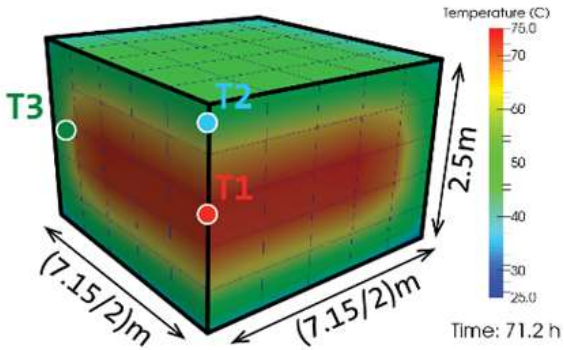
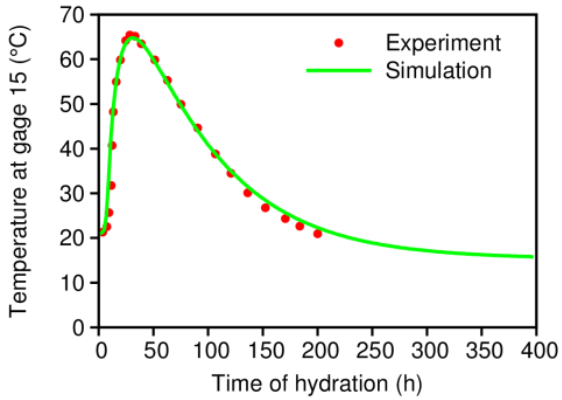
Modelování tvrdnutí betonových konstrukcí – spolupráce s firmou LafagreHolcim / Modelling of hardening concrete structures - collaboration with LafargeHolcim company





Česko-slovenské fórum VVVV 2016 - Věda, Výzkum, Vzdělávání a Výroba v Silikátových oborech, 10. 5. 2016, Praha

Vít Šmilauer, Karolina Hájková, **Petr Havlásek**, Luis Baquerizo

Czech Technical University in Prague
Faculty of Civil Engineering

LafargeHolcim R&D
St Quentin Fallavier, France

Outline

- Czech Technical University in Prague
- Department of Mechanics, research activities
- Collaboration with industry - Nanocem
- Multiscale modeling of hardening concrete
  - Temperature
  - Mechanics
- Conclusions

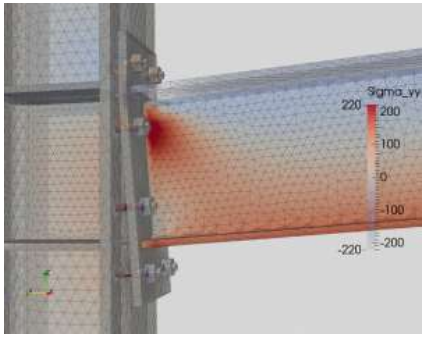
Czech Technical University in Prague

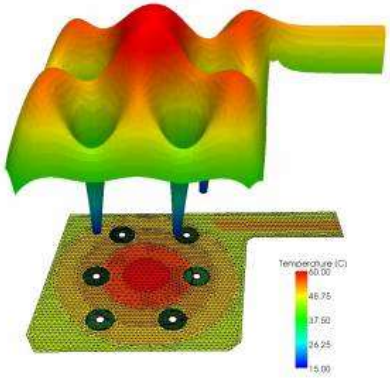
- The oldest non-military technical university in Europe, founded 1707
- Notable alumni: Ch. Doppler, J. Gerstner, J. Hlávka, F. Křižík, J. Božek, V. Prelog, E. Votoček, E. Jiřičná, …
- 8 faculties, 150 study programmes
- 24 000+ students, 3000 international
- 1900 academic staff, 1500 non-academic staff
- QS World University Rankings 2015 451-460 (Civil & Structural 51-100)

Department of Mechanics at Faculty of Civil Engineering

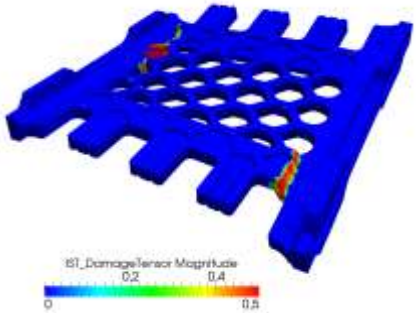
- 38 academic staff, 41 Ph.D. students
- Research projects FP7, GAČR, TAČR, NSF, MŠMT
- Contracts with 30+ companies (Knauf, Hilti, LafargeHolcim, ...)
- Member of COST, RILEM, Nanocem

