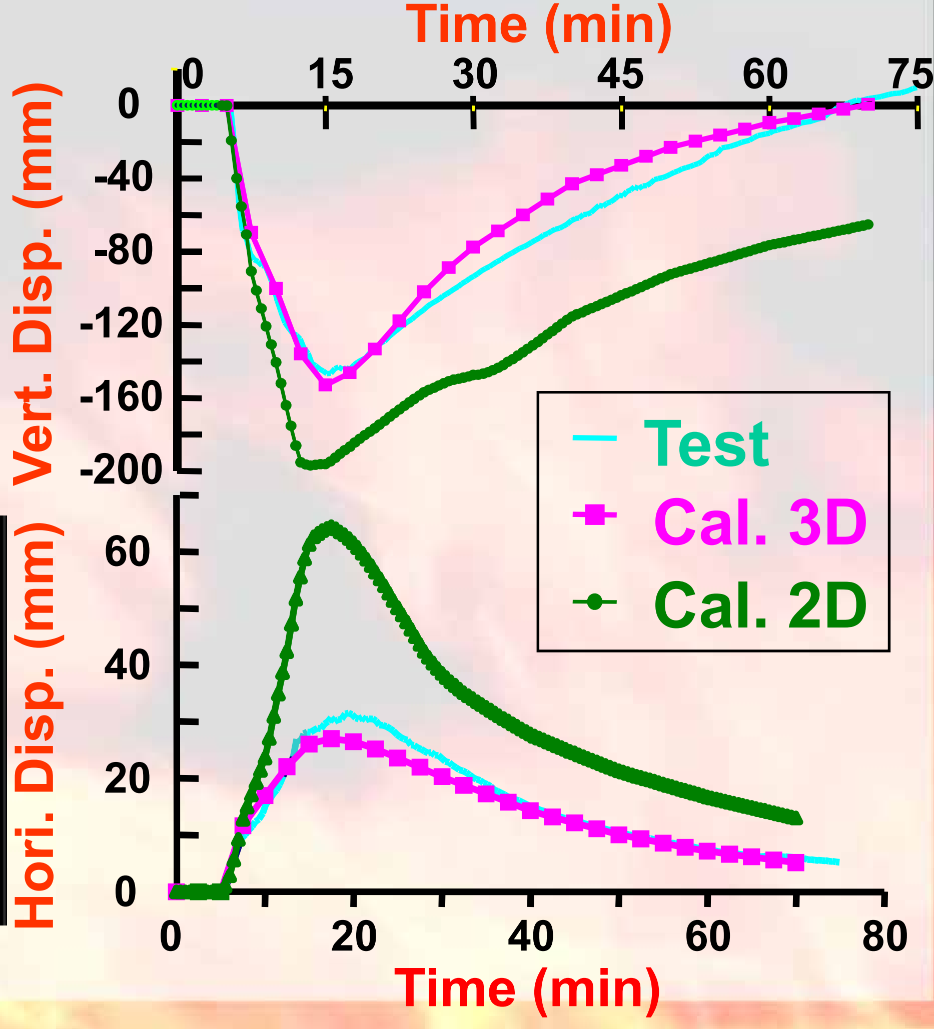
- Two different structural models may be adopted
  - 2D composite frame model (beam elements)
    - membrane effect is limited to one direction due to 1D effect slab model
    - load redistribution is not possible between parallel beams
  - 3D composite floor model (multi-type element)
    - membrane effect over whole floor area
    - load redistribution becoming possible with help of shell elements
- More realistic to apply 3D composite floor model

