ADVANCED DESIGN FIRE MODELS

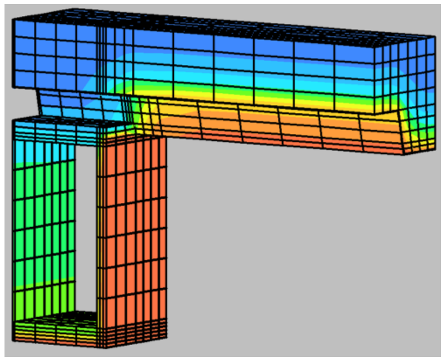
Travelling fire

Ing. Kamila Cábová, Ph.D.

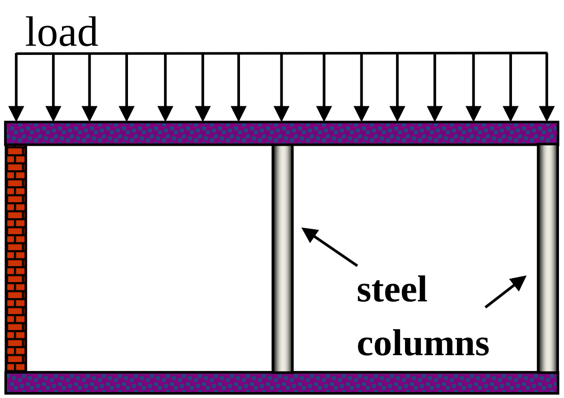
Fire design of structures

1: Ignition

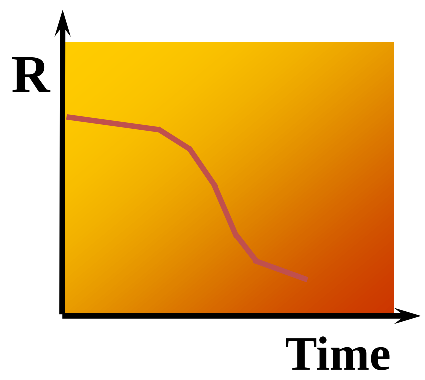
2: Thermal analysis



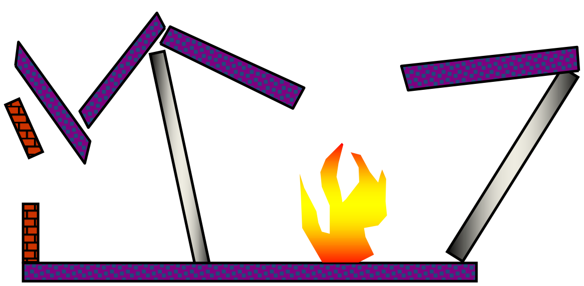
3: Temperature of the structure



4: Mechanical load



5: Structural analysis

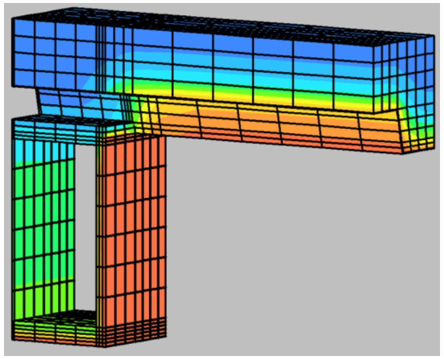


6: Collapse?

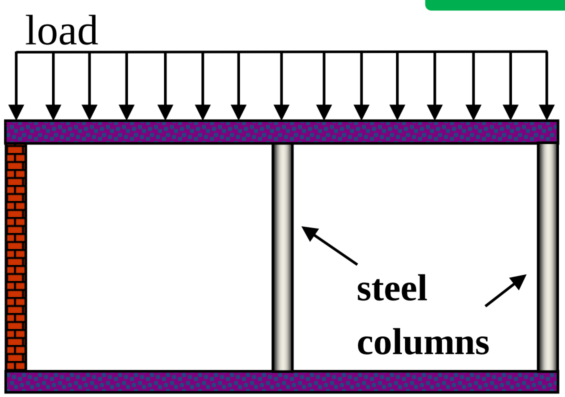
Thermal analysis

1: Ignition

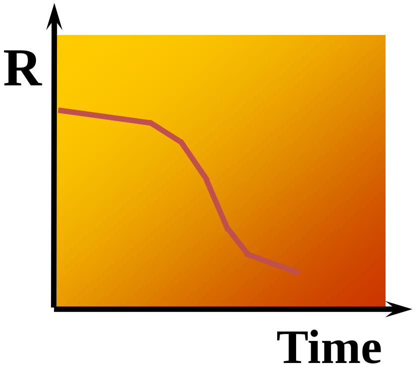
2: Thermal analysis



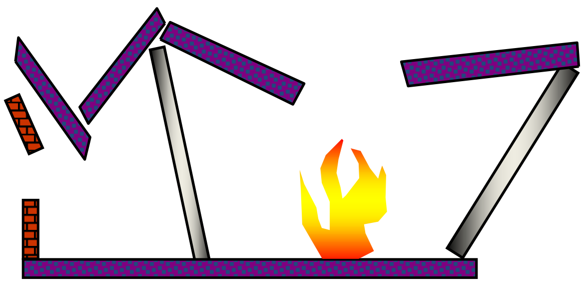
3: Temperature of the structure



4: Mechanical load

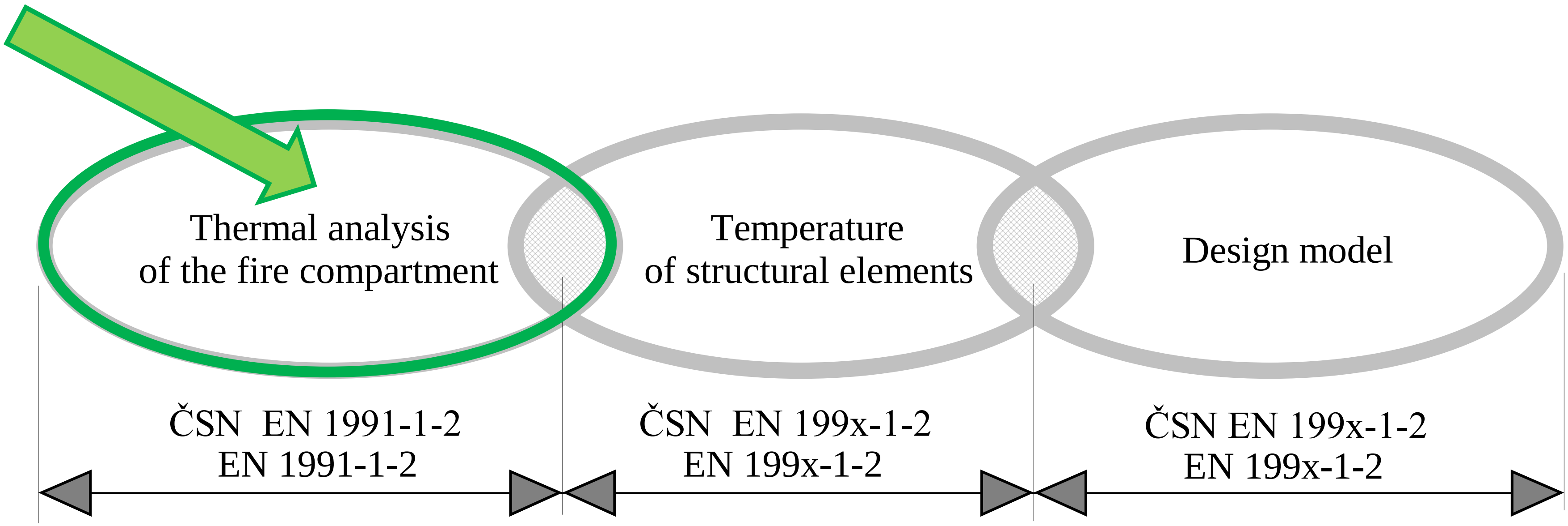


5: Structural analysis



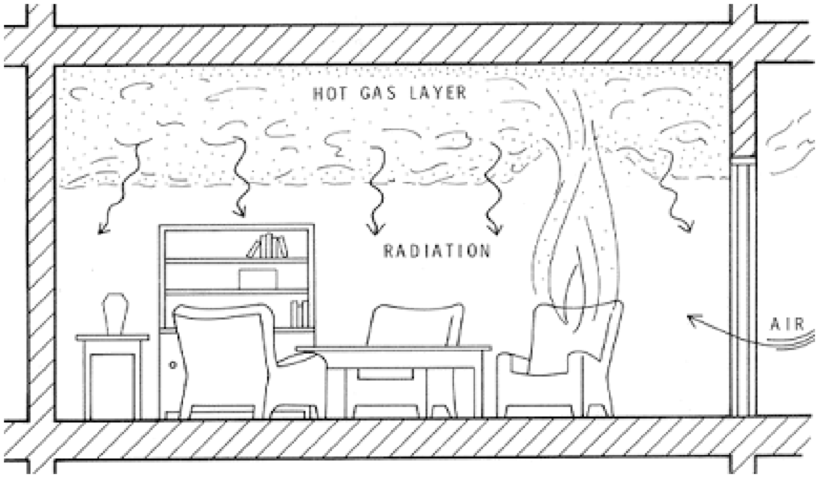
6: Collapse?

Thermal analysis



The principles and methods for thermal analysis are given in EN 1991-1-2.

Compartment fire

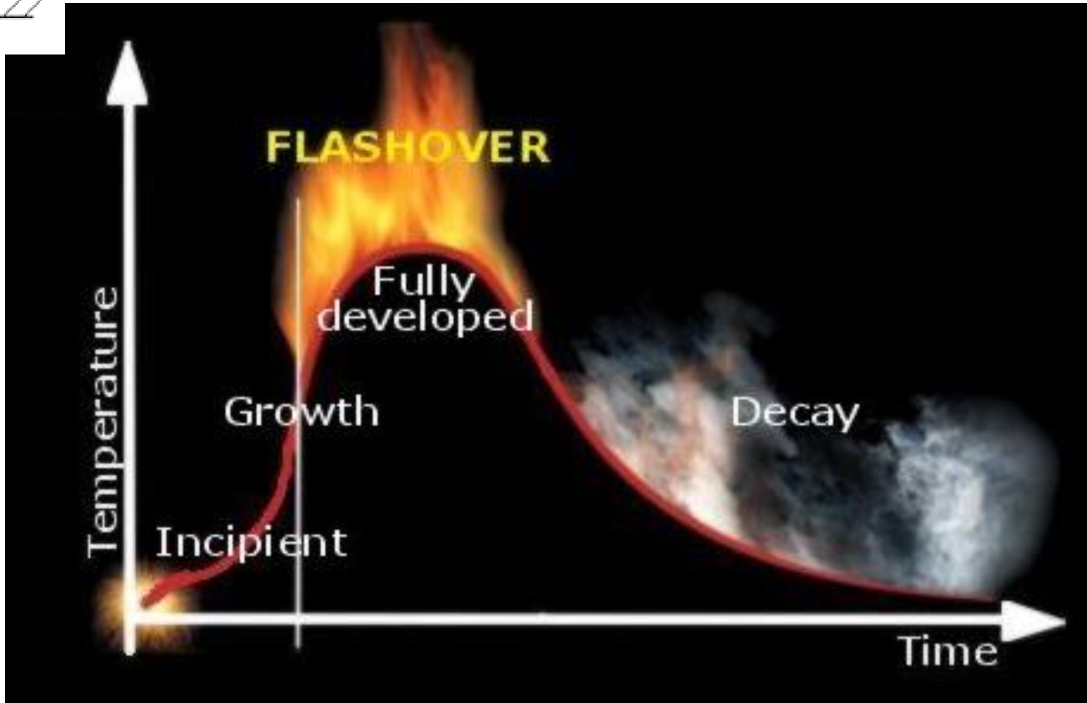


Flashover – as the hot gas layer increases all combustibles are heated by radiation. If the temperature is enought high, the room breaks out into open flame at once.

It generates big heat, smoke and pressure (window breakage).

Phases of the fire

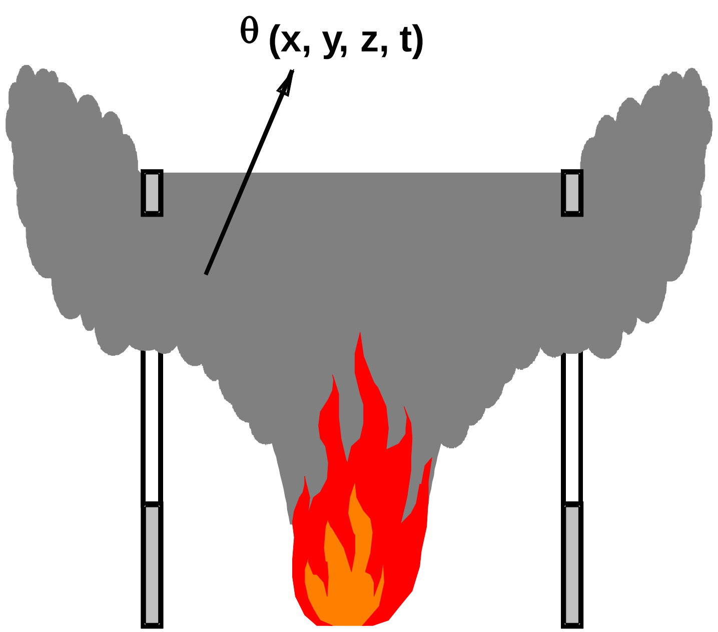
- ignition
- smouldering
- flash over
- heating
- cooling

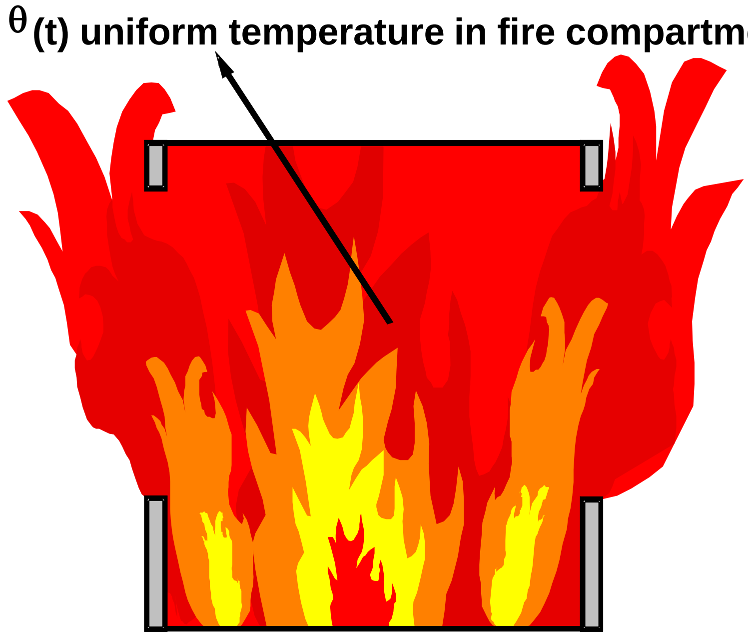


Modelling of fire

What kind of the fire? Is there flashover or not?

