DIFISEK

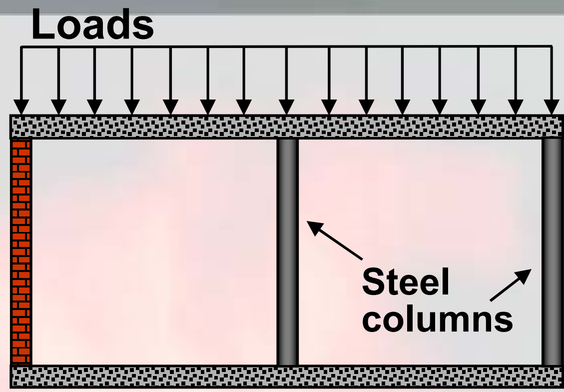
PART 2

THERMAL RESPONSE

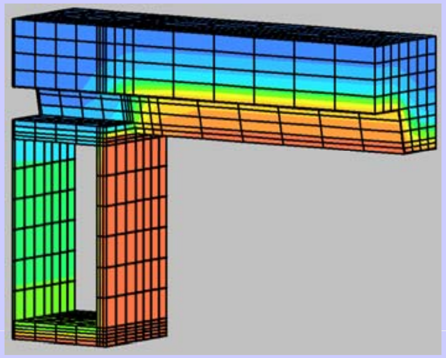
Resistance to fire - Chain of events

1: Ignition

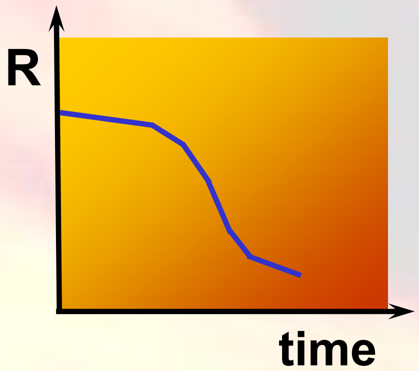
2: Thermal action



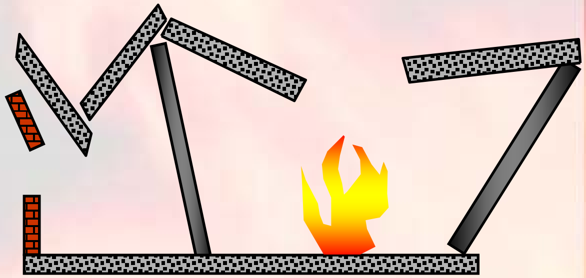
3: Mechanical actions



4: Thermal response



5: Mechanical response

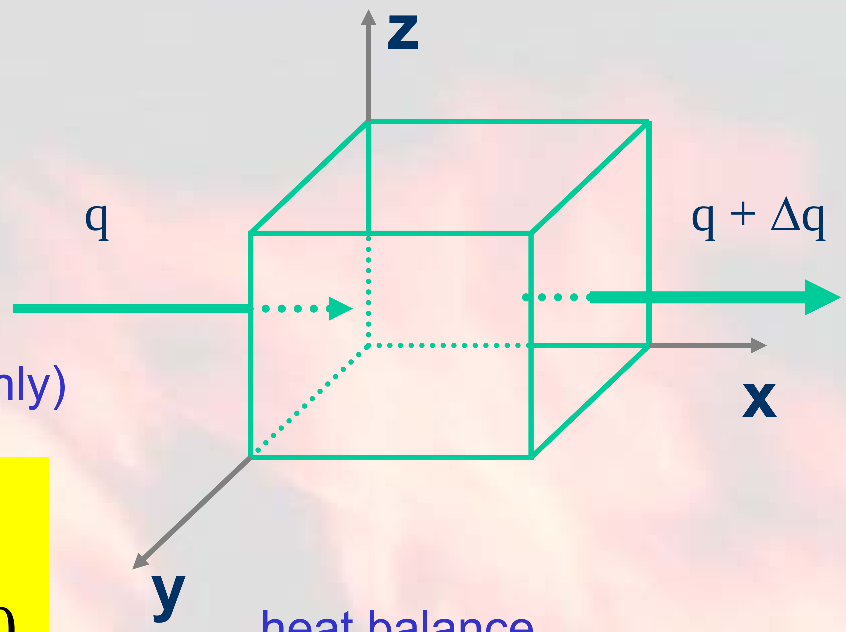


6: Possible collapse

Contents

Thermal response
Basics

- Thermal conduction (= λ)
- Thermal capacity (= $\rho \cdot c_p$)



DV: (shown for 1direction only)

$$\frac{\partial(\rho c_p \Theta)}{\partial t} + \frac{\partial(\lambda \frac{\partial \Theta}{\partial x})}{\partial x} = 0$$

heat balance

$$\Delta q / \Delta x + \Delta(\rho c_p \Theta) / \Delta t = 0$$

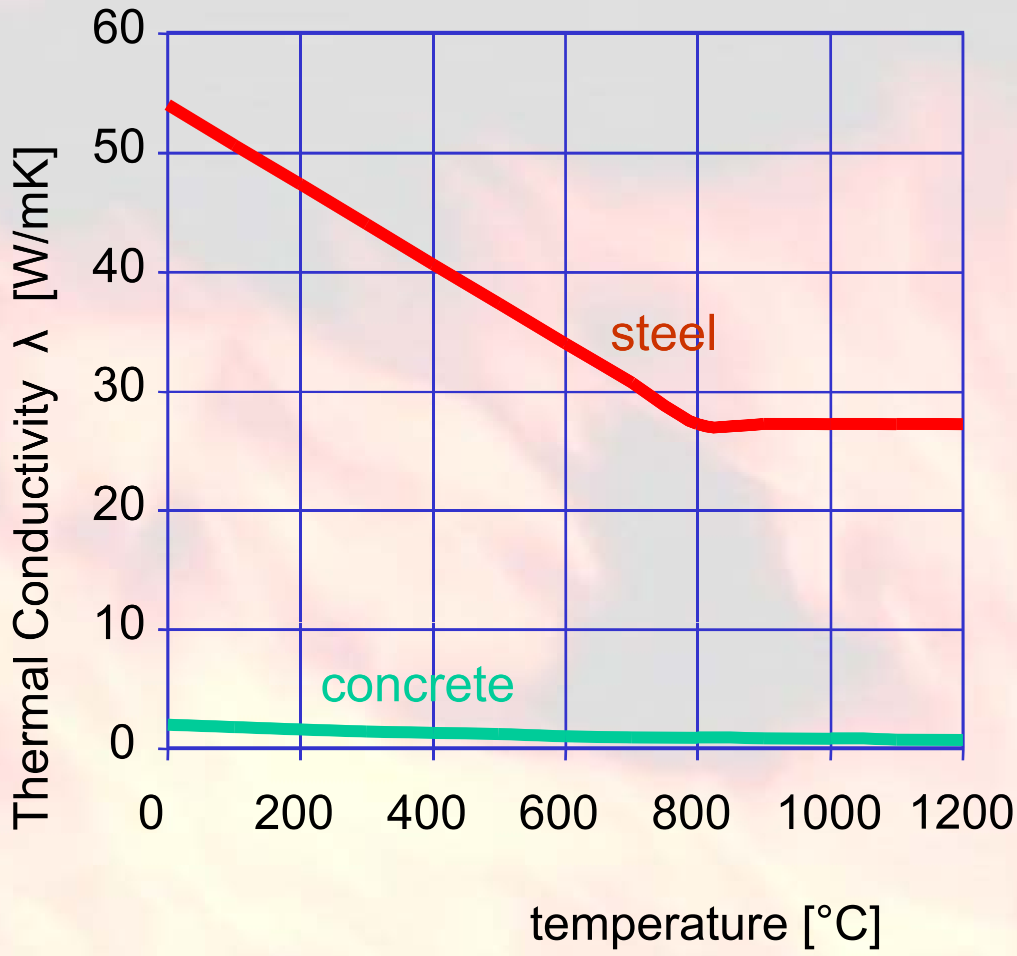
boundary condition: incoming/outgoing flux at surface: $h_{net,tot}$

