International Conference on Recent Advances in Nonlinear Models
Structural Concrete Applications – CoRAN 2011

Structural behavior of concrete columns under natural fires including cooling down phase

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Context

Collapse during the cooling phase

Concrete structure subjected to natural fire

No failure at the time of temperature peak

Is there a risk of **delayed collapse**?

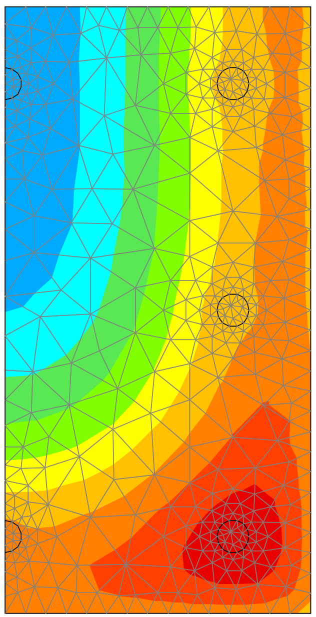
Windsor Building – Madrid 2005

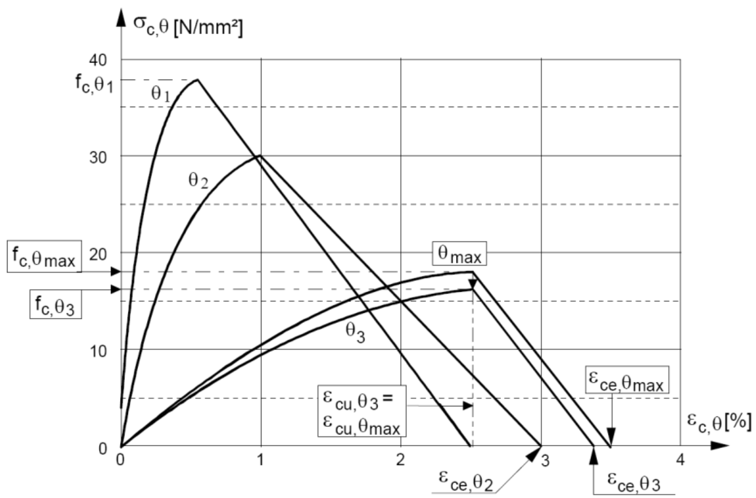
Context

➢ Possibility of occurrence

- ❑ The temperatures in the structure continue increasing
  thermal inertia → concrete

- ❑ Material behavior
  EN 1994-1-2 fig. C 2
  loss of strength → concrete





Context

- Possible consequence

  - ❑ Collapse during the cooling phase: threat for the fire fighters
  - ❑ Collapse after the cooling phase: time of first inspection!

⇒ There is a risk of delayed collapse for RC structures exposed to natural fire

Context

Analysis on the risk of delayed collapse

- Performance-based analysis
  - Verification of the structural integrity at the time of maximum gas temperature does not guarantee against delayed collapse
- Insight into the concrete material law
  - Validation for the numerical analysis under natural fire
- Numerical analysis of concrete columns in natural fire
  - Conditions that lead to collapse during or after the cooling phase

Material Models

Material models for the numerical analysis

- Steel and concrete
- Key for the validity of the numerical simulations
- Capture the material behavior during heating and cooling
- Thermal properties → EN 1994-1-2