Localised fire **Compartment fire**





Design fire models

According to EN 1991-1-2

Simple models

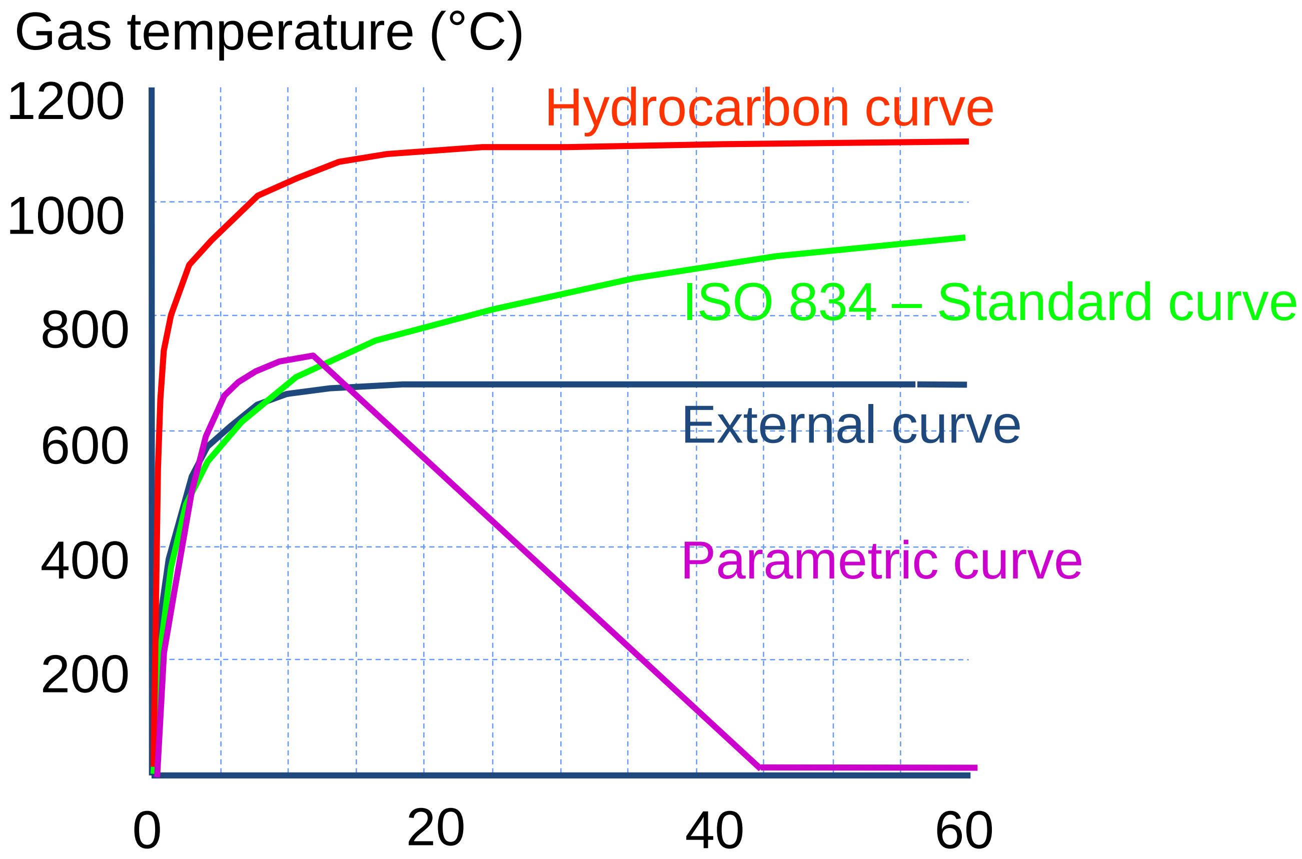
- nominal curves
  - standard temperature-time curve (ISO 834)
  - hydrocarbon temperature-time curve
  - external temperature-time curve
- parametric curve

Advanced models

- localised fire
- one zone model
- two zone model
- CFD model

Simple design fire models

- **Simple models**

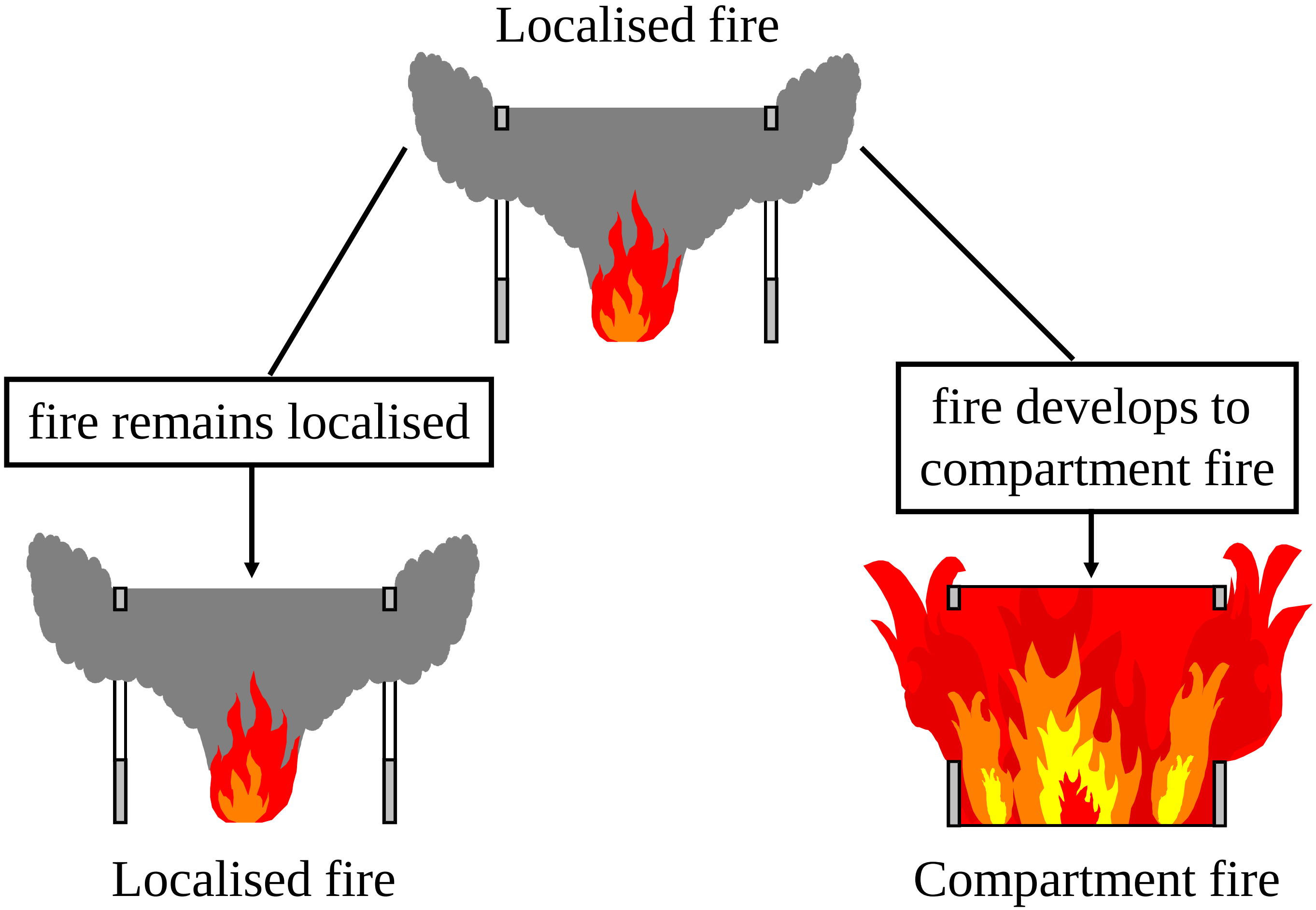


Advanced design fire models

- **Advanced models**
  - Local fires
  - One zone model
  - Two zone model
  - CFD models

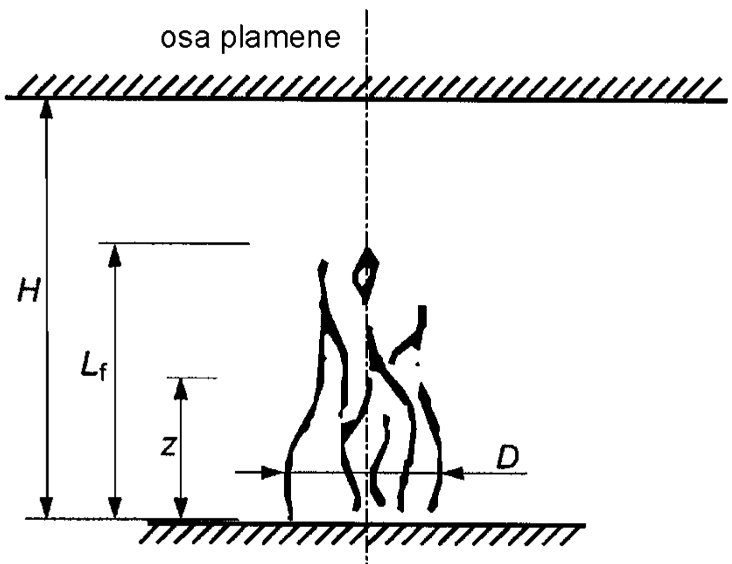
Advanced design fire models

- Local fire and zone models

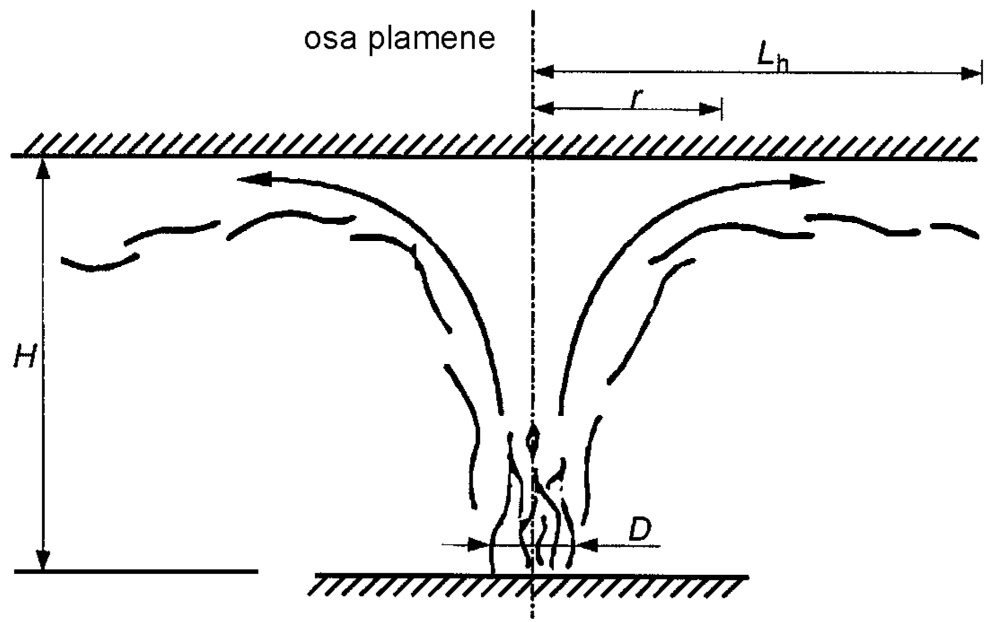


Advanced design fire models

- Local fire models



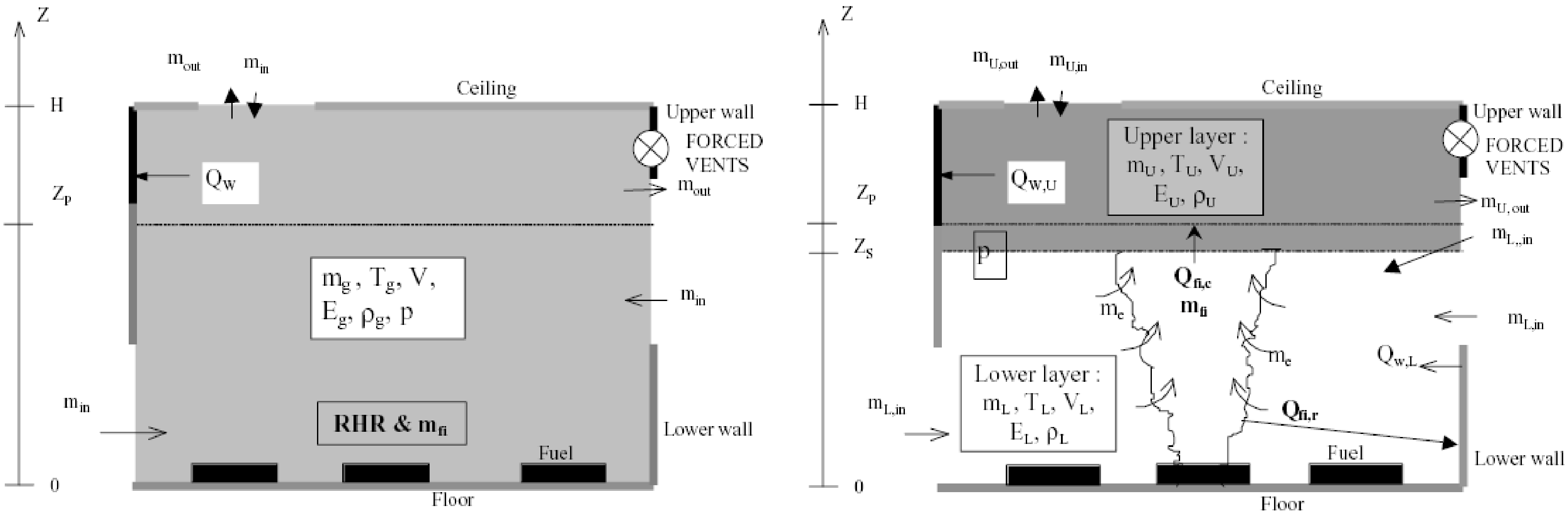
the flame does not reach the ceiling
(Heskestad)



the flame impacts the ceiling
(Hasemi)