Validity of 3D composite floor model

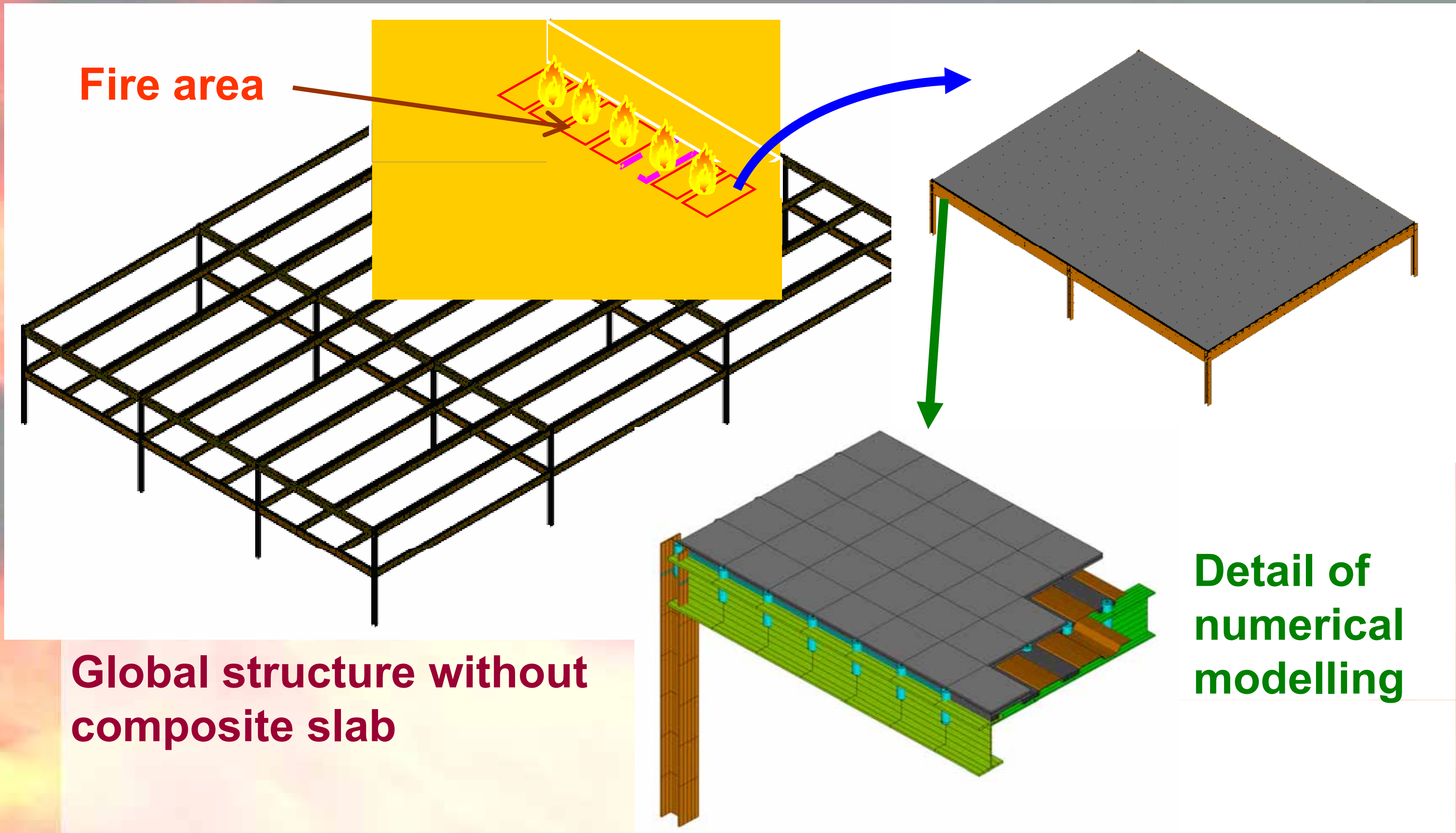
Test



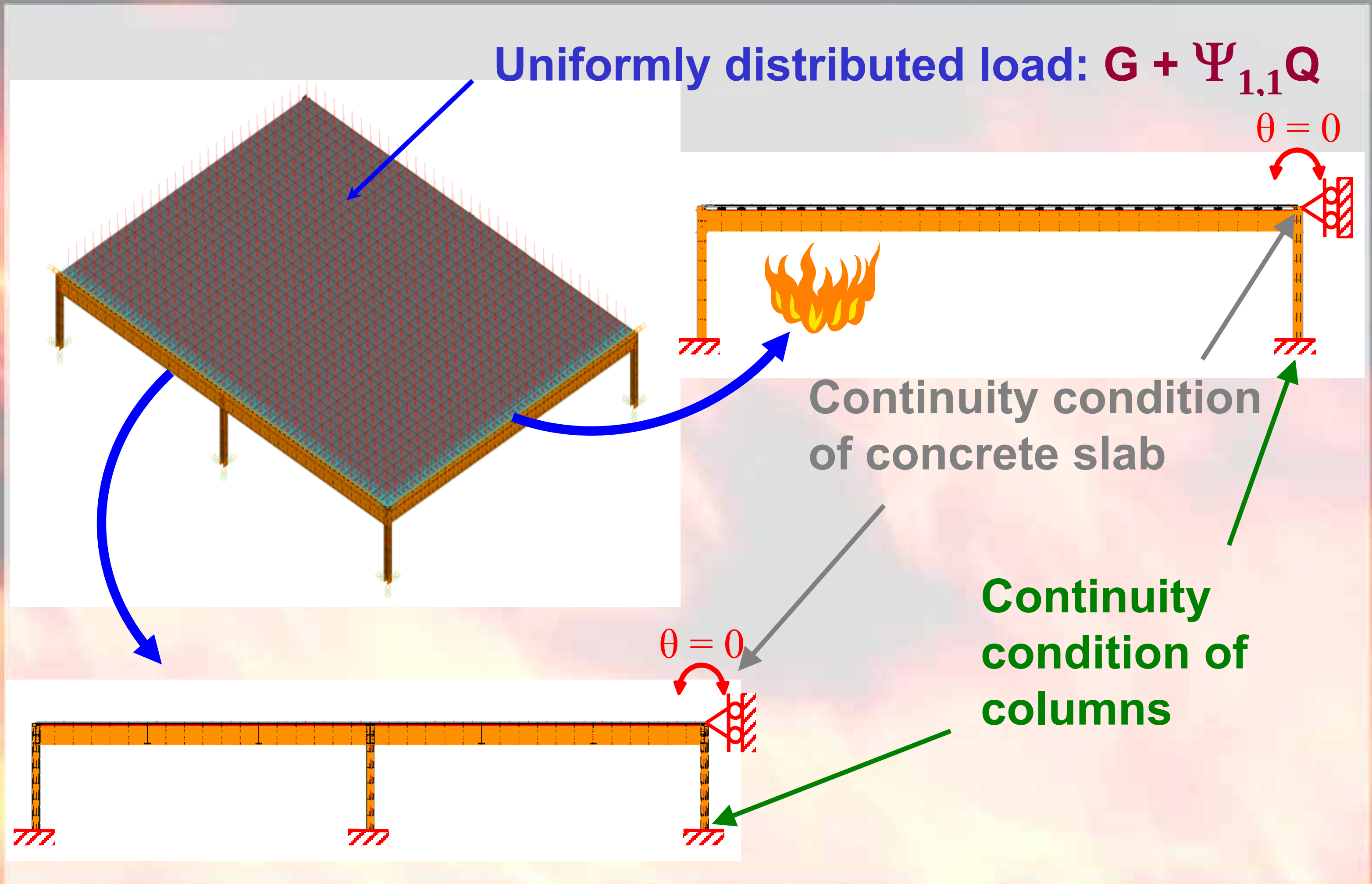
3D calculation model



Strategy of 3D composite floor modelling

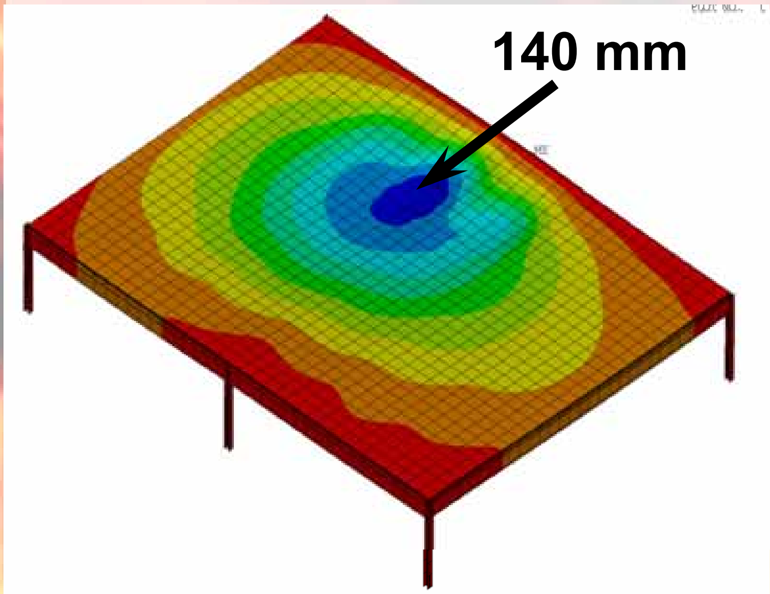