Material Models

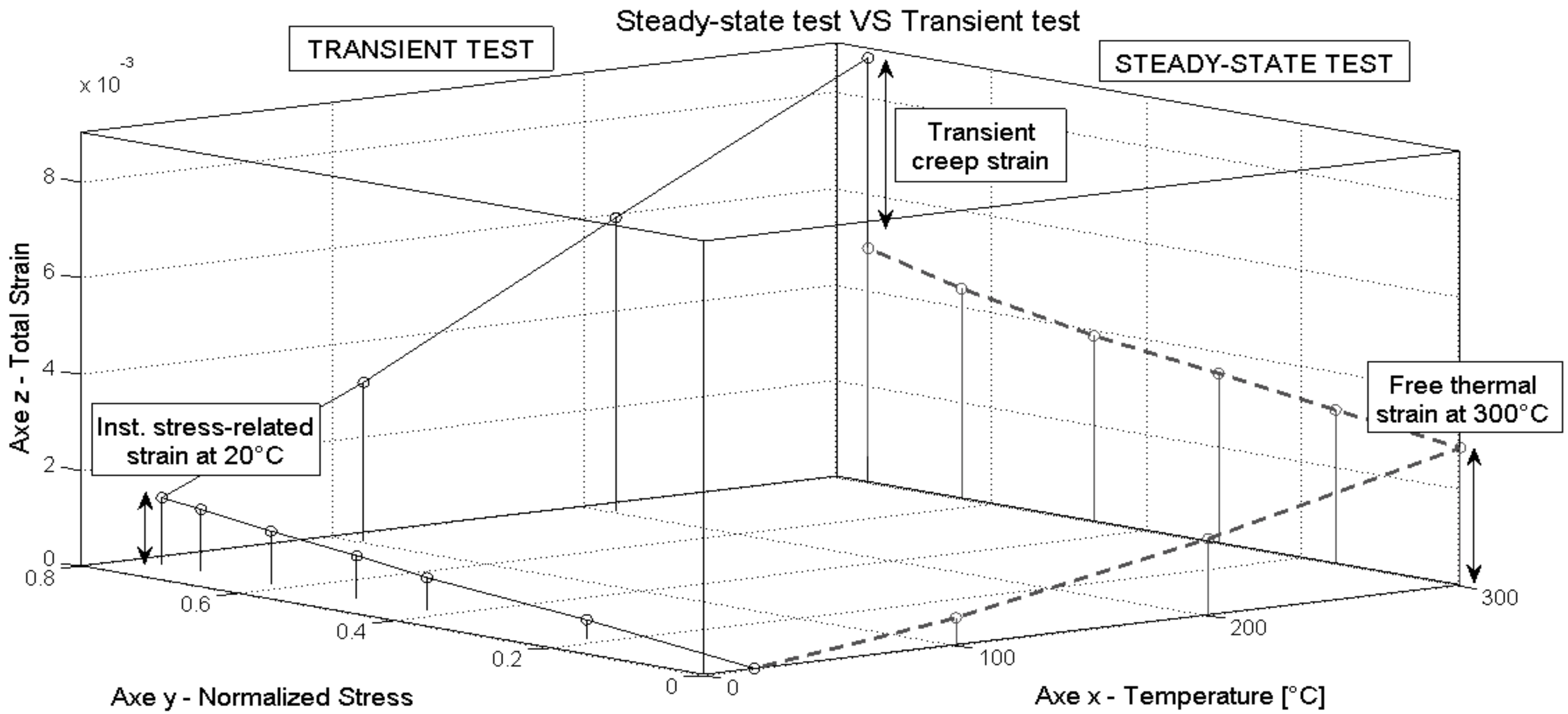
- Mechanical properties for steel
  - According to EN 1994-1-2
  - Reversible properties (recovered during cooling)

- Mechanical properties for concrete
  - Compressive strength of concrete not recovered during cooling
<u>Additional loss of 10%</u> [EN 1994-1-2 ; Yi-Hai & Franssen 2011]
  - Transient creep strain develops and is irrecoverable

Concrete Model

What is Transient Creep Strain?

- TCS develops in **concrete** that is (first-time) **heated under stress**



Concrete Model

2 types of TCS model

Explicit models: $\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{\sigma} + \varepsilon_{tr}$

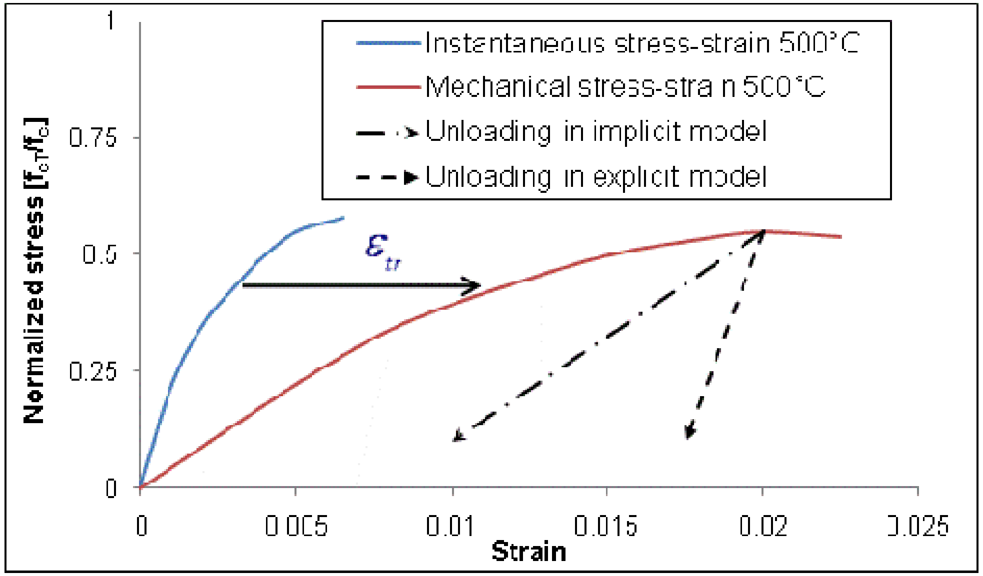
TCS depends on the "history"