Advanced design fire models

- Zone models



Software available:

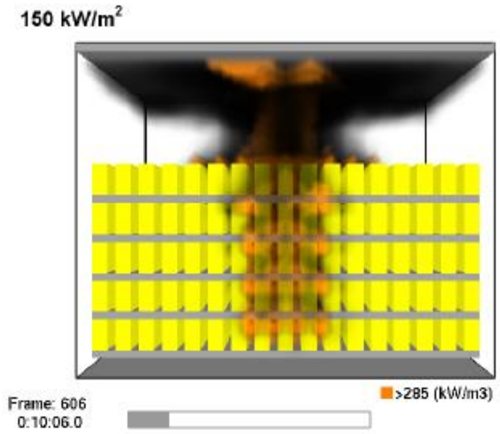
- OZONE, C-FAST, Argos, …

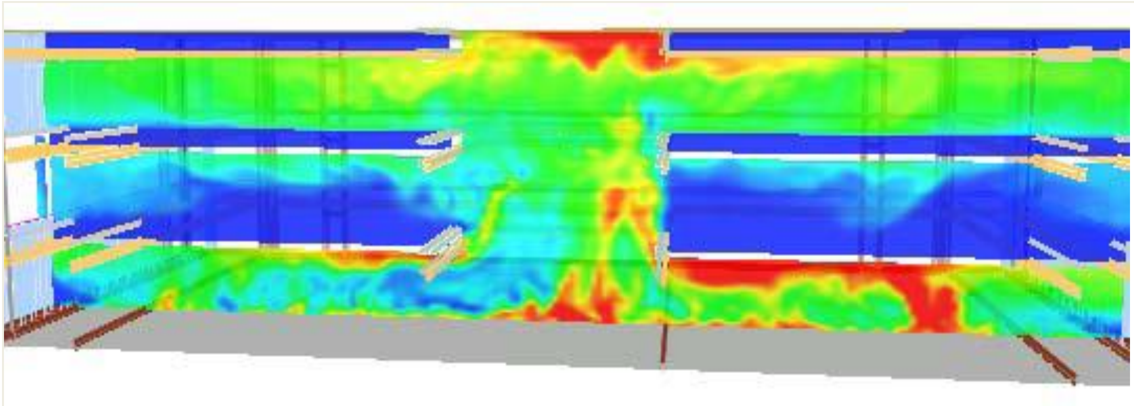
Advanced design fire models

- Computational Fluid Dynamics models (CFD)

Principles:

- numerical solution of partial differential equations
  thermodynamic and aerodynamic variables
  at any location in the compartment
- mathematical description of equations:
  - mass balance of gas and fuel;
  - energy balance;
  - Newton´s law
  - ….



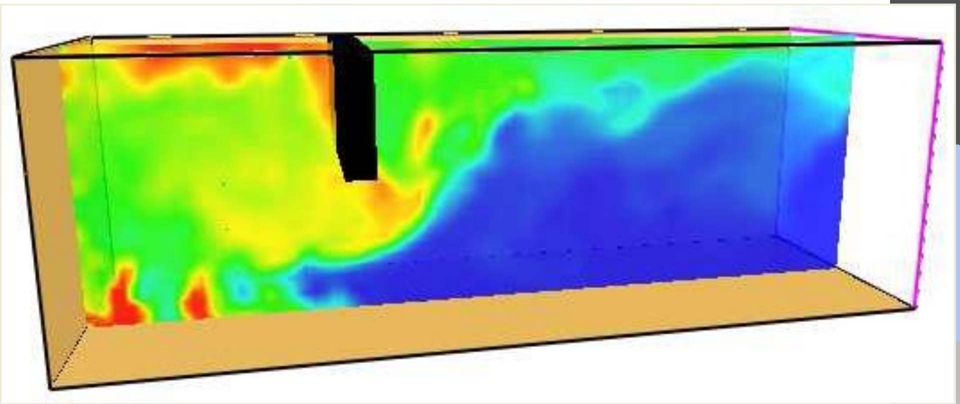


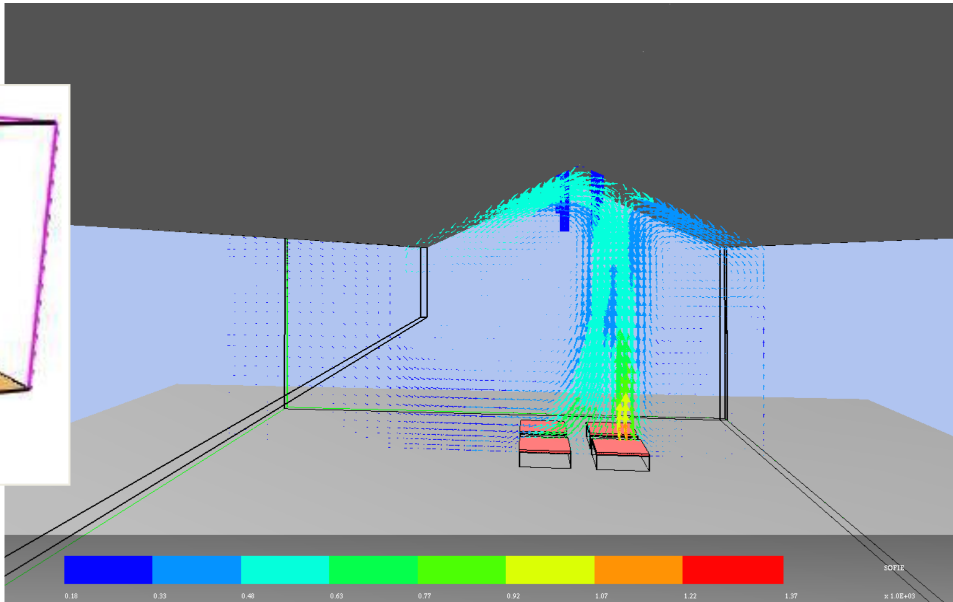
Advanced design fire models

CFD models

\+ Complicated geometry, all materials, prediction of smoke development, verification/validation needed

– Hardware demands, huge amount of input/output data, long computational time





Application of design fire models

Application

- **Nominal curves**

  for heating phase in simple cases

- **Parametric temperature curve**

  also for cooling phase

- **Zone models**

  for difficult geometry, ventilation conditions

Application of design fire models

Application

- **Local fire models**

  new application also to vertical members (columns)

- **CFD models**

  for all types of fires

  difficult geometry, boundary conditions

  for large space buildings

  cost and time consuming

Design fire models

Simple models

nominal curves

- standard temperature-time curve (ISO 834)
- hydrocarbon temperature-time curve
- external temperature-time curve

parametric curve

Advanced models

localised fire

one zone model

two zone model

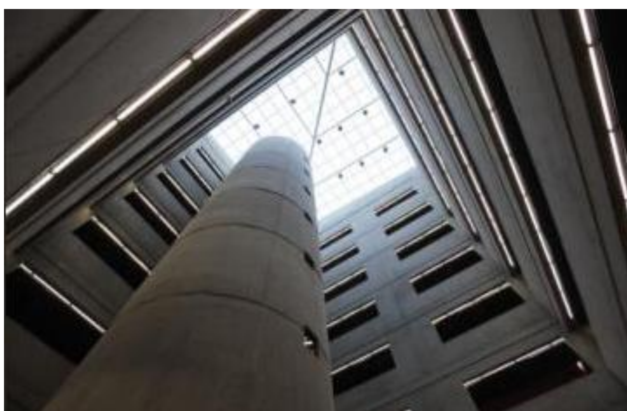
- models of travelling fire

CFD model

Travelling fire - motivation

<u>Increase of architectural demands</u>

- Missing compartmentalization
  - Large open spaces
  - Connected floors, atria
- Modern materials



Travelling fire - motivation

Extension of desing fire models

Full-developed fire

- ISO, parametric, HRR-paramteric, zone models
- **uniform temperature assumption**

Design fire models

Travelling fire

- **moving non-uniform temperature fields**

Localised fire

- Heskestad, Hasemi, Alpert
- **temperature changes with horizontal direction, the core does not move**

Travelling fire - motivation

<u>Travelling fire</u>

- In real fires and experiments
- Fields with higher and lower temperatures, longer duration
- Closer to real fire behaviour

↓

Design fire models of TF

Madrid, 2005

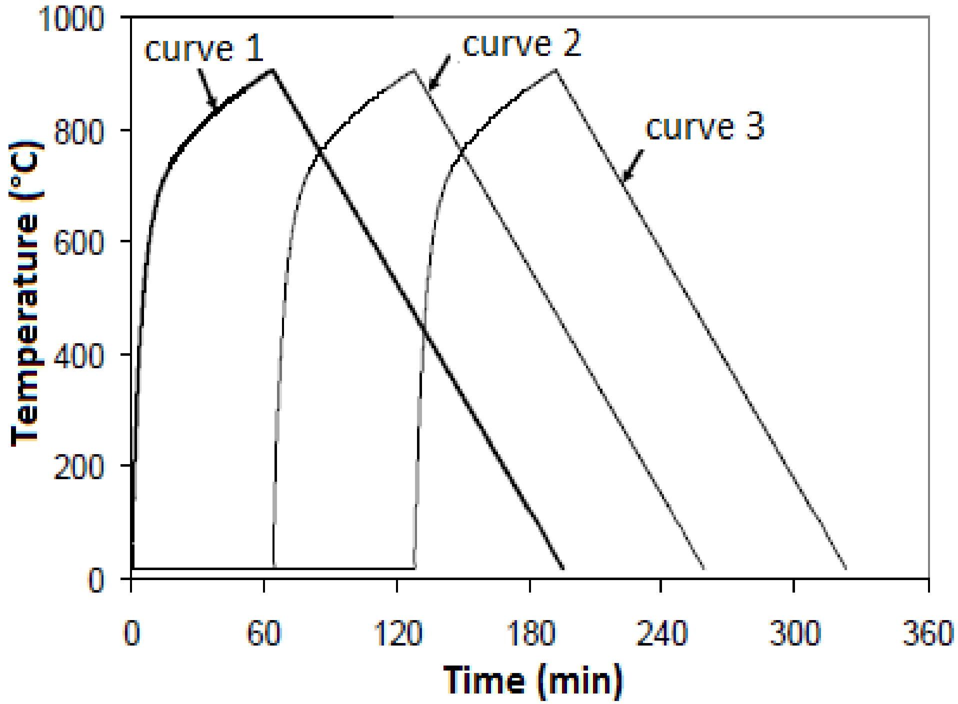
Shanghai, 2010

WTC, 2001

Delft, 2008

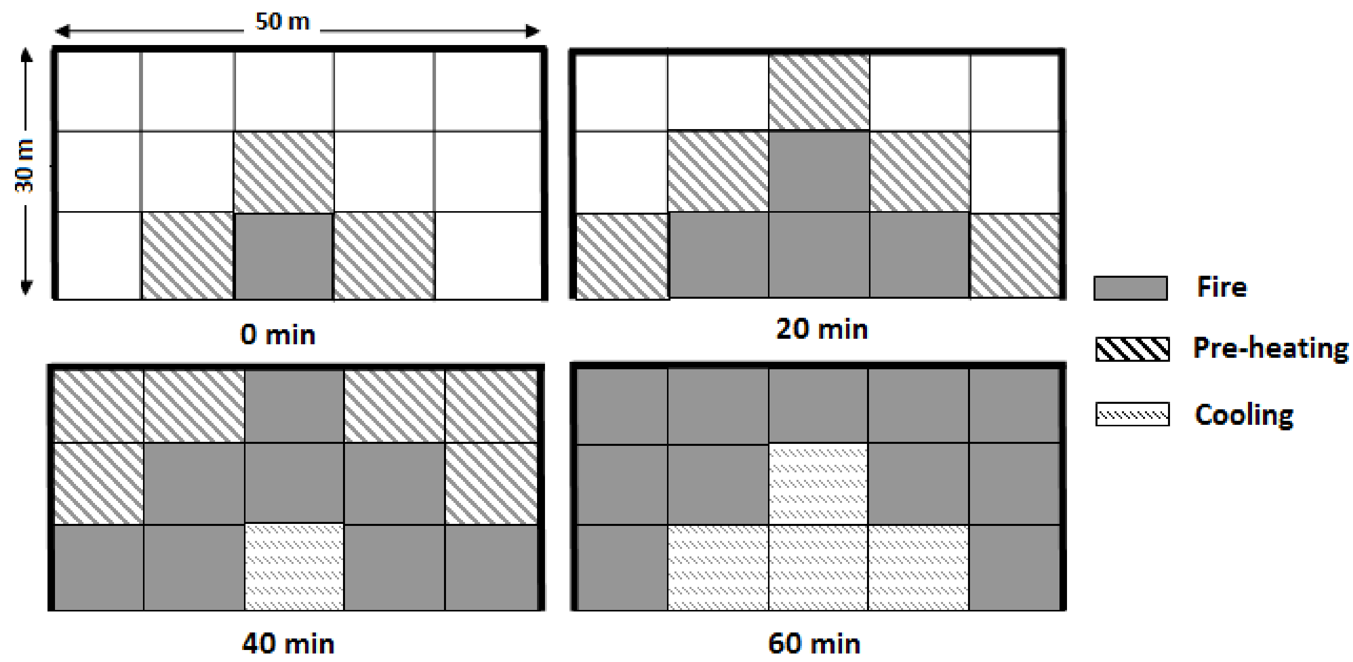
Models of travelling fire

- Bailey (1996)
  - Parametric temperature-time curve
  - Time offset equal to peak temperature