Mechanical loading and boundary conditions

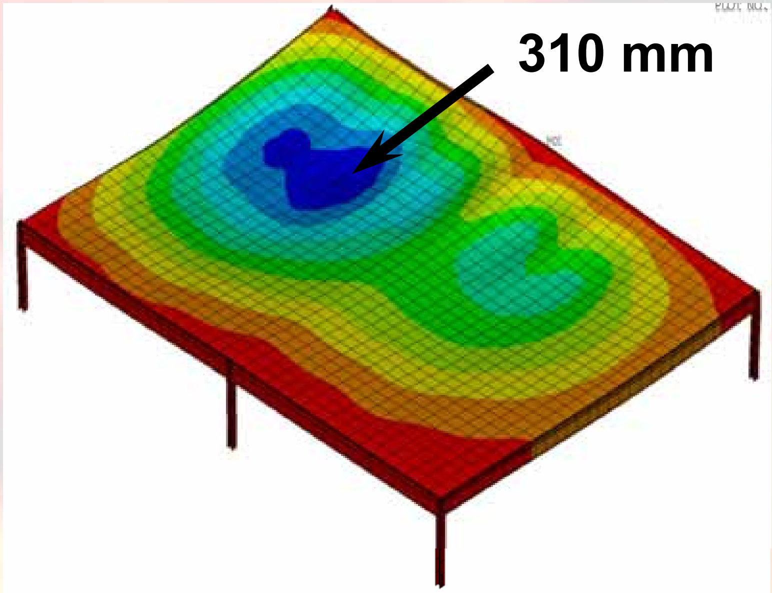


Mechanical response of the structure

- Total deflection of the floor and check of the corresponding failure criteria