TCS = permanent strain
→ Actual unloading stiffness

Implicit models: $\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{m}$

Univocal at given temperature

TCS, not known, is recovered
→ "Apparent" unloading stiffness



Concrete Model

- ➢ Assets of the Eurocode 2 concrete model
  - ❑ Generic model
  - ❑ Proposed by experts, well accepted by authorities
  - ❑ Widely used, good results for prescriptive design (ISO fire)

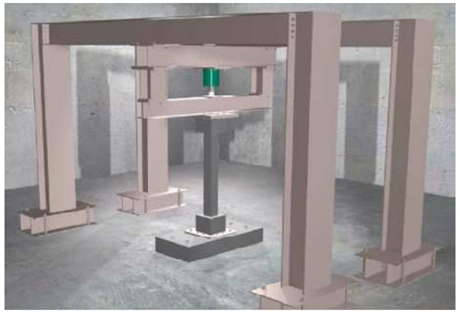
- ➢ Limitations of the EC2 model
  - ❑ Implicit model for TCS → validity for performance-based analysis?

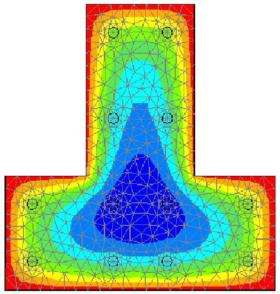
⇒ Reformulate the EC2 model with an explicit term for TCS

⇒ Explicit Transient Creep Model (ETC) developed and implemented in SAFIR

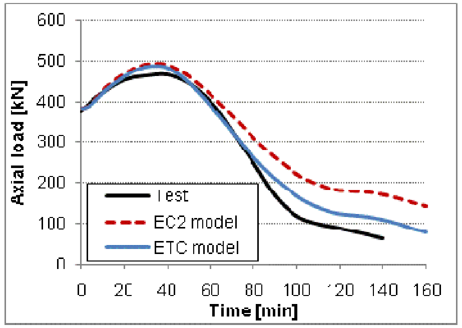
Concrete Model

- Experimental validation of ETC model
  - RC columns subjected to heating and cooling [Wu et al., 2010]

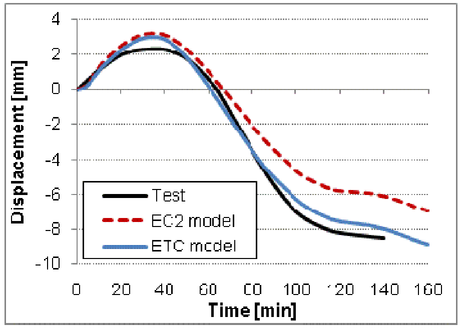




Axially restrained RC columns
Load 375 kN (ratio 0.34)
Axial restraint 34.5 MN/m
Heating during 90 minutes