initial condition: room temperature conditions

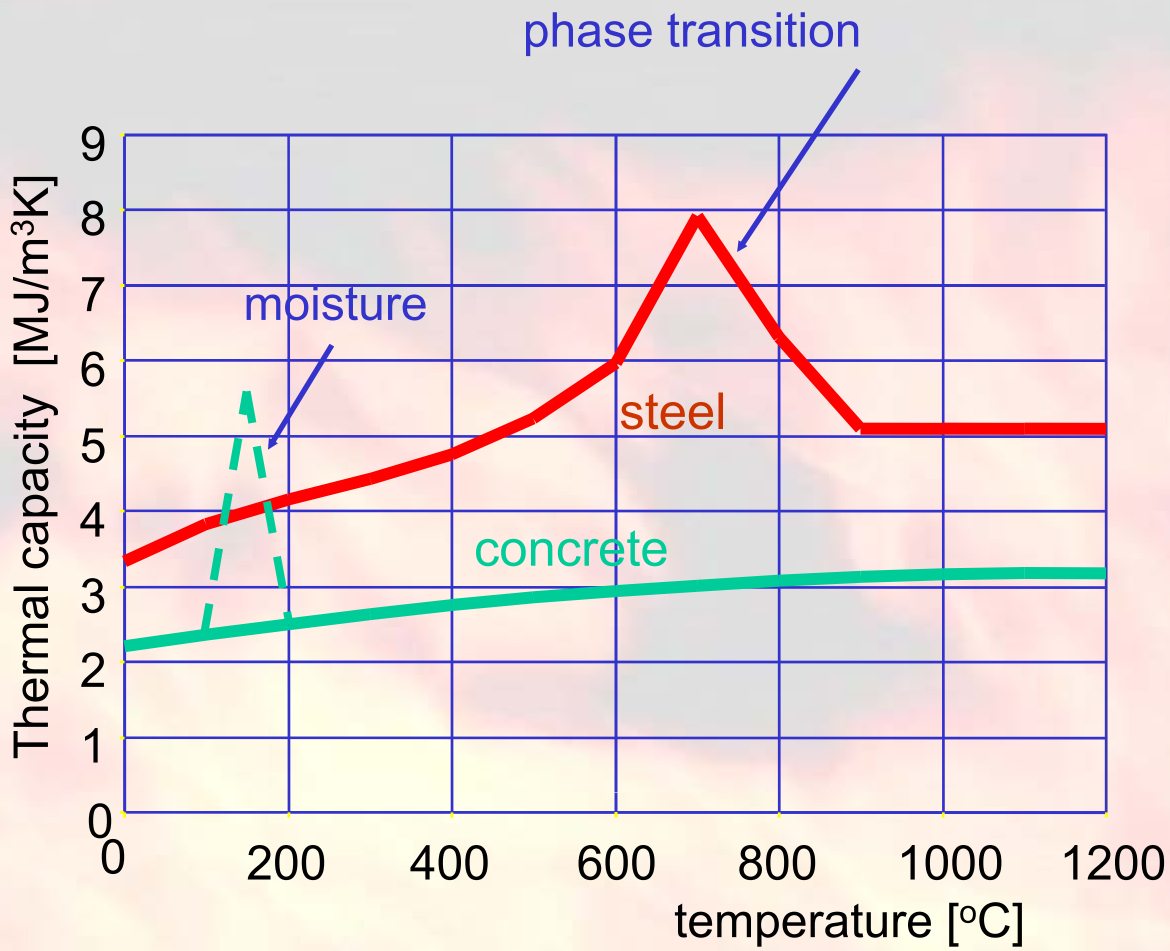
Fourier's law

$$q = \lambda \, \Delta \, \Theta / \Delta x$$

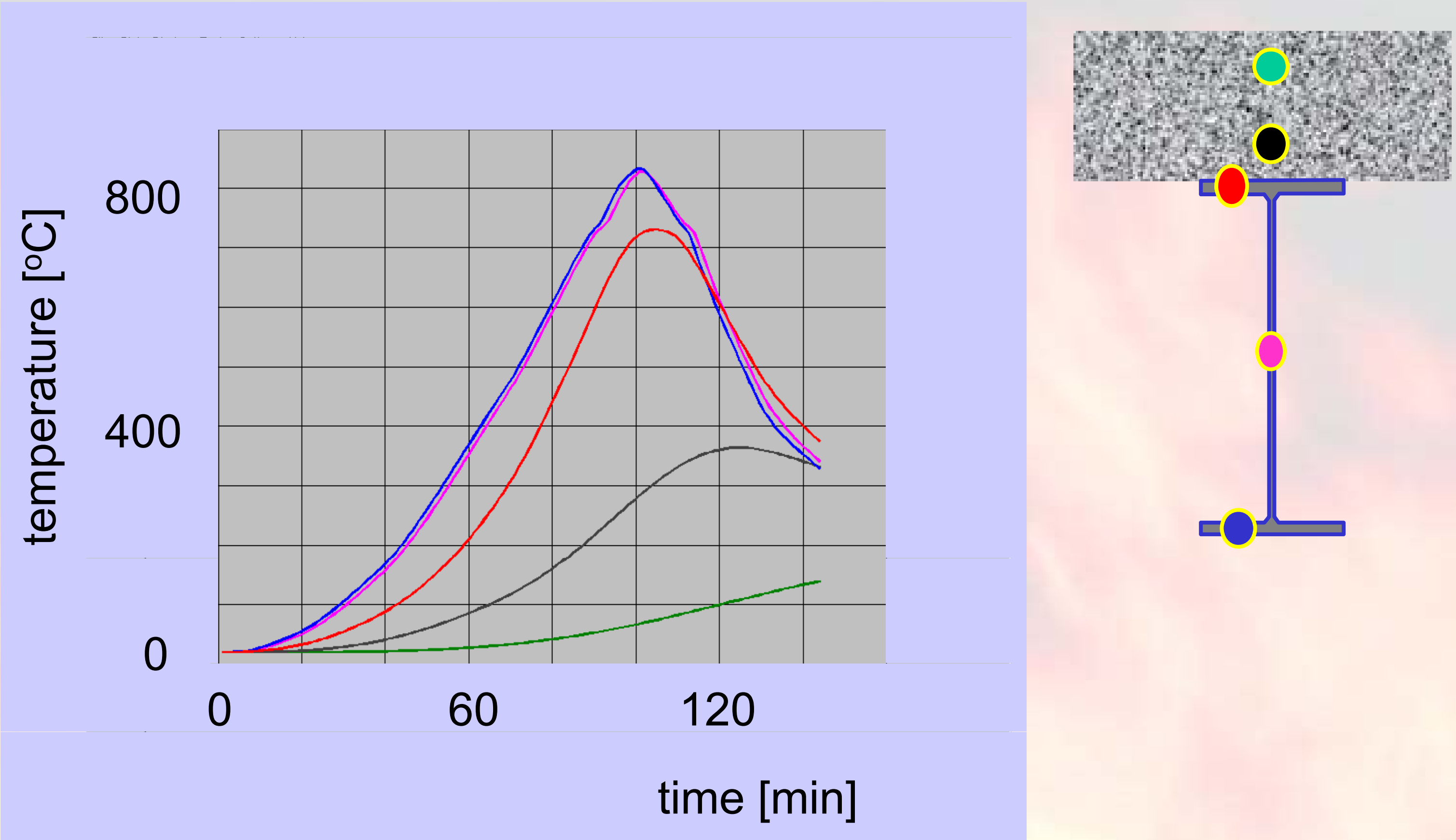
Thermal conductivity
Concrete vs. steel



Thermal capacity
Concrete vs. steel



Thermal response
Steel beam/concrete slab (2D)



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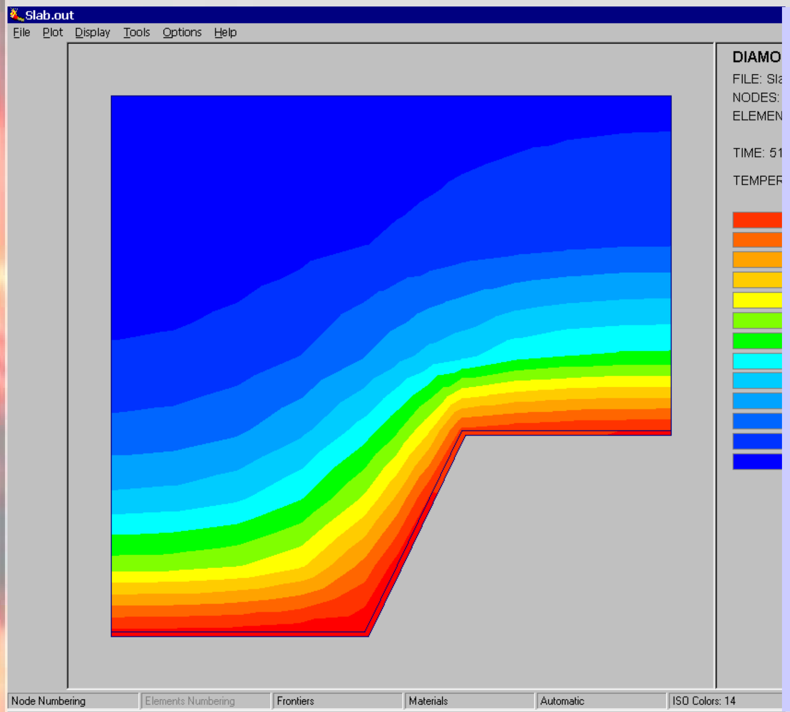
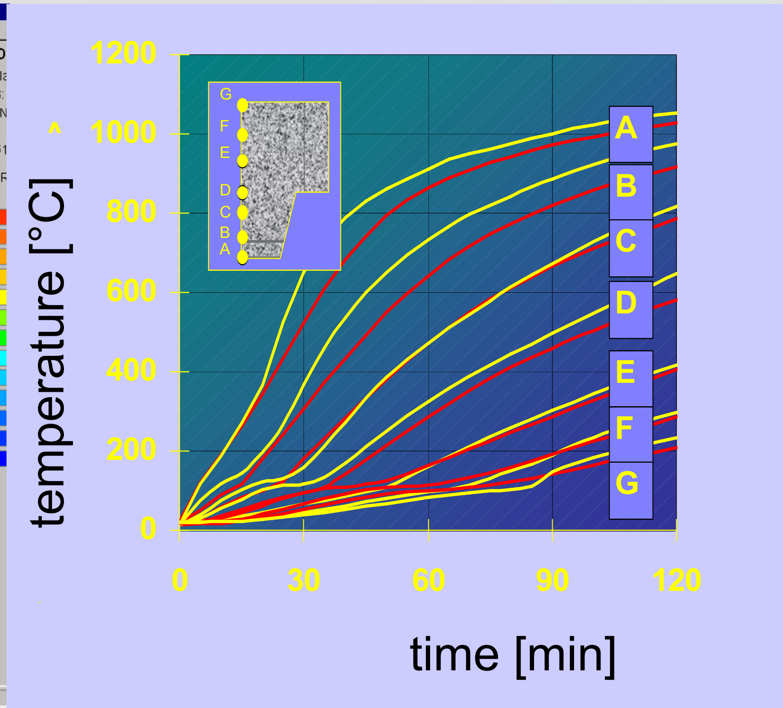
Thermal response
Composite slab (2D)

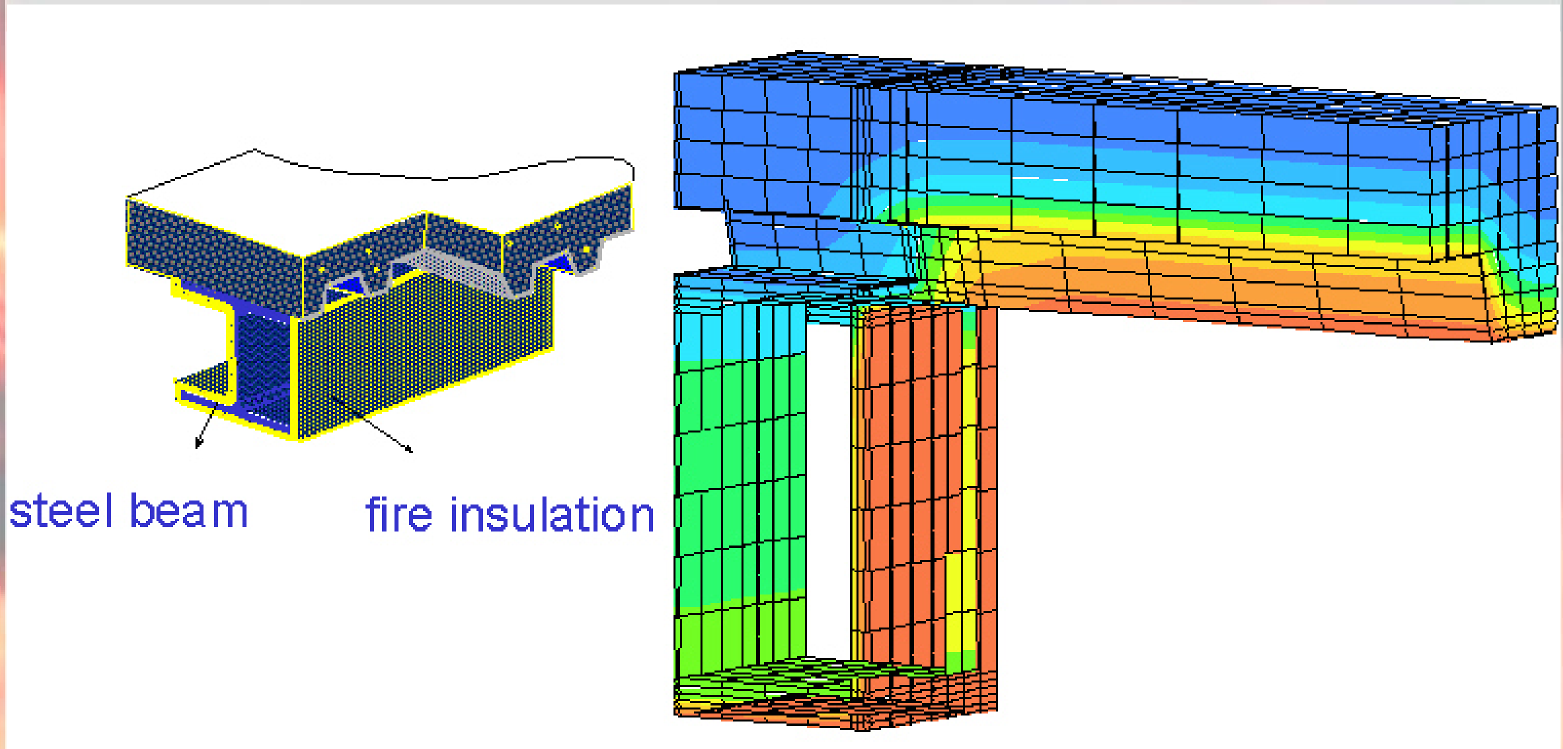


computer simulation



test vs. simulation

Thermal response
Composite edge beam (3D)



