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Performance-Based **Fire Safety Engineering**: Challenges and Opportunities

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Fire safety: a major issue

The Great Fire of London in 1666 (unknown artist, c. 1700)

Fire safety: a major issue

L'Innovation Fire, Brussels, 1967

World Trade Center attacks, NYC, 2001

Fire safety: a major issue

- First and foremost: **life safety**

- But also: property protection, infrastructure protection

- Total cost of fire: ≈ **1% of GDP** in developed countries[1]
  - Cost of direct fire losses (casualties, property losses, etc.)
  - Cost of indirect fire losses (rehousing, business interruption, etc.)
  - Cost of fire fighting organizations
  - Cost of fire protection to buildings
  - Cost of fire insurance administration

[1]Geneva Association World Fire Statistics Centre (WFSC)

Fire Safety Engineering: a multidisciplinary field

To achieve the goal in Fire Safety Engineering, it requires implementation of **multiple objectives** based on **various disciplines**

↘ proba of ignition

↘ proba of fire spread

allow safe evacuation

Structural fire engineering is a key component

Design the structures for adequate response under fire

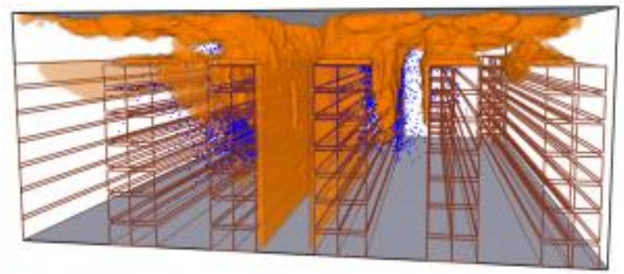
→ **compartmentation** and **structural stability**

Prescriptive vs Performance-Based approach

DESIGN APPROACH
For a structure against fire hazard

PRESCRIPTIVE
following codes and standards

PERFORMANCE-BASED
based on the physics of the problem



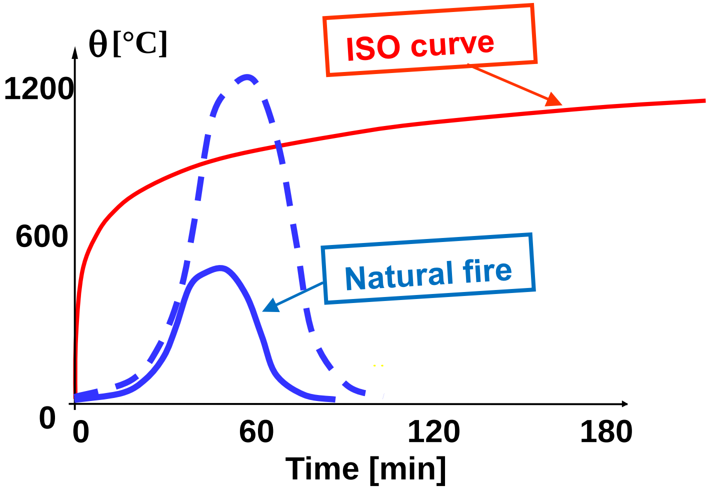
Prescribes methods to build vs Prescribes a result (performance)

→ Simplicity vs → Flexibility

PBD: **opportunity** for **more efficient**, **economic** and **elegant** design solutions, but requires a more advanced **understanding** of the physics of the problem

Performance-Based: Why it matters? What can we gain?

- Realistic **fire scenarios**



Performance-Based: Why it matters? What can we gain?

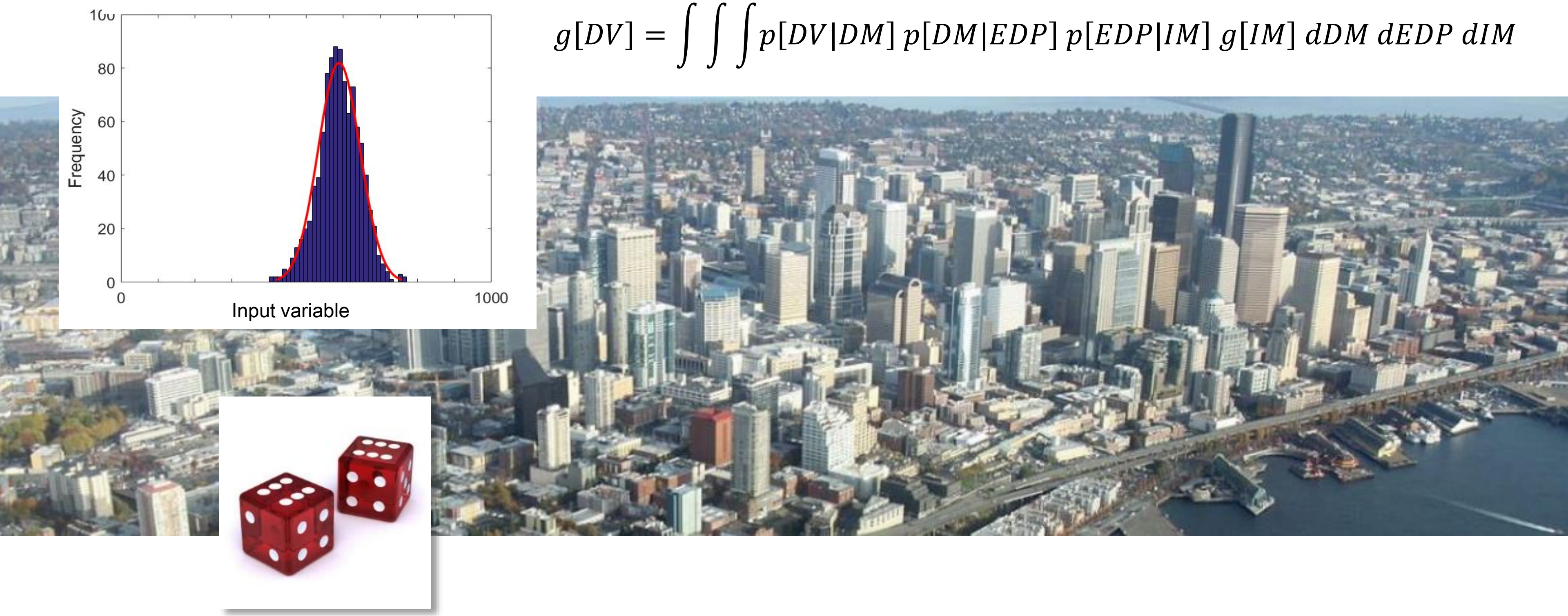
- Realistic **fire scenarios**
- Robustness and **whole building** behavior

Cardington fire test, UK, 1997

Performance-Based: Why it matters? What can we gain?