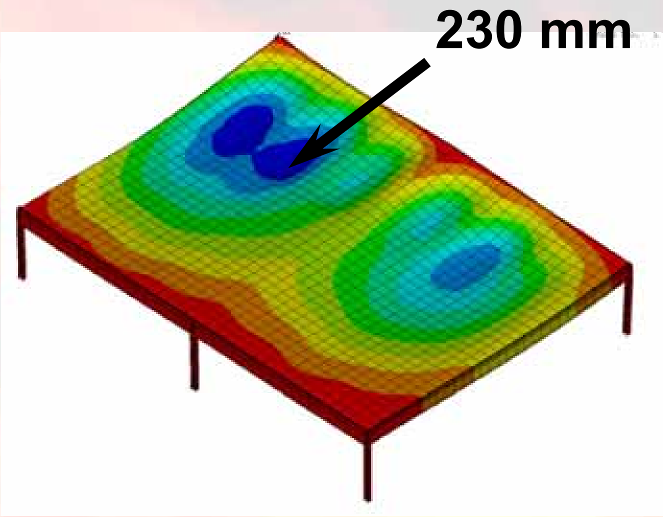
20 min



40 min

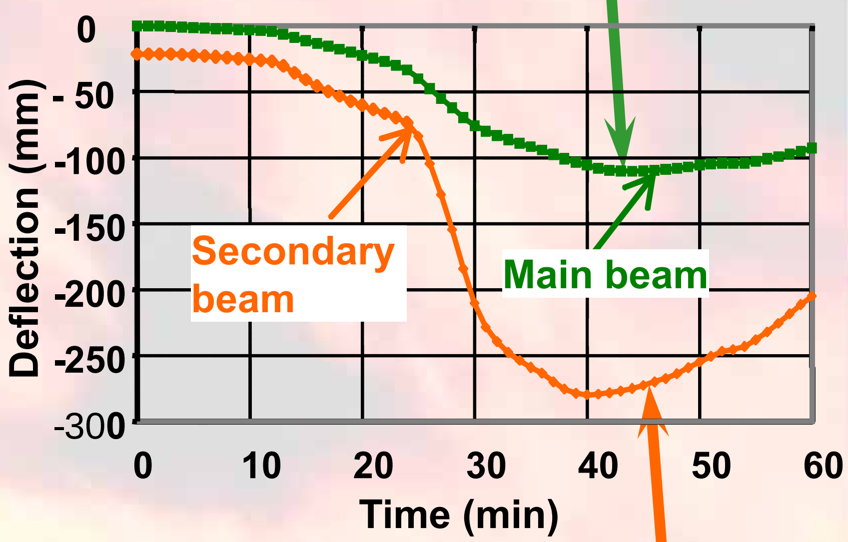
Mechanical response of the structure

➢ **Total deflection of the floor and check of the corresponding failure criteria**