Axial load response



Deformation response

SAFIR analysis with EC2 and ETC

Difference in unloading stiffness

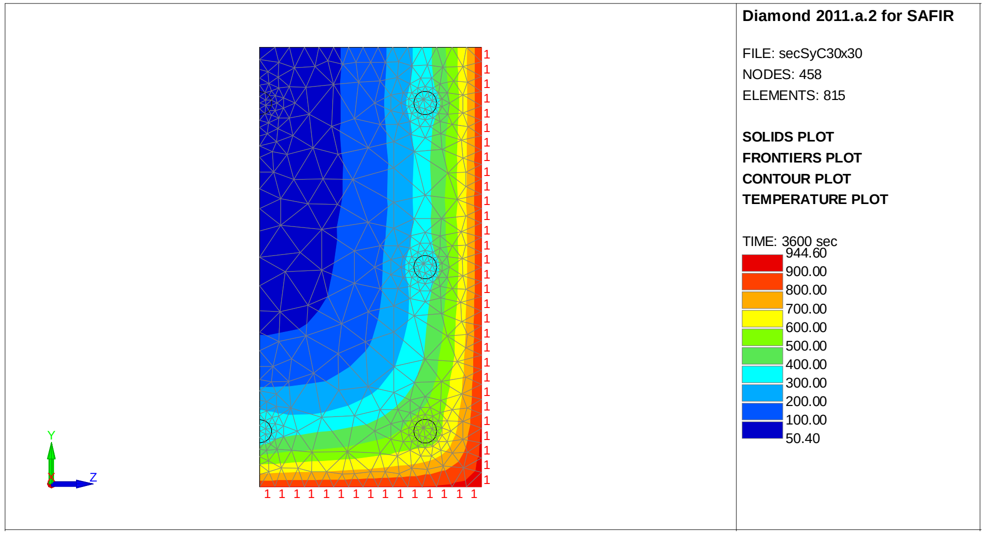
EC2 model → TCS is recovered

⇒ Explicit model of TCS needed for performance-based analysis

Column Analysis

Delayed collapse: study case

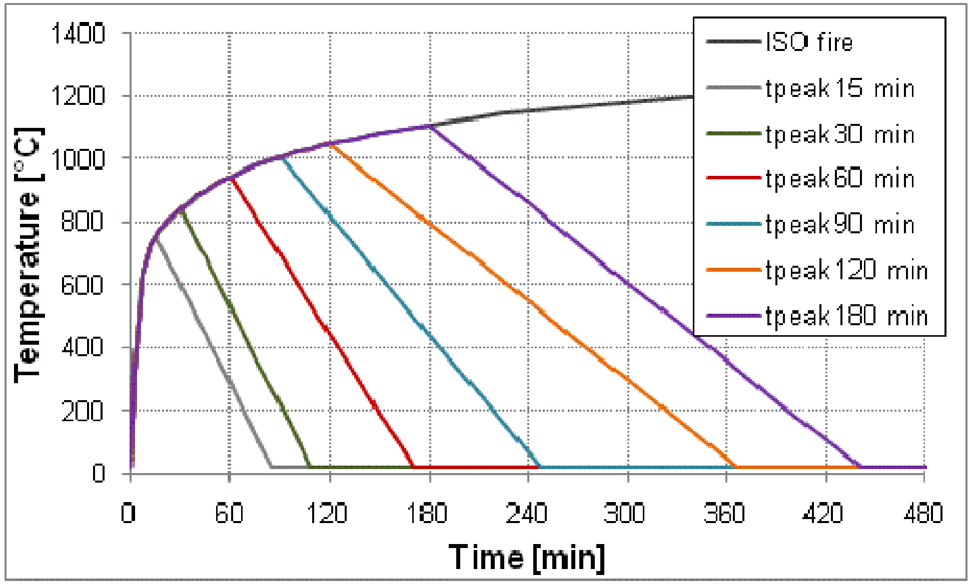
- Structural concrete columns
  - Section 300 x 300 mm² with 8 Φ16 steel rebars
  - Simply supported column of 4 m length
  - Sinusoidal imperfection L/300