- Realistic **fire scenarios**
- Robustness and **whole building** behavior
- Consideration of **specific risk** associated with the building

$$g[DV] = \int\int\int p[DV|DM]\, p[DM|EDP]\, p[EDP|IM]\, g[IM]\, dDM\, dEDP\, dIM$$



T. Gernay, 2017

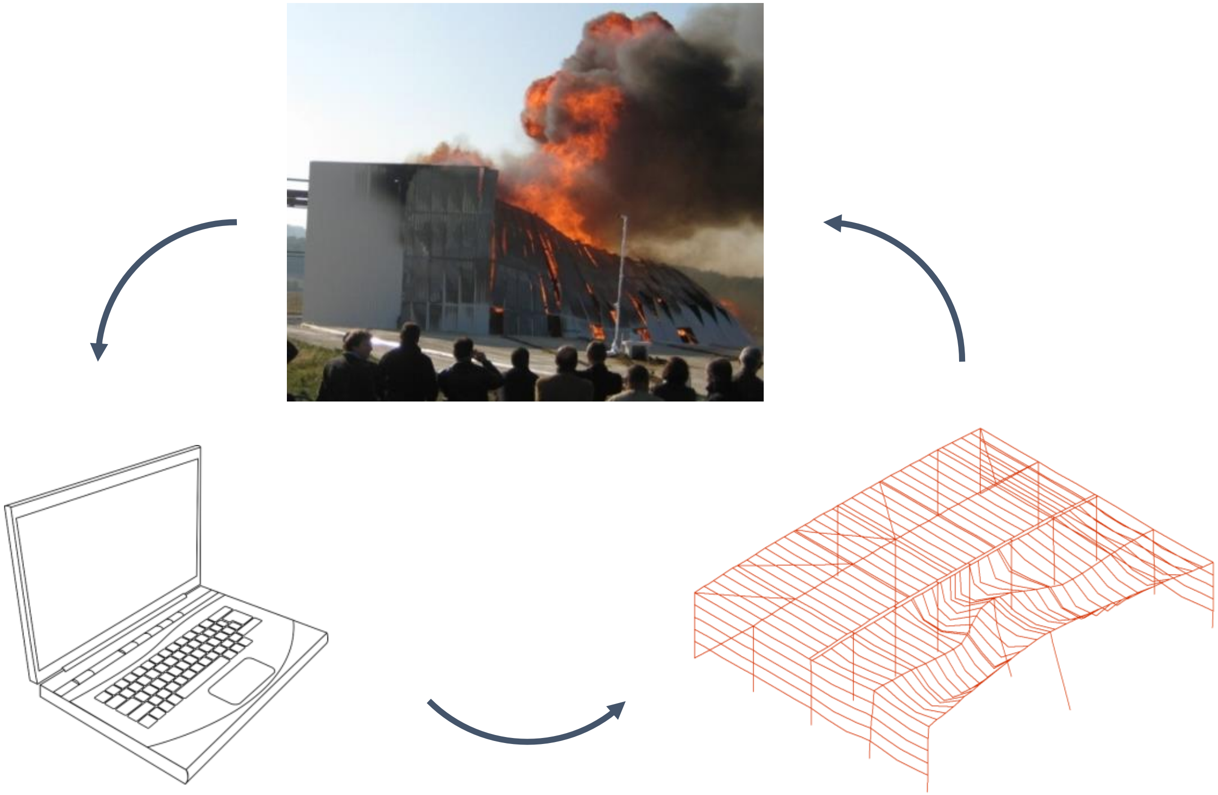
Performance-Based: Why it matters? What can we gain?

- Realistic **fire scenarios**
- Robustness and **whole building** behavior
- Consideration of **specific risk** associated with the building
- **Cost effective** fire resistance designs

The Shard, London

Research goal: Develop Performance-Based design in SFE

- Comprehend the behavior of building **materials** and **structures** in **fire**
- Propose **models** to accurately capture this behavior
- Develop **numerical tools** for structural fire engineering analysis



Example of research project: How to model concrete in fire?

Need

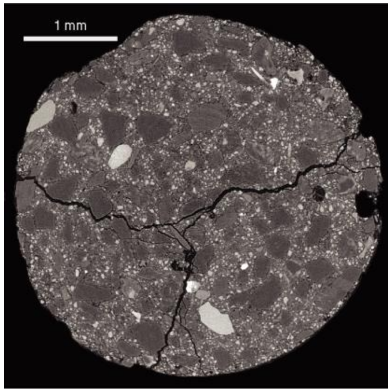
- Concrete is one of the most used materials
- Its behavior is affected by fire
- There was no satisfying model available for concrete at elevated temperature