60 min

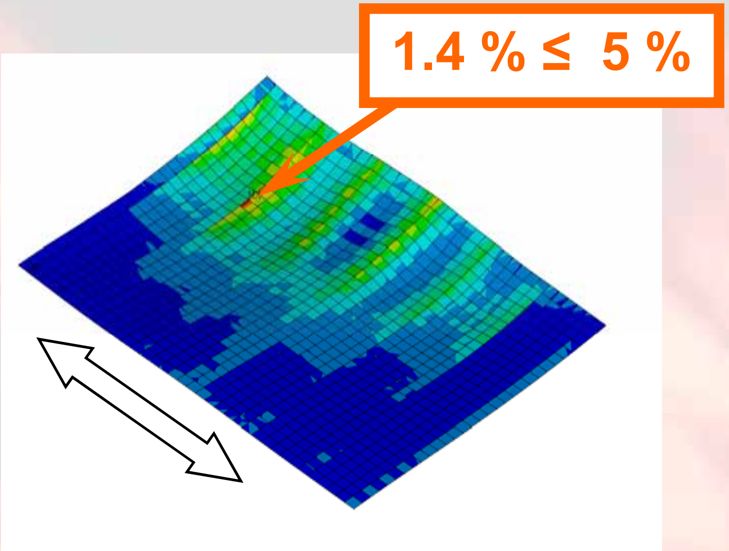
110 mm ≤ L/20 = 500 mm

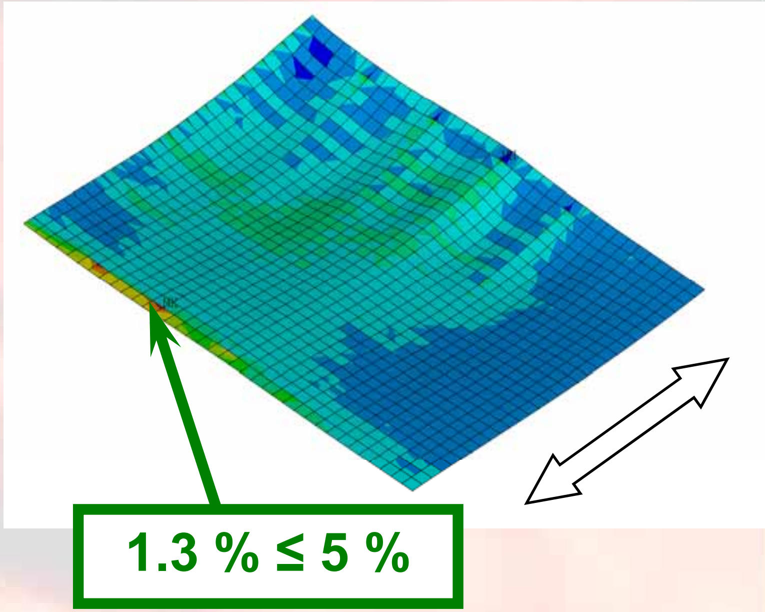


280 mm ≤ L/20 = 750 mm

Mechanical response of the structure

➤Check of failure criteria: elongation of reinforcing steel