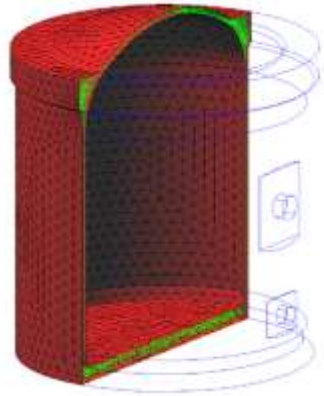
Software development
OOFEM, SIFEL, T3D



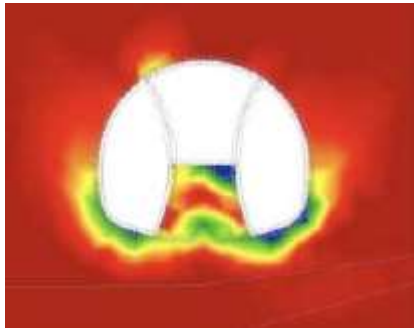


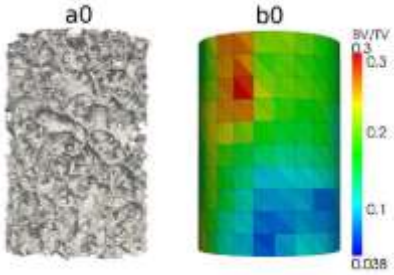
Material models
Plasticity, fracture



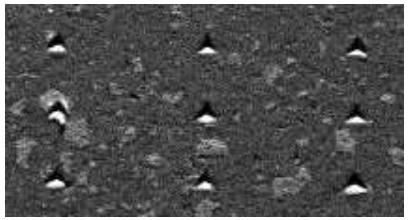


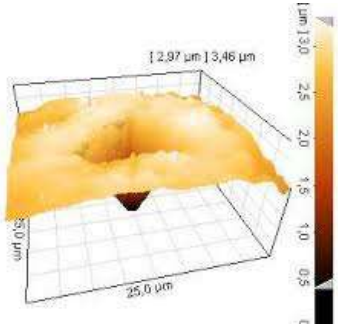
Geo/bio mechanics

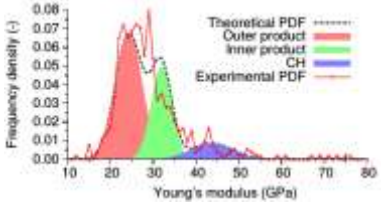




Nanoindentation







Nanocem Consortium

- Fundamental research of cement and concrete
  - Founded 2004, coordinated by prof. K. Scrivener, EPFL
  - 23 academic partners
  - 10 industrial partners

HEIDELBERGCEMENT
Italcementi Group
A world class local business
LafargeHolcim
TITAN
Sika
BASF
The Chemical Company
SCG CEMENT
vdz.
aalborgportland

- CTU involved in industrially funded project “Micromechanical analysis of blended cement-based composites” - effect of clinker substitution


Cement and Concrete Research 83 (2016) 188–202

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

ELSEVIER

Micromechanical multiscale fracture model for compressive strength of blended cement pastes

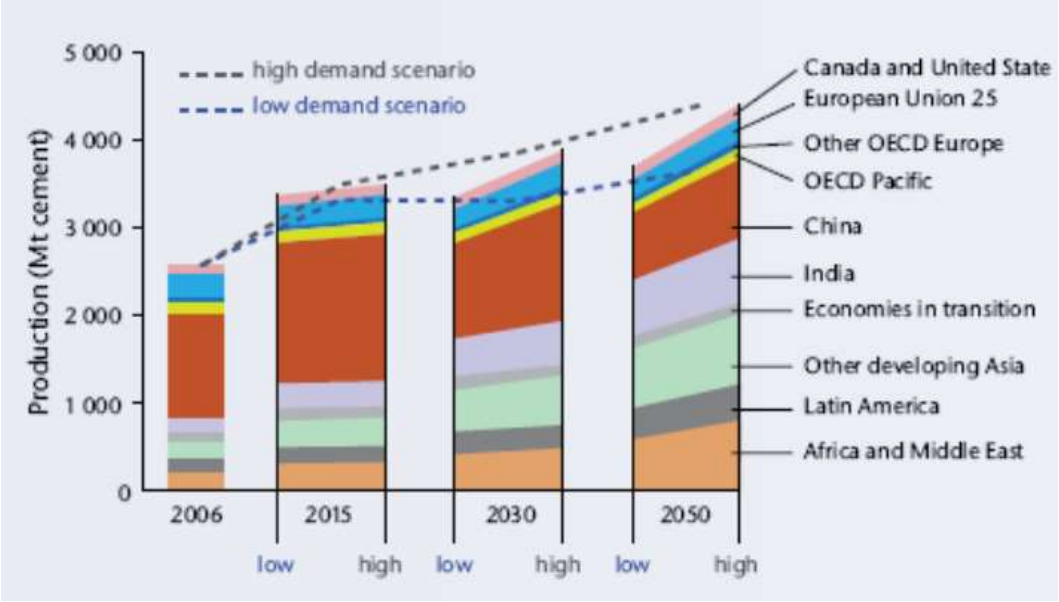
Michal Hlobil [a,b,*], Vít Šmilauer [a], Gilles Chanvillard [c,1]