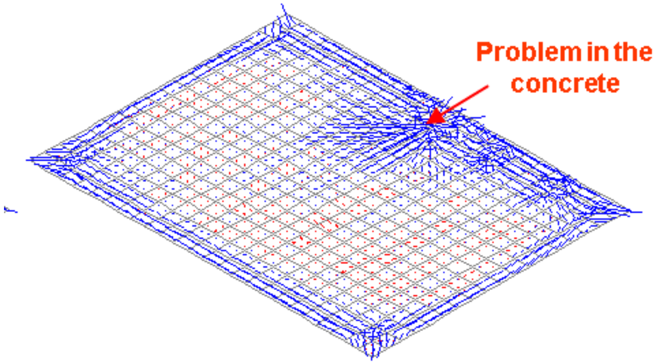
Challenges

material behavior
+ at elevated temperature

numerically robust

applicable to large structures

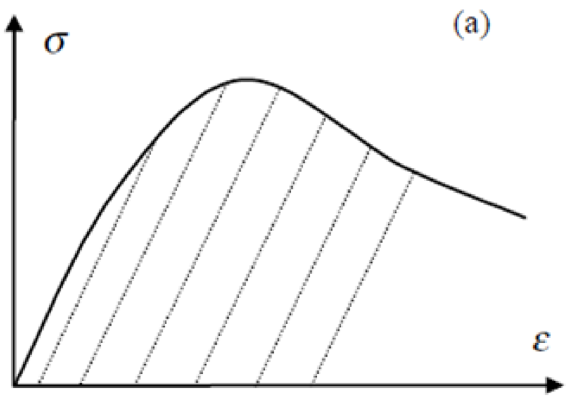




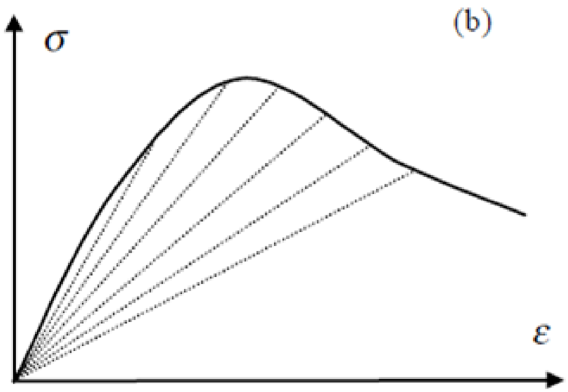
Modeling

- Traditional plasticity approach
- Damage proposed at ambient temperature
- Actually concrete exhibits a combination of both

