



# DIFHSEK

**PART 2**  
THERMAL RESPONSE

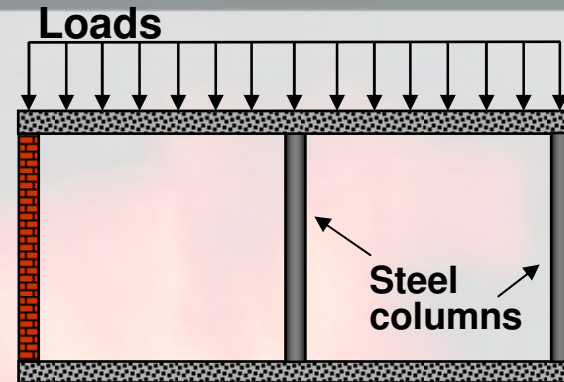
# Resistance to fire - Chain of events



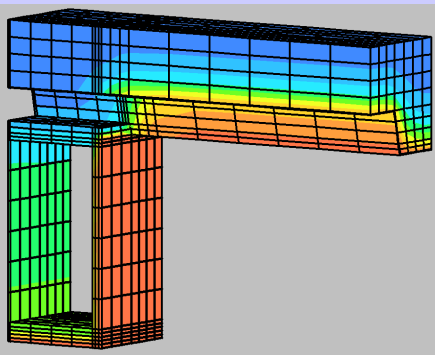
1: Ignition



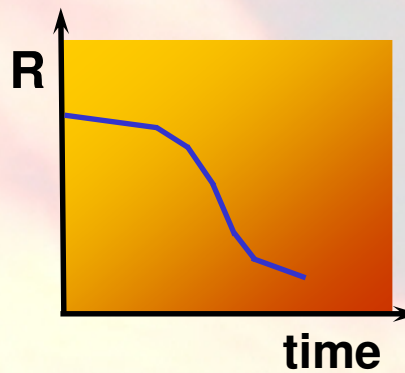
2: Thermal action



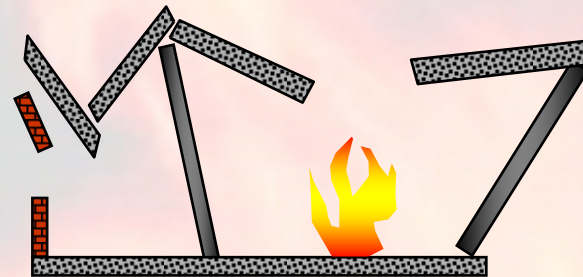
3: Mechanical actions



4: Thermal response



5: Mechanical response



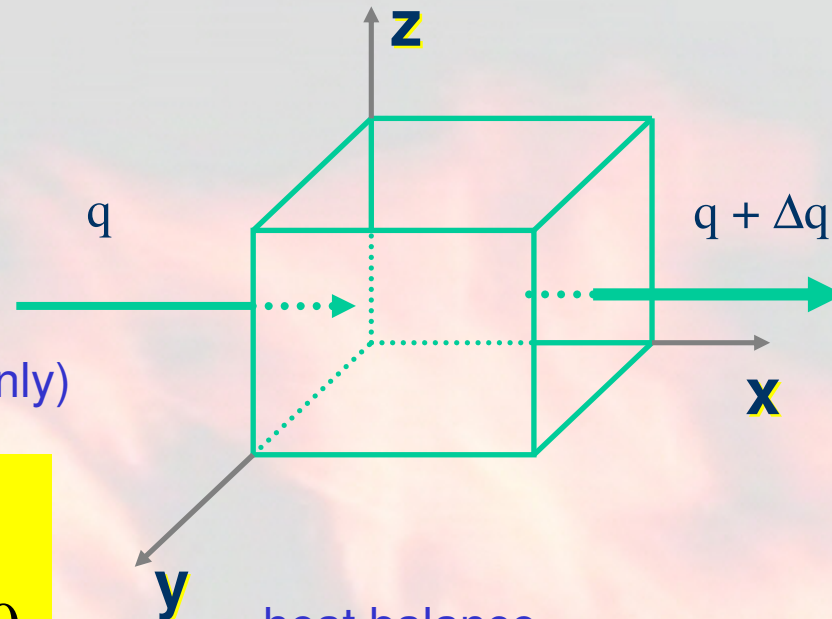
6: Possible collapse

# Contents

- 1. Introduction
- 2. Basics & illustrations
- 3. Calculation rules for steel elements
- 4. Calculation rules for composite elements
  
- Annexes
  - ✧ Fourier's differential equation
  - ✧ Thermal response of steel elements
  - ✧ Tabulated data & simple models according to EN 1994-1-2
  - ✧ EC rules for FR w.r.t. insulation of composite slabs
  - ✧ EC rules for temperature sagging reinforcement in composite slabs

# Thermal response Basics

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



DV: (shown for 1 direction only)

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

heat balance

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

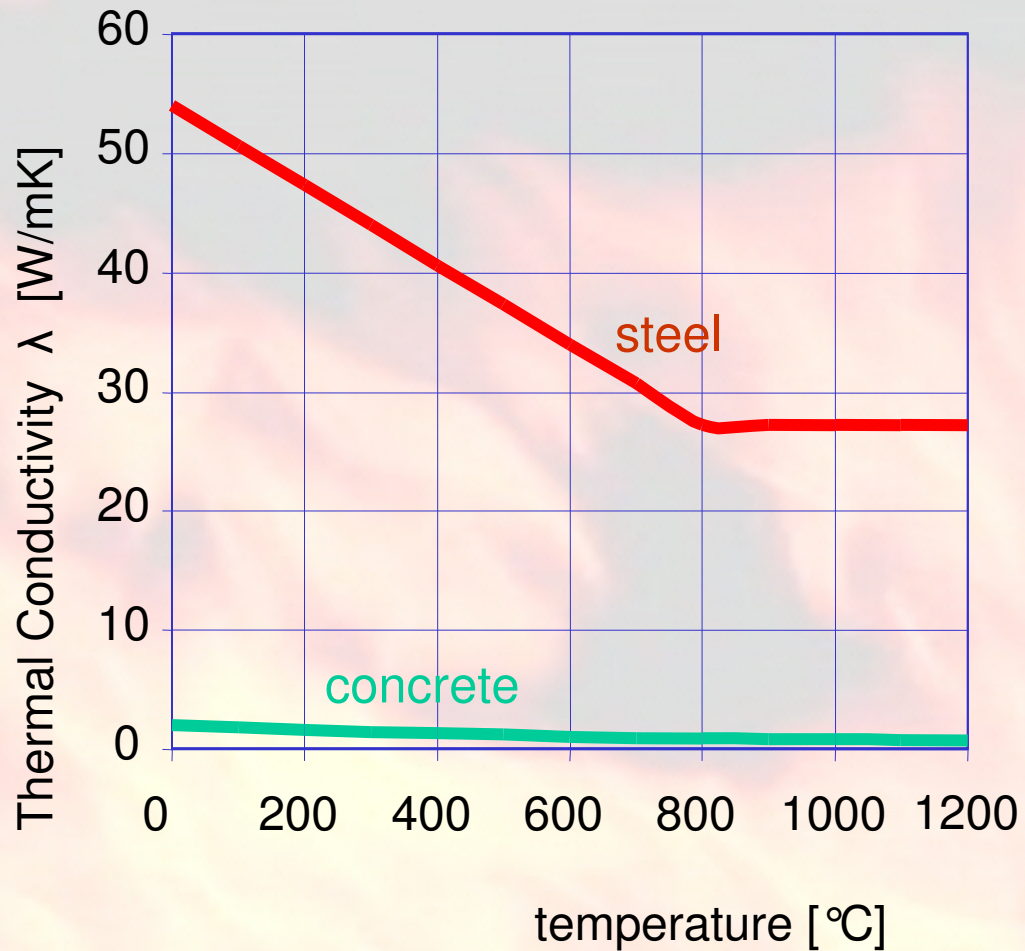
boundary condition: incoming/outgoing  
flux at surface:  $h_{\text{net,tot}}$   
initial condition: room temperature  
conditions

Fourier's law

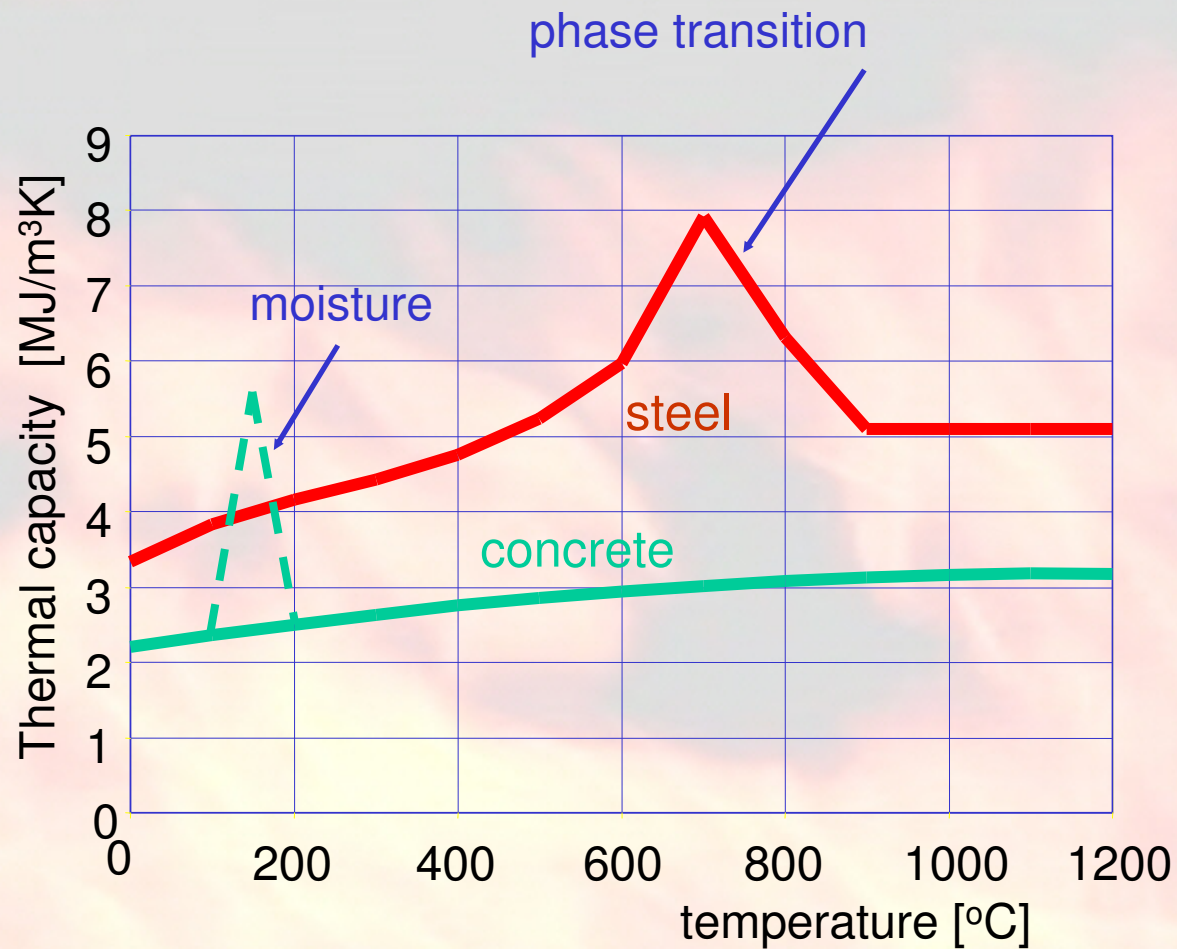
$$q = \lambda \Delta \Theta / \Delta x$$