Column Analysis

Delayed collapse: study case

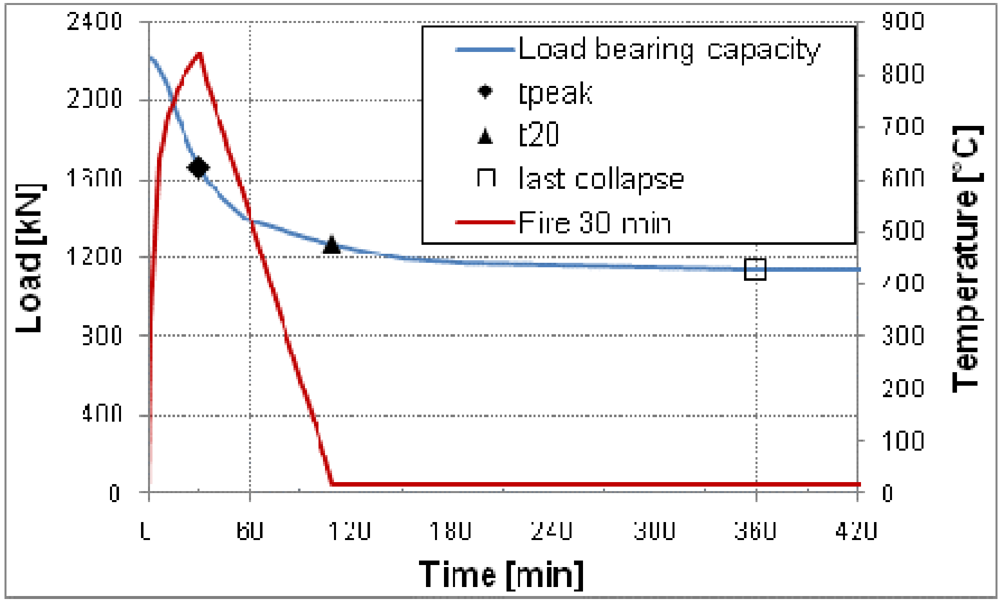
- Natural fire curves
  - Parametric fire model Annex A EN1991-1-2
  - Factor Γ = 1 for heating phase corresponding to ISO834



Column Analysis

Delayed collapse: numerical results

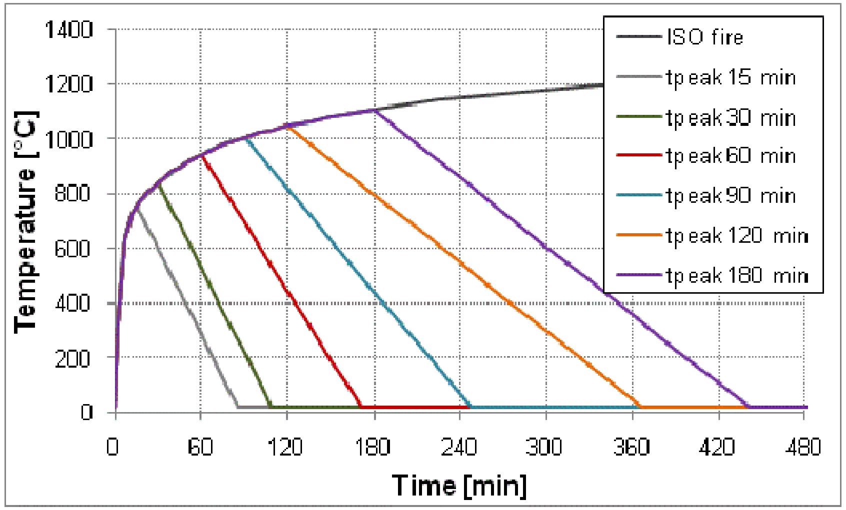
- Load bearing capacity of the column (fire 30 min)
  - Continue decreasing after the time of maximum gas temperature
  - Possibility of delayed collapse: + 4 hours after the end of the fire