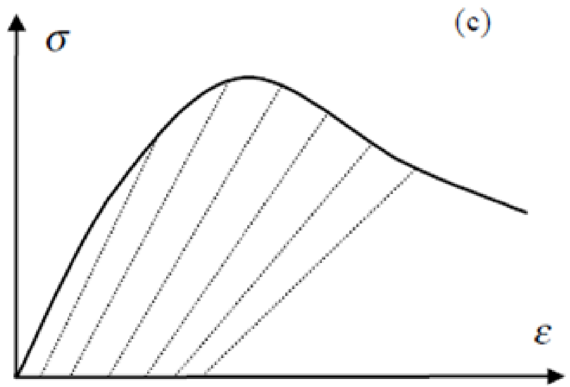
Plasticity



Damage

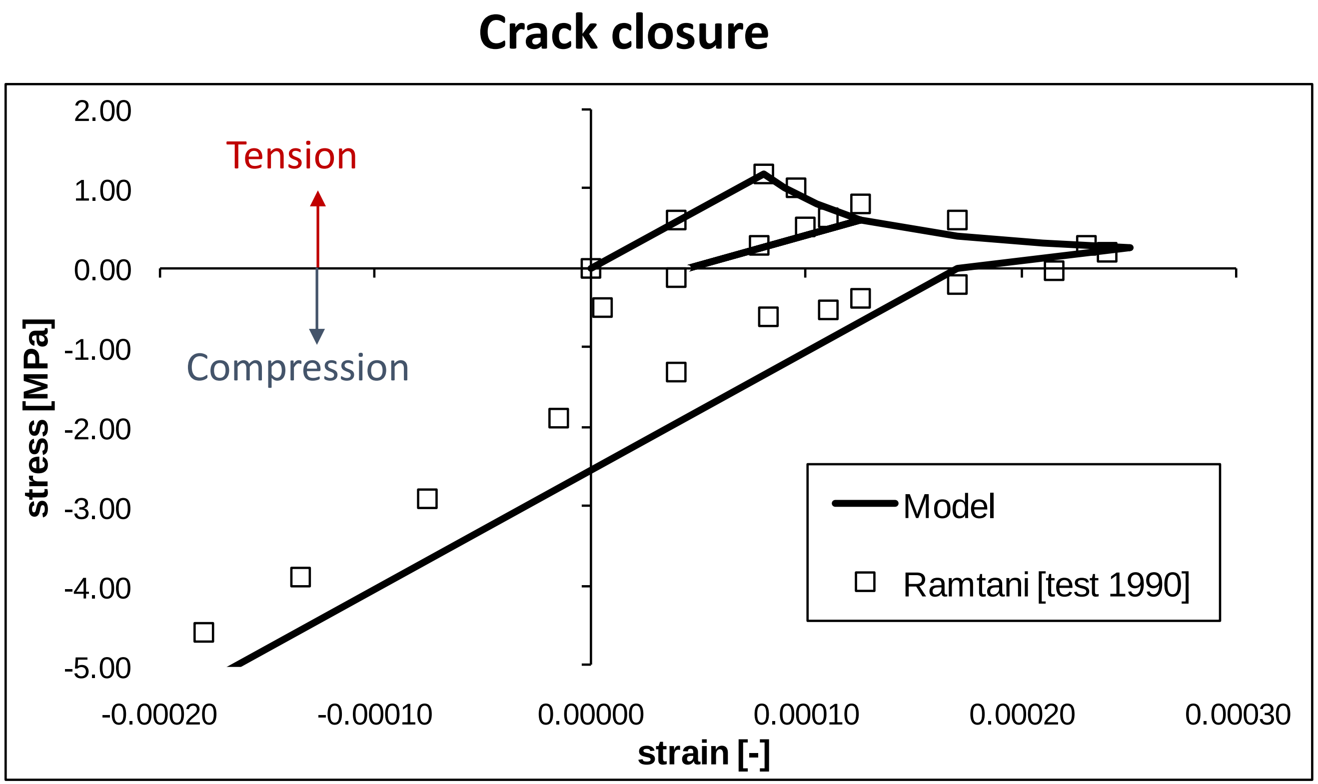


Plastic-damage



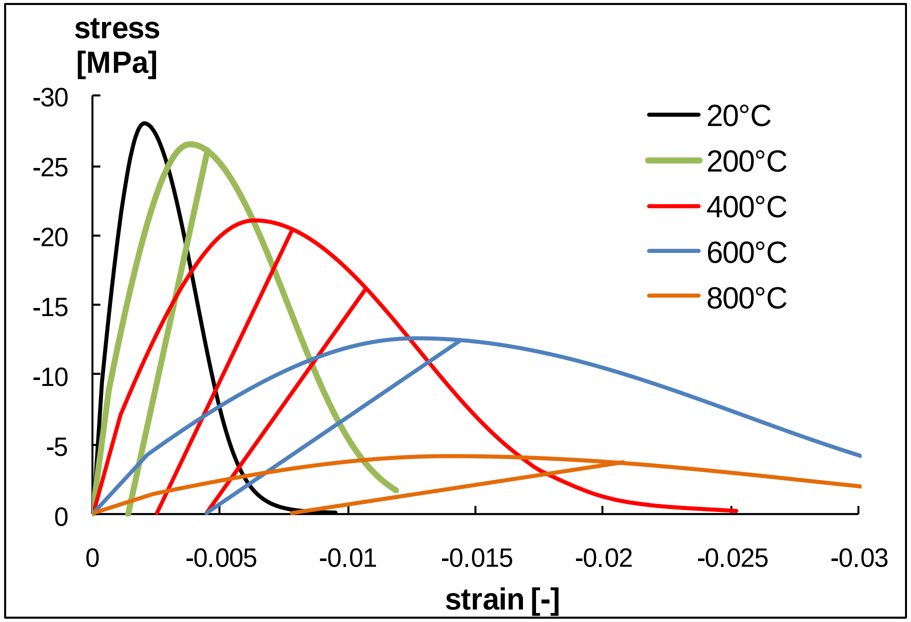
Modeling

- Different in tension and in compression
- Can handle the shift from one to the other
- Essential because of thermal stresses

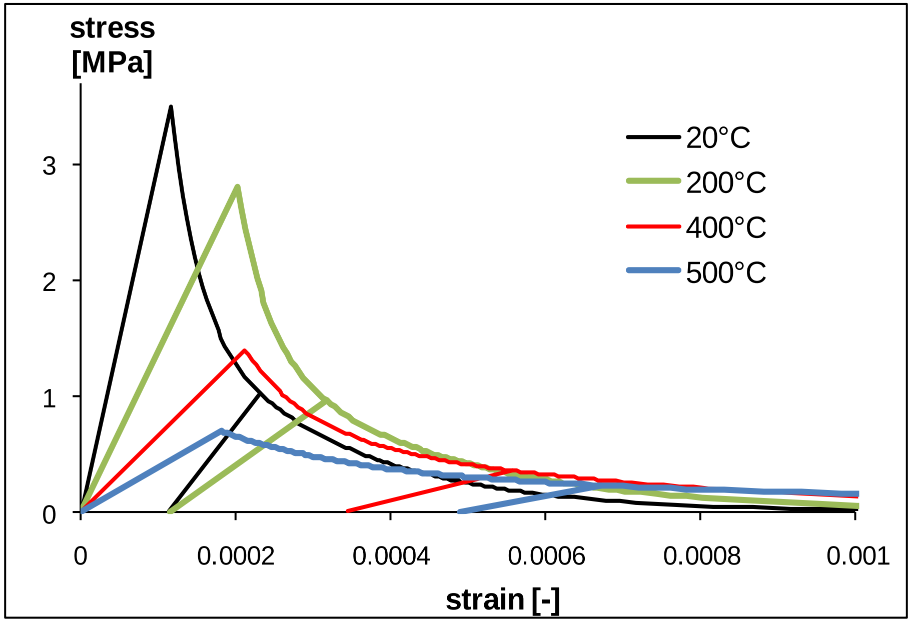


Effects of temperature on stress-strain relationships

Compression



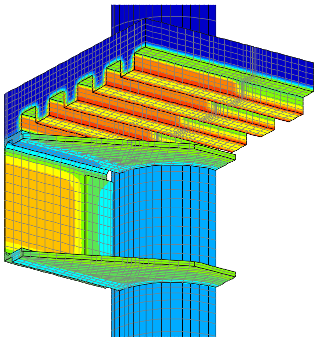
Tension

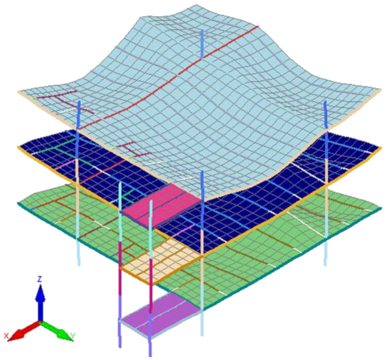


A model for concrete in fire: Implementation

To achieve the greatest impact in practice and be useful to the community:

- The model is **implemented in a Finite Element software**
  - SAFIR®: non linear FE software for modeling structures in fire
  - Widely available to the SFE community (+200 licensees)





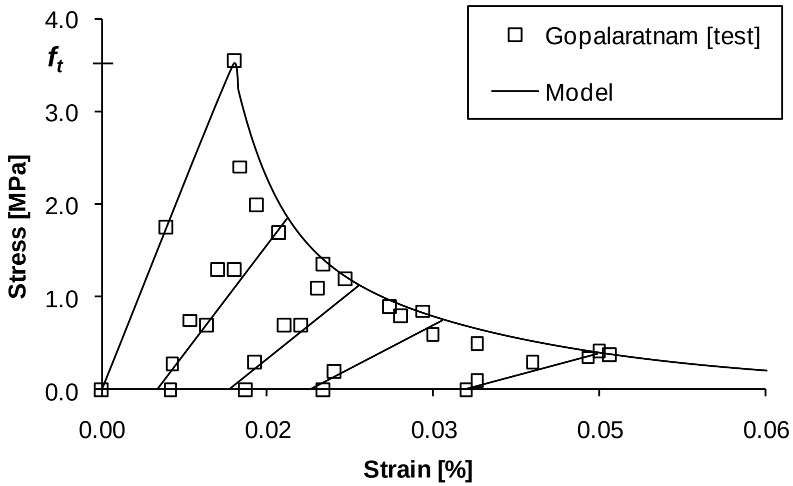
- Compatibility is ensured with the **different types of FE**:
  - Model formulated in fully triaxial stress (SOLID FE)
  - Algorithm for solving in plane stress (SHELL FE)
  - Also a uniaxial formulation (BEAM FE)