# Thermal conductivity

## Concrete vs. steel

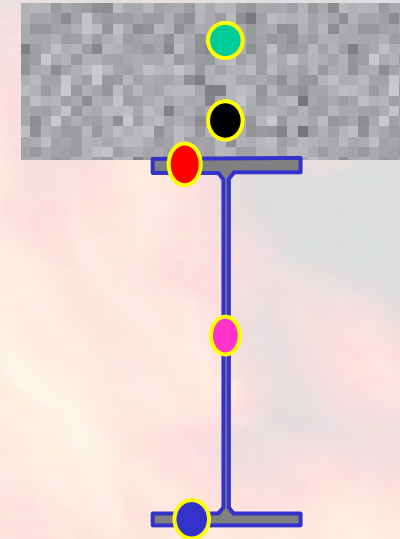
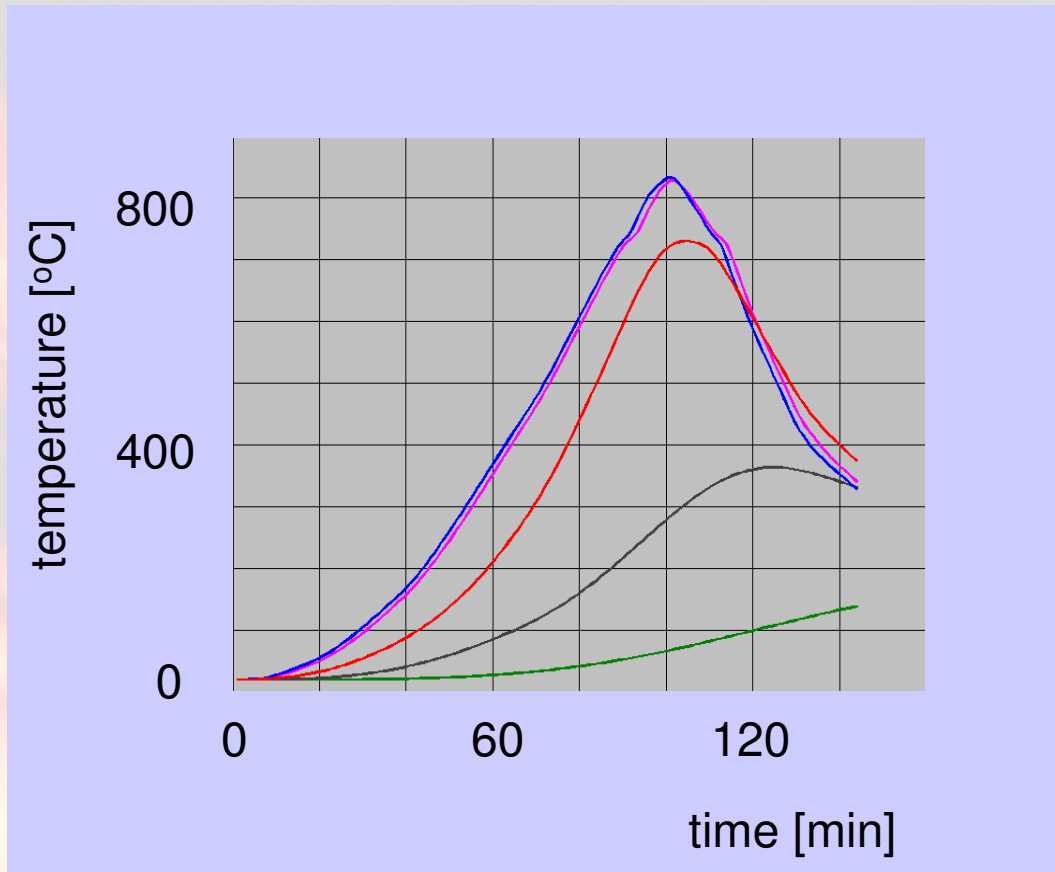


# Thermal capacity Concrete vs. steel

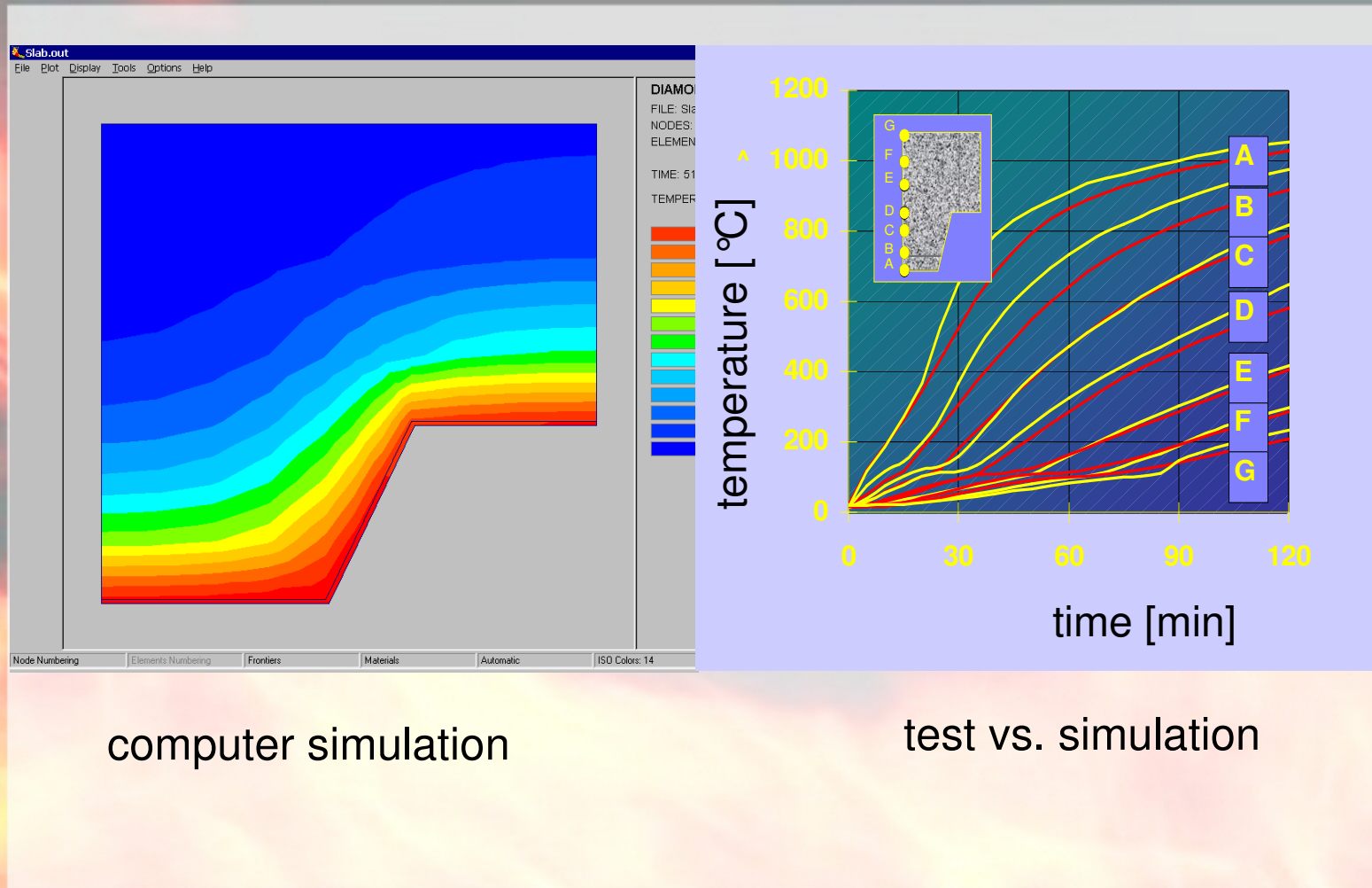


# Thermal response

## Steel beam/concrete slab (2D)



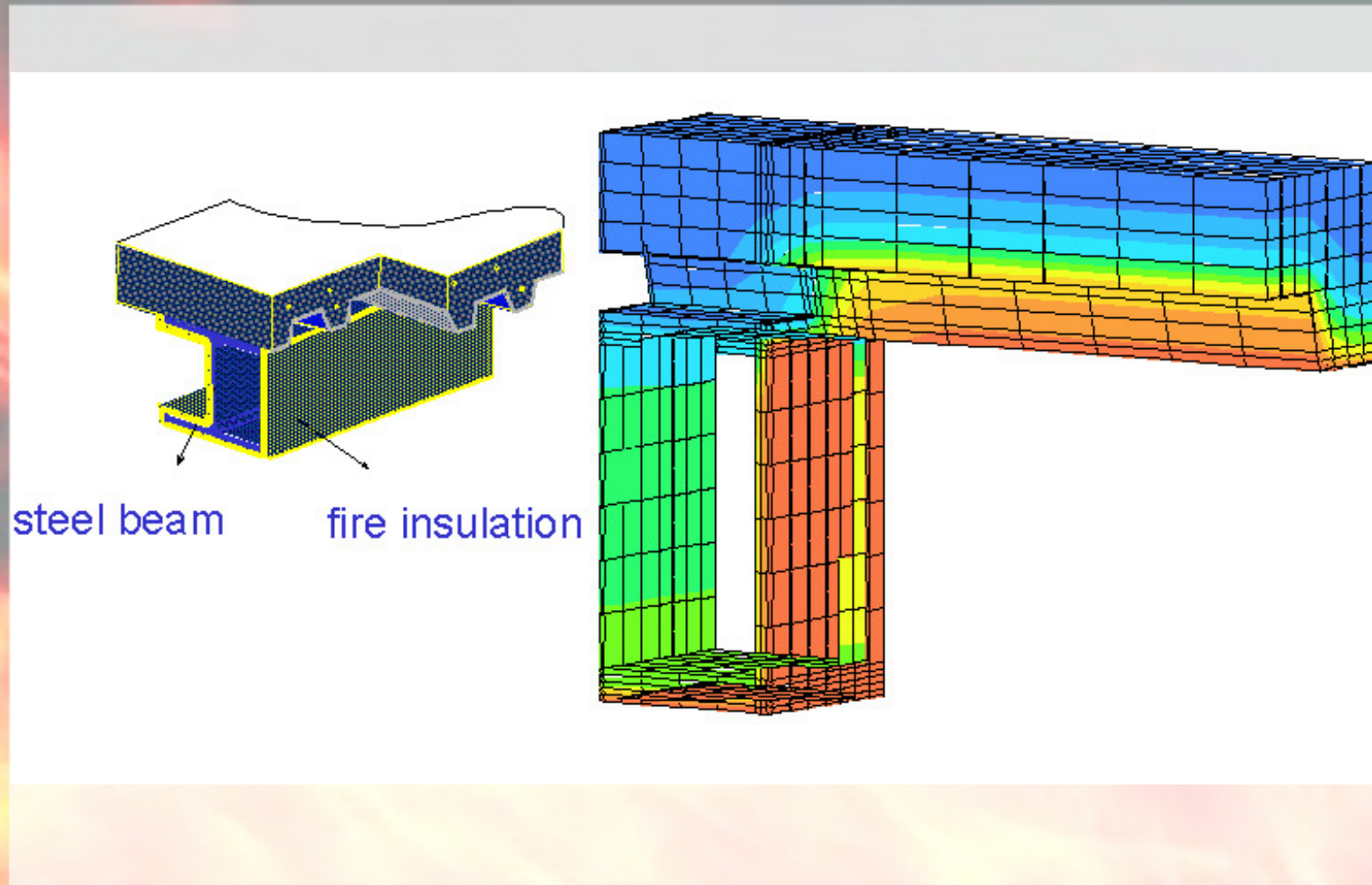
# Thermal response Composite slab (2D)