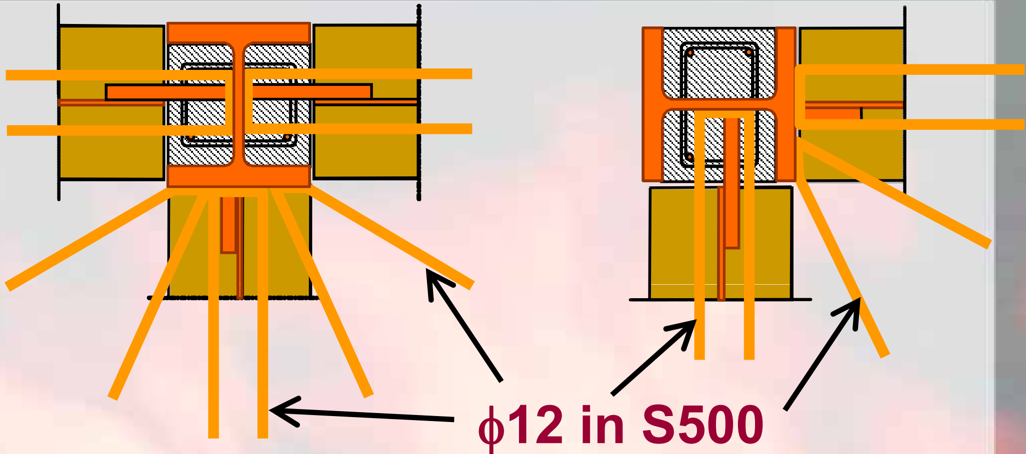


Strain of reinforcing steel
// slab span

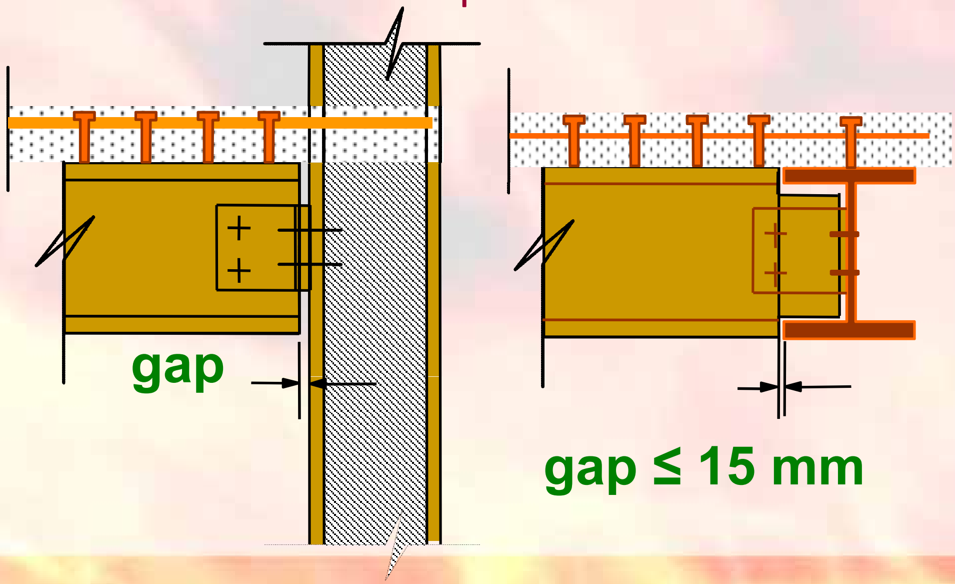
Strain of reinforcing steel
⊥ slab span

Construction details shall be respected in prder to consistent with numerical models