A model for concrete in fire: Validation

At the material scale

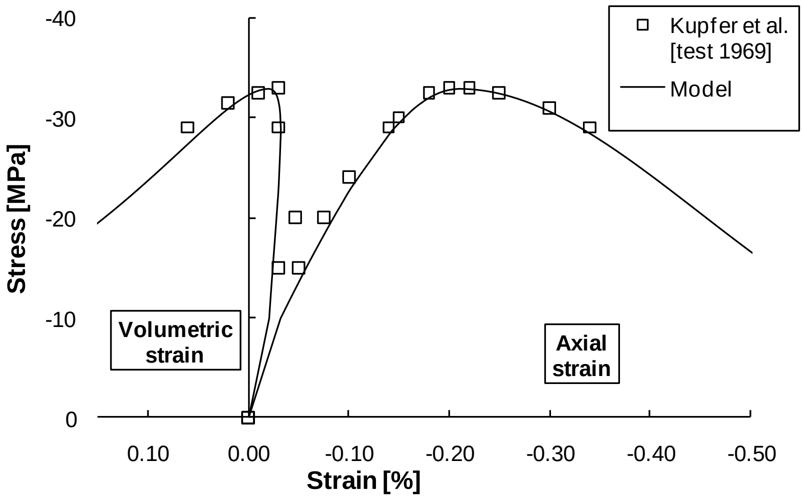
Uniaxial tension

- ✓ Softening
- ✓ Stiffness reduction
- ✓ Permanent strains



Uniaxial compression

- ✓ Post-peak
- ✓ Dilatancy



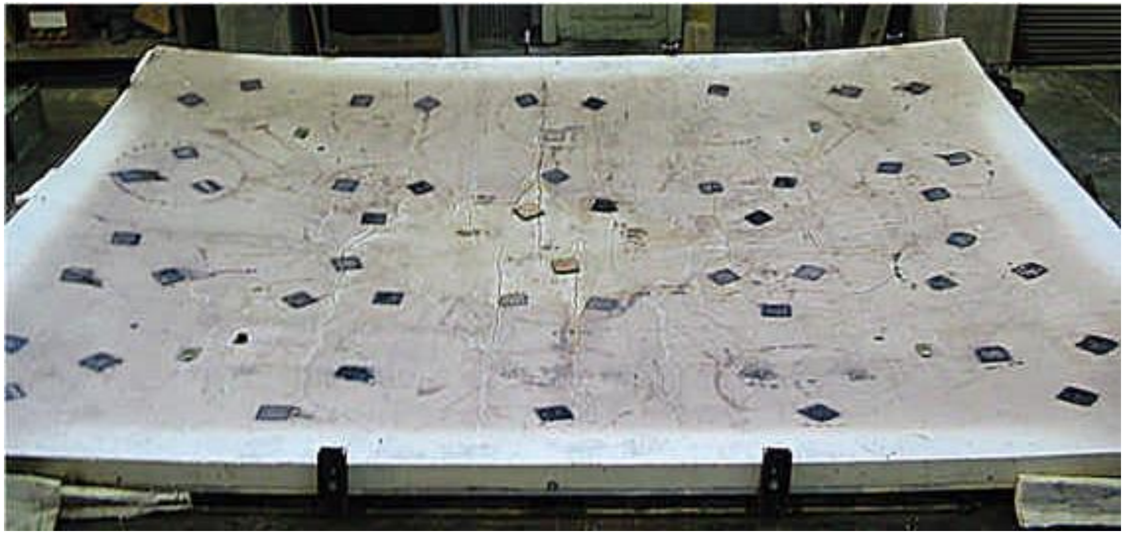
A model for concrete in fire: Validation

At the structural scale

Reinforced concrete slab in fire

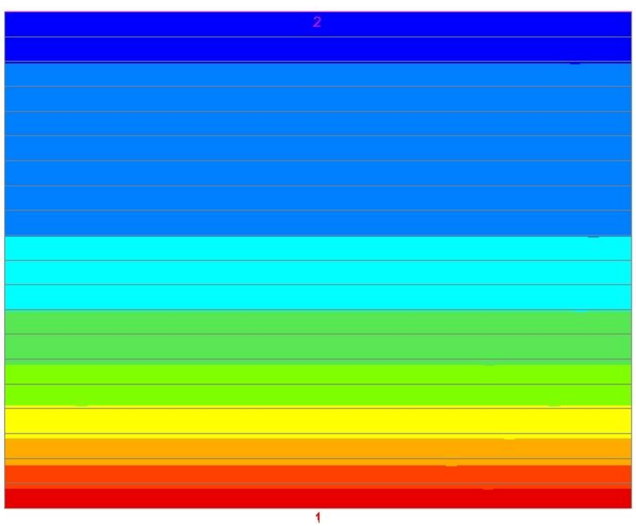
- Slab 4.30m x 3.30m
- Applied load 3.0 kN/m²
- ISO fire during 180 minutes