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

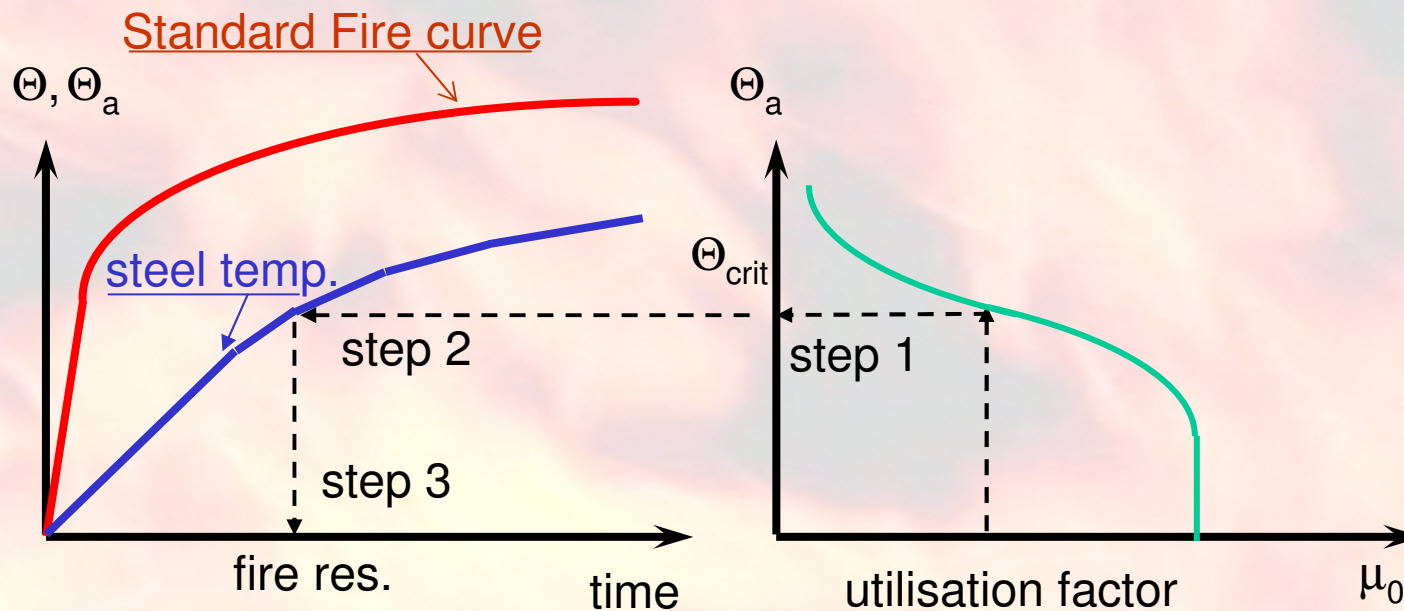
- Load bearing function only
  - ⇒ Load bearing capacity
- Uniform temperature distribution
  - ⇒ Critical steel temperature concept

Note: refer to EN1993-1-2 (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:

$$\dot{h}_{net,r} = \Phi \cdot \varepsilon_m \cdot \sigma \cdot [(\Theta_r + 273)^4 - (\Theta_m + 273)^4]$$

- Convective heat transfer:

$$\dot{h}_{net,c} = \alpha_m \cdot (\Theta_g - \Theta_m)$$

with:

$\Theta_{rad}$  is radiation temperature [°C]  $\Rightarrow \Theta_{rad} \rightarrow \Theta_g \rightarrow$  fire curve

$\Theta_m$  is surface temperature [°C]  $\Rightarrow$  thermal response

$\varepsilon_m$  is surface emissivity [-]  $\Rightarrow$  steel: 0.7

$\alpha_c$  is coefficient convection  $\Rightarrow$  25 - 50 W/m<sup>2</sup>K  
(depending on fire model)

$\Phi$  is configuration factor [-]  $\leq 1.0 \Rightarrow$  safe: 1.0

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

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

# Thermal response

## Steel profiles

$$\frac{\partial(\rho_a c_a \Theta)}{\partial t} + \frac{\partial(\lambda \frac{\partial \Theta}{\partial x})}{\partial x} = 0$$

boundary & initial conditions

$$\frac{d \Theta_a}{dt} = \frac{k_{tot} A_m}{\rho_a c_a V}$$

with

$A_m$  is exposed surface area member [m<sup>2</sup>/m]

$V$  is volume member [m<sup>3</sup>/m]

Note: key is uniform temperature distribution

# Temperature rise bare steelwork

## Basic equation

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

Legend:

$\Delta\Theta_a$  : increase steel temp.

$\Delta t$  : time step

$A_m/V$  section factor

$K_{bare}$  : heat transfer coef.

$k_{sh}$  : corr. coef. shadow effect



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

with

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

# Shadow effect

## Basics

- Shadow effect caused by local shielding of radiative heat transfer, due to shape of steel profile, i.e.:
  - ✧  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:

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

with:

✧ for I – sections:

$$k_{sh} = 0.9 [A_m/V]_b / [A_m/V]$$

✧ for “all” other sections:

$$k_{sh} = [A_m/V]_b / [A_m/V]$$

➤ Protected members: no effect

# Temperature rise insulated steelwork

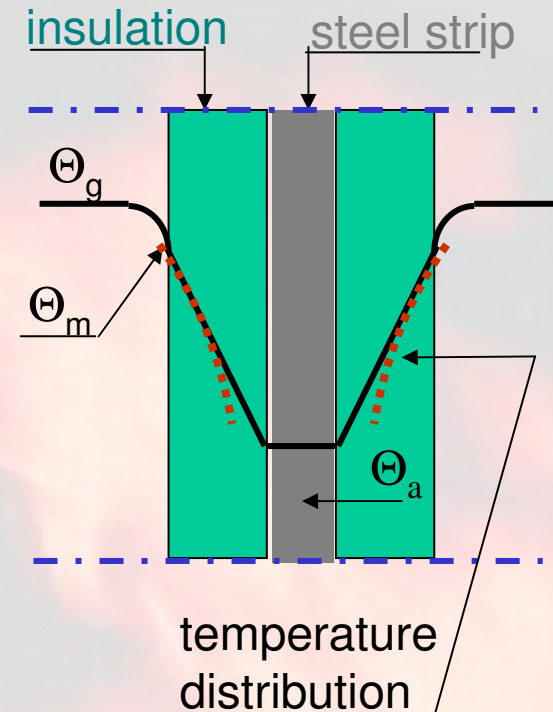
## Basic equations

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

with

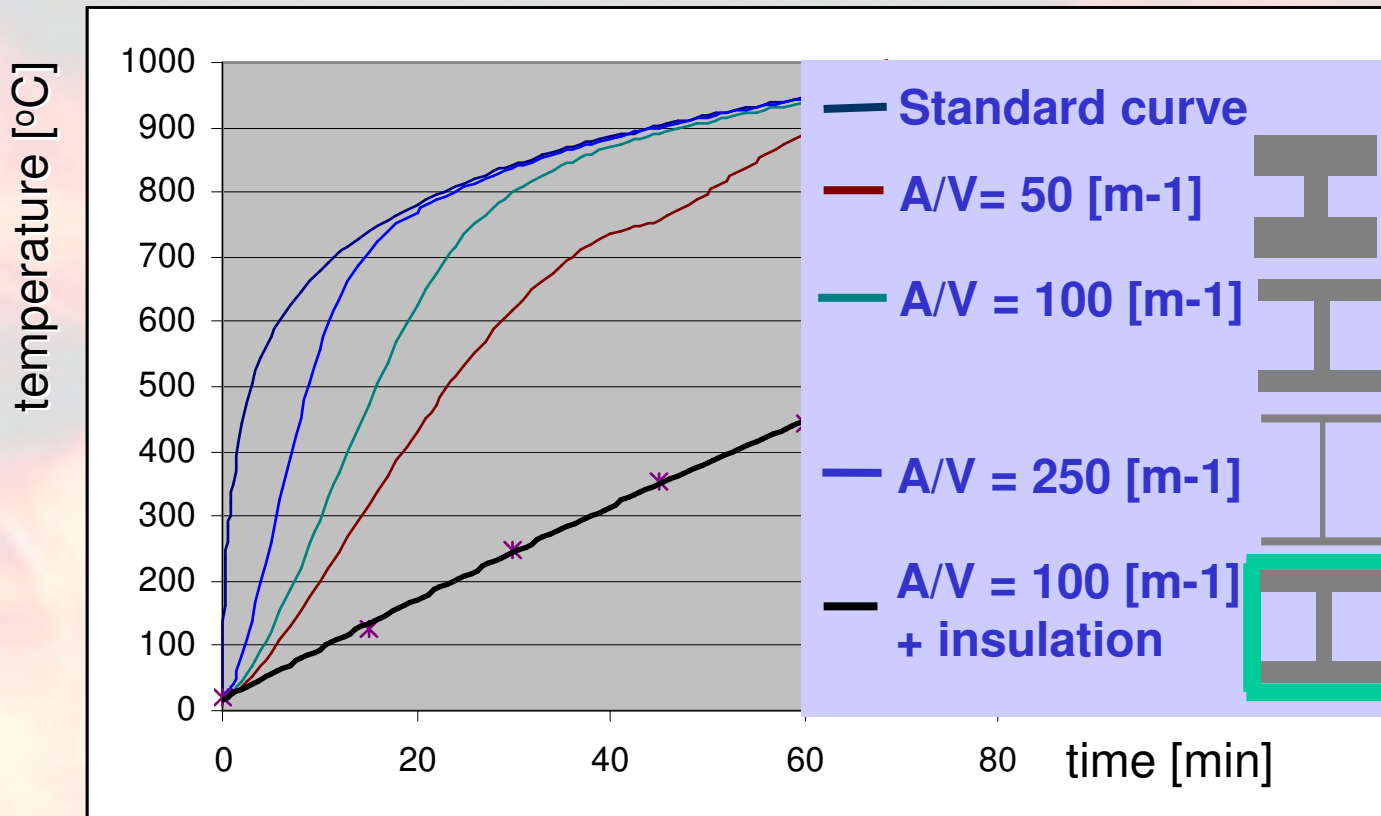
$$K_{ins} = K_{ins} \left( \frac{\lambda}{d}, \rho_p, c_p, \rho_a, c_a \right) \quad \dots (b)$$