Calculation rules for steel elements

- Scope
- Bare steelwork
- Insulated steelwork
- Design parameters for the temperature development
  - General
  - Section Factor
  - Characteristics fire protection
  - Non-standard fire conditions

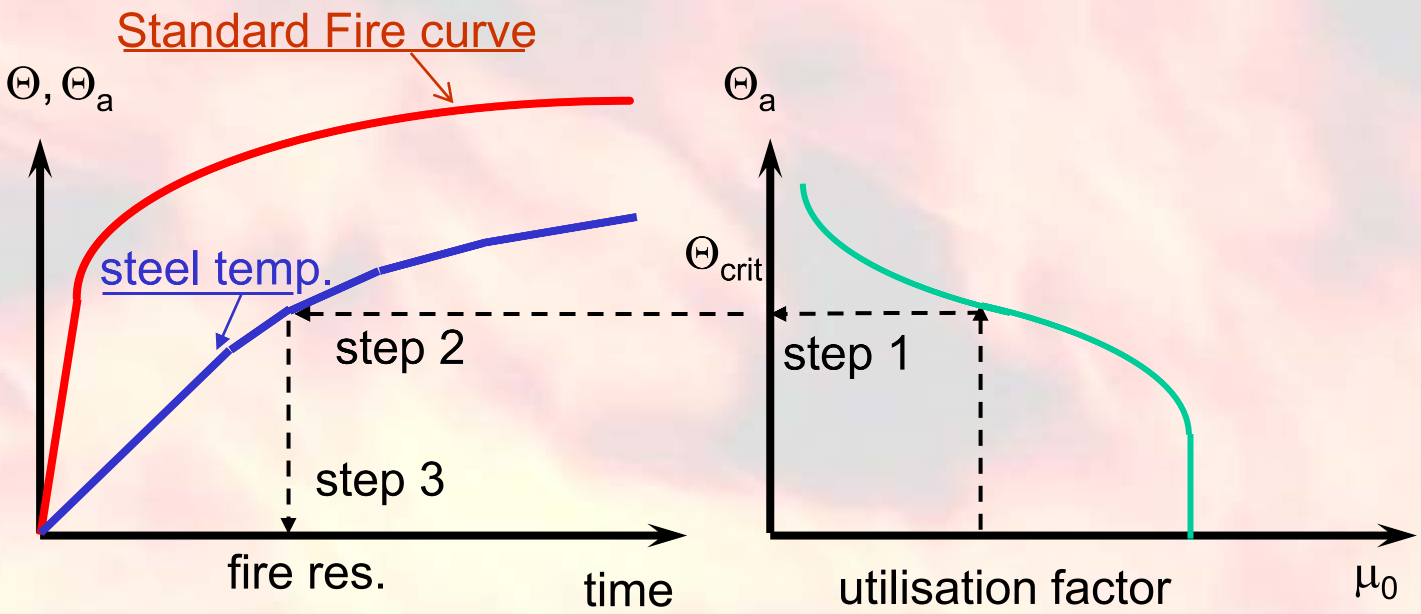
Resistance-to-Fire of Steel Elements
Principles

- Load bearing function only
  - ⇒ Load bearing capacity
- Uniform temperature distribution
  - ⇒ Critical steel temperature concept

Note: refer to ČSN EN 1993-1-2 (simple calculation models)

Resistance-to-Fire “Steel elements” Calculation procedure

- Step 1: determine mechanical response $\mu_a \Rightarrow \Theta_{crit}$
- Step 2:determine thermal response $\Rightarrow \Theta_a$
- Step 3: determine fire resistance $\Rightarrow$ fire res.



Thermal actions
Heat transfer exposed side

- Radiative heat transfer: $$\dot{h}_{net,r} = \Phi \cdot \varepsilon_m \cdot \sigma \cdot \left[(\Theta_r + 273)^4 - (\Theta_m + 273)^4 \right]$$
- Convective heat transfer: $$\dot{h}_{net,c} = \alpha_m \cdot (\Theta_g - \Theta_m)$$

with:

Θ_{rad} is radiation temperature [°C] ⇒ Θ_{rad} → Θ_g → fire curve

Θ_m is surface temperature [°C] ⇒ thermal response

ε_m is surface emissivity [-] ⇒ steel: 0.7

α_c is coefficient convection ⇒ 25 - 50 W/m^2K (depending on fire model)

Φ is configuration factor [-] ≤ 1.0 ⇒ safe: 1.0

ρ is Stephan Boltzmann constant = $5.67 \cdot 10^{-8}$ W/m^2K^4

Note: simplified!; for details: see ČSN EN 1991-1-2

Thermal response
Steel profiles

$$\frac{\partial(\rho\, c\,\Theta)}{\partial t} + \frac{\partial\left(\lambda \frac{\partial \Theta}{\partial x}\right)}{\partial x} = 0$$

boundary & initial conditions

$$\Rightarrow \quad \frac{d\,\theta_a}{dt} = \frac{\dot{h}_{tot}\, A_m}{\rho_a\, c_a\, V}$$

with

A_m is exposed surface area member [m^2/m]

V is volume member [m^3/m]

Note: key is uniform temperature distribution

Temperature rise bare steelwork
Basic equation

$$\frac{d\Theta_a}{dt} = k_{sh}\frac{A_m/V}{\rho_a c_a}\cdot \dot{h}_{net,tot} \quad \dots (1)$$

$$\Delta\Theta_a = k_{sh}\frac{K_{bare}}{\rho_a c_a}\cdot\frac{A_m}{V}\cdot(\Theta_g - \Theta_a)\cdot\Delta t \quad \dots (2)$$

Legend:

$\Delta\Theta_a$: increase steel temp.

Δt : time step

A_m/V section factor

K_{bare}: heat transfer coef.

k_{sh} : corr. coef. shadow effect

with

$$K_{bare} = \alpha_c + \frac{\varepsilon_m \sigma\left[\left(\Theta_g + 273\right)^4 - \left(\Theta_a + 273\right)^4\right]}{\Theta_g - \Theta_a} \quad \dots (3)$$

Shadow effect
Basics

- Shadow effect caused by local shielding of radiative heat transfer, due to shape of steel profile, i.e.:
  - I profiles, shadow effect: yes
  - □ profiles, shadow effect: no

- Without thermal radiation, no shadow effect; hence:
  - bare members, shadow effect: yes
  - insulated members, shadow effect: no

Shadow effect
Consequences

- Unprotected members:

$$\Delta\Theta_a = k_{sh} \frac{A_m/V}{c_a \rho_a} \dot{h}_{net} \Delta t$$

with:

- for I – sections: $k_{sh} = 0.9\ [A_m/V]_{box}/[A_m/V]$
- for “all” other sections: $k_{sh} = [A_m/V]_{box}/[A_m/V]$

- Protected members: no effect

Temperature rise insulated steelwork
Basic equations

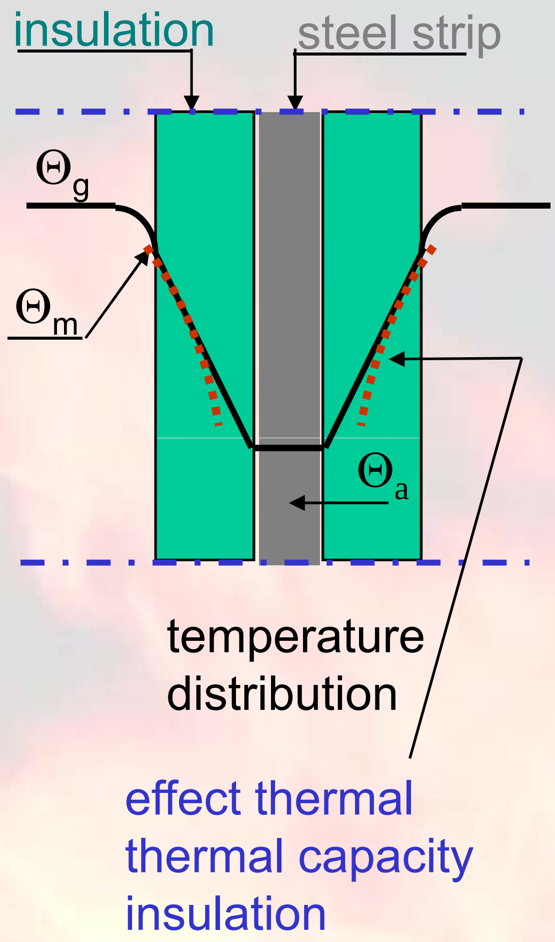
$$\Delta\Theta_a = \frac{K_{ins}}{\rho_a c_a} \cdot \frac{A_m}{V} \cdot (\Theta_g - \Theta_a) \cdot \Delta t \quad \text{... (a)}$$

with

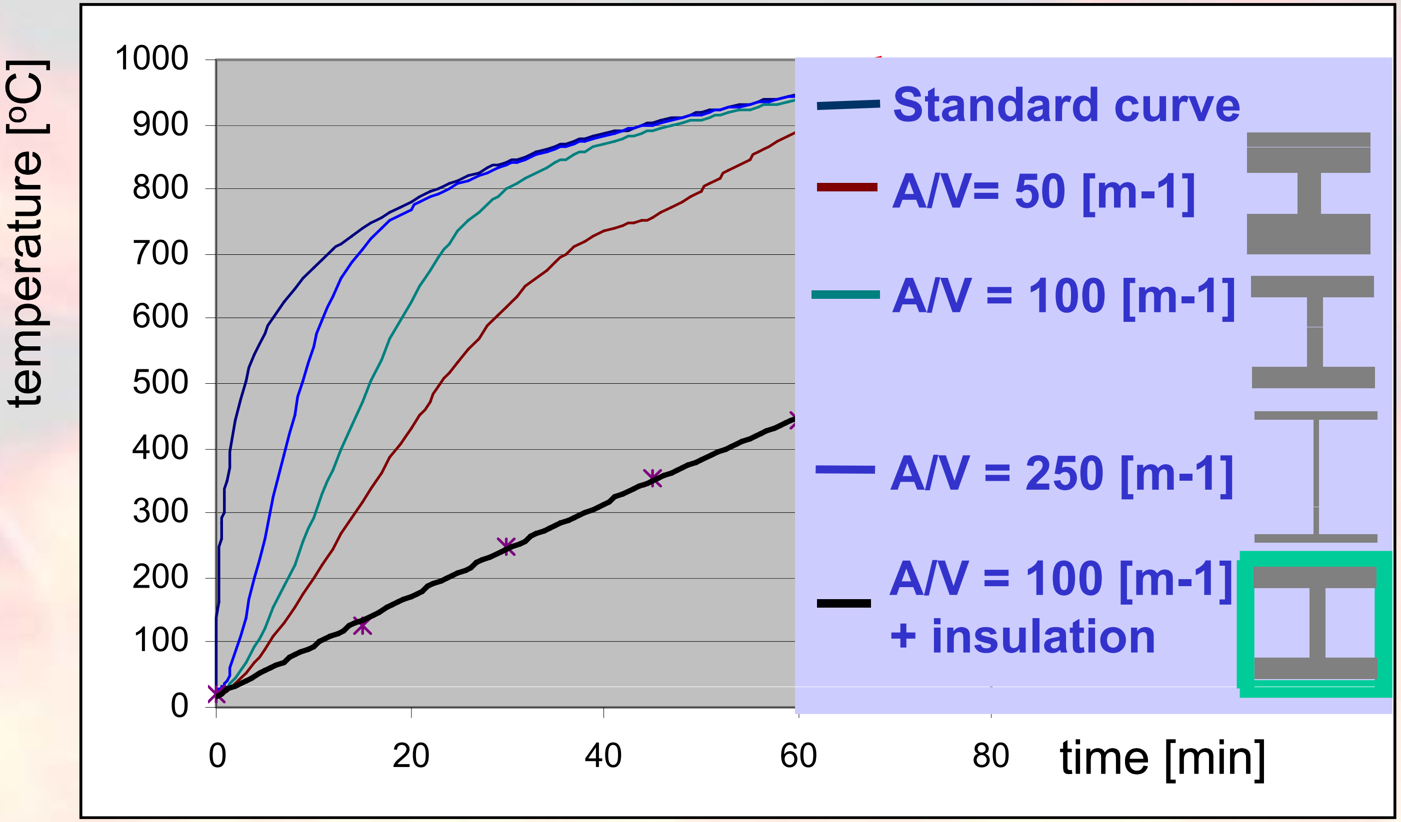
$$K_{ins} = K_{ins}\left(\frac{\lambda}{d}, \rho_p, c_p, \rho_a, c_a\right) \quad \text{... (b)}$$

