Performance-Based Fire Safety Engineering: Challenges and Opportunities

Dr. Thomas Gernay
F.R.S.-FNRS, University of Liege, Belgium
Fire safety: a major issue

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

T. Gernay, 2017
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**

- Lower proba of ignition
- Lower 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**

T. Gernay, 2017
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
→ Simplicity

vs

Prescribes a result (performance)
→ Flexibility

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

T. Gernay, 2017
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

\[ g(DV) = \int \int \int \frac{p(DV|DM) p(DM|EDP) p(EDP|IM) g(IM)}{G(DV|DM) G(DM|EDP) G(EDP|IM)} \ dDM \ dEDP \ dIM \]
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
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

T. Gernay, 2017
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

Crack closure

- Tension
- Compression

T. Gernay, 2017
Effects of temperature on stress-strain relationships

Compression

Tension

T. Gernay, 2017
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)

T. Gernay, 2017
At the material scale

**Uniaxial tension**
- Softening
- Stiffness reduction
- Permanent strains

**Uniaxial compression**
- Post-peak
- Dilatancy
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

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**

![Graph showing central deflection over time with test data and model comparison.]

T. Gernay, 2017
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/m²
- Fire load: 700 MJ/m² (wood cribs)
A model for concrete in fire: Simulation of a large-scale fire test

T. Gernay, 2017
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
Results

Evolution of the vertical deflection

Deflected shape and forces

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

T. Gernay, 2017
A model for concrete in fire: Implications for the field

Example: composite building design taking advantage of tensile membrane action

Prescriptive design

Performance-based design

Protect all elements individually

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
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
Concrete constitutive model


SAFIR® software


Fire tests simulated

Thank you!

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

Dr. Thomas Gernay
F.R.S.-FNRS, University of Liege, Belgium