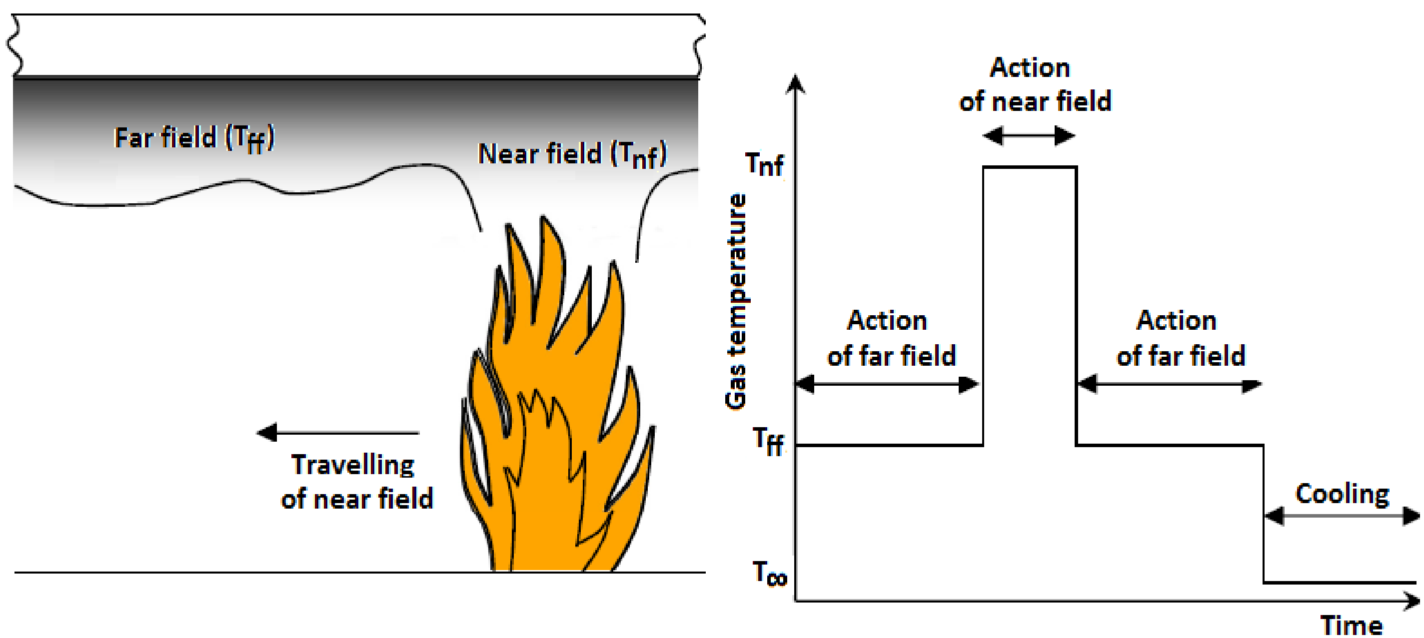
Models of travelling fire

- Clifton (1996)
  - Design areas with fully-developed burning
  - Parametric temperature-time curve
  - Moving into next area in 20 min



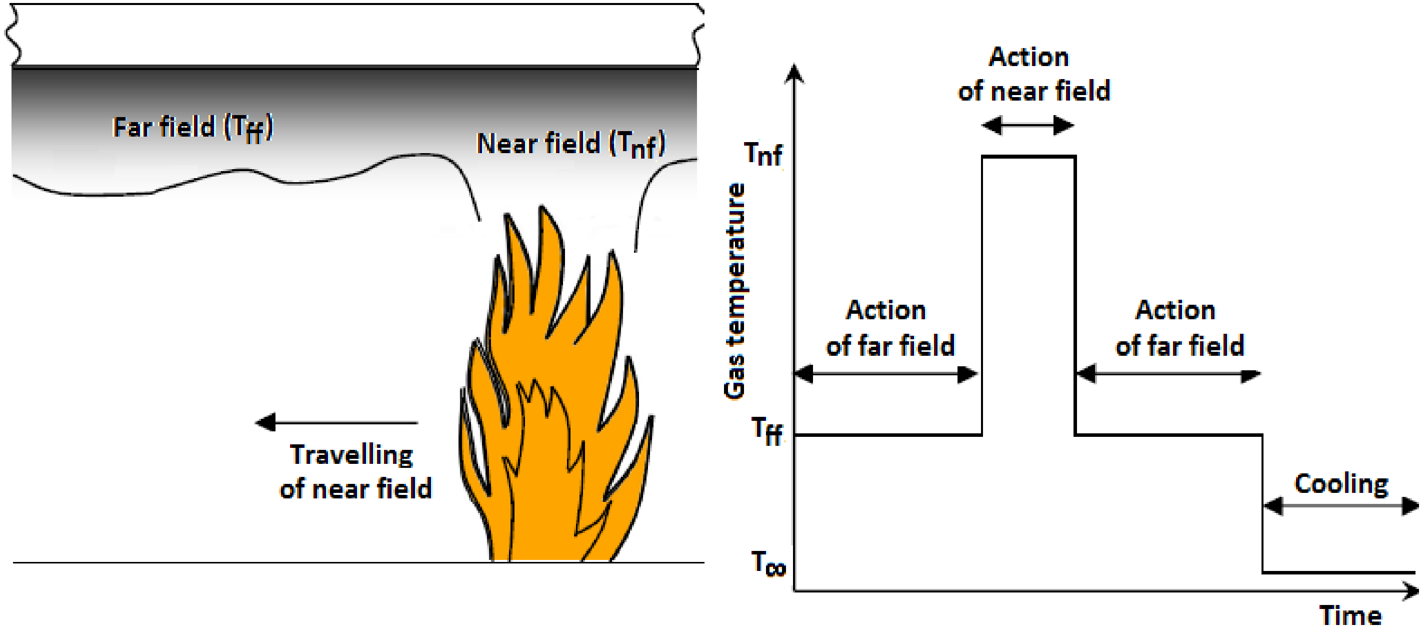
Models of travelling fire

- Rein, Stern-Gottfried (2007) - TFM
  - Near-field temperature (flames, 1200 °C)
  - Far-field temperature (hot layer gases)
  - Description of various sizes of fire (from 1 % to 100 %)
  - Fire spread along longer side of an enclosure



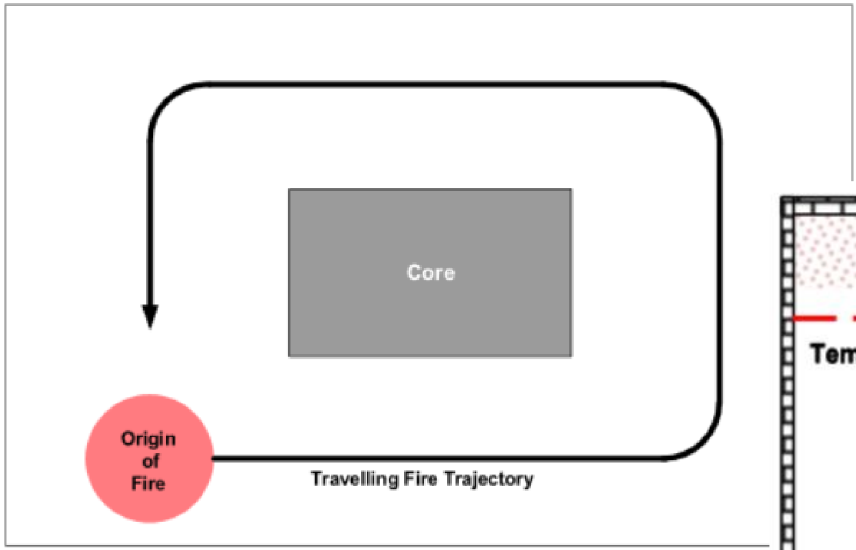
Models of travelling fire

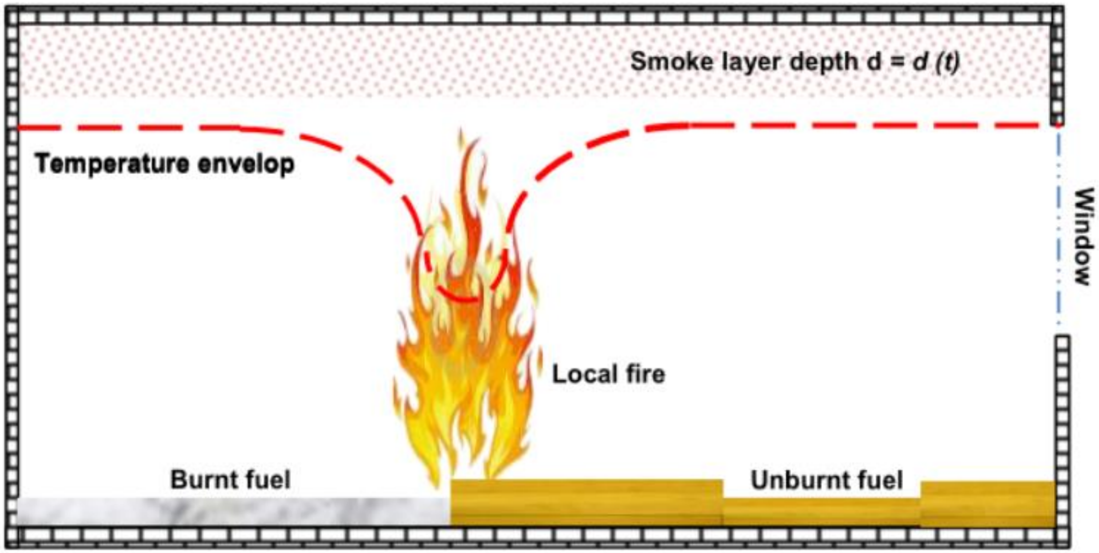
- Rackauskaite, Rein (2015)
  - Improvement of TFM – iTFM
  - Reducing range of fire sizes
  - Modifying T_{ff}
  - Flame flapping



Models of travelling fire

- Dai (2016)
  - Combination of Hasemi´s localized fire and hot smoke layer
  - Propagation along a trajectory
  - Implementation into SIFBuilder

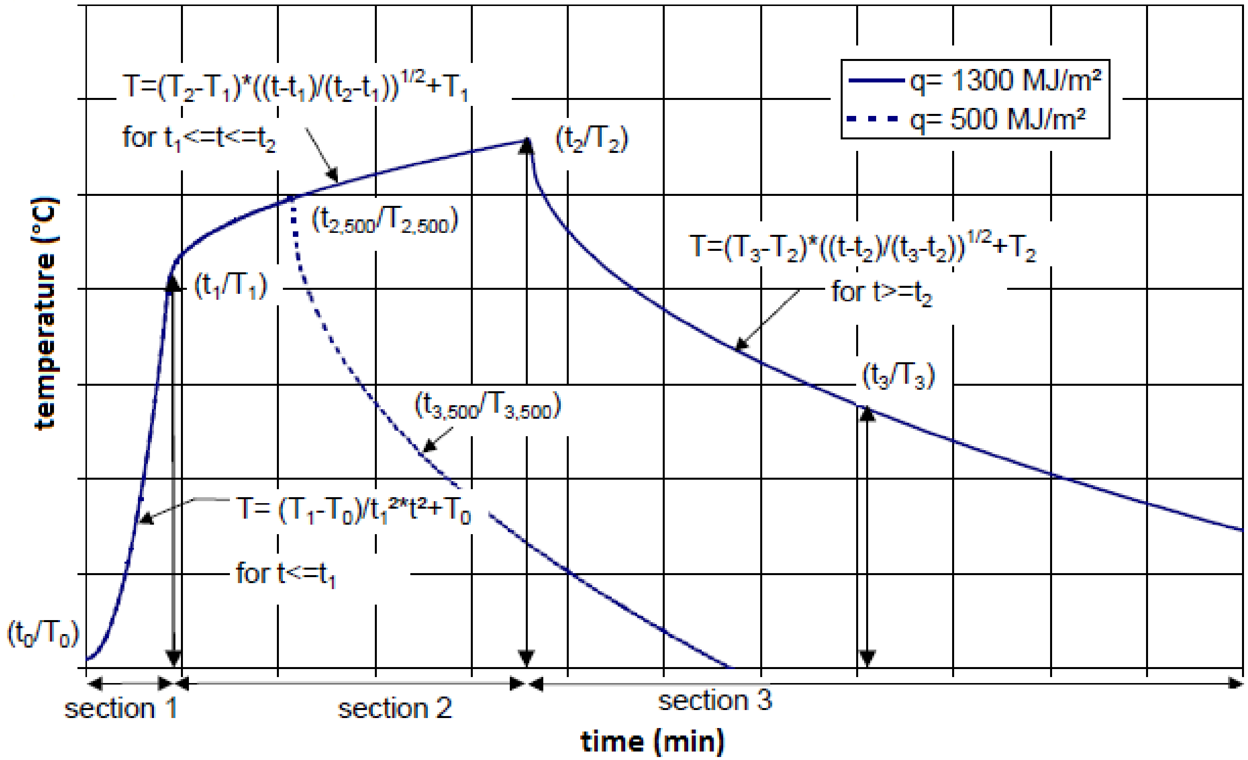




Models of travelling fire

HRR parametrical model

- Zehfuss, 2002
- Relationship with HRR – more realistic description of fire
- Implemented in DIN code