[a] Department of Mechanics, Faculty of Civil Engineering, CTU in Prague, Thákurova 7, 166 29 Prague 6, Czech Republic
[b] Institute for Mechanics of Materials and Structures (IMWS), Vienna University of Technology (TU Wien), Karlsplatz 13/202, A-1040 Wien, Austria
[c] Lafarge Centre de Recherche, 95 Rue du Montmurier, 38290 Saint-Quentin Fallavier, France

- Strong interest of industry in mechanical modeling, especially early age

A few facts about concrete

- The most man produced material in the world (1.5 m^3/capita/year)
- 70% of the world population lives in concrete structures
- Concrete in a standard family house costs less than € 7000 (0.04 €/kg)
- Every € 1 spent on construction output generates a total of € 3 in total economic activity (GDP increase)
- The value of concrete production in Europe is € 74 billion
- The concrete industry in UK uses over 18 times more waste, by-products and secondary materials than it sends to landfill



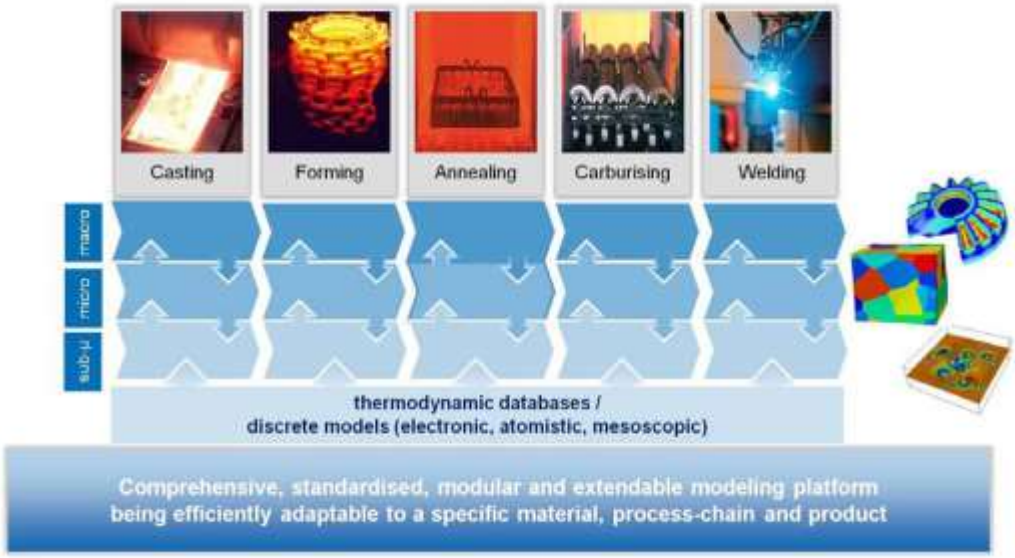
Cement Technology Roadmap 2009, World Business Council for Sustainable Development (WBCSD): An Industrial Perspective on the Future

W. (WBCSD): An Industrial Perspective on the Future

International Energy Agency (IEA), December 2009.