Notes: (a)  $\Theta_g - \Theta_m \ll \Theta_m - \Theta_a$   
 (b) for light weight insulation:  
 $K_{ins} \approx \lambda/d$



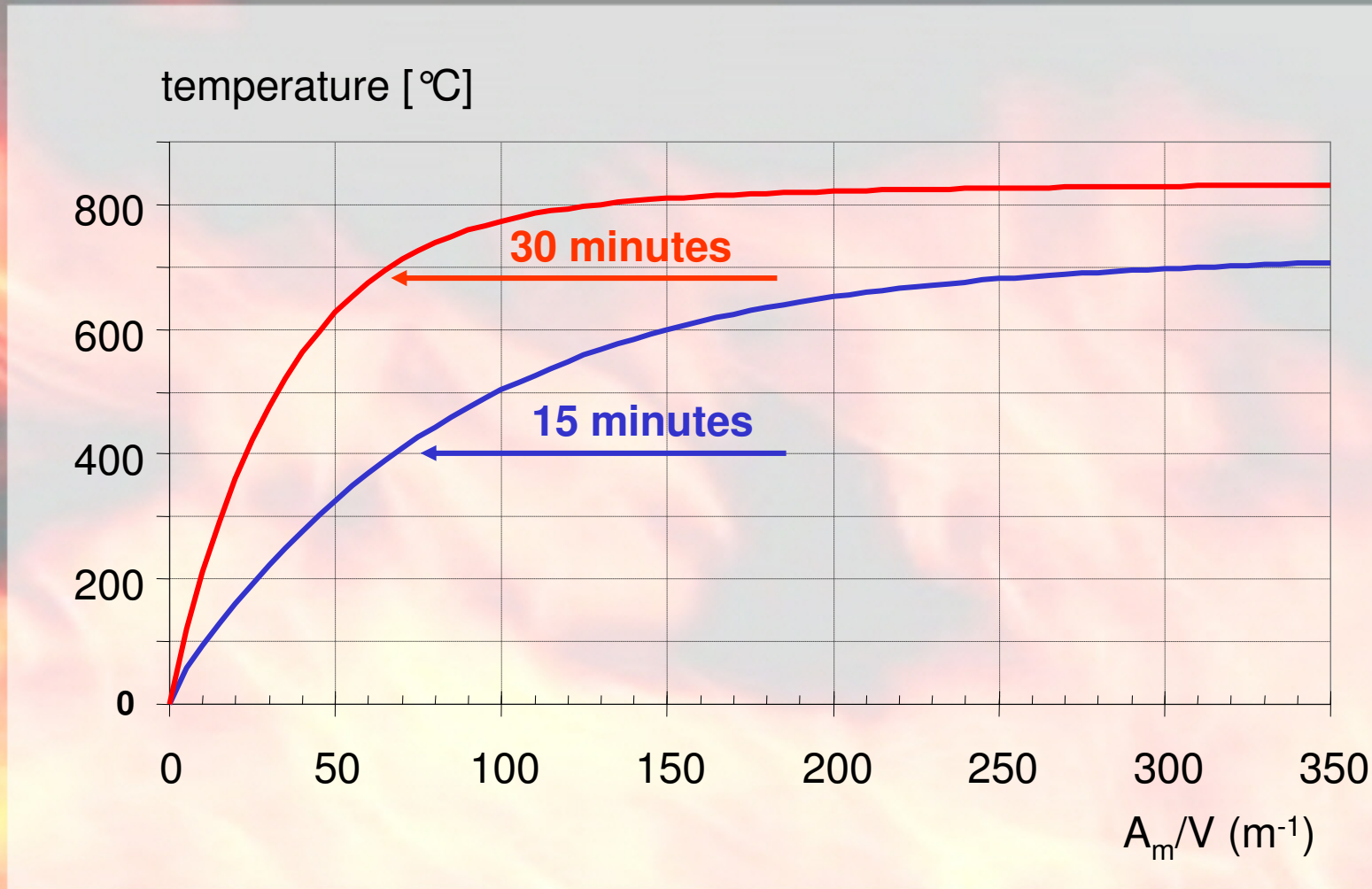
effect thermal  
 thermal capacity  
 insulation