Models of travelling fire

HRR parametrical model

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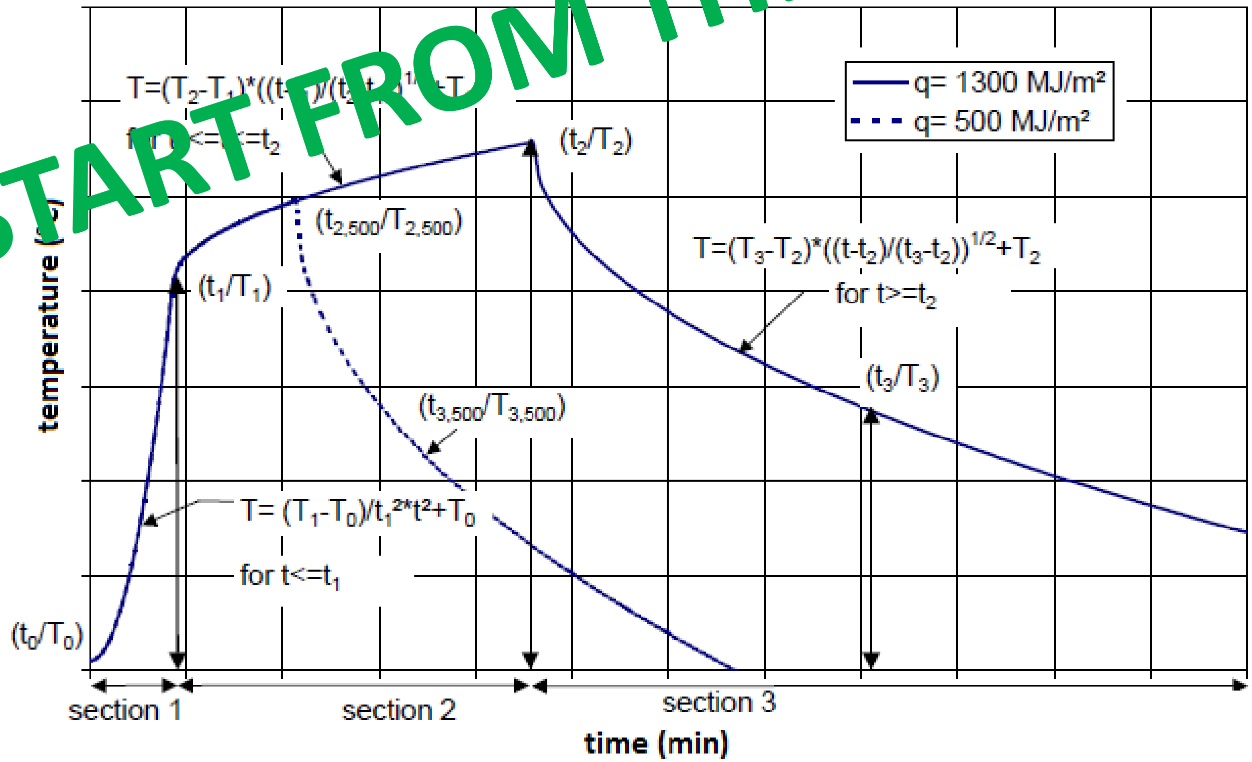
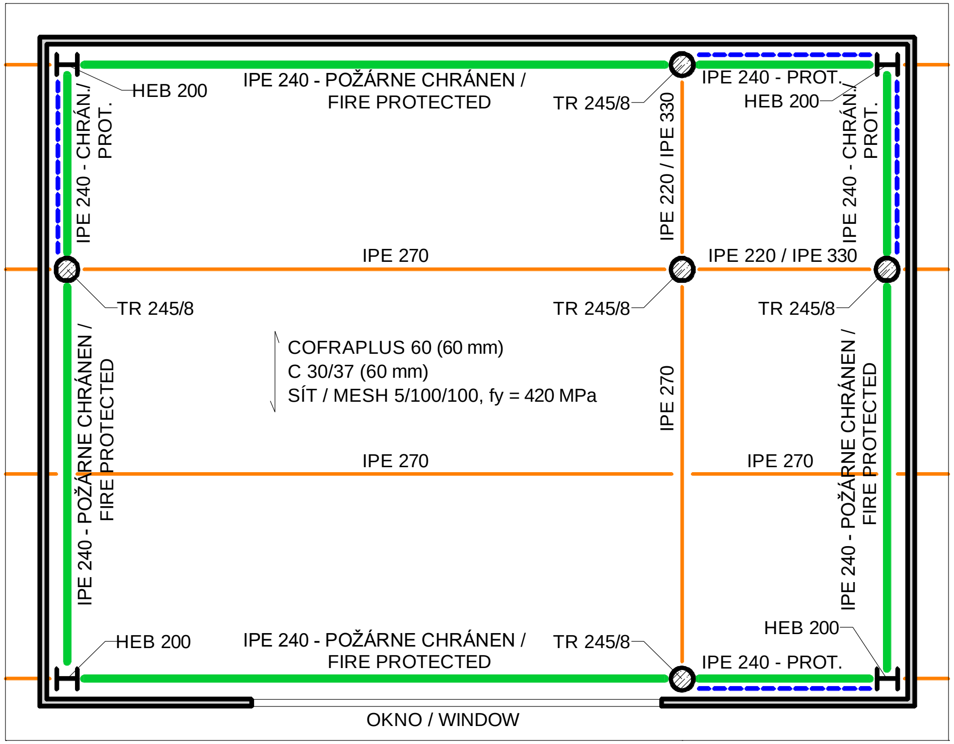
START FROM THE BEGINNING



Experimental study

Fire Test in Veselí n. L.

- 6th September 2011
- fire test on two floors administrative building
- travelling fire scenario in upper floor



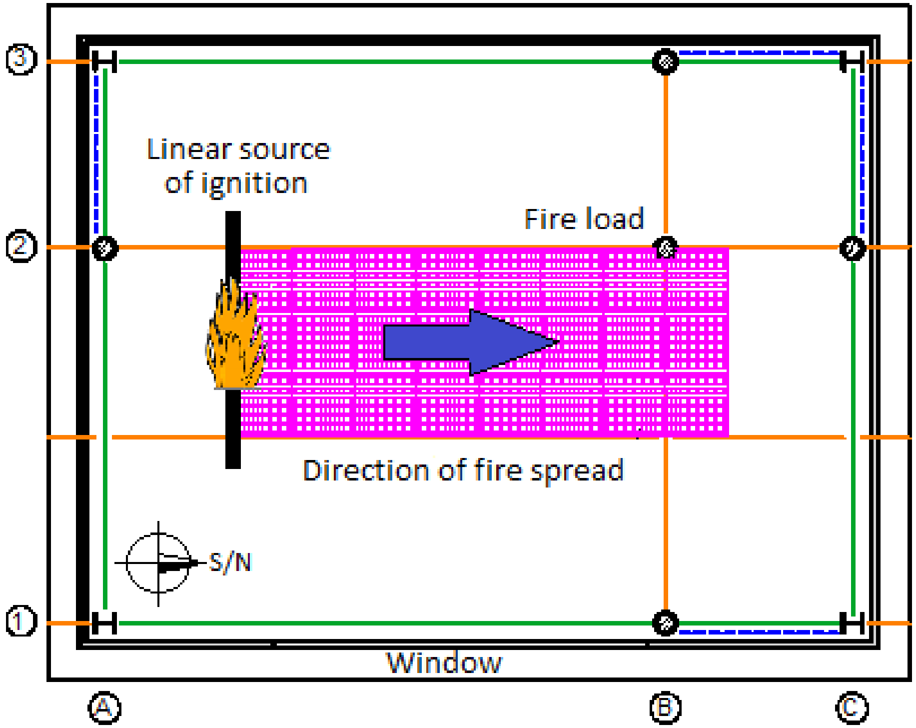
- 10.4 x 13.4 x 9.0 m
- composite structure
- steel wires reinforcement
- IPE beams
- CFT columns
- window 2.0 x 5.0 m

- 20 thermocouples Ø 3 mm (gas)
- 8 thermocouples and 7 plate thermometers (steel beam)

Experimental study

Fire Test in Veselí n. L.

- 24 wooden piles on area of 24 m^2
- 7 cribs of 50 x 50 x 1000 mm in 6 layers
- 2,52 m^3 of wood (173,5 MJ/m^2)
- linear ignition source
  (U profile, mineral wool, paraffin)



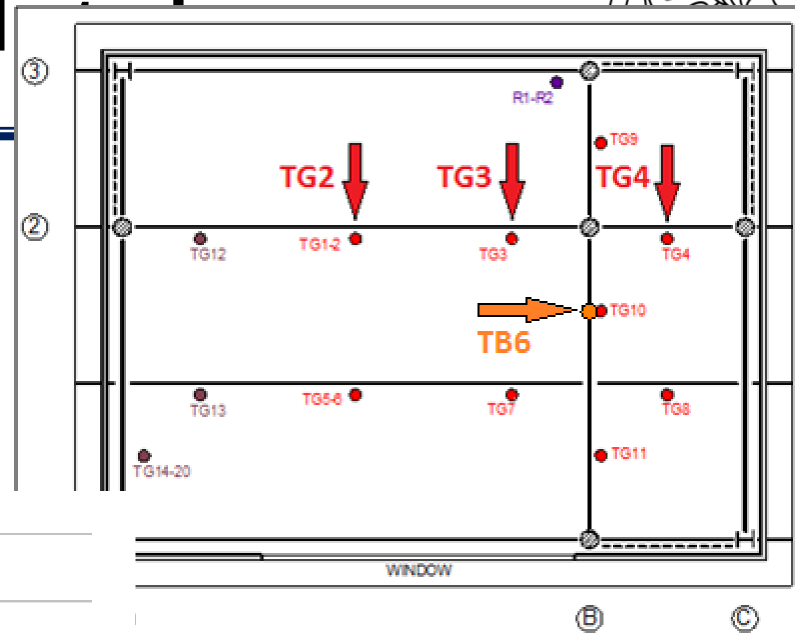
Fire load before the test

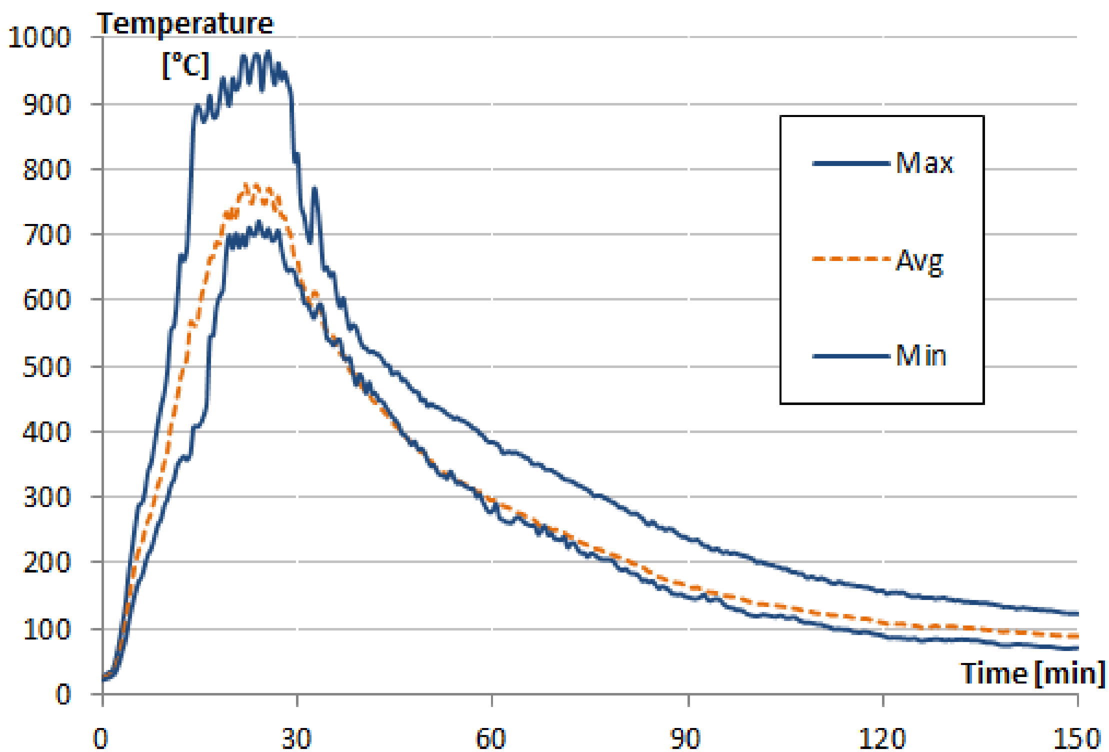
Fire load after the test

Experimental study

Experimental

- T_{max} 979 °C in 26. min, TG3
- **difference 400 °C, distance 6 m**
- T_{max} 855 °C at TB6

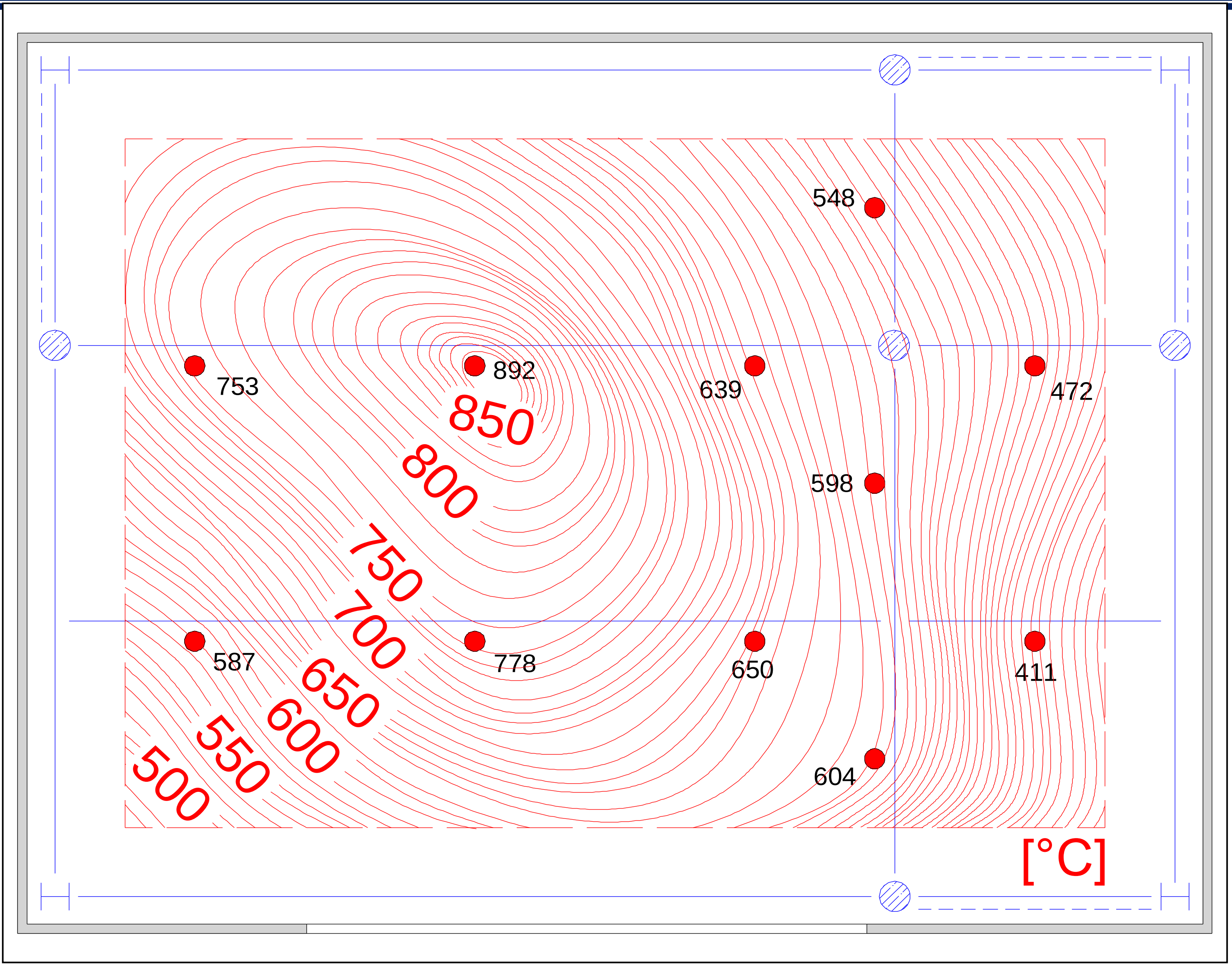




Time [min]	TG2 [°C]	TG3 [°C]	TG4 [°C]
1.0	32.29	29.46	25.68
5.0	238.49	199.48	153.31
10.0	495.32	398.94	301.71
15.0	**891.56**	639.31	**471.85**
20.0	938.74	901.64	740.21
25.0	925.08	966.34	769.57
30.0	721.32	788.65	773.57