Notes: (a) $\Theta_g - \Theta_m << \Theta_m - \Theta_a$

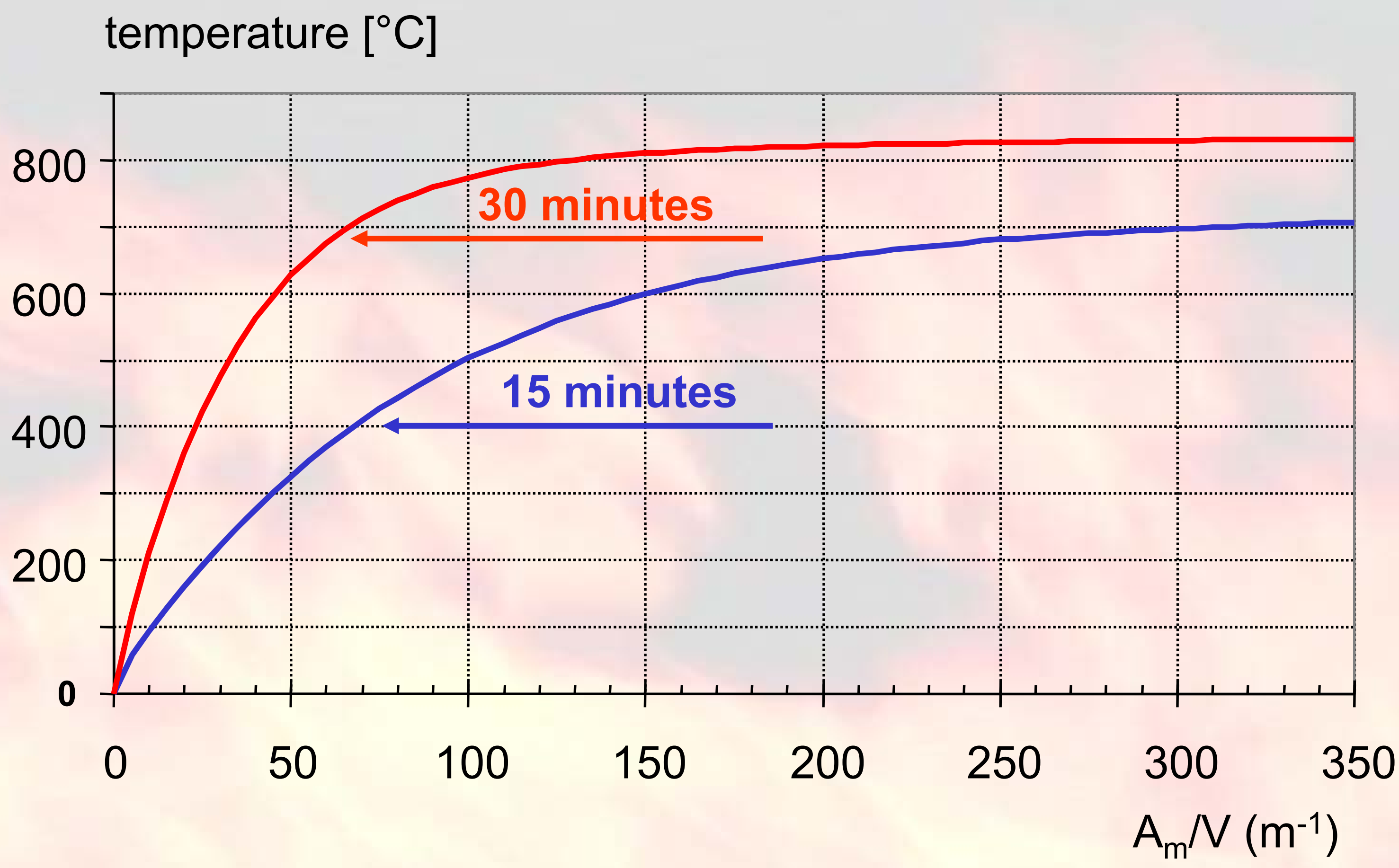
(b) for light weight insulation: $K_{ins} \approx \lambda/d$



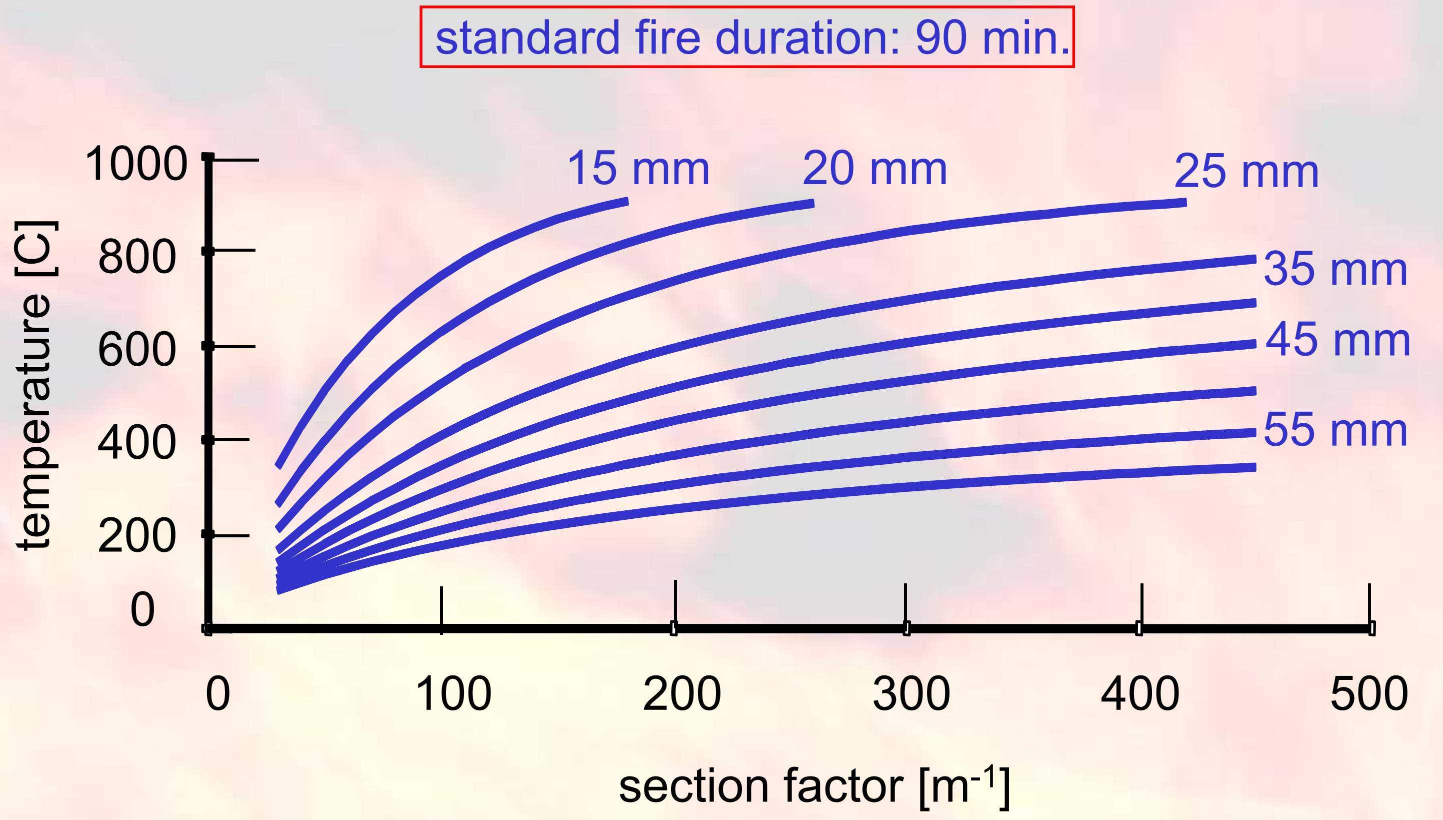
Temperature development in steel profiles



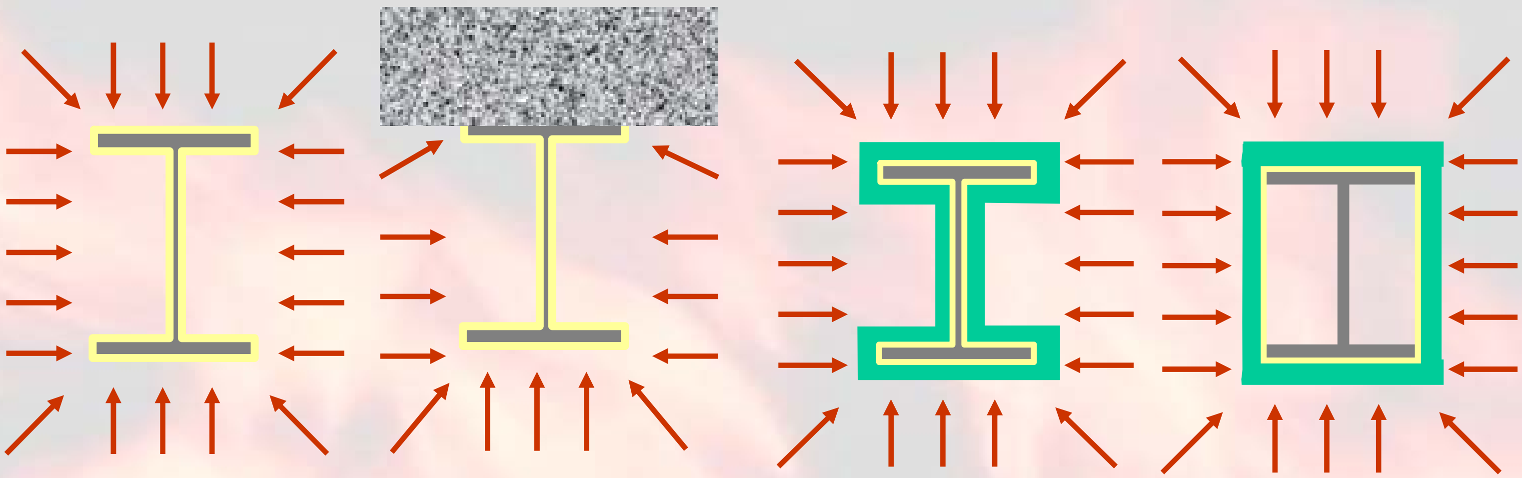
Steel temperature as function of Section Sector
Bare steel profiles