# Temperature development in steel profiles

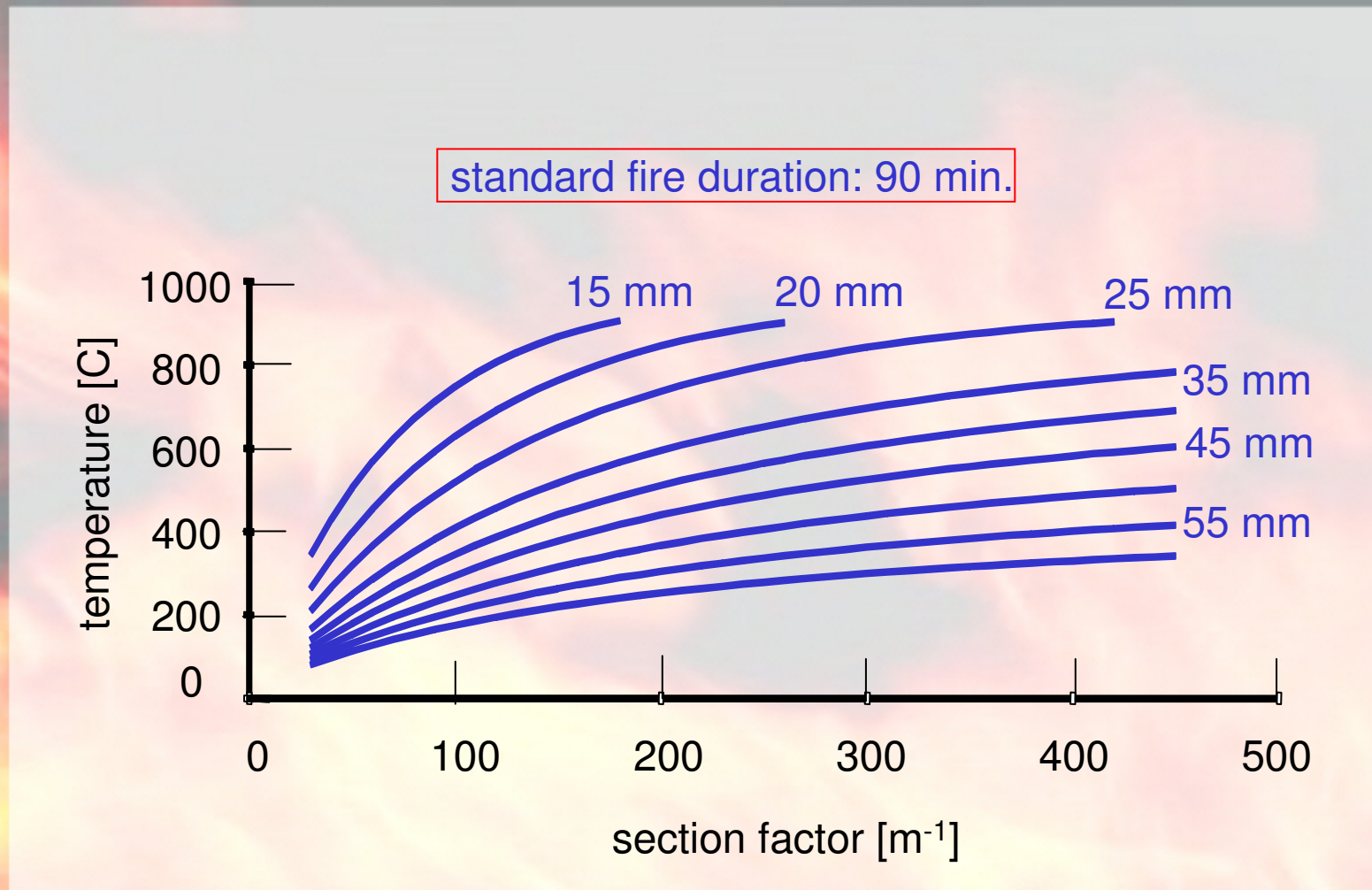


# Steel temperature as function of Section Sector

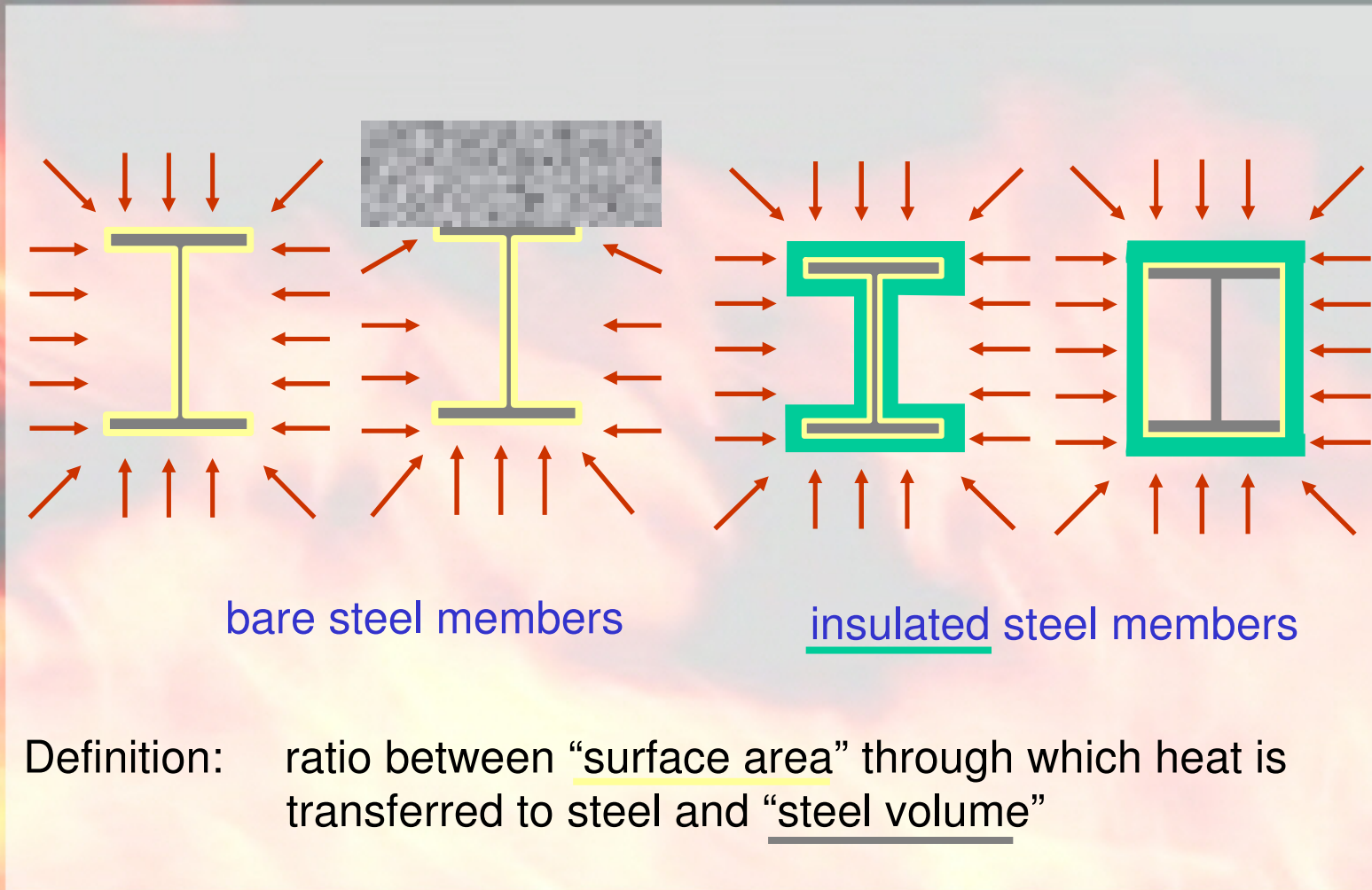
## Bare steel profiles



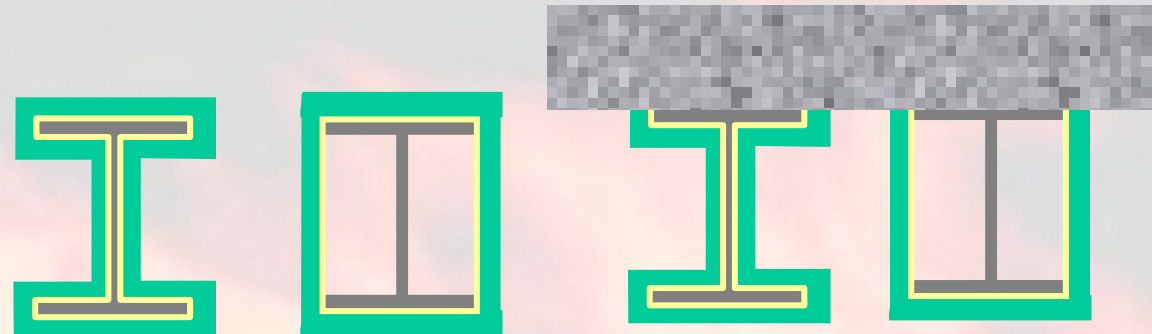
# Steel temperature as function of Section Factor Insulated steel profiles



# Section Factor steel profile Concept



# Section Factor (A/V) Numerical values



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

Note: range:  $\approx 50 - 400 \text{ [m}^{-1}\text{]}$

# Heat transfer coefficient Insulated steel members

- Approximation:  $K_{\text{ins}} \approx \lambda/d$  (for light weight insulation)  
with:  $d$  is thickness insulation material  
 $\lambda$  is coefficient of thermal insulation
- Determination: semi-empirical approach  
⇒ ENV 13381, p. 4

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

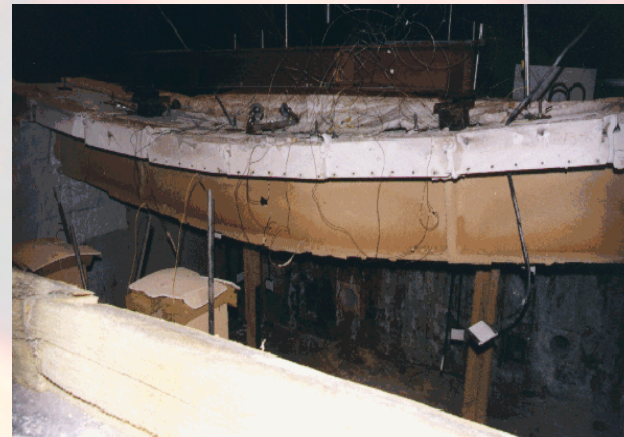
# Characterisation tests

## 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

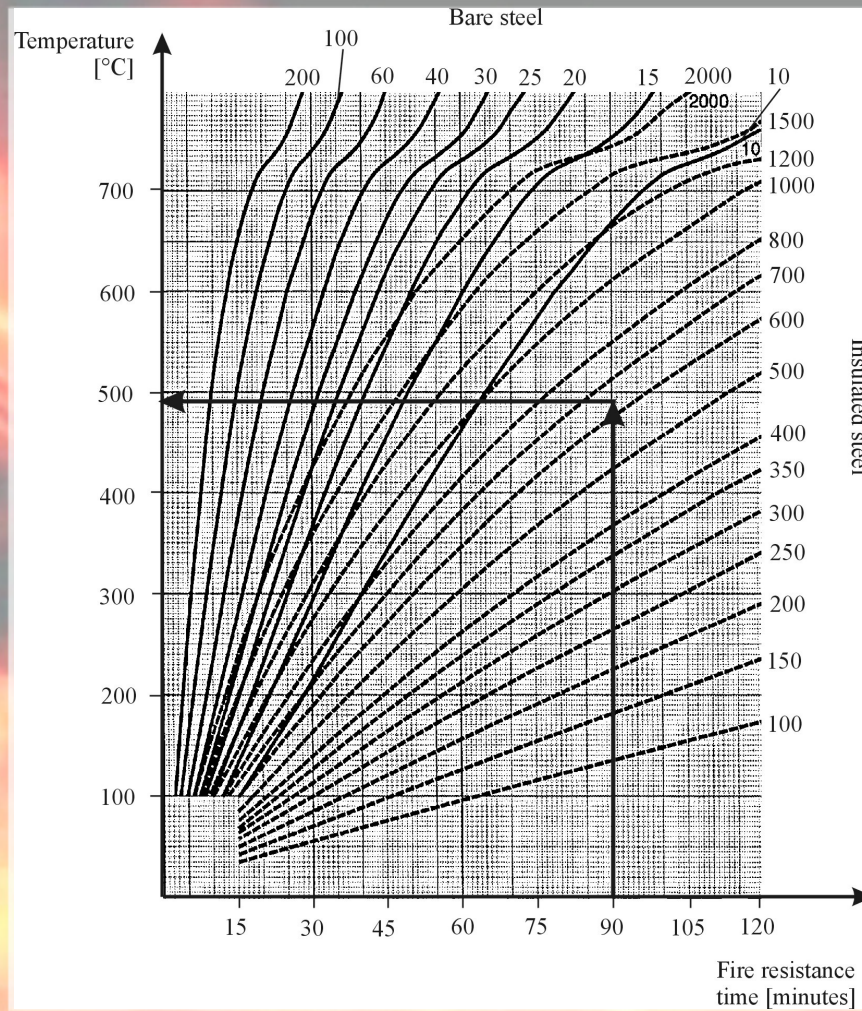
# Fire insulation systems

## Options

- Boards
- Sprays
- Intumescent
  
- 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



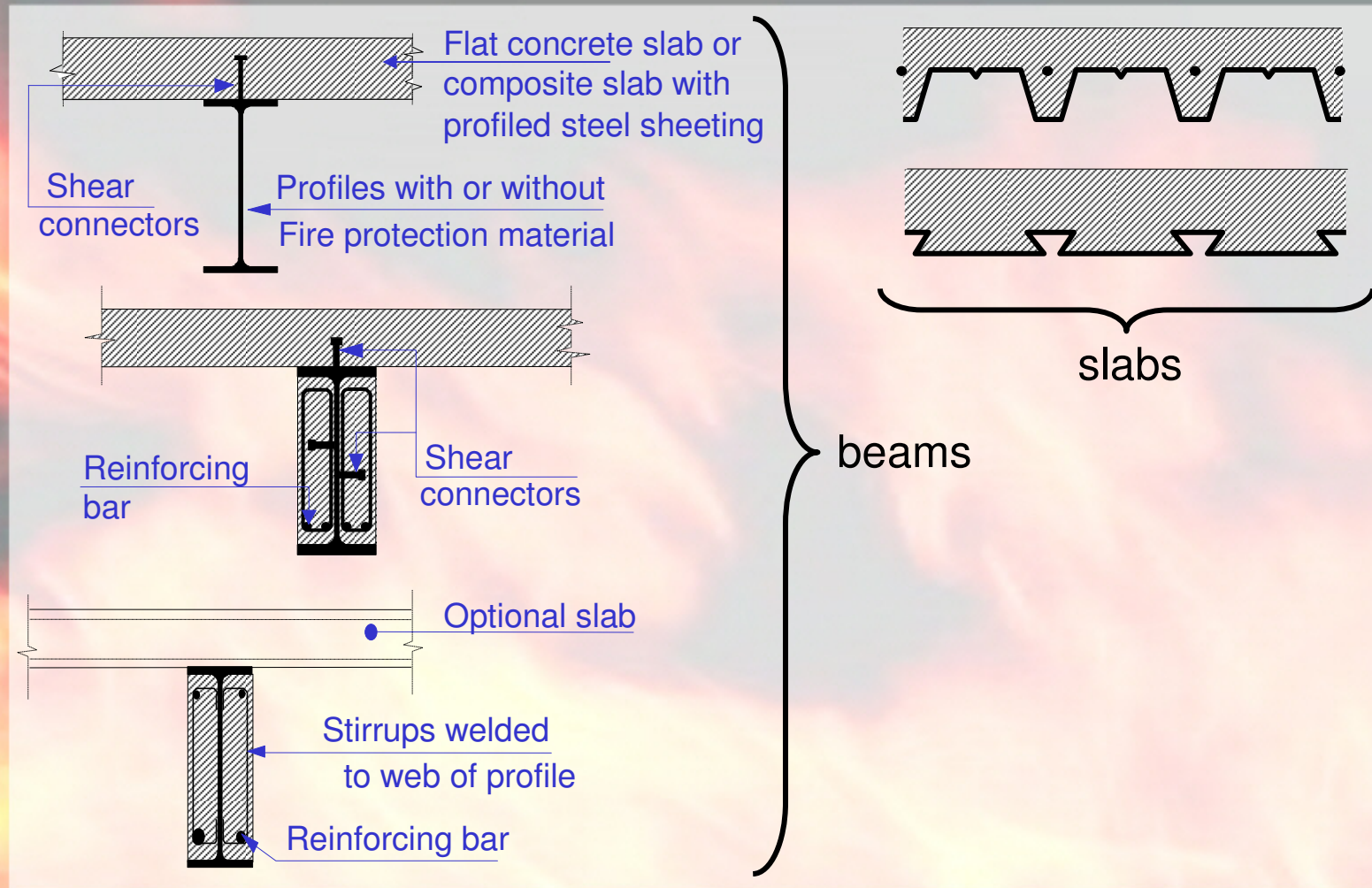
for insulated steelwork;  
to be used as first  
approximation