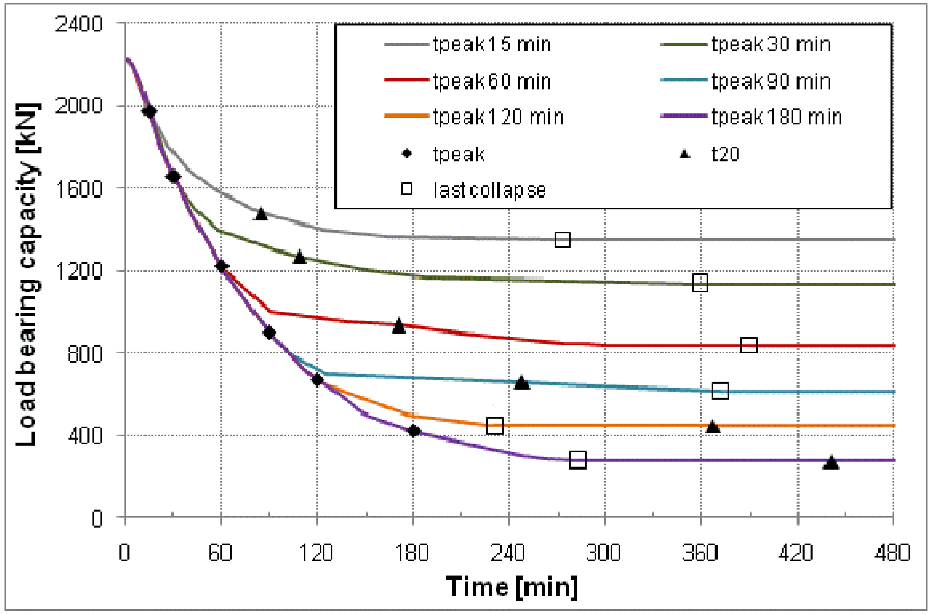


load 1200 kN
→ collapse after 165 min

Column Analysis

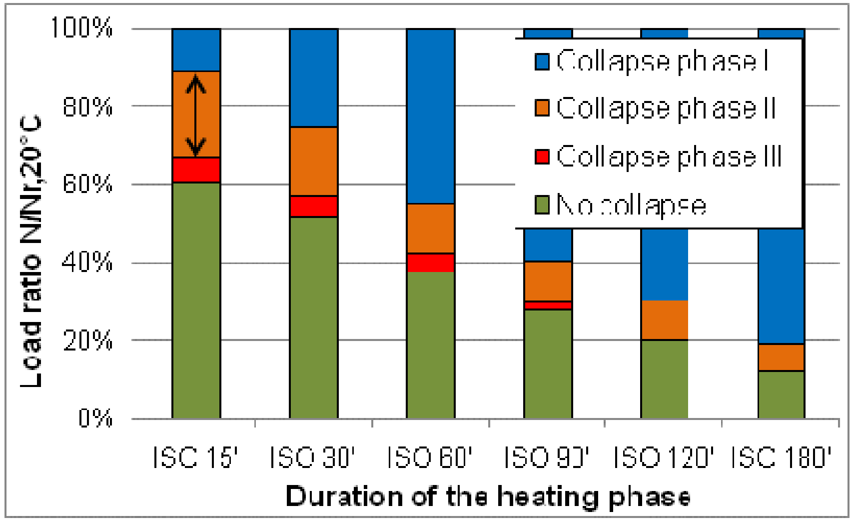
- Possibility of occurrence increases for shorter fire
  - Collapse during the cooling phase: observed for every fire duration
  - Collapse after the cooling phase: only for heating phase ≤ 90 min
  - Effect of thermal inertia of the section