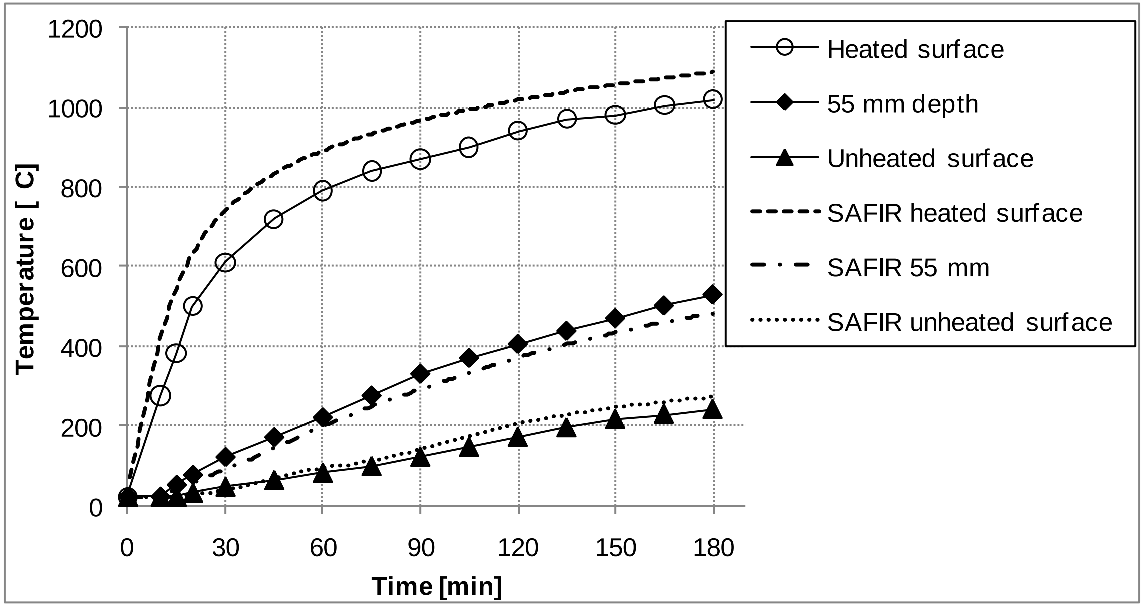
from Lim et al., Eng. Struct. (2004)



At the structural scale

Reinforced concrete slab in fire: **Thermal model**

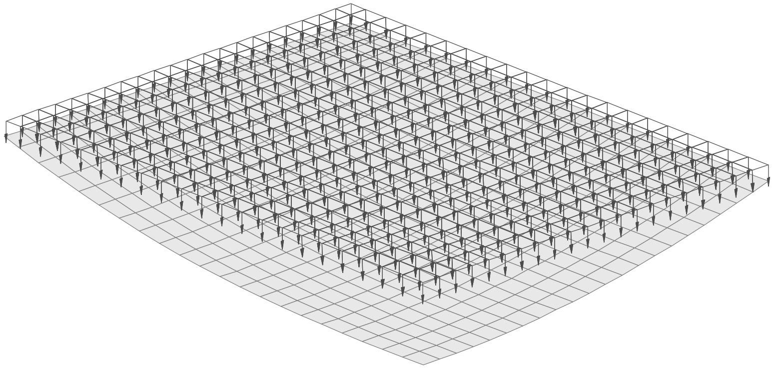


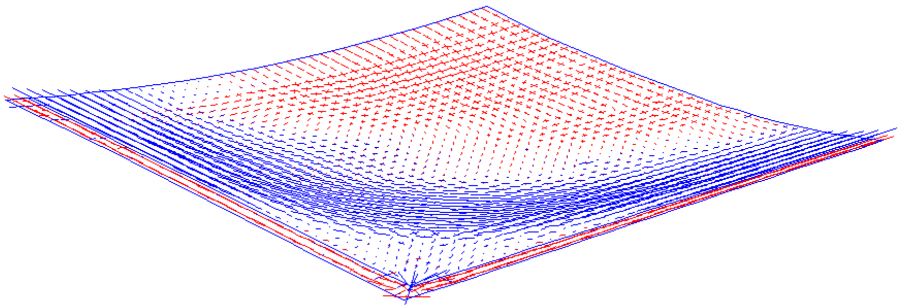


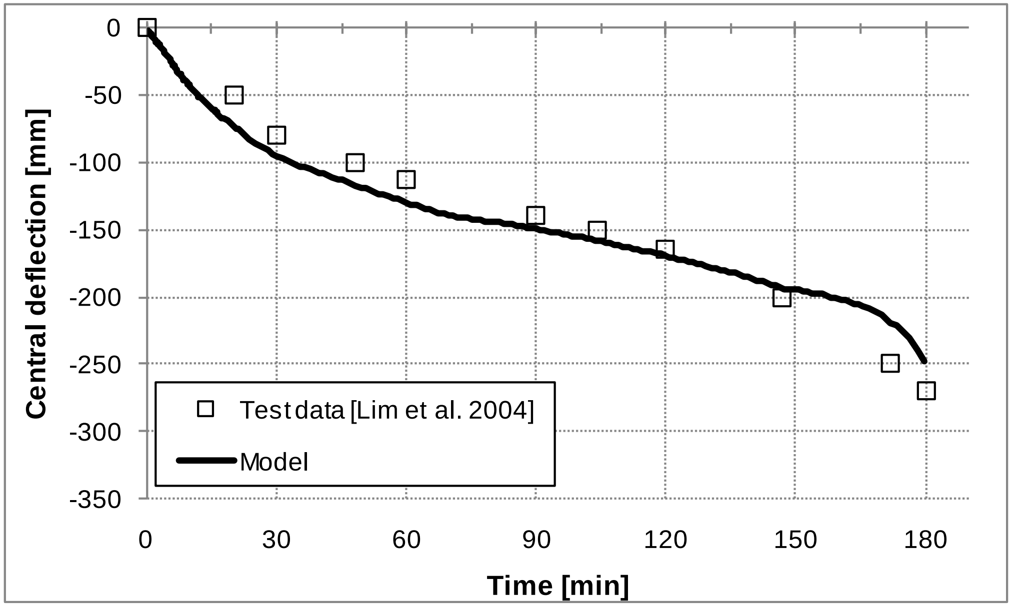
A model for concrete in fire: Validation