Steel temperature as function of Section Factor
Insulated steel profiles



Section Factor steel profile
Concept

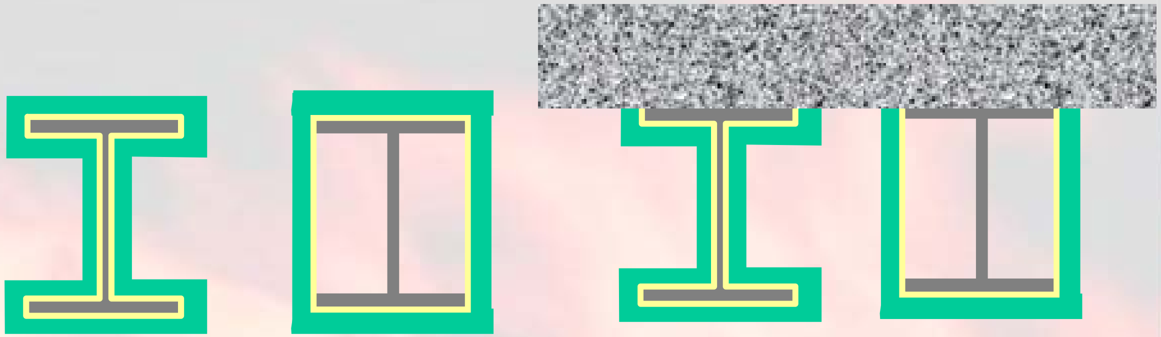


bare steel members

insulated steel members

Definition: ratio between "surface area" through which heat is transferred to steel and "steel volume"

Section Factor (A/V)
Numerical values



IPE100	387	300	334	247
HE280A	165	113	136	84
HE320B	110	77	91	58

Note: range: ≈ 50 - 400 [m^{-1}]

Heat transfer coefficient
Insulated steel members

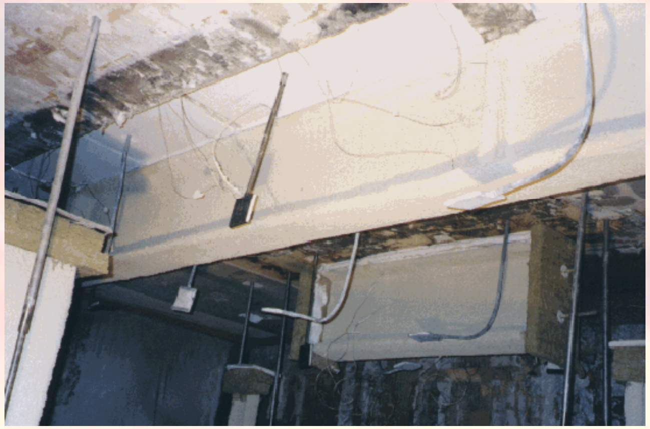
- Approximation: $K_{ins} \approx \lambda/d$ (for light weight insulation)
  with: d is thickness insulation material
  λ is coefficient of thermal insulation
- Determination: semi-empirical approach

  $\Rightarrow$ ENV 13381, p. 4

Note: Do not use “room temperature handbook values” for λ in fire design calculations!

Characterisation tests
Fire insulation steel elements

- Aim: insulation characteristics fire protection steelwork
- Complication: “Stickability”
- Methodology:
  - loaded & unloaded beam (2 pairs)
  - unloaded columns (10 x)
- Ref.: EN 13381-4



beam before fire test

beam after fire test

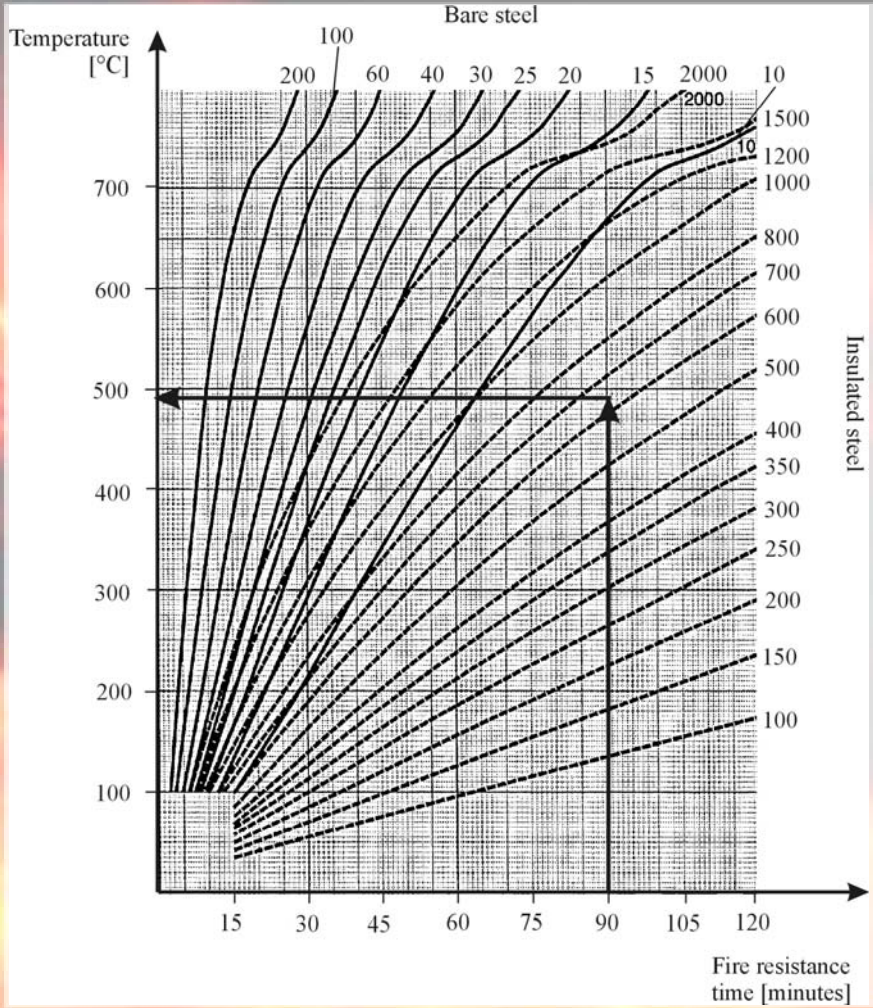
Fire insulation systems
Options

- Boards
- Sprays
- Intumescents

- Screens
  - to protect horizontal elements (→ floor construction) (EN 13381-1)
  - to protect vertical elements (→ partitions) (EN 13381-2)

Note: for details on insulation characteristics refer to:
(a) test reports fire labs
(b) information manufacturers

Euronomograms

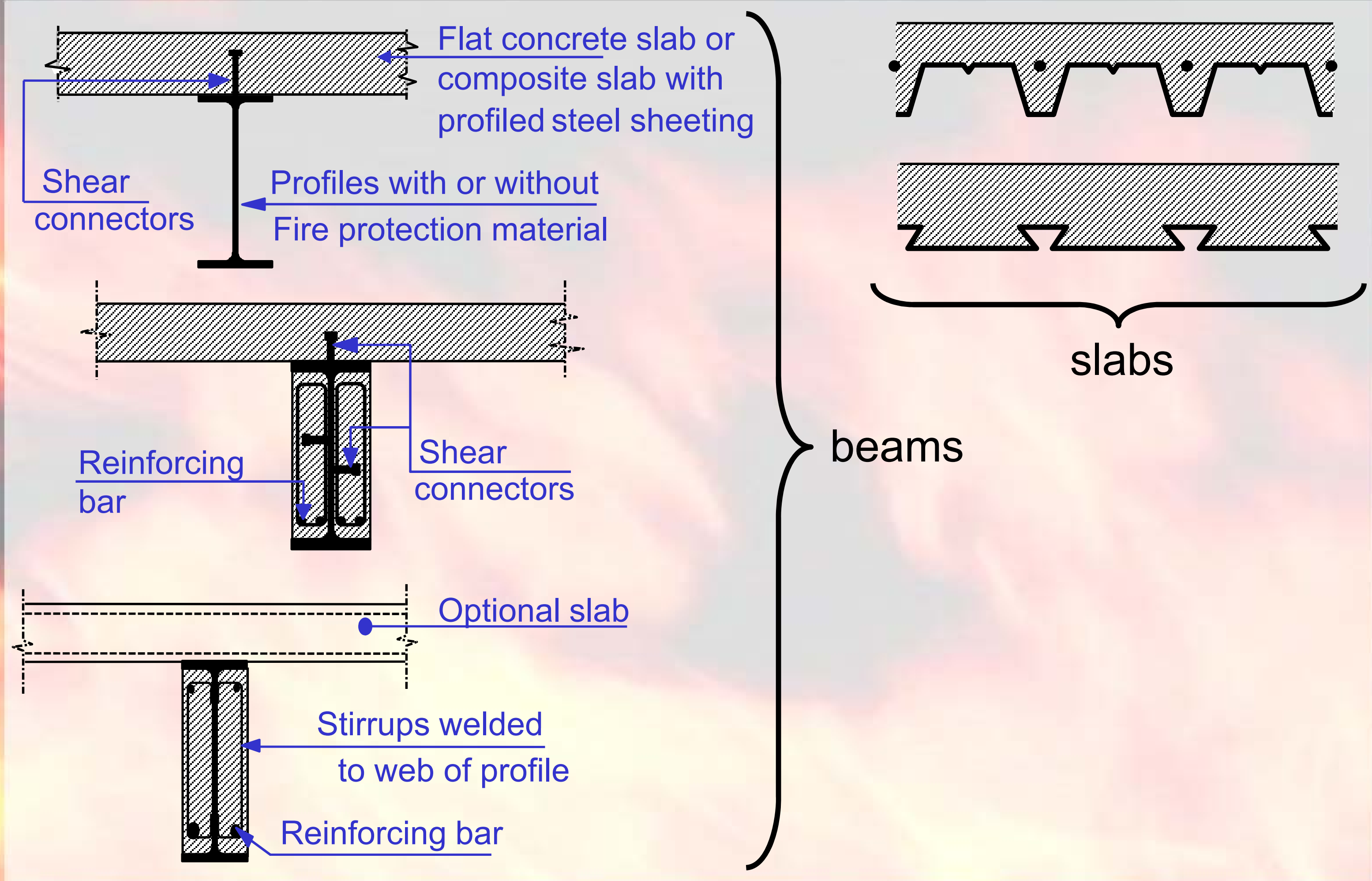


for insulated steelwork; to be used as first approximation

Calculation rules for composite elements

- Scope
- Thermal response steel columns with concrete between flanges
- Verification of the insulation criterion for composite slabs
- Temperature in additional reinforcement in composite slabs
- Thermal response of concrete filled SHS columns
- Evaluation