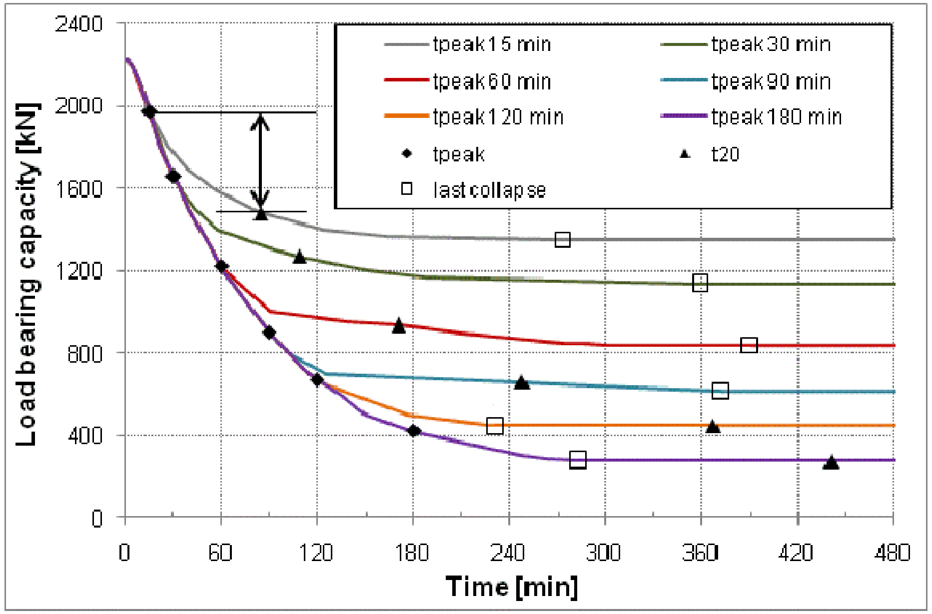




Column Analysis

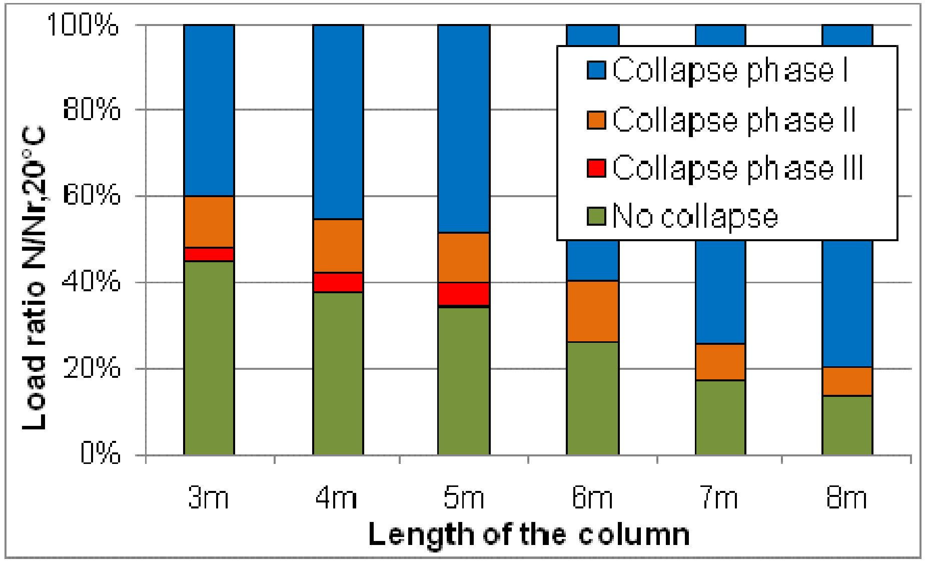
- Possibility of occurrence increases for shorter fire
  - Other presentation of the results
  - The relative range of loads that leads to delayed collapse decreases when the fire duration increases





Column Analysis

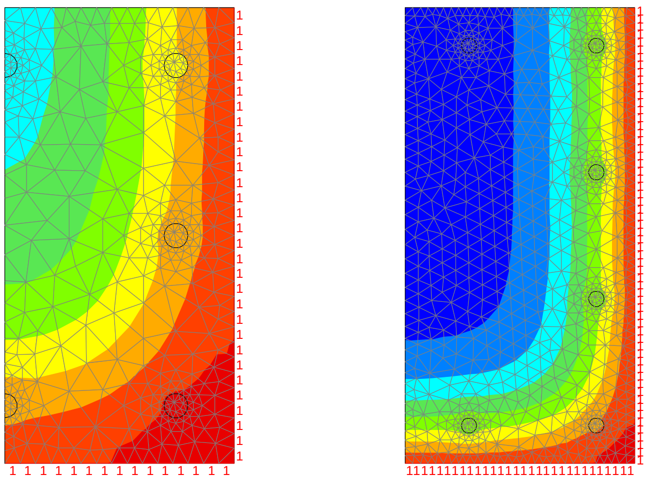
- Possibility of occurrence increases for low slenderness
  - Columns with high slenderness: effect of thermal gradient exceeds effect of variation of neutral axis position
    During cooling: lateral displacement decreases
  - However, collapse during the cooling phase always observed