Experimental study

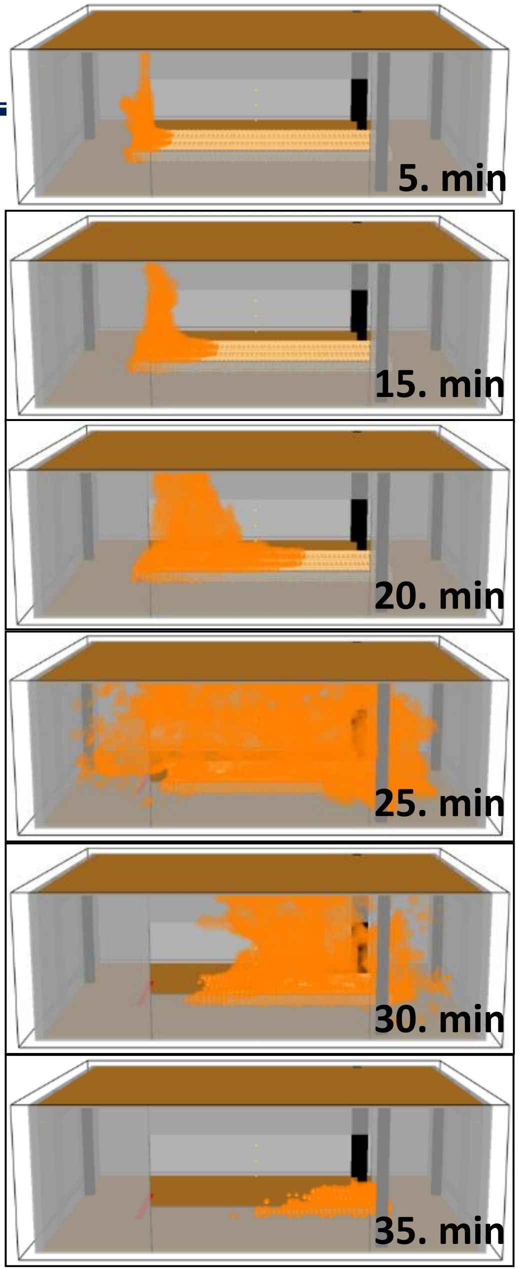
15 min



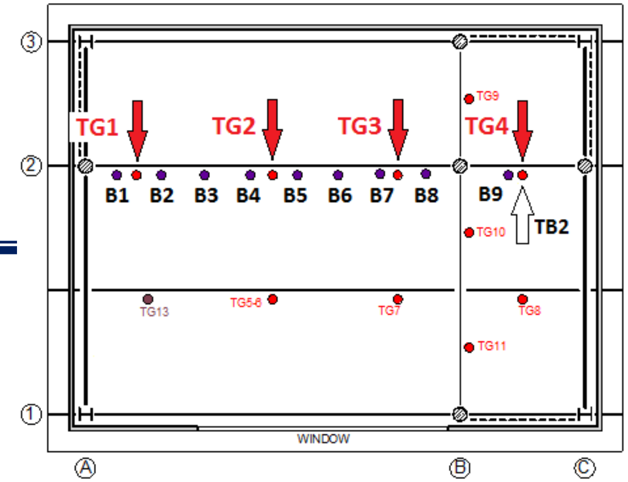
Numerical study

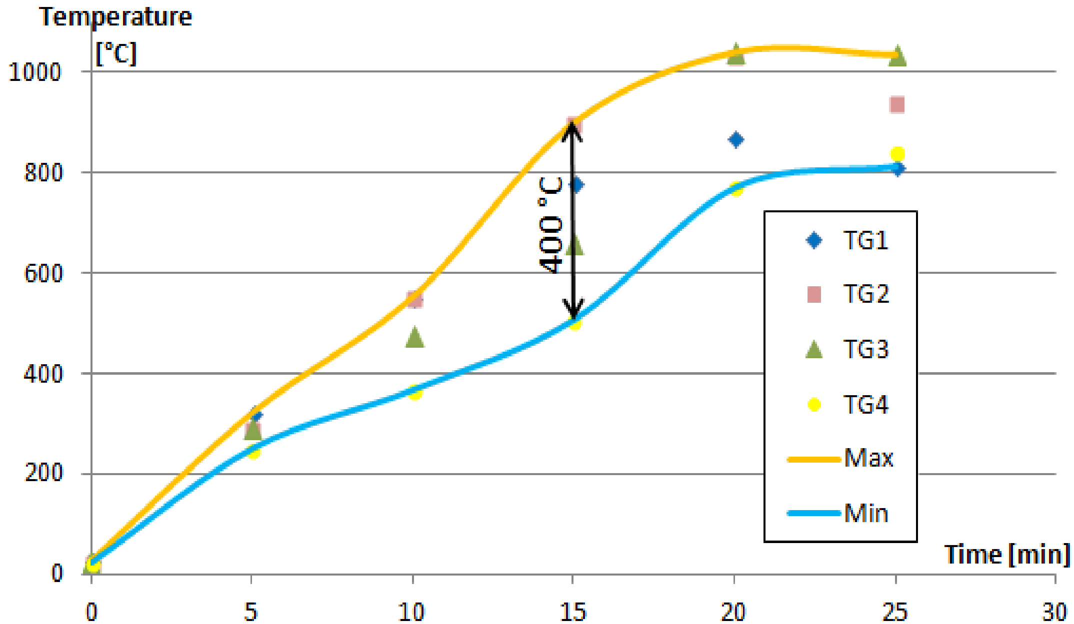
Software FDS (Fire Dynamics Simulator)

- model of FC from Veselí n. L.
- 4 materials ⟹ wood (cone calorimeter)
  T_{ign}, HRRPUA, ramp function
- fire outbreak „burner“ (0.15 x 3 x 0.05 m^3)
  ⟹ HRRPUA, ramp func. (300 s)
- cell sizes: 10 x 10 x 10 cm, 5 x 5 x 5 cm
- calculation of RHR, gas temperature, beam temperature
- spreading phenomena and high degree of temperature heterogeneity confirmed