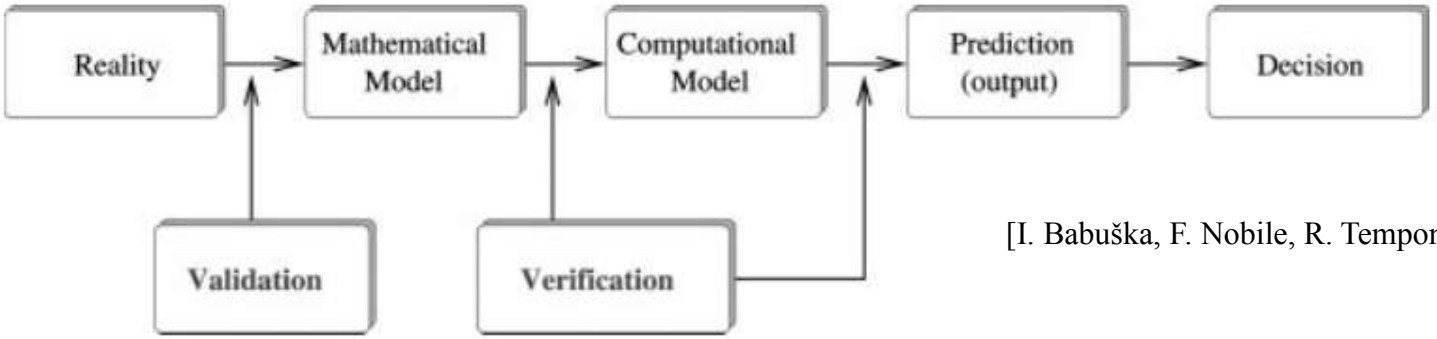
Integrated Computational Materials Engineering

- Design products, the materials that comprise them, and their associated materials processing methods by linking computational models at multiple length scales



[G. Schmitz, U. Prahl: ICMEg – the Integrated Co

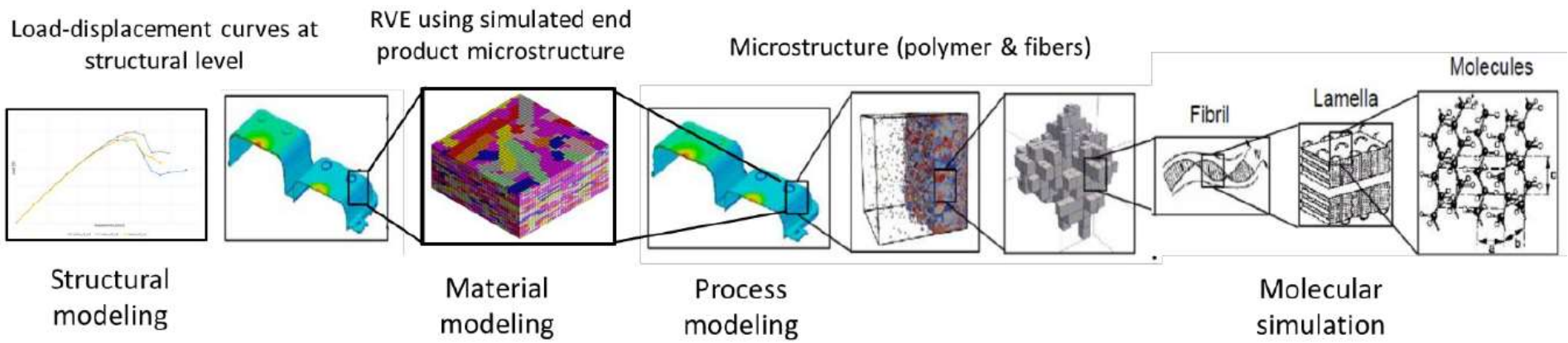
- Return of investment between 3:1 and 9:1 (Goldbeck consulting data)
- Each scale uses computational science



[I. Babuška, F. Nobile, R. Tempone: Reliability of Computational Science,

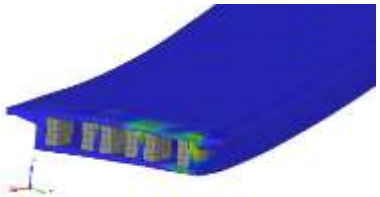
Sandbox scenarios - modeling of materials and performance

- Discontinuous fiber materials (car + aircraft industry)



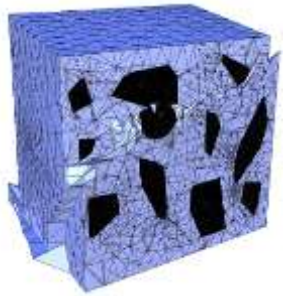
[Production of parts made of discontinuous fiber composites materials, 2nd International Workshop on S