At the structural scale

Reinforced concrete slab in fire: **Mechanical model**



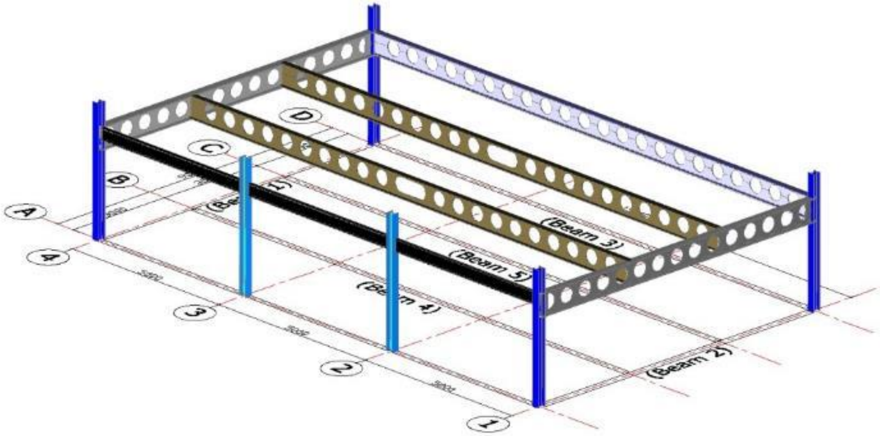




A model for concrete in fire: Simulation of a large-scale fire test

European project to investigate tensile membrane action

- Compartment 15m x 9m
- Composite structure with cellular steel beams
- Two central steel beams are unprotected
- Mechanical load: 3.25 kN/m^2
- Fire load: 700 MJ/m^2 (wood cribs)

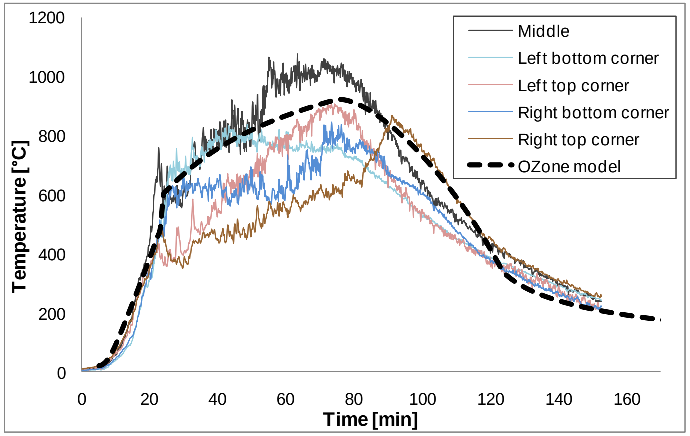


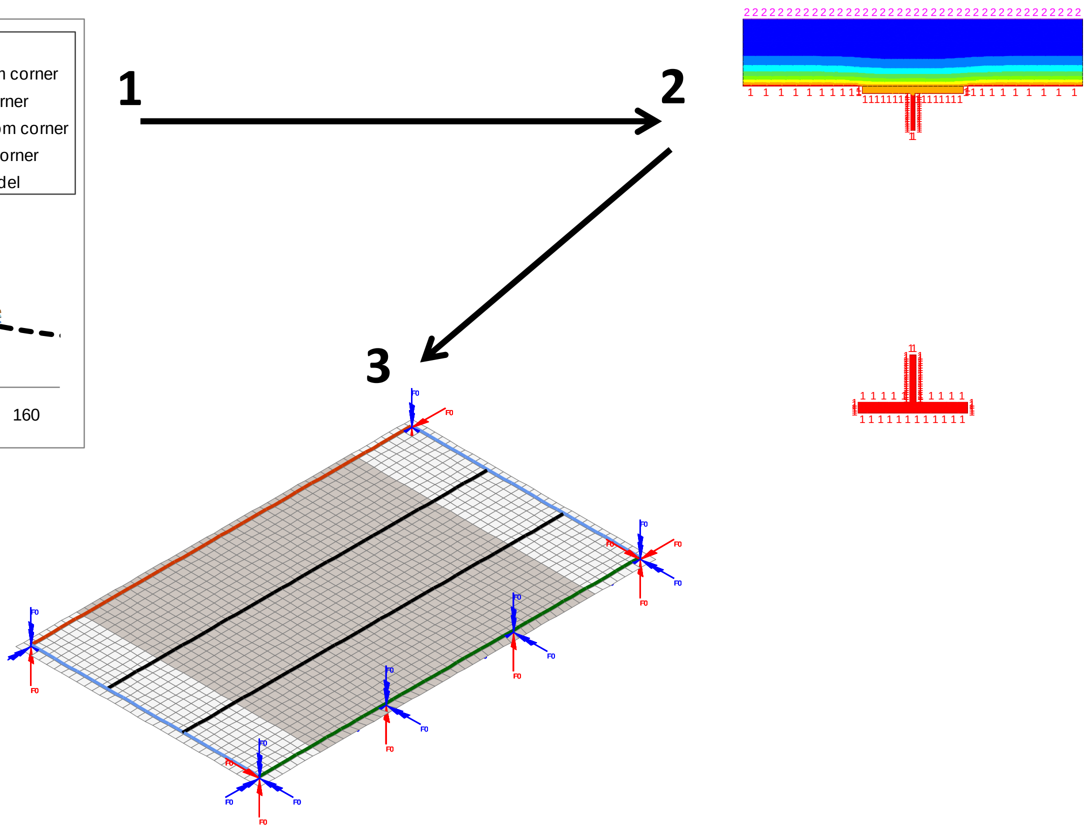
A model for concrete in fire: Simulation of a large-scale fire test

A model for concrete in fire: Simulation of a large-scale fire test

A model for concrete in fire: Simulation of a large-scale fire test

1. **Fire model** to get the gas temperature evolution in the compartment
2. **Thermal analysis** of the sections of the structural components
3. **Structural analysis** of the composite floor and beams system