# 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

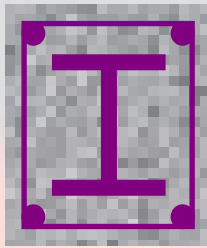
# Composite slabs & beams

## Options

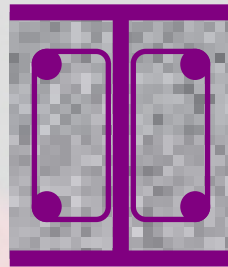


# Composite columns

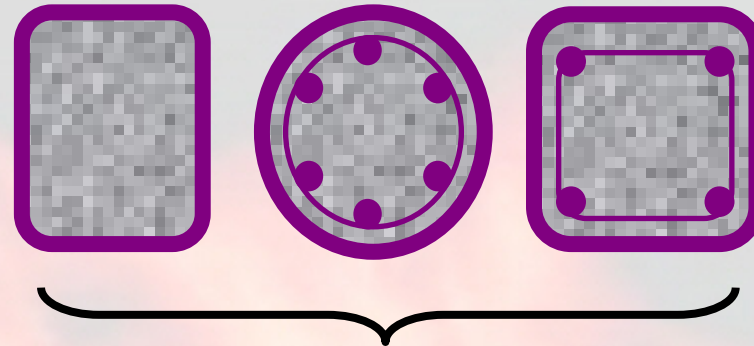
## Options



(a)



(b)



(c)

- 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: EN 1994-1-2

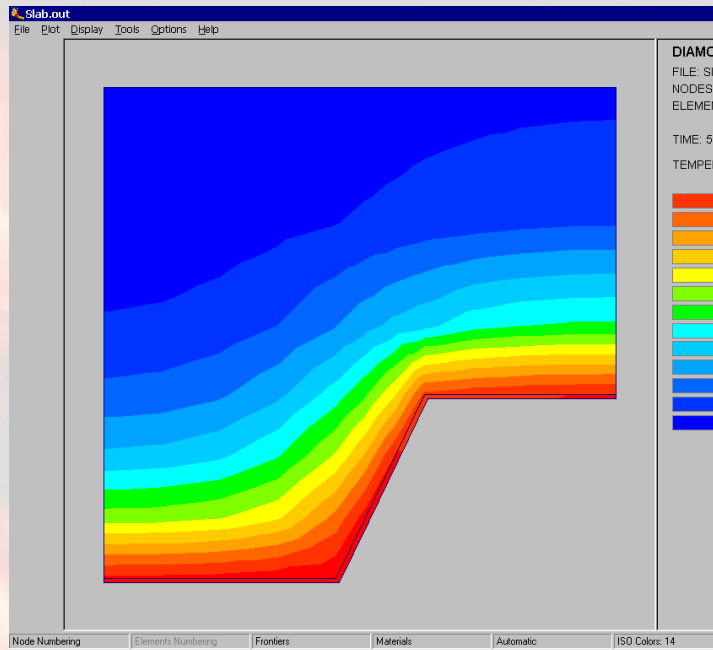
# Composite elements

## Calculation rules thermal response

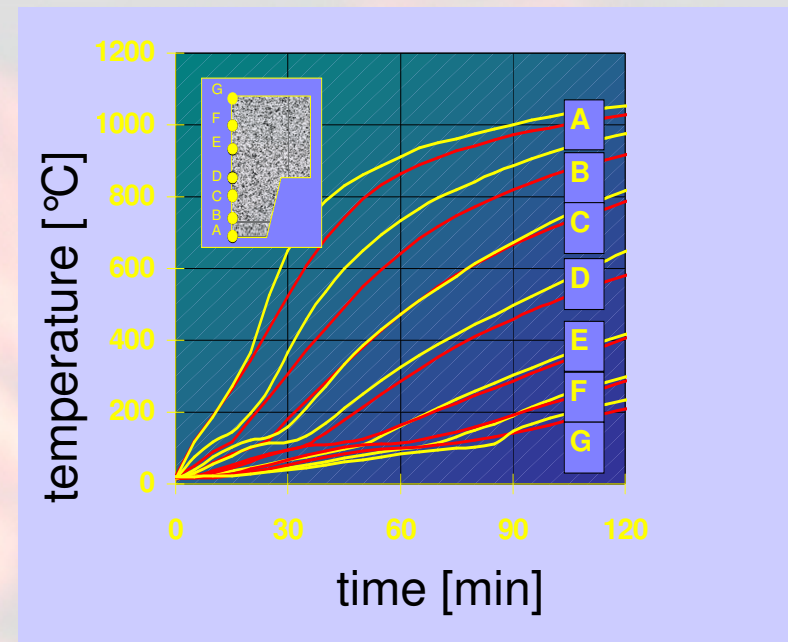
- Similar to concrete elements
- Complications due to shape
- Simple calculation rules available
  - ✧ variety of backgrounds
  - ✧ see EN 1994-1.2

# Thermal response composite elements

## Advanced model (illustration)



computer simulation



test vs. simulation

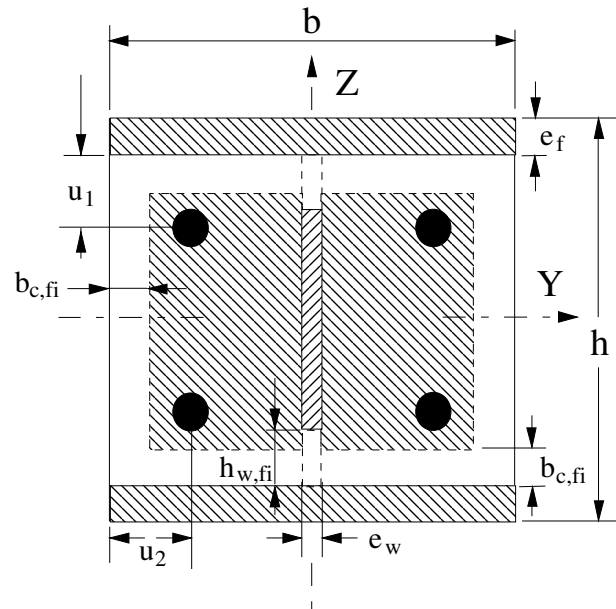
# Composite elements

## 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 EN 1994 -1-2

# Simple calculation models

## Parameter study approach

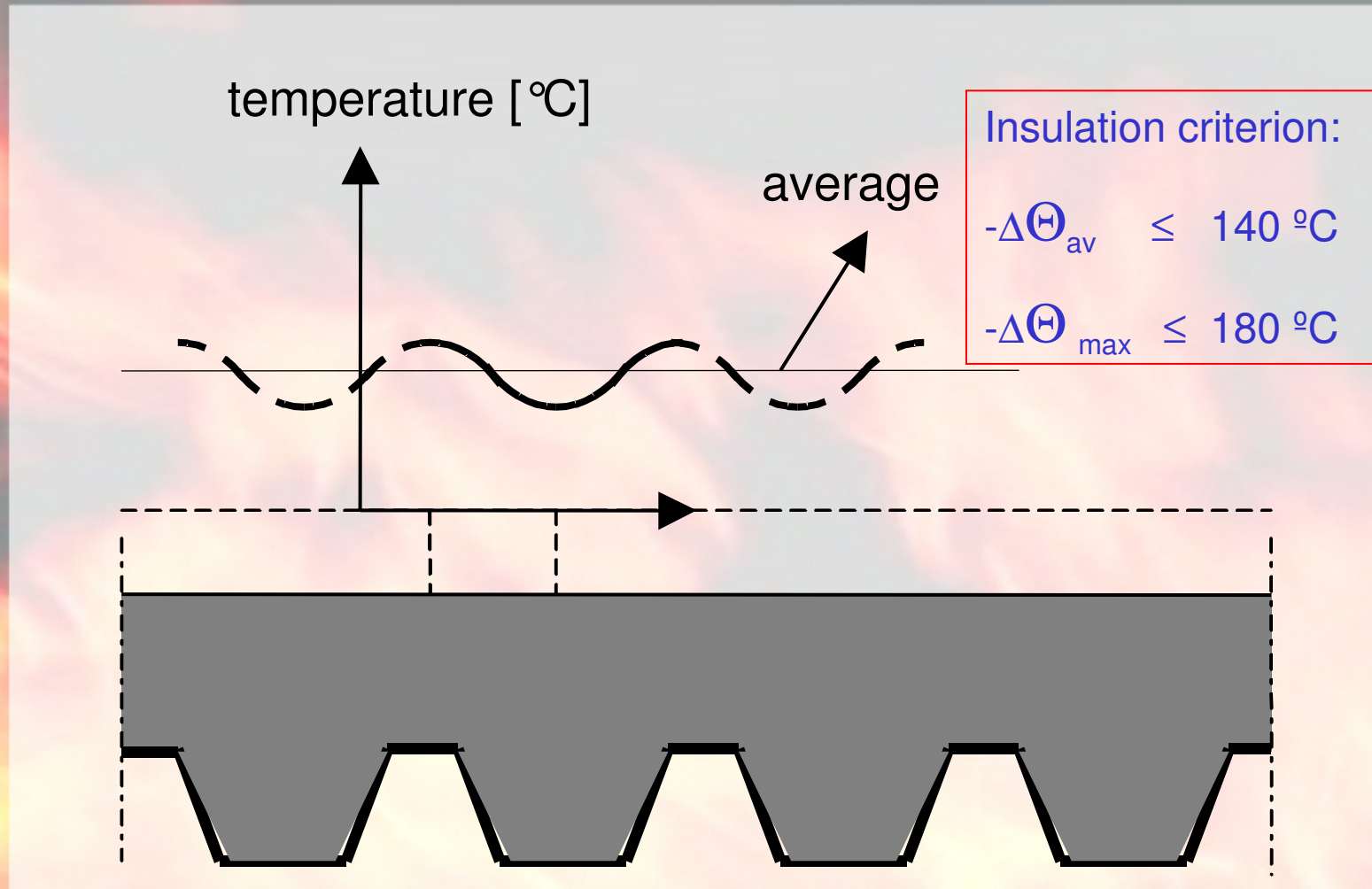
- Composite slabs with profiled steel sheet