Reinforcing bars between slab and edge columns



Maximum gap of 15 mm between beam and column and between lower flange of the beam



Real building with bare steel frames based on global structural analysis

During construction

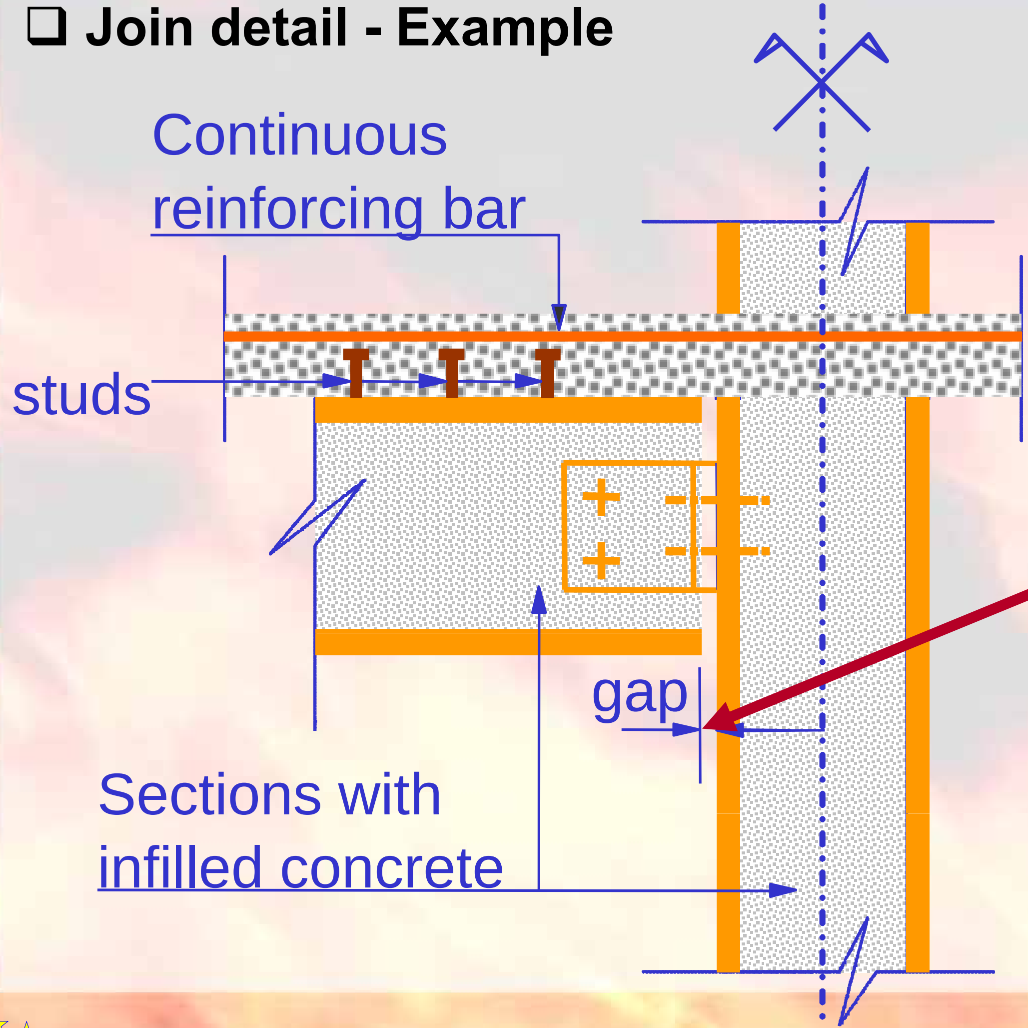
Finished

Specific consideration in fire design of steel and composite structures

- **Constructional details**
  - **Joint details (steel and composite)**
  - **Connection between steel and concrete**
    - **Connectors**
    - **Reinforcing steel**
- **Behaviour during cooling phase under natural fire**
  - **Joint**