- Structural concrete



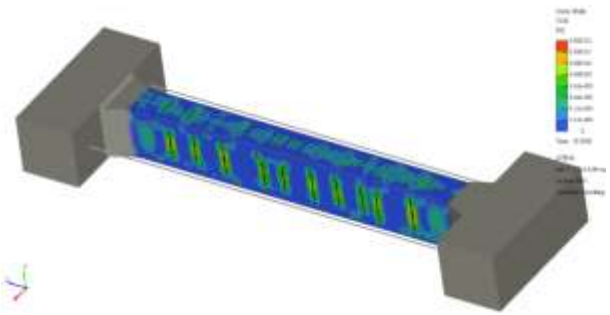
Structural modeling
(mature concrete)

Structural design



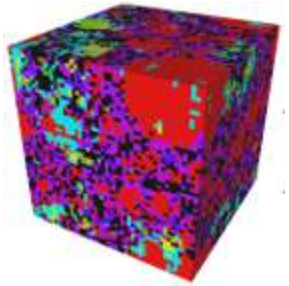
Material modeling
(mature concrete)

Mix design



Process modeling
(hardening concrete)

Initial and boundary conditions
What happens on construction site



Cement hydration
(hardening paste)

Binder design

Structural properties of concrete

INPUT

Composition
c, w/c, a/c, cement type, admixtures, additives, aggregate type

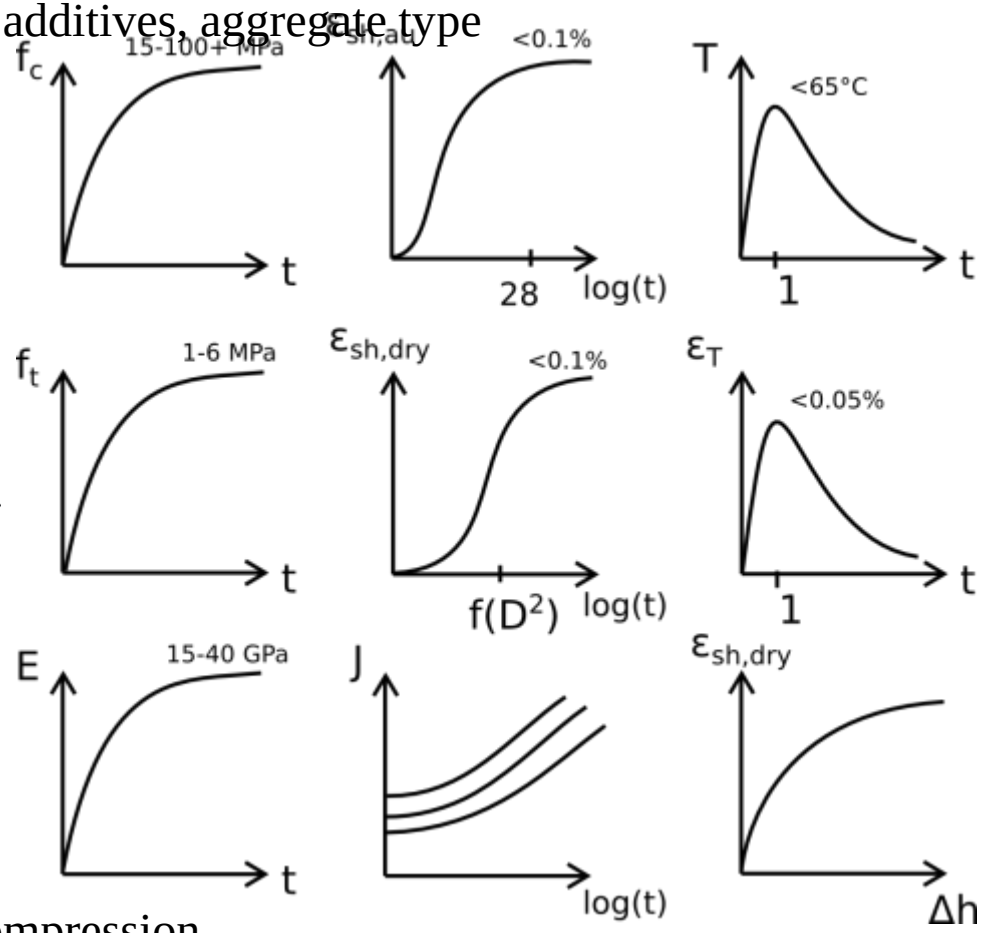
Curing
type, duration

Structural member
effective thickness, shape

Environment
temperature, humidity

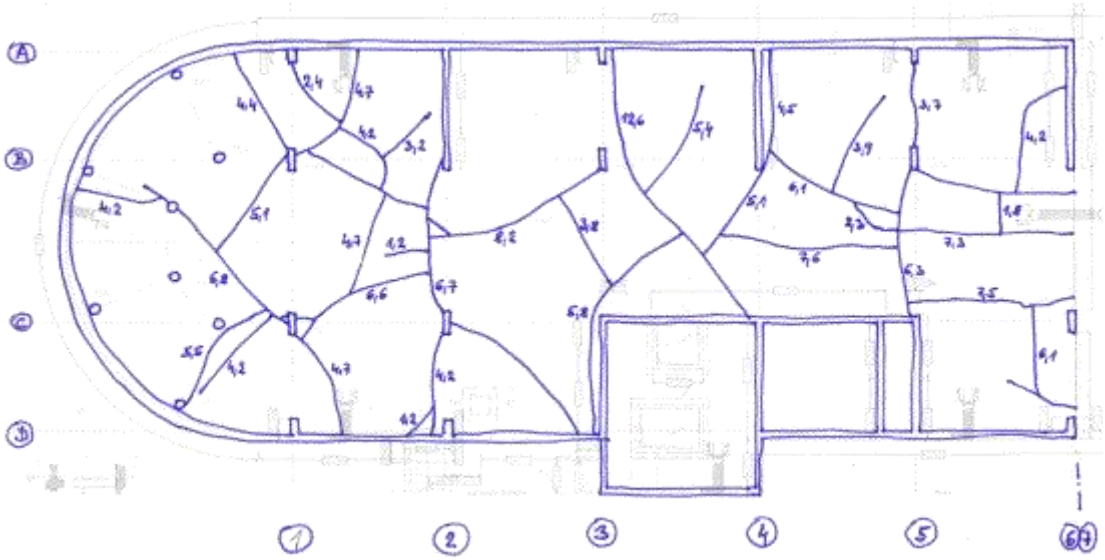
Loading
age at loading, load level, tension-compression

MATERIAL BEHAVIOR



?