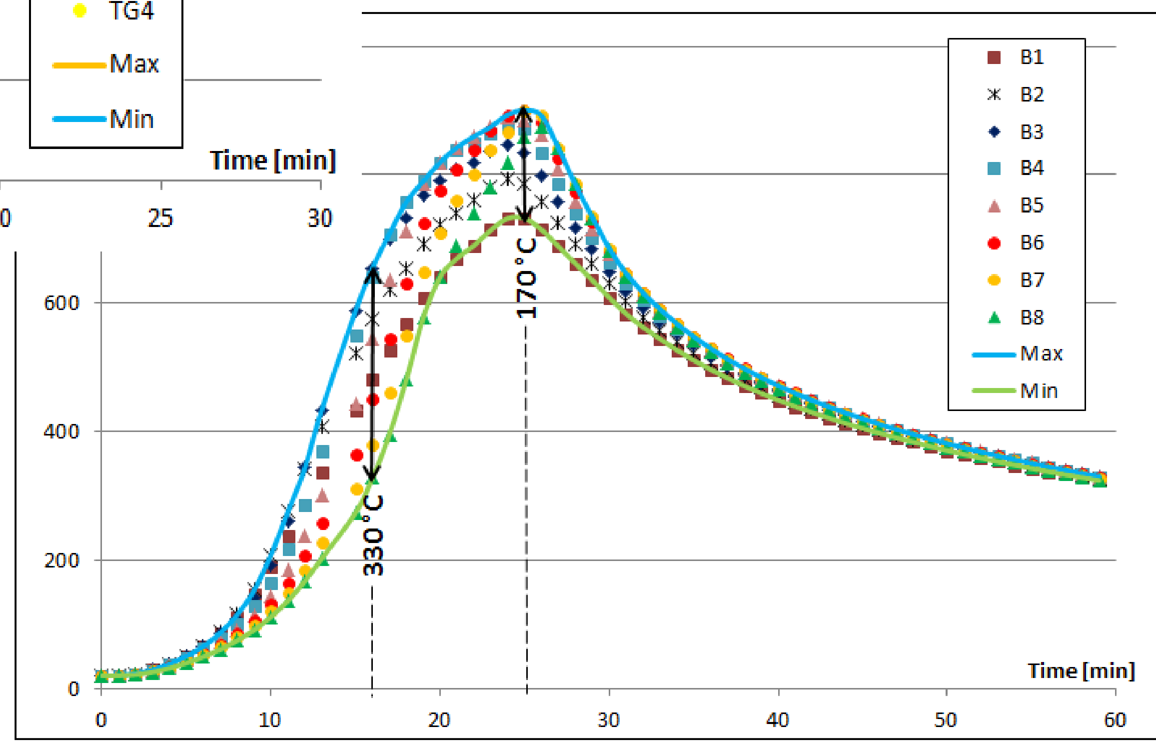
Numerical study



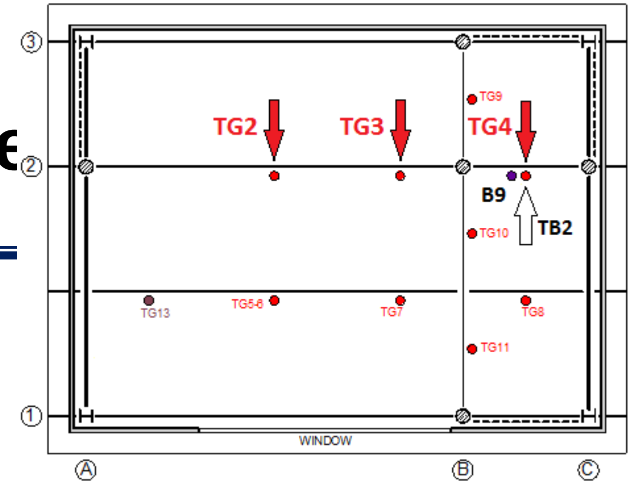


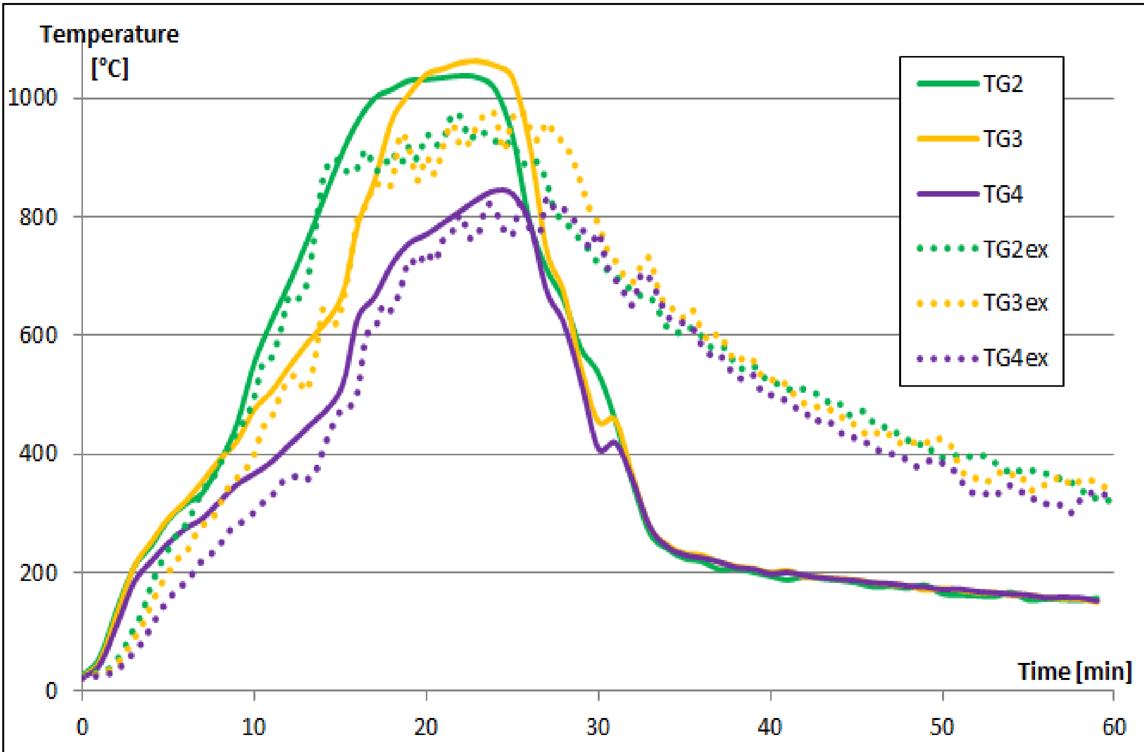
Gas temperature

Steel beam temperature



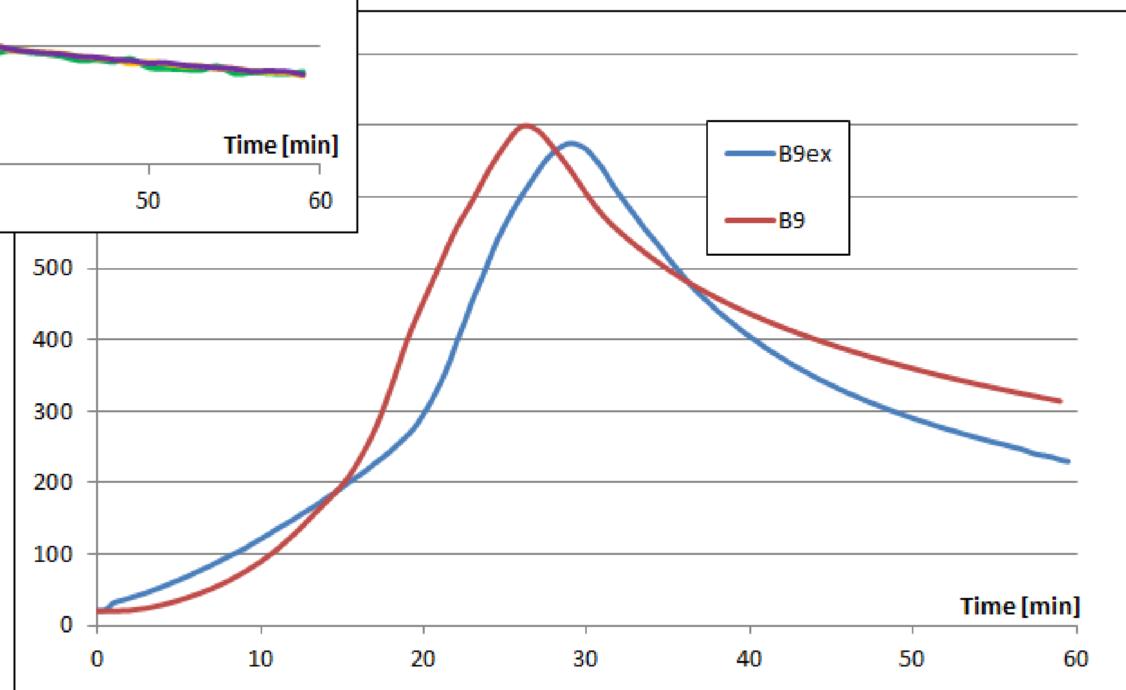
Validation of the mode





Gas temperature

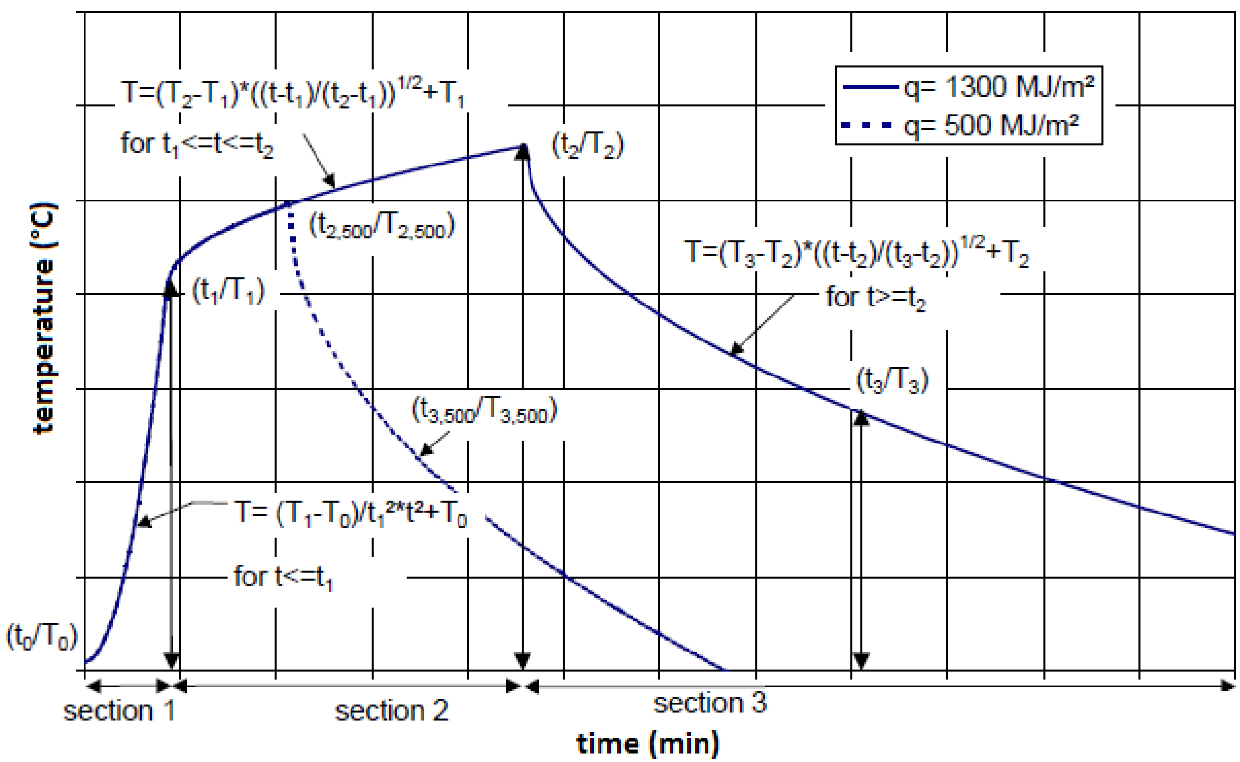
Steel beam temperature



Analytical model of TF

HRR parametrical model

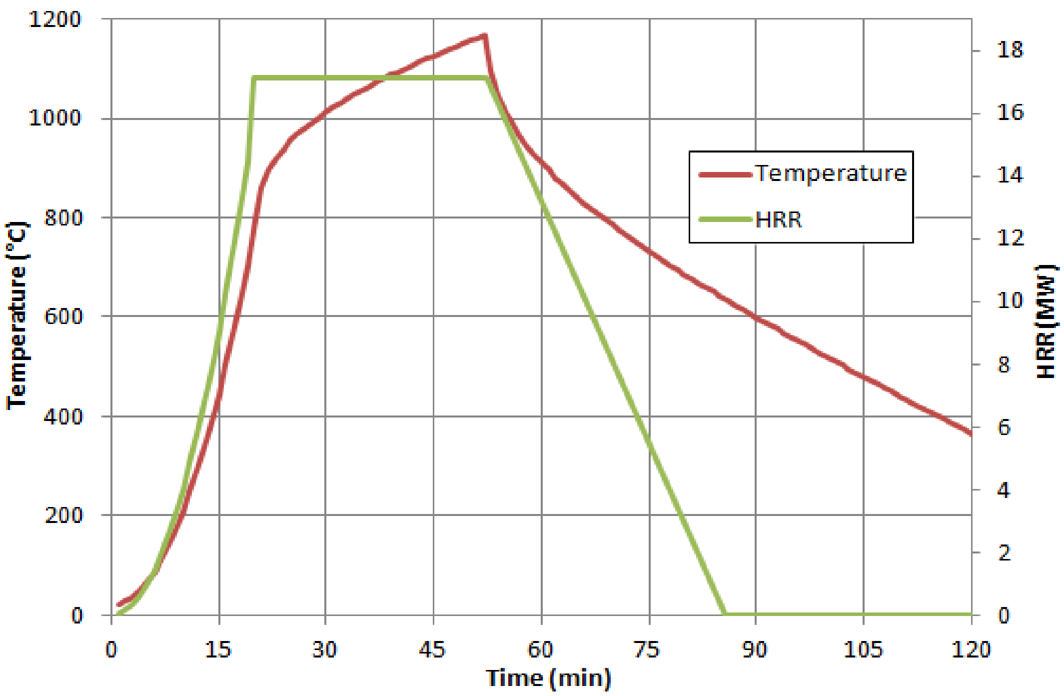
- Zehfuss, 2002
- Relationship with HRR – more realistic description of fire
- Implemented in DIN code



Analytical model of TF

Validation to fire test n. 2 in Veseli

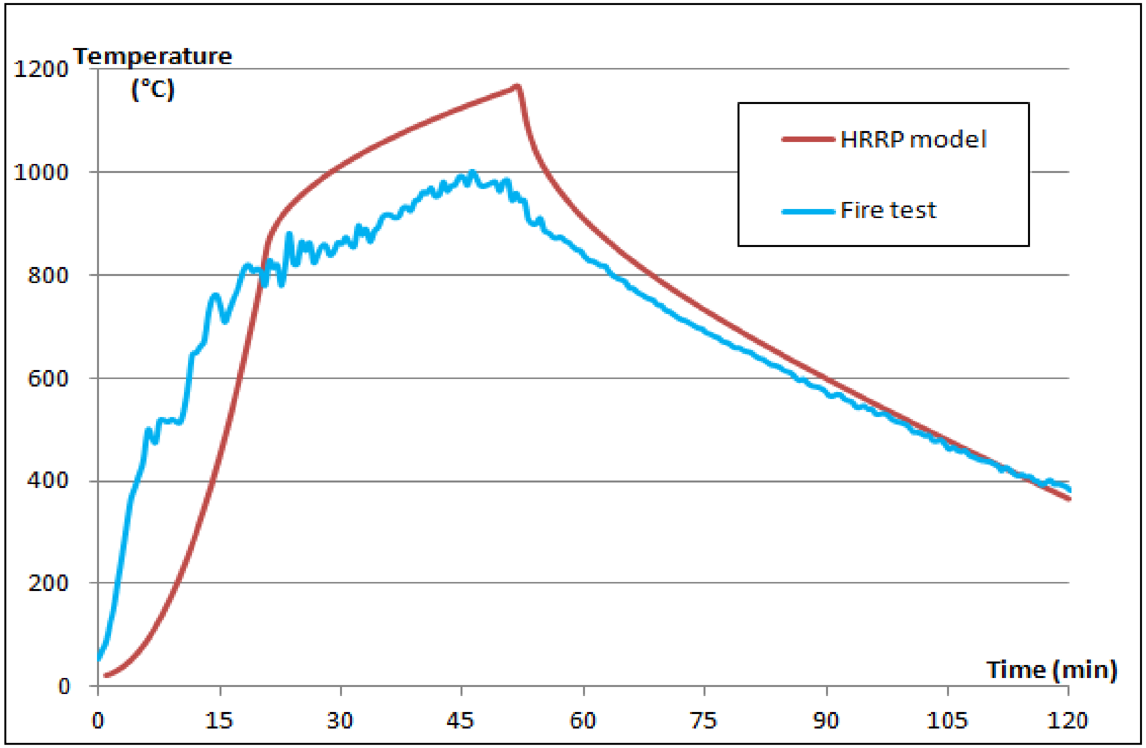
- Uniformly distributed fire load (28 wooden piles)
- Fire load density 525 MJ/m^2
- Ventilation opening 2 m x 5 m



Analytical model of TF

Validation to fire test n. 2 in Veseli

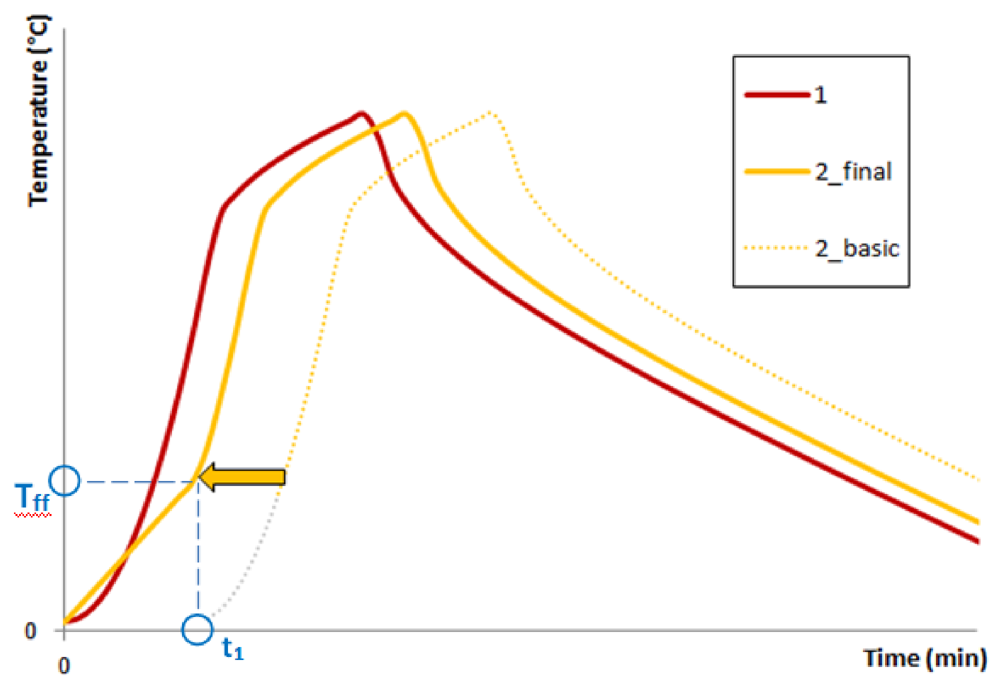
- Lower temperature till 19 min
- Peak temperature 160°C higher
- Decay phase in good agreement



Analytical model of TF

Methodology

- Fire travells in one horizontal direction
- Divison of enclosure into fields
- Temperature described by HRRP curve
- Spread rate influenced by HRR
  - $HRR_{max}(t_1)$ initiate curve 2
- Pre-heating given by T_{ff}
  - T_{ff} shifted back into t_1
  - Linear connection



Analytical model of TF

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  - T_{ff} shifted back into t_1
  - Linear connection

(Stern-Gottfried, 2011)