Construction details to get hogging moment resistance in fire situation (ČSN EN 1994-1-2)

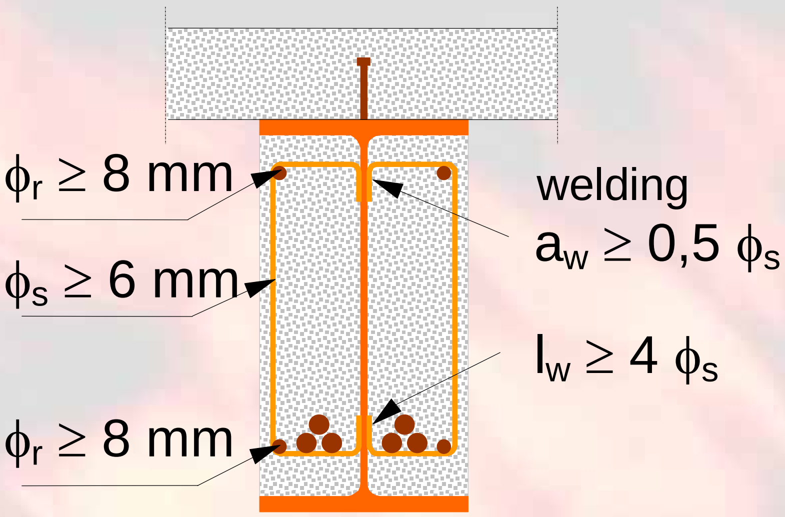
- Join detail - Example



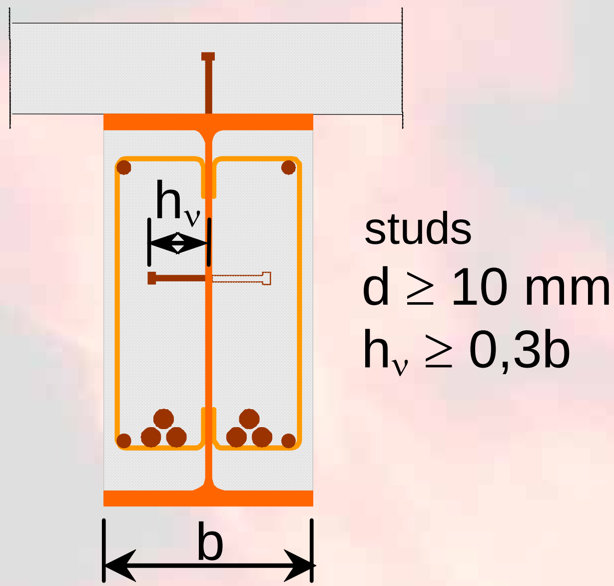
A limited gap allowing to develop a hogging moment in the fire situation

Construction details for connection between concrete and steel (ČSN EN 1994-1-2)

❑Connection between steel profile and encased concrete



Welding of stirrups to the web



Welding of studs to the web

National Annex to ČSN EN 1993-1-2 and ČSN EN 1994-1-2

ČSN EN 1993-1-2 (steel structures)

- Allows to choose parameters in 6 paragraphs
- The values from EN 1993-1-2 accepted without modification
- The only change is critical temperature for Class 4 sections:
  - elements loaded by bending moment: θ_{cr} = 500 ºC
  - element loaded in compression: θ_{cr} = 450 ºC
- In addition: critical temperature of fire-resistant steel FRS 275 N
- critical temperature of cold-formed elements in tension

ČSN EN 1994-1-2 (composite structures)

- Allows to choose parameters in 8 paragraphs
- The original values are accepted
- Allows to use European software without modifications

Thank you for your attention