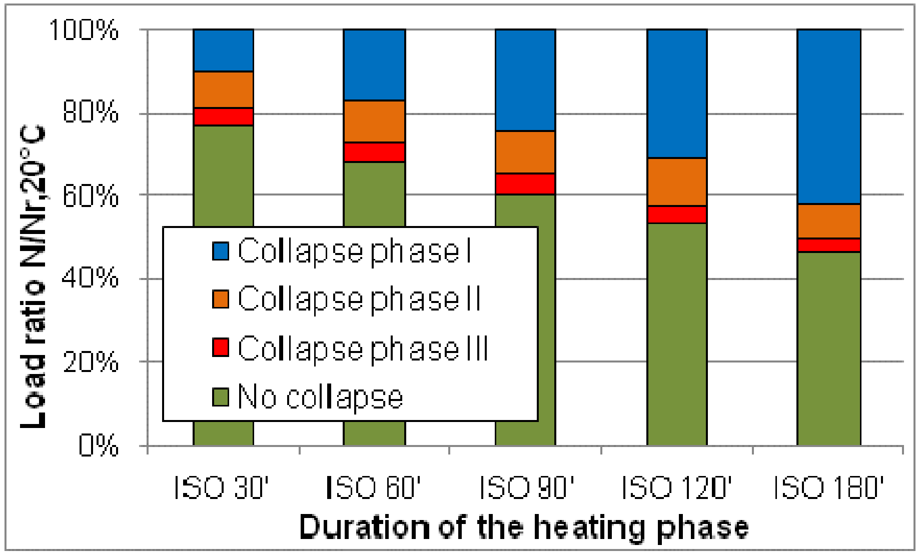


Column Analysis

- Possibility of occurrence increases for wider section
  - Wider section = lower slenderness
  - Moreover, effect of thermal inertia increases for wider section

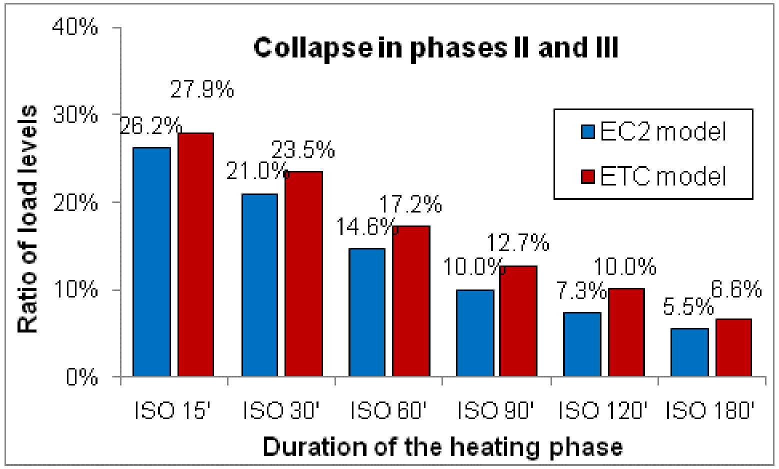
300x300 → 600x600

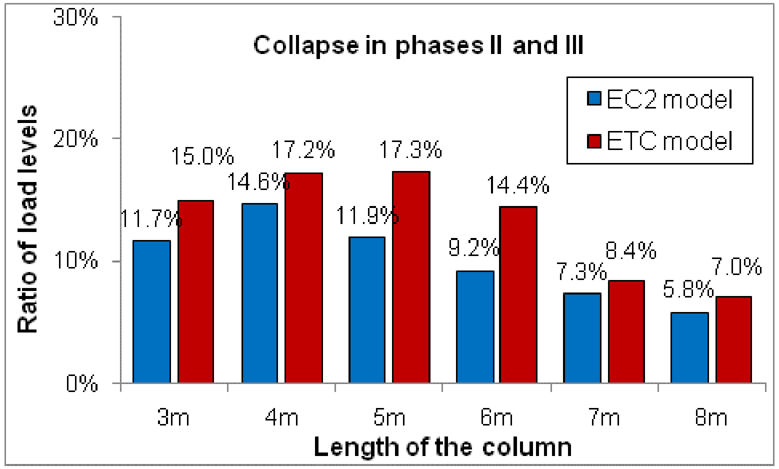




Column Analysis

- Effect of the concrete material model
  - x % is the percentage of load ratio that leads to delayed collapse (sum of orange and red zones)





  - Numerical analysis performed with ETC concrete model predict more occurrence of delayed collapse than with EC2 model

Conclusion

- Concrete constitutive law
  - Validated material models required (including for cooling)
  - Transient Creep Strain irrecoverable → explicit models
  - The ETC model has been developed and implemented in SAFIR
- Structural behavior of RC columns subjected to natural fire
  - Load bearing capacity continue decreasing during and after the cooling phase of the fire
  - Structural failure possible several hours after the end of the fire
  - Risk ↑ because consequence ↑↑↑

Conclusion

- Occurrence of delayed collapse increases for:
  - Short fires
  - Columns with low slenderness (short length – massive section)
  - Predicted more often with the ETC concrete model than with EC2

- Futures works
  - Columns with axial and/or rotational restraint (frames)
  - Experimental basis

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Thank you for your kind attention

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