Typical damage in concrete structures



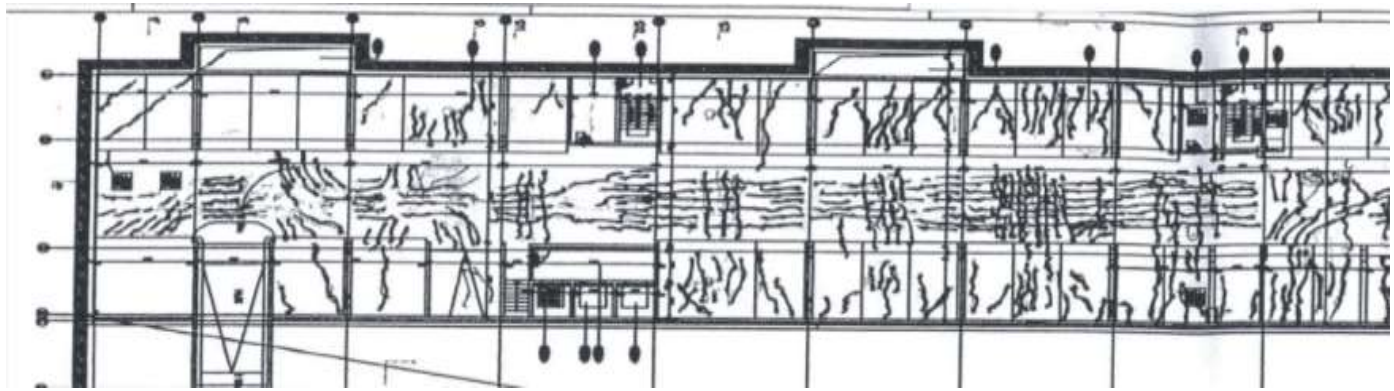
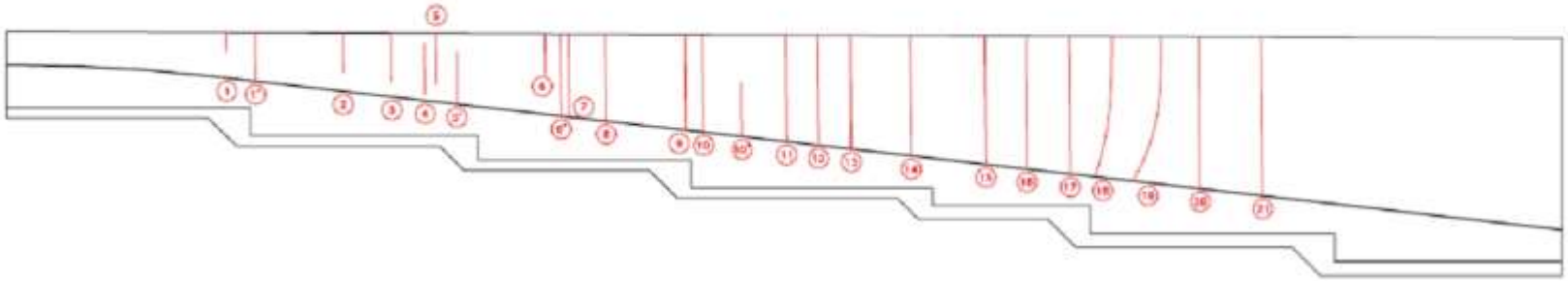
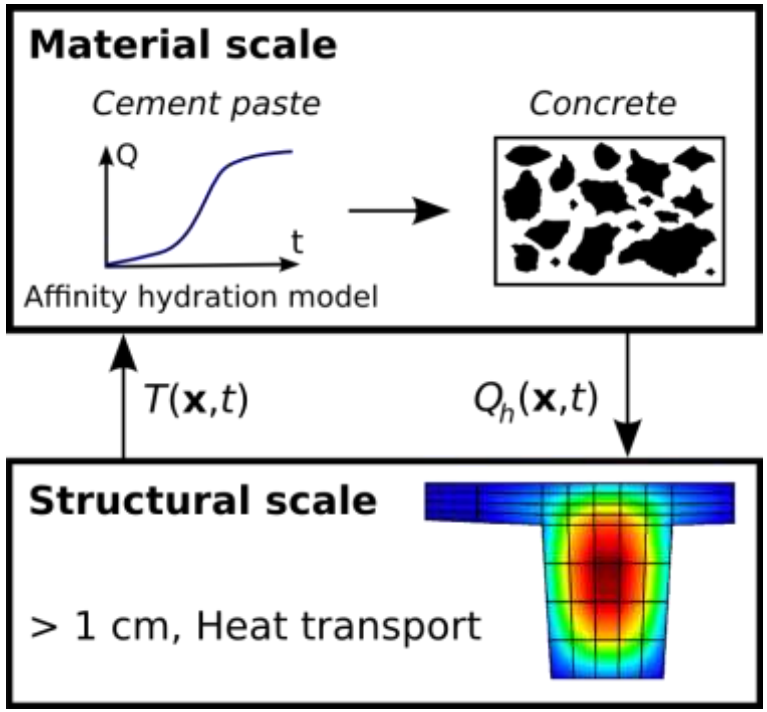


SCHÉMA TRHLIN NA KONSTRUKCI OPĚRNÉ STĚNY C1



Multiscale modeling of hydrating concrete

- Cement paste level is coupled with structural level
  - Evolving temperature field



$$\tilde{A}_{25}(DoH) = B_1\left(\frac{B_2}{DoH_\infty} + DoH\right)(DoH_\infty - DoH)\exp\left(-\eta\right.$$

$$\frac{dDoH}{dt} = \tilde{A}_{25}(DoH)\exp\left[\frac{E_a}{R}\left(\frac{1}{273.15+25} - \frac{1}{T}\right)\right]$$