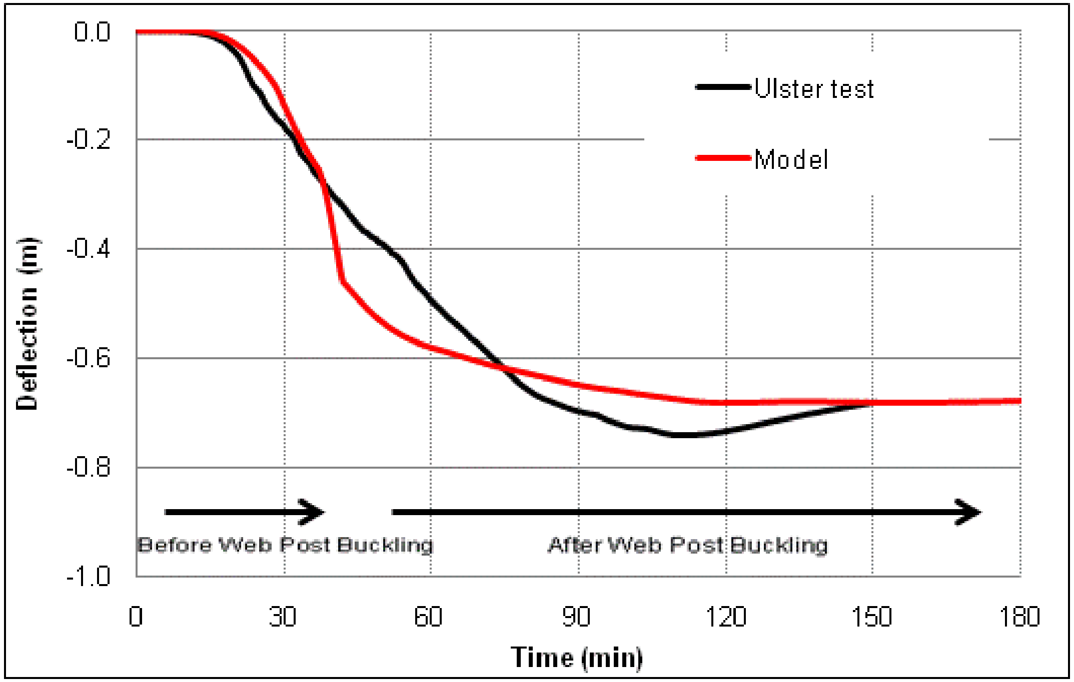




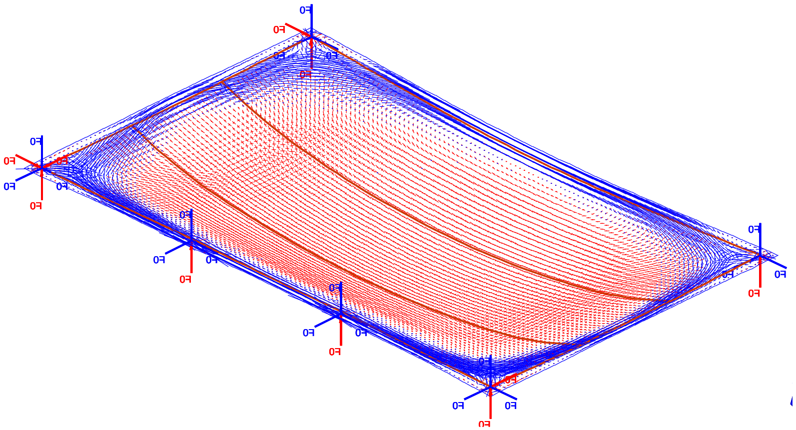
A model for concrete in fire: Simulation of a large-scale fire test

Results

Evolution of the vertical deflection



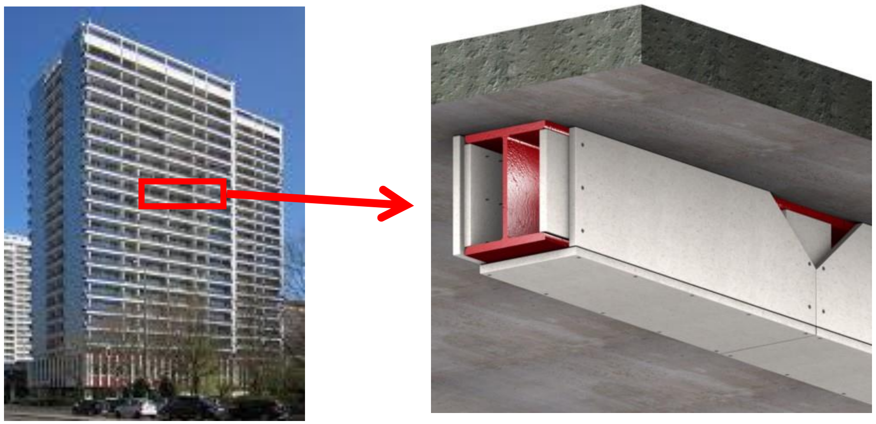
Deflected shape and forces



A model for concrete in fire: Implications for the field

Example: composite building design taking advantage of tensile membrane action

Prescriptive design



Protect all elements individually

Performance-based design

40-55% of steel beams can be left unprotected

The target performance (stability) can be achieved with the PBD

→ significant **cost reduction**

→ but to demonstrate it, **advanced analysis** tools are needed

Conclusion

Performance based design in Structural Fire Engineering

- Challenge: not a simple recipe… but a physically-based, specific solution
- Opportunities: flexibility, efficiency and cost reduction for safe design
- To understand the physics: models and numerical methods are crucial

New concrete model

- For multiaxial stress states and elevated temperature
- Successfully applied in a large range of applications

Impact

- Better understanding of the behavior of materials and structures
- Enables advanced analyses of structures in fire for innovative solutions
- Implemented in SAFIR® thus available to the SFE community

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Concrete constitutive model

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Fire tests simulated

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Thank you !

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