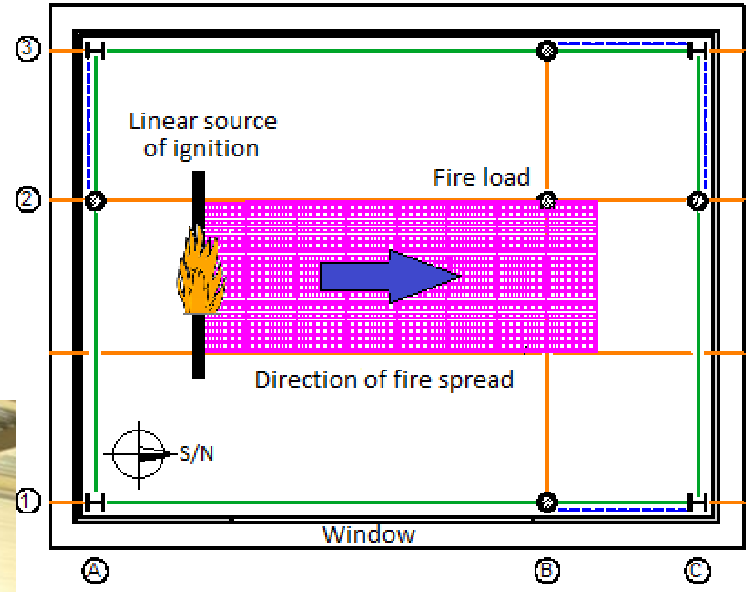
$$T_{ff} = \left[\frac{5}{3}\cdot\left(5.38\frac{Q^{\frac{2}{3}}}{H}\right)^4 \cdot \frac{x_{nf}^{-\frac{5}{3}} - x_{ff}^{-\frac{5}{3}}}{x_{ff} - x_{nf}} + 4T_\infty \cdot \left(5.38\frac{Q^{\frac{2}{3}}}{H}\right)^3 \cdot \frac{x_{nf}^{-1} - x_{ff}^{-1}}{x_{ff} - x_{nf}} + 18T_\infty^{\ 2} \cdot \left(5.38\frac{Q^{\frac{2}{3}}}{H}\right)^2 \right.$$

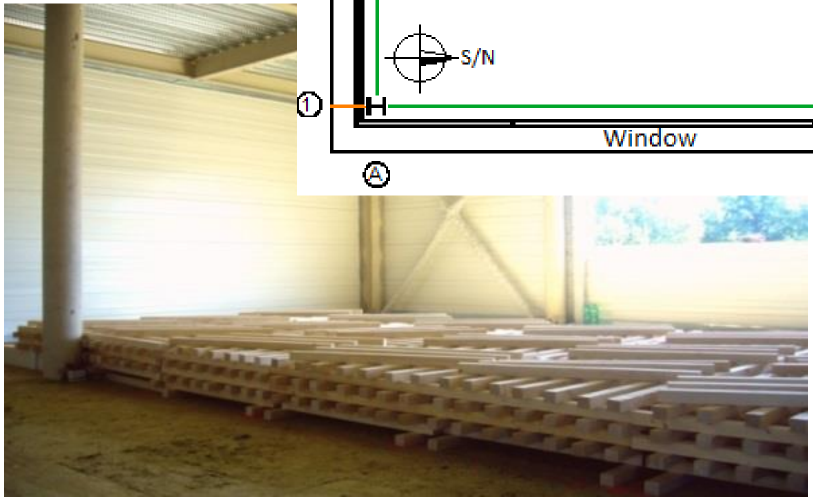
$$\left. \cdot \frac{x_{nf}^{-\frac{1}{3}} - x_{ff}^{-\frac{1}{3}}}{x_{ff} - x_{nf}} + 12T_\infty^{\ 3} \cdot \left(5.38\frac{Q^{\frac{2}{3}}}{H}\right) \cdot \frac{x_{ff}^{\frac{1}{3}} - x_{nf}^{\frac{1}{3}}}{x_{ff} - x_{nf}} + T_\infty^{\ 4}\right]^{1/4}$$

Analytical model of TF

Validation to fire test n. 1 in Veseli

- Composite structure of 10.4 m x 13.4 m x 9.0 m
- Window 2.0 m x 5.0 m
- 24 wooden piles (2.52 m^3 of wood)
- Linear ignition source
- No flashover – travelling fire

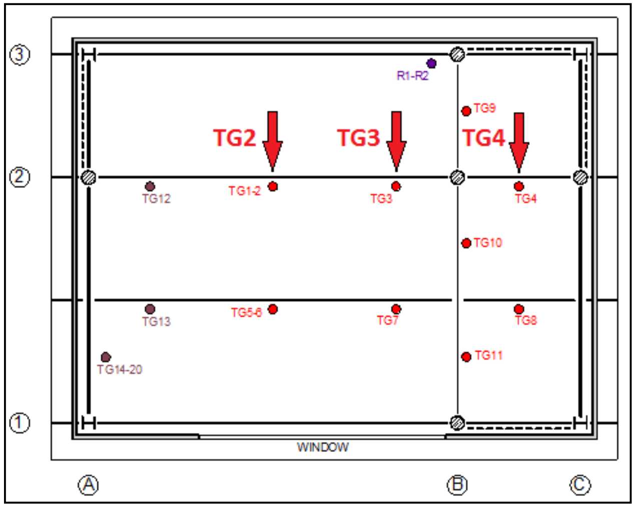




Analytical model of TF

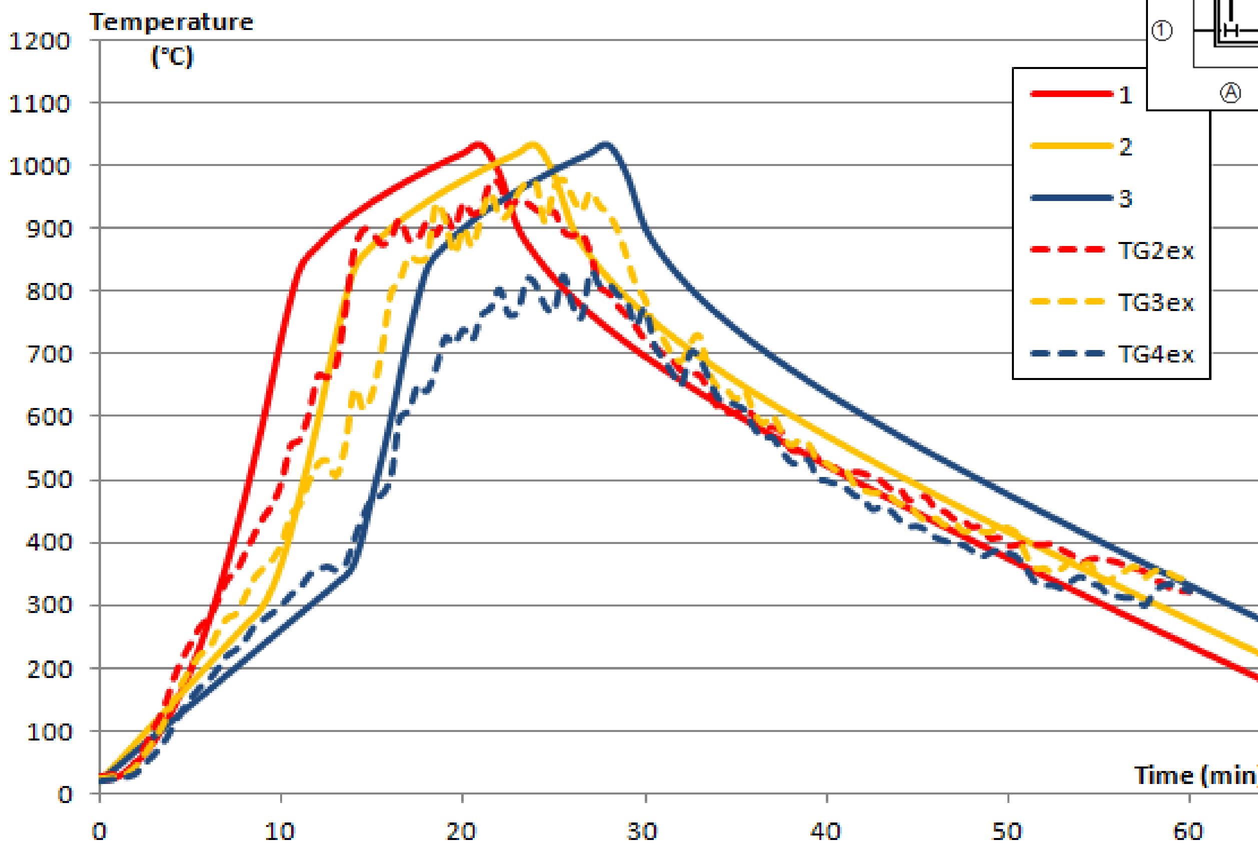
Validation to fire test n. 1 in Veseli

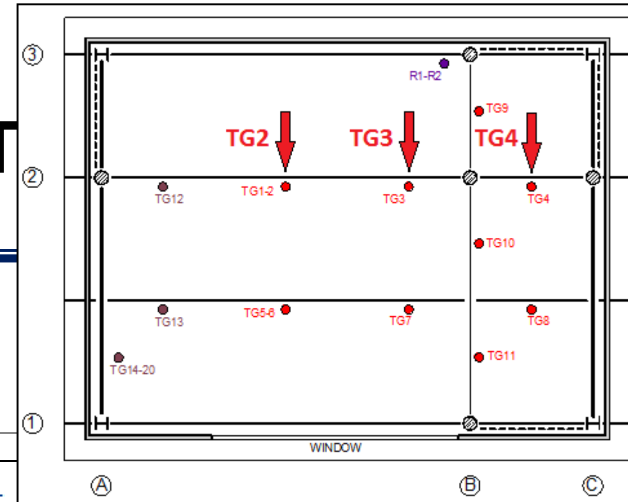
- Division into 3 fields
- Time t_{α} is equal to 150 s
- RHR_f is equal to 700 kW/m^2
- Peak HRR = 16.8 MW
- Fuel-controlled fire
  - t_1 = 10.25 min
  - t_2 = 21.83 min
  - t_3 = 34.49 min
- Max temperature is 1020°C



Analytical model of T

Validation to fire test n. 1 in Veseli





- Good agreement

Analytical model of TF - summary

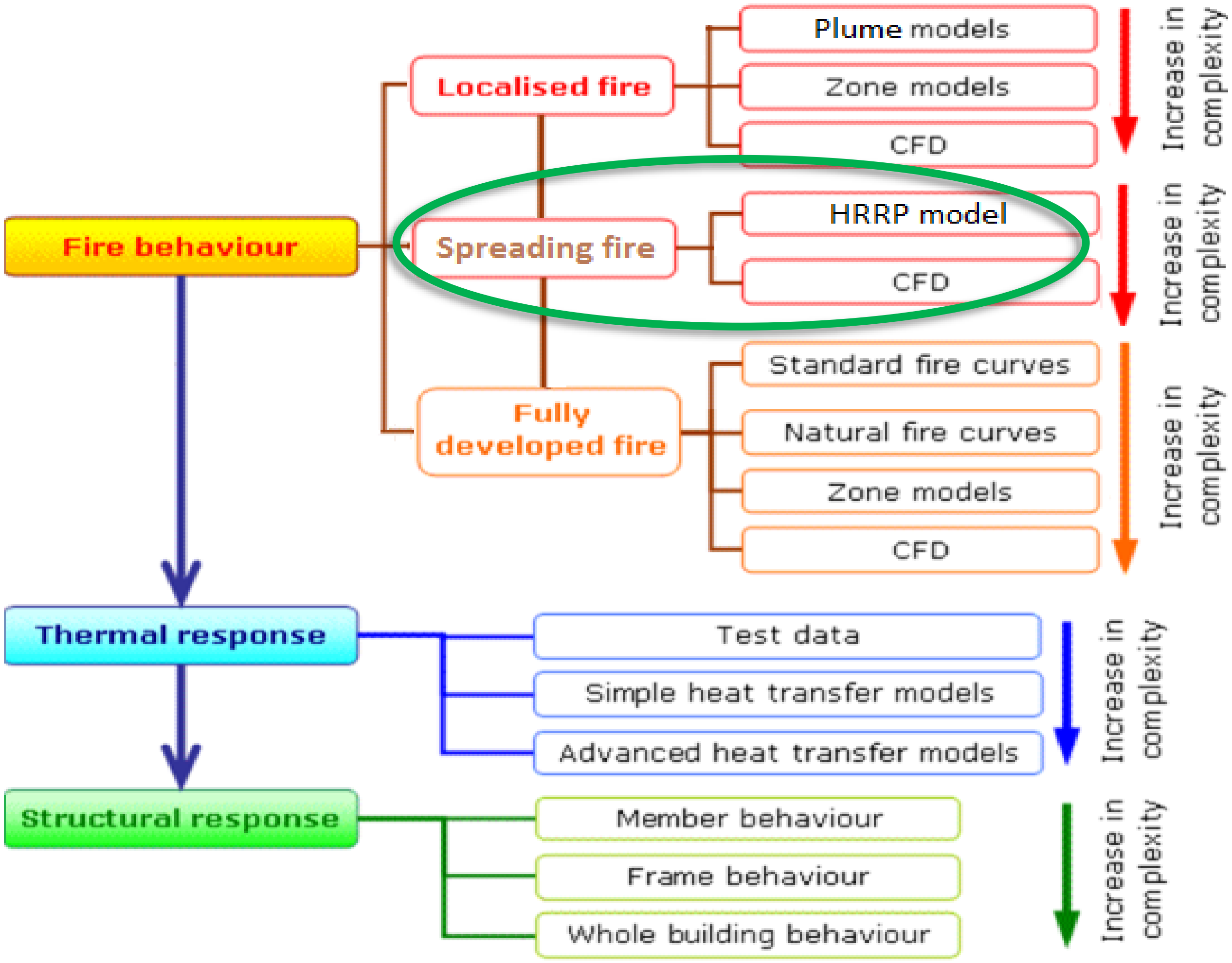
HRRP model of travelling fire

- Based on repetitious HRRP (iBMB) temperature-time curve
- Including pre-heating by application of T_{ff}

- Simple describtion of gas temperature during TF
- Investigate mechanical behaviour of structures involved in TF

- Validated to full-scale fire test in Veselí

Analytical model of TF - summary



Summary

- The thermal analysis is often simplified to standard curve
- The standard curve is usually very conservative (compare to natural fire)
- Parametric curve can be used when more accurate solution is required. In this case, additional input data are required.
- Advanced mathematical models as zone model and CFD may be used for complex systems where simplified methods can not be applied.
- CFD is very complicated, it needs detailed input data, powerfull hardware, skilfull user, etc.
- Model of travelling fire may be implemented into the family of traditional design fire models.

Thank you for your attention!

kamila.cabova@fsv.cvut.cz

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