Composite slabs & beams
Options



Composite columns
Options

a: steel embedded in concrete (traditional approach)

b: concrete between flanges (f.r. dependent on reinforcement)

c: concrete filled SHS
- without reinforcement (f.r. ca. 30 minutes or less)
- with reinforcement (f.r. dependent on reinforcement)

Calculation procedure thermal response
Composite elements

- Non-uniform temperature distribution
- Load bearing and (possibly) separating function
  - Load bearing capacity
  - Thermal insulation
  - Integrity

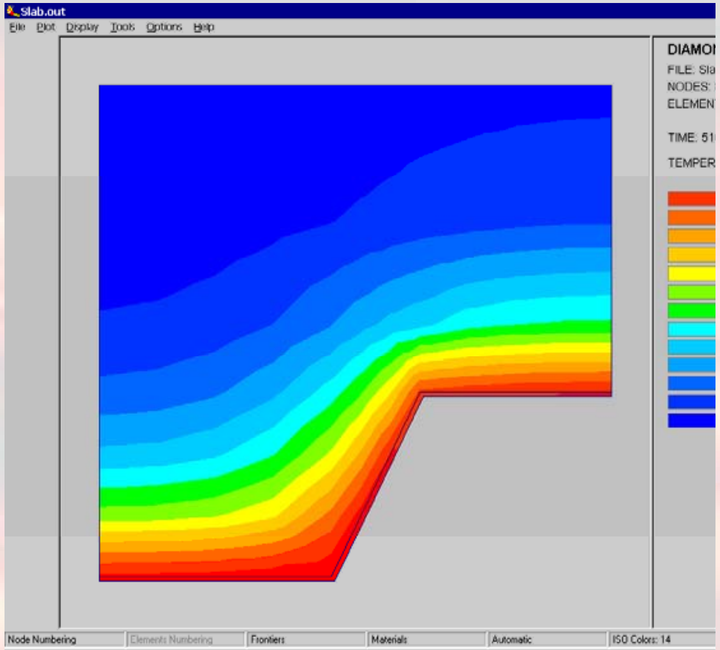
- Options
  - tabulated data
  - simple calculation model
  - advanced calculation model

Note: Reference: ČSN EN 1994-1-2

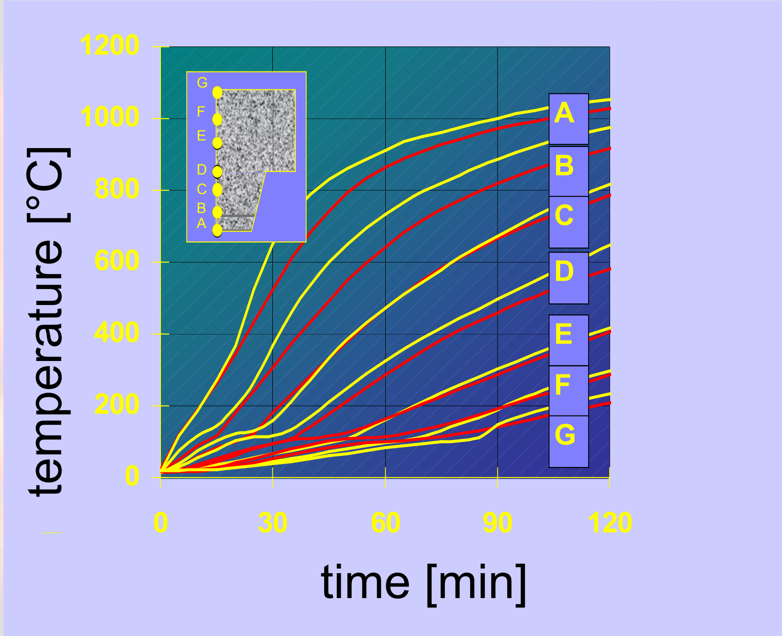
Composite elements
Calculation rules thermal response

- Similar to concrete elements
- Complications due to shape
- Simple calculation rules available
  - variety of backgrounds
  - see ČSN EN 1994-1-2

Thermal response composite elements
Advanced model (illustration)



computer simulation

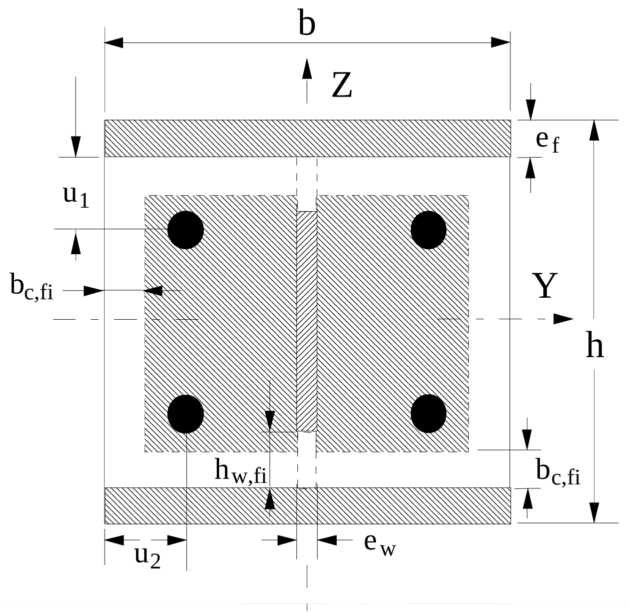


test vs. simulation

Composite elements
Simple calculation models thermal response

- Semi-empirical approach
- Parameter study based on systematic calculation with advanced calculation model
- Direct application of advanced calculation model

Simple calculation models
Semi-empirical approach



Reduced cross section

Components cross section:
- flanges steel section
- web steel section
- concrete
- re-bars

For each component:
-reduced strength
and/or
-reduced area

For details: see ČSN EN 1994 -1-2

Simple calculation models
Parameter study approach

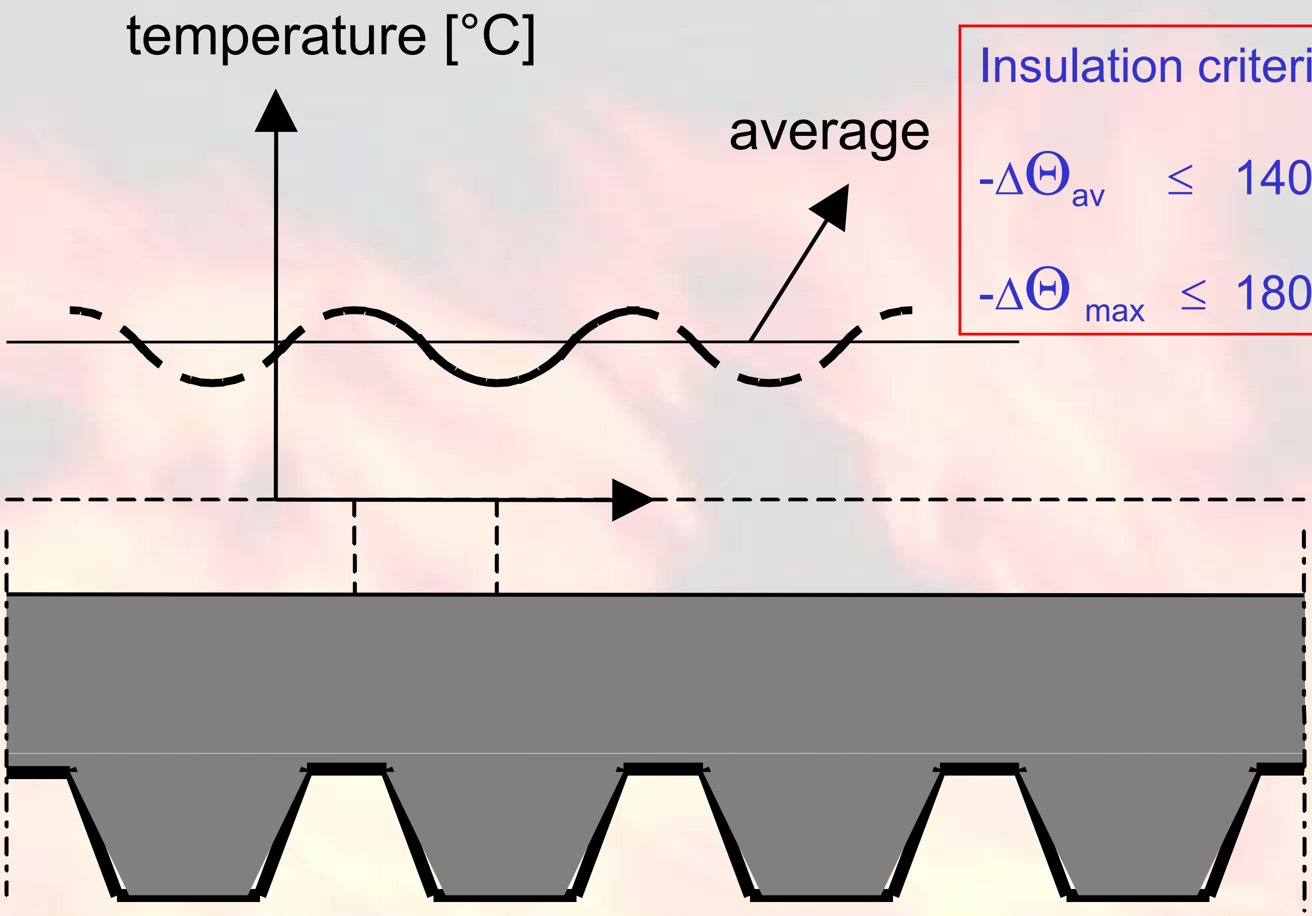
- Composite slabs with profiled steel sheet

Decking type	Concrete depth H_B [mm]	Concrete type
re-entrant (6x)	50, 60, 70, 80, 90, 100, 110, 120	NCW and LWC ČSN EN 1994-1-1
trapezoidal (49x)		

- standard fire conditions
- profiled shape deckings taken into account
- thermal properties according to EC
- average moisture content: 4% (NWC) and 5% (LWC)

Note: total number of simulations: 880

Typical temperature distribution at the unexposed side of a composite slab

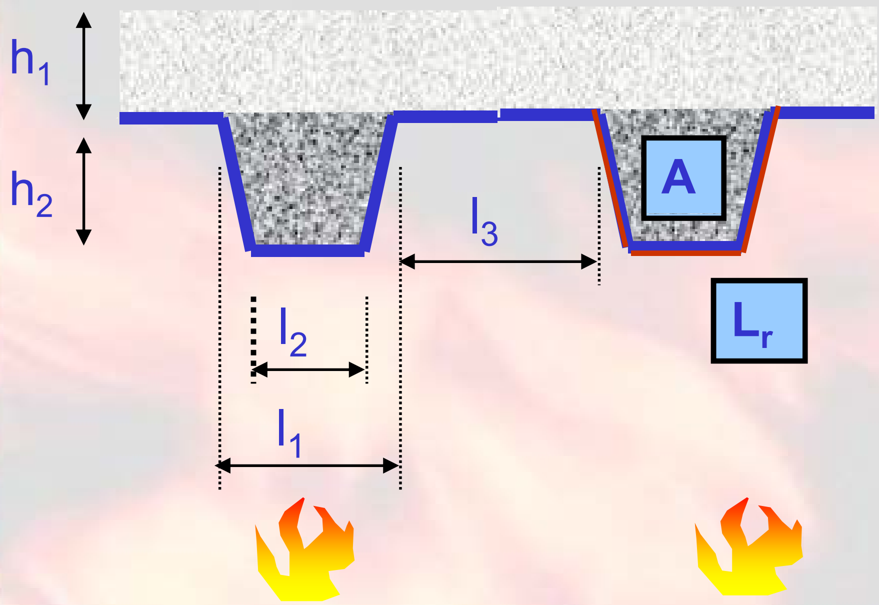


Insulation criterion:

$-\Delta\Theta_{av} \leq 140\ °C$

$-\Delta\Theta_{max} \leq 180\ °C$

Composite slabs
Thermal insulation (illustration)



Issues:

$t_f = t_f\,(l_1, l_2, \ldots, A/L_r, \phi)$

with:

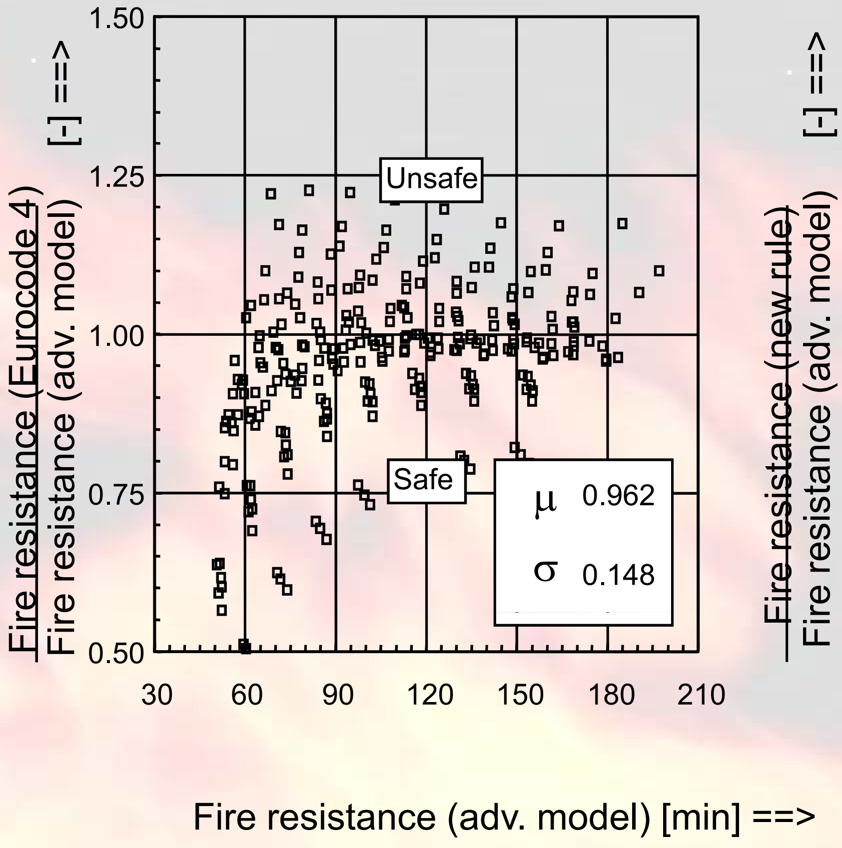
$l_1, l_2, ..$	geometry slab
A	volume rib
L_r	exposed surface rib
ϕ	configuration factor

$t_f = a_0 + a_1 \cdot h_1 + a_2 \cdot \phi + a_3 \cdot A/L_r + a_4 \cdot 1/L_3 + a_5 \cdot A/L_r \cdot 1/l_3$ [min]

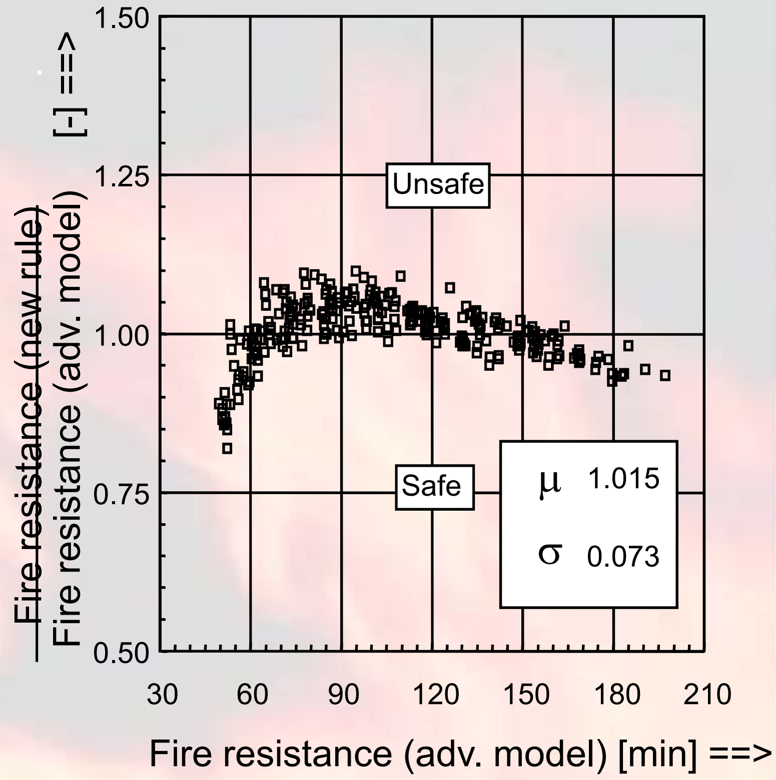
with:

a_i coefficients, depending on duration of s.f.c. exposure

Thermal insulation composite slabs
Verification simple calculation rule

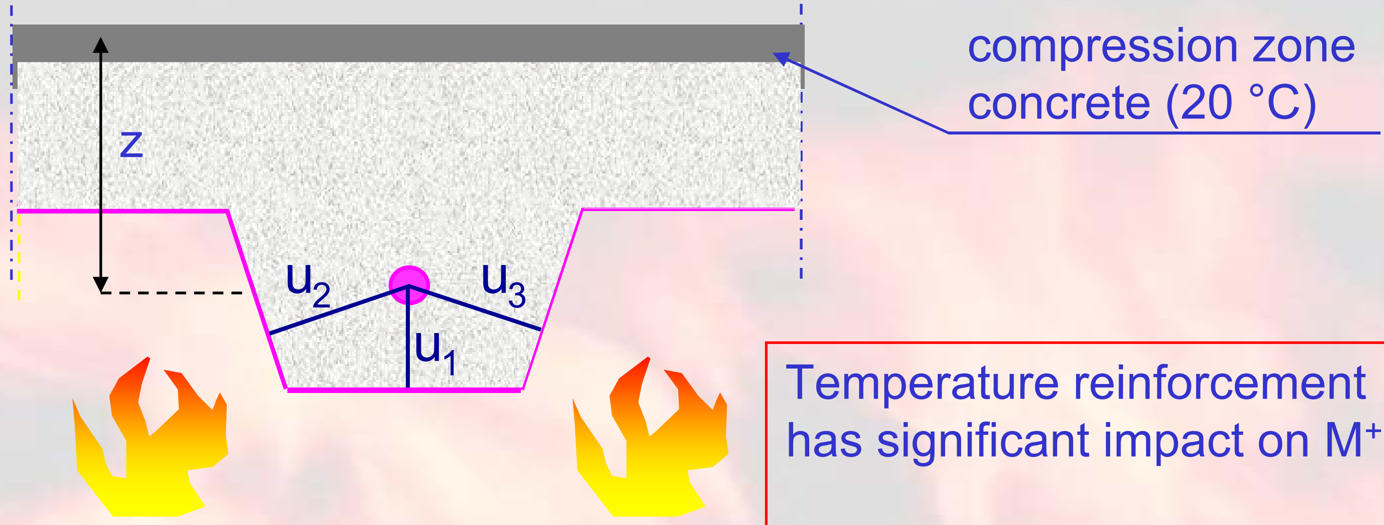


(a) ČSN P ENV rule



(b) new rule

Composite slabs
Thermal response positive reinforcement



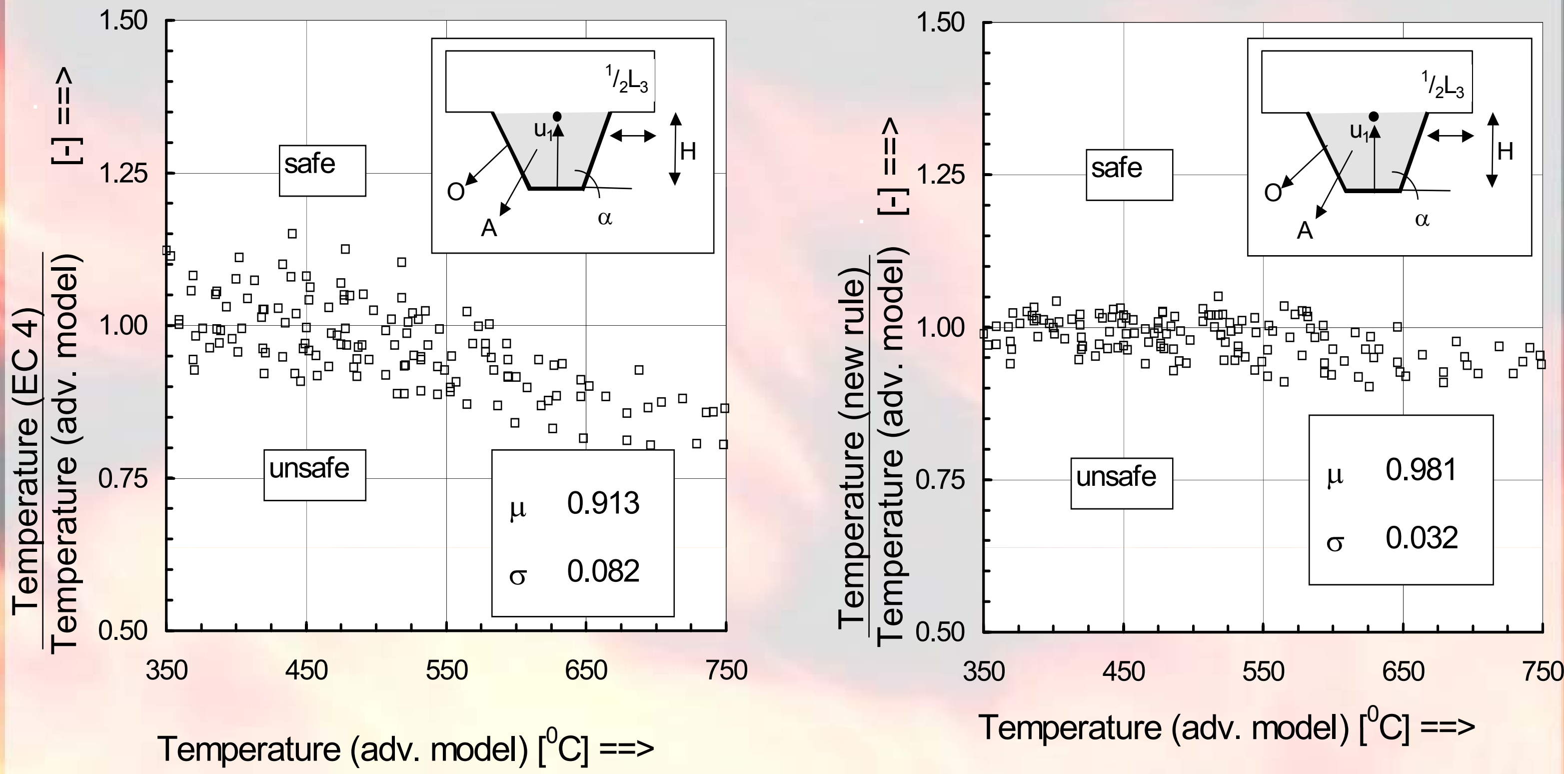
Temperature reinforcement has significant impact on $M^{+}_{p,\Theta}$

⟹ $\Theta_r = \Theta_r(u_1, A/O, l_3, z ..)$

⟹ $z = z(u_1, u_2, u_3)$

Note: steel sheet may significantly contribute to the load bearing capacity!