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

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

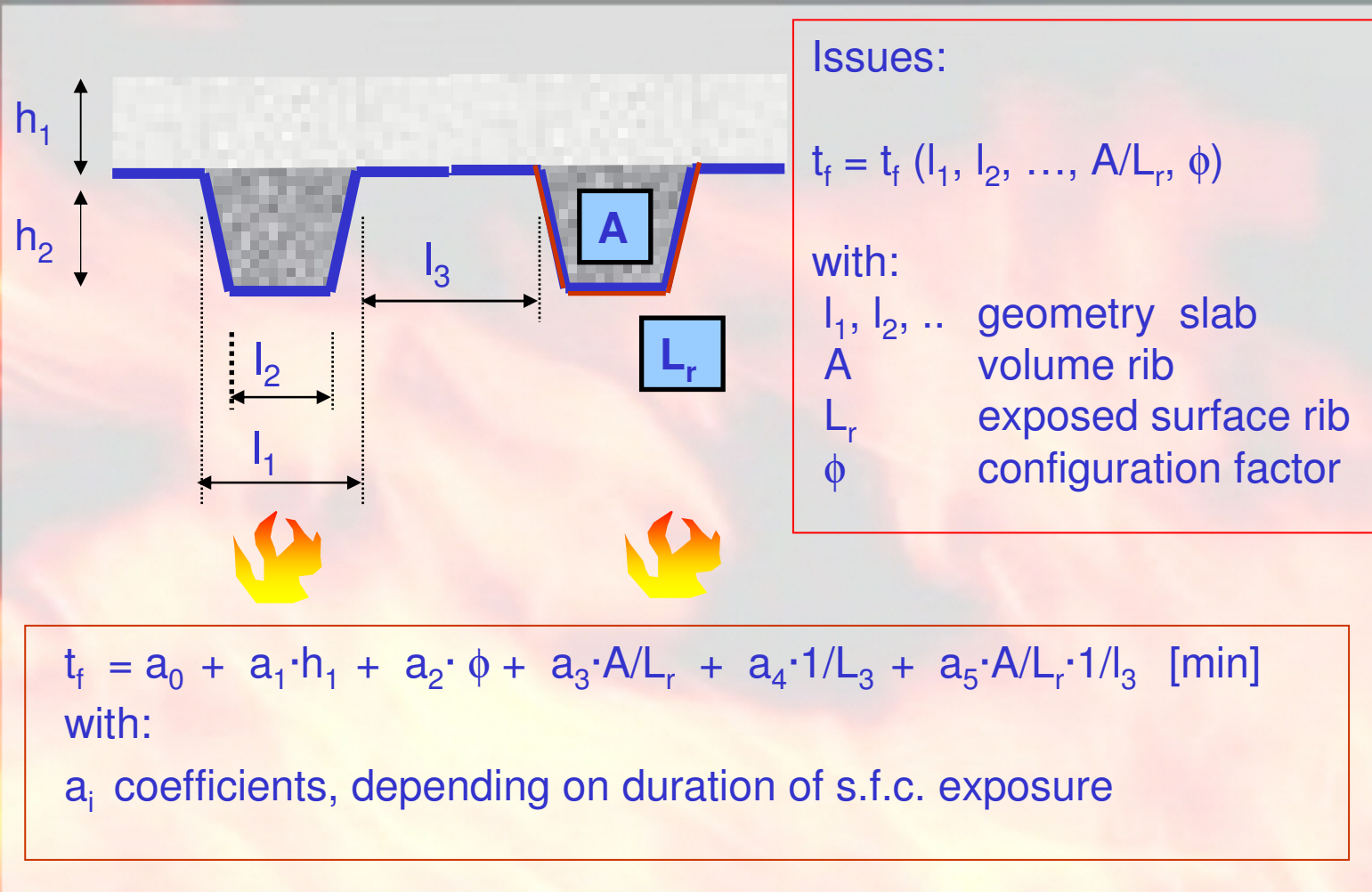
Note: total number of simulations: 880

# Typical temperature distribution at the unexposed side of a composite slab



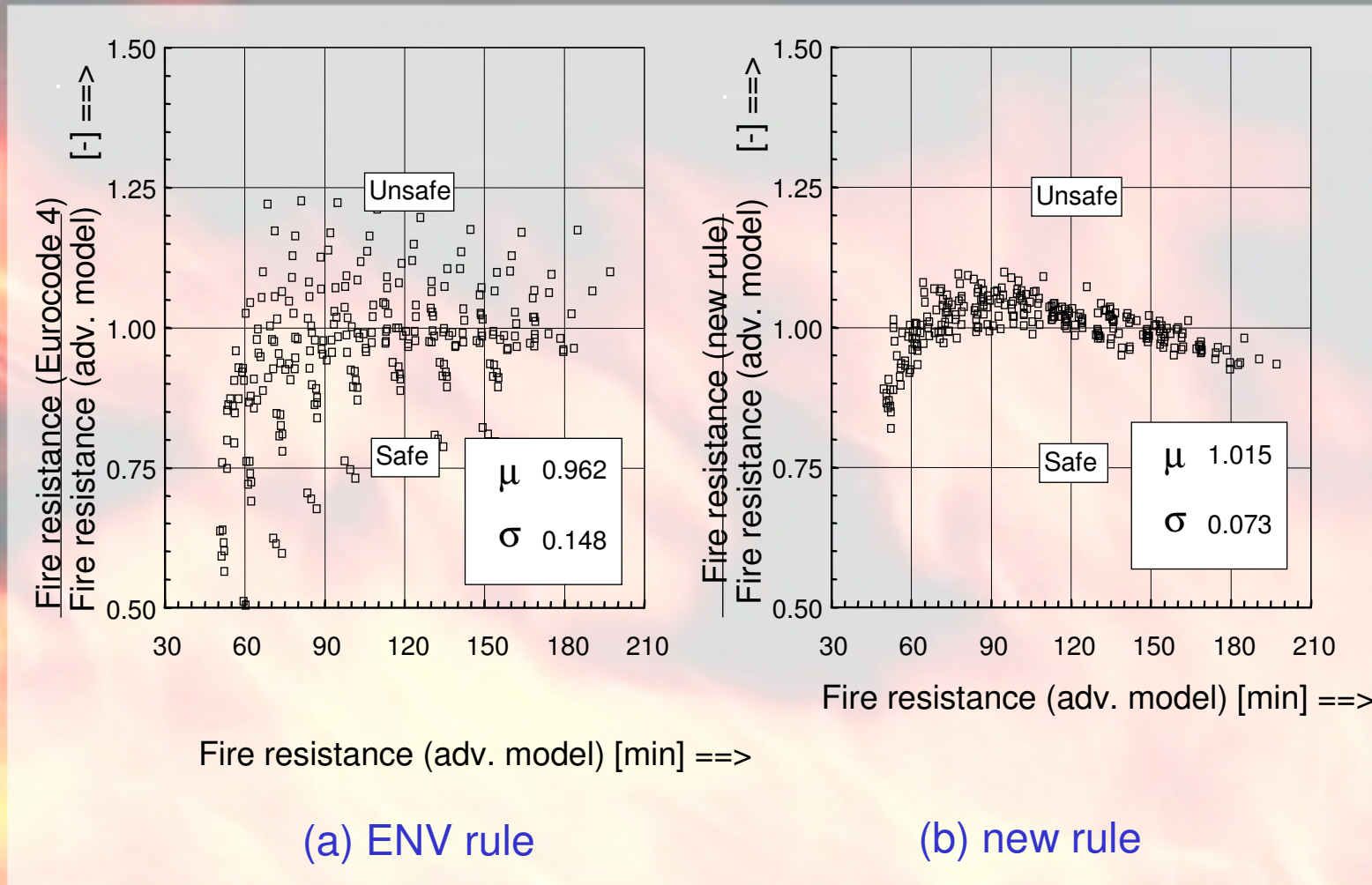
# Composite slabs

## Thermal insulation (illustration)



# Thermal insulation composite slabs

## Verification simple calculation rule

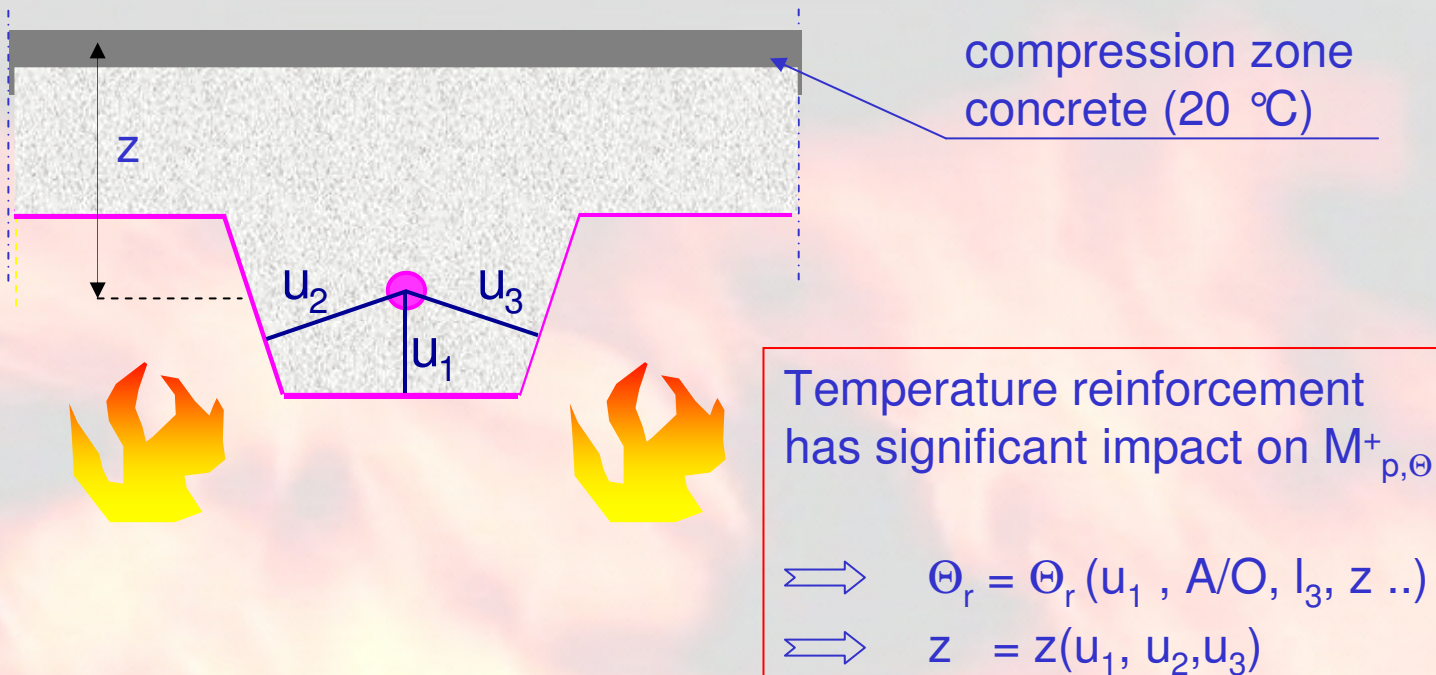


(a) ENV rule

(b) new rule

# Composite slabs

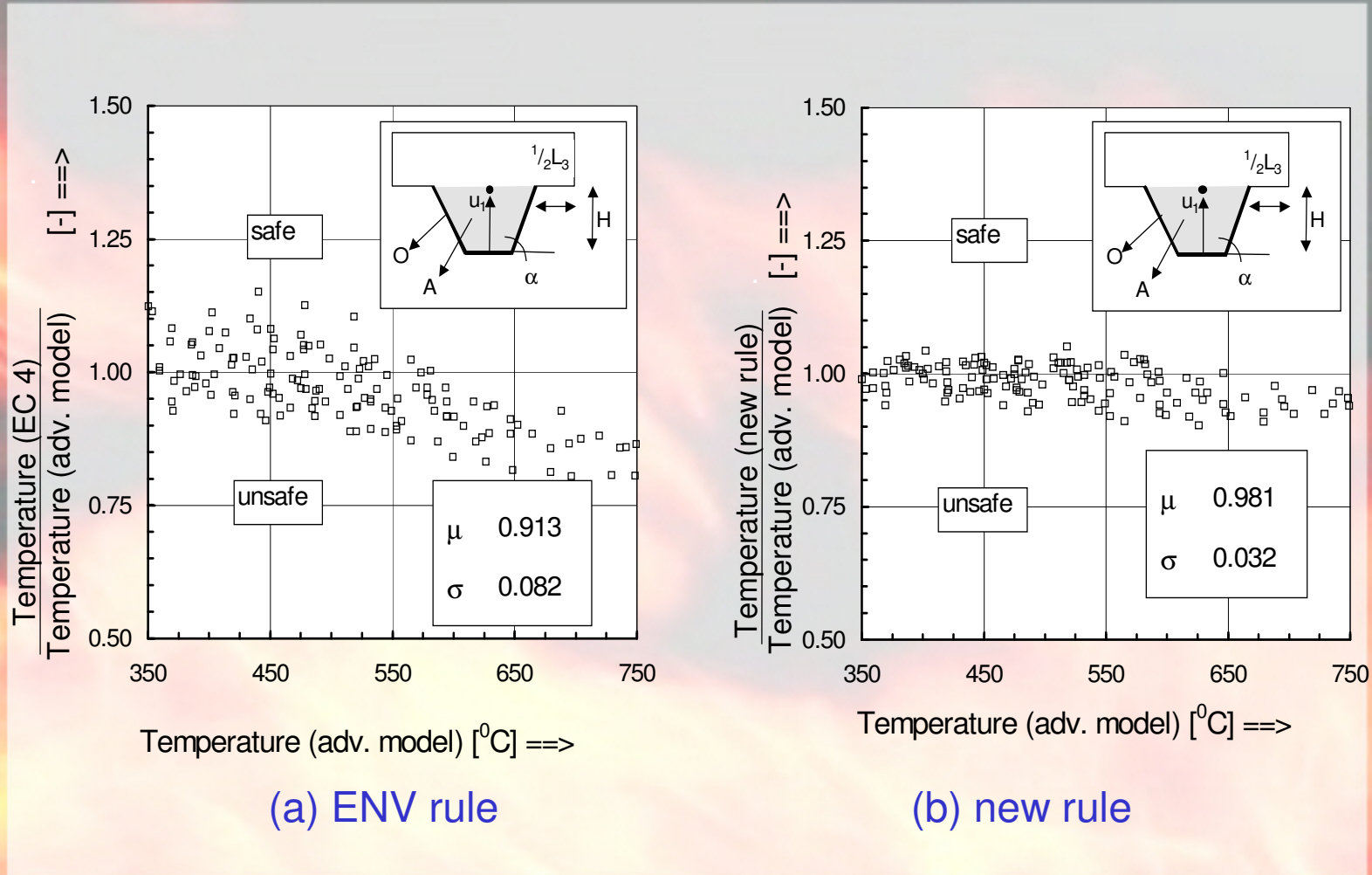
## Thermal response positive reinforcement



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

# Thermal response positive reinforcement

## Simple calculation rule

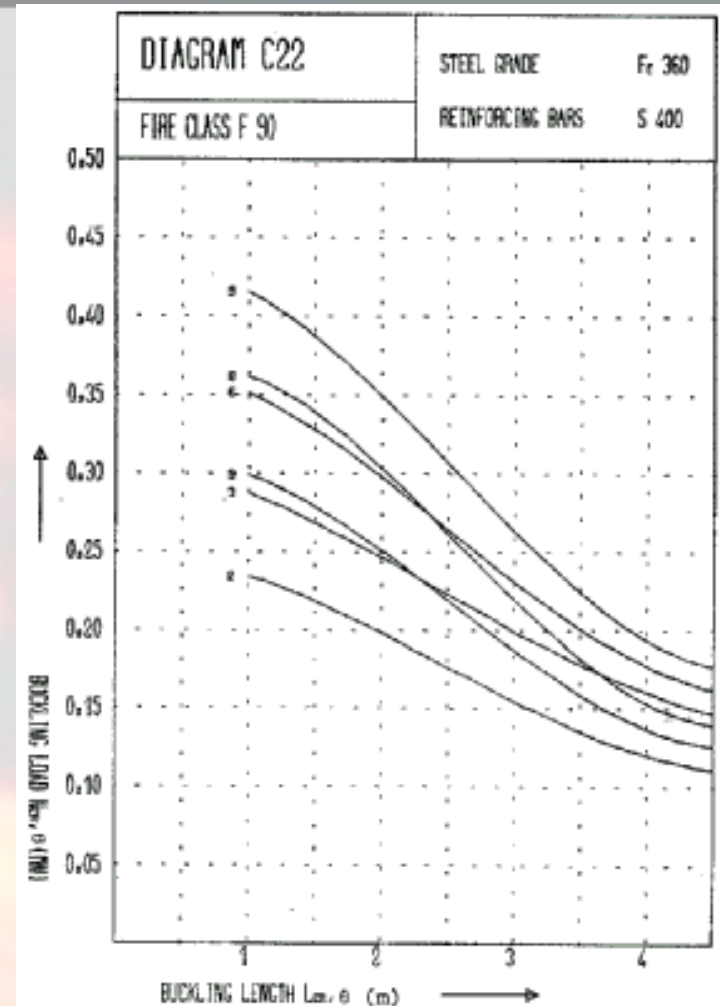
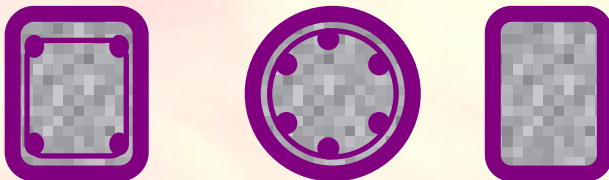


# Concrete filled SHS columns

## Resistance to fire (traditional approach)

- Design charts available
- Unpractical
- Need for “user friendly” design tool
- ⇒ e.g. POTFIRE

no.	concrete rebar 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

**PotFire**

Section

Type of section:

Dimensions of steel section

Diameter:  mm

Wall thickness:  mm

Reinforcement bars

By nr of bars  By %

Re-bars: #   mm

Concrete covering from rebar axis:  mm

Equal to:  %

Buckling length

Buckling length:  m

Material characteristics

Yield strength of steel section:  N/mm<sup>2</sup>

Yield strength of re-bars:  N/mm<sup>2</sup>

Compressive strength of concrete (cylinder at 28 days):  N/mm<sup>2</sup>

Eccentricity of the load

Eccentricity  $\perp$  to buckling axis:  mm

Calculation of

Ultimate load  Fire resistance duration

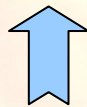
Fire duration:  min

Result

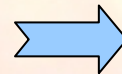
Non-dimensional slenderness: **0.4185**

Ultimate load: **2912** kN

input



output



pot1.txt - Notepad

File Edit Search Help

Calculation nr 18

-----

Section :

-----

Type of Section : Square  
 Width : 240 mm  
 Wall thickness : 8 mm

Reinforcement bars :

-----

Number of re-bars :  
 - In the corner : 4  
 Diameter : 24 mm  
 - In the mid-size : None  
 Percentage of re-bars : 3.739 %  
 Concrete covering : 40 mm

Buckling length : : 1.8 m

-----

Material characteristics :

-----

Steel section : 275 N/mm<sup>2</sup>  
 Reinforcement bars : 500 N/mm<sup>2</sup>  
 Concrete : 30 N/mm<sup>2</sup>

Eccentricity

-----

(perp. to buckling axis) : 0 mm

Calculation of : Ultimate load

-----

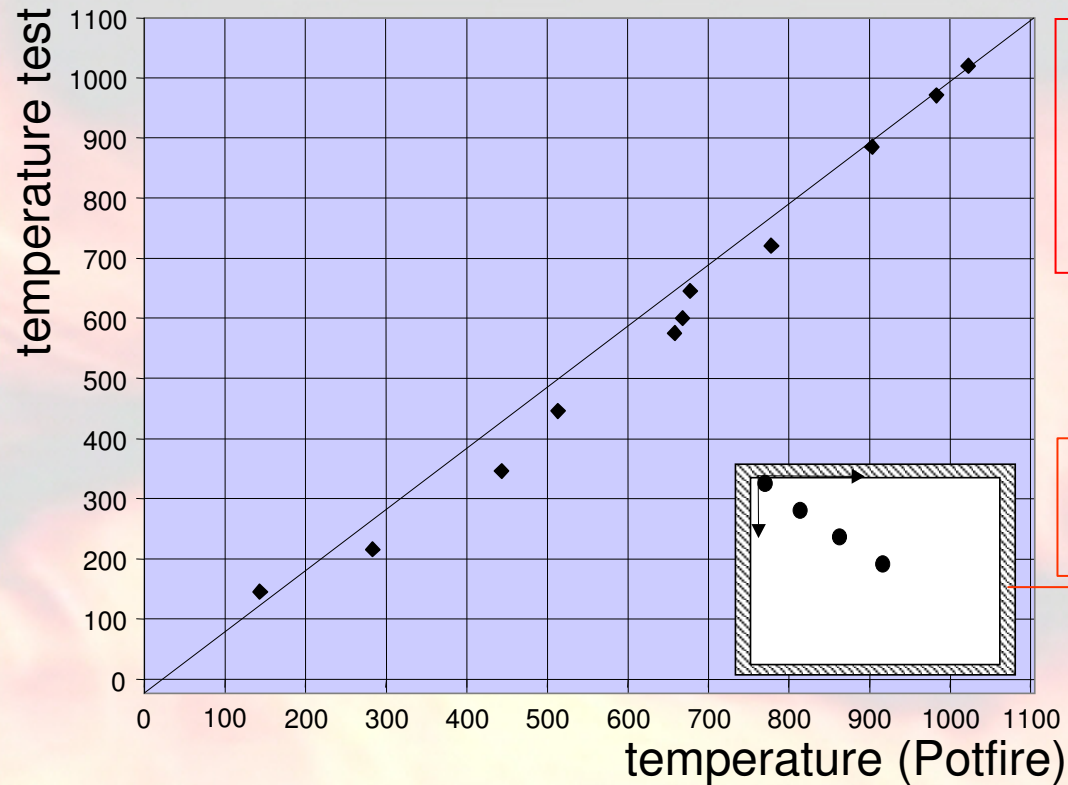
Fire duration : 90 min

Result :

-----

NON-DIMENSIONAL SLENDERNESS : .2718  
 ULTIMATE LOAD : 618 kN

# Validation POTFIRE



assumptions:

- $\alpha_{\text{conv}} = 25 \text{ W/m}^2\text{k}$
- $\epsilon_{\text{res}} = 0.7$

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!