Thermal response positive reinforcement
Simple calculation rule



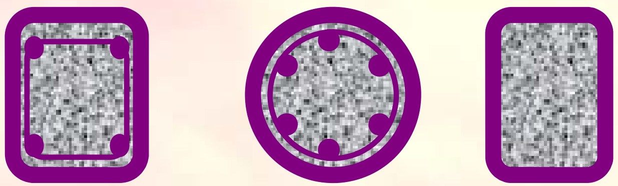
(a) ČSN P ENV rule

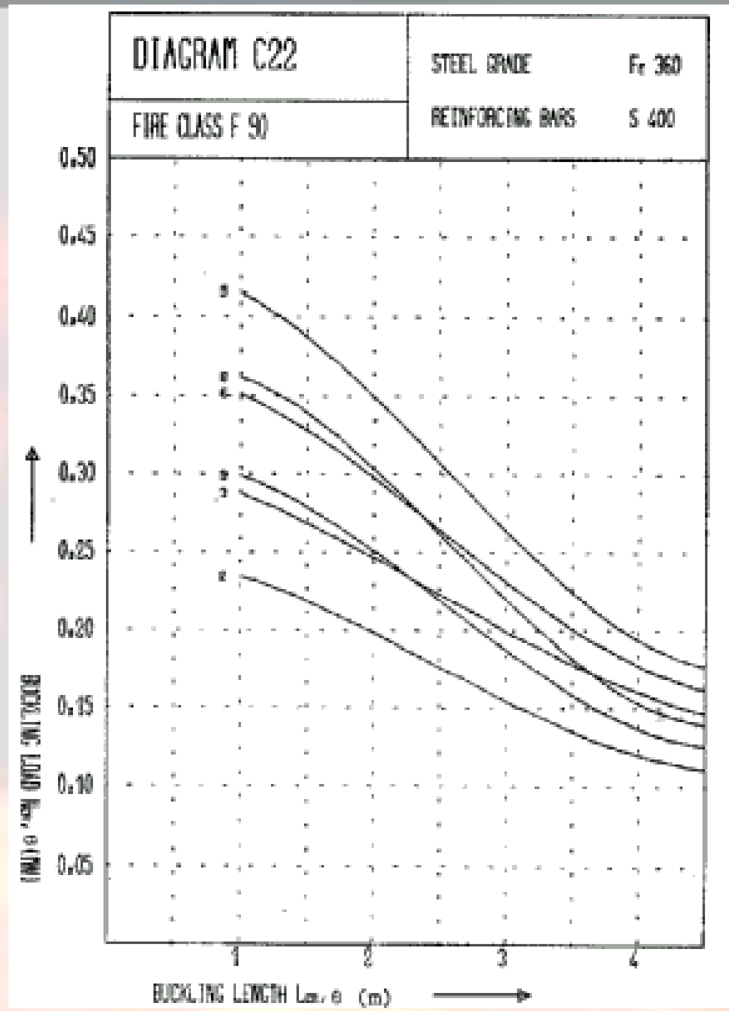
(b) new rule

Concrete filled SHS columns
Resistance to fire (traditional approach)

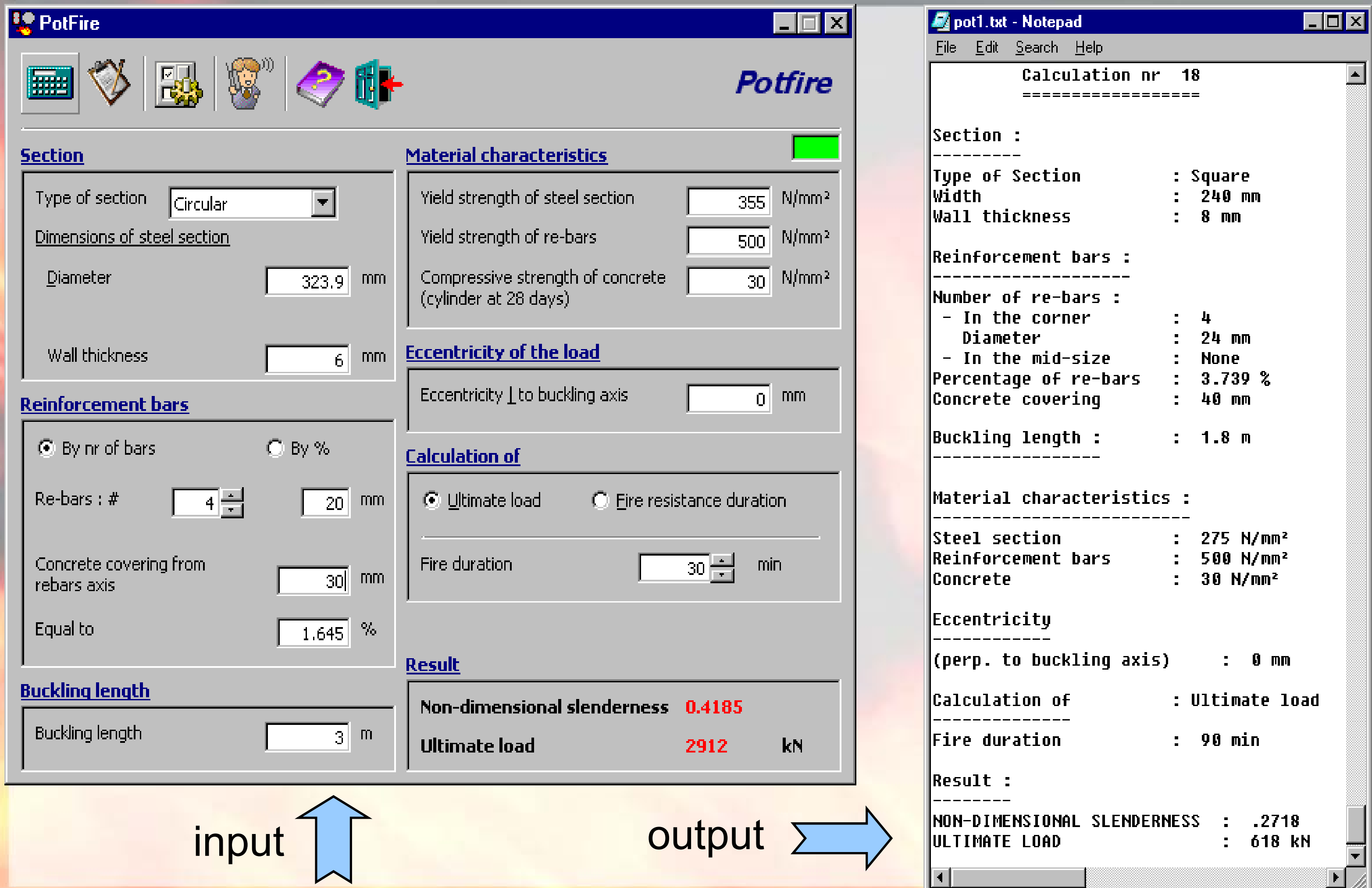
- Design charts available
- Unpractical
- Need for "user friendly" design tool
- $\Rightarrow$ e.g. POTFIRE

no.	concrete quality	rebar %
1	C20	1.0
2	C20	2.5
3	C20	4.0
4	C30	1.0
5	C30	2.5
6	C30	4.0
7	C40	1.0
8	C40	2.5
9	C40	4.0

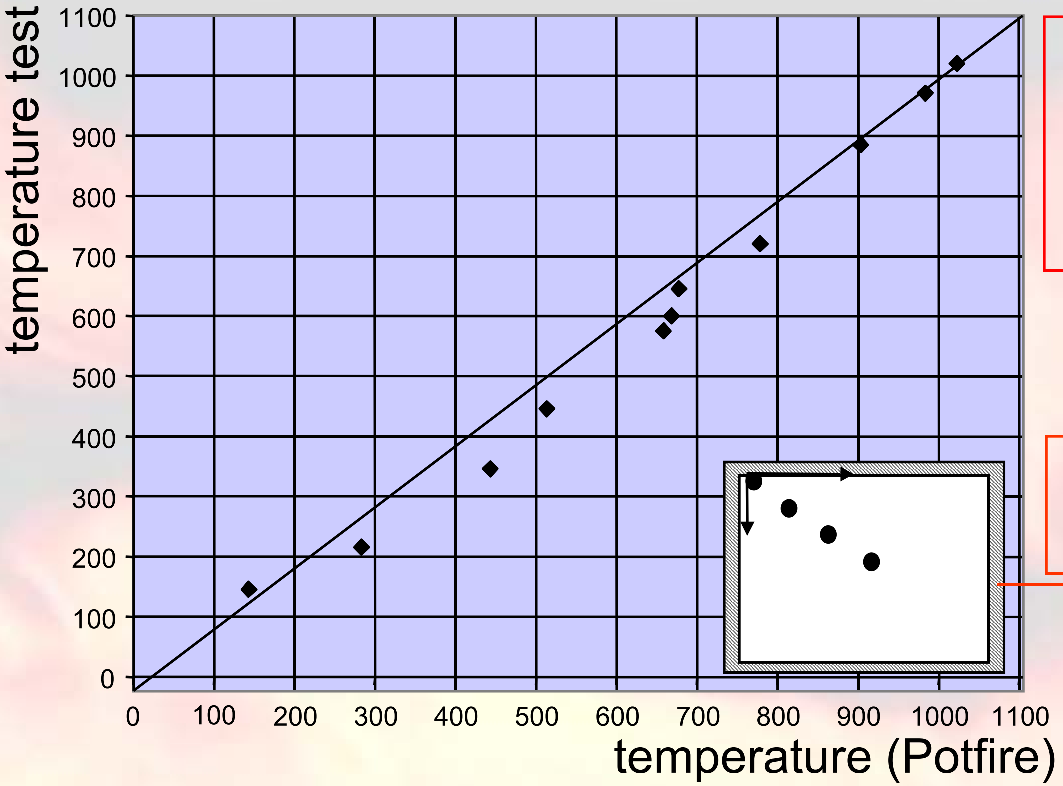




POTFIRE
In- & output



Validation POTFIRE



assumptions:

- α_{conv} = 25 W/m²k
- ε_{res} = 0.7

Concrete Filled Steel Hollow Section

Composite elements
Evaluation thermal response

- Thermal response is relative complicated
- “Simple” verification rules are available*):
  - tabulated data
  - design graphs
  - special purpose computer programmes (e.g. POTFIRE)
- Alternative: “advanced” calculation models;
  - feasible for NFSC

*) “Simple rules” have a limited field of application!

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 the critical temperature of thin-walled elements (see Part 3 for details)

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