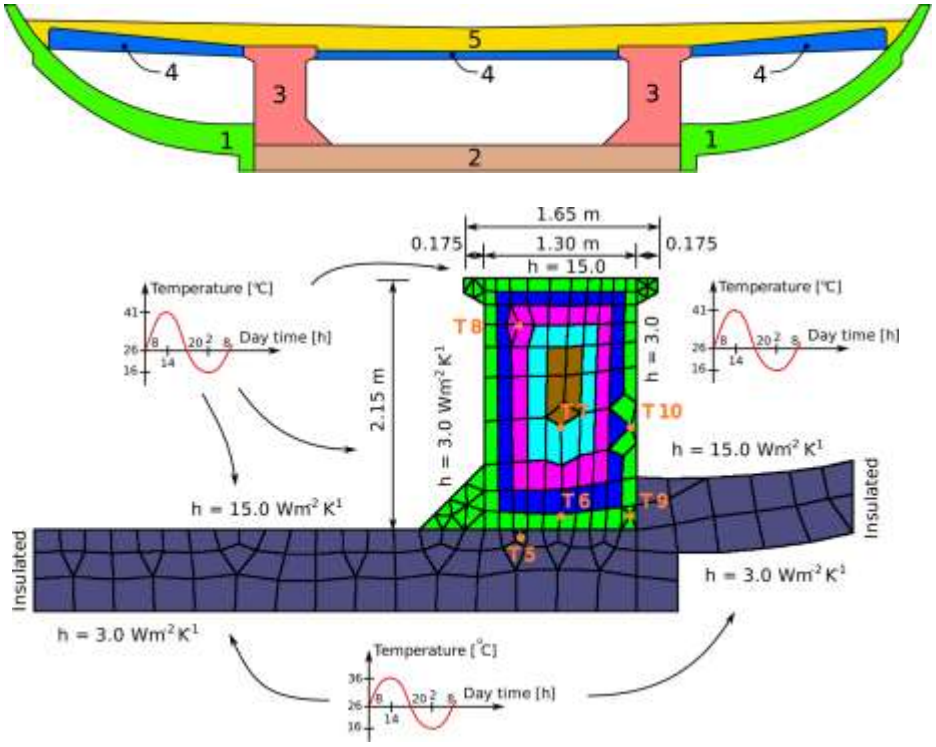
$$\lambda\frac{d^2T(\mathbf{x},t)}{dx^2} + \bar{Q}(\mathbf{x},T,t) = \rho c_m\frac{\partial T(\mathbf{x},t)}{\partial t}$$

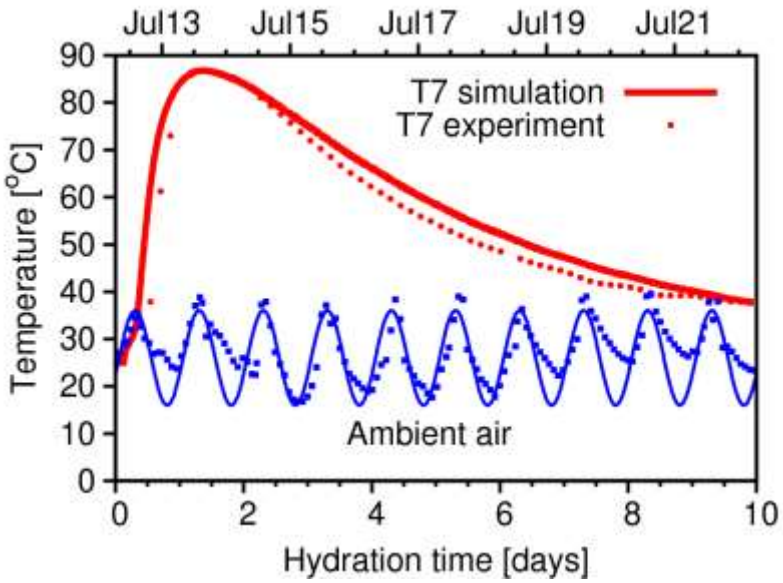
- Temperature coupled with mechanical model on structural scale
  - Creep + autogenous shrinkage + thermal strains + damage
  - Evolving stresses, strains, cracks

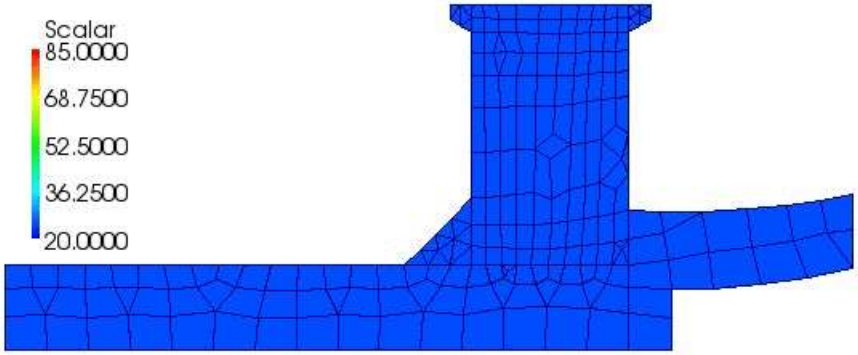
$$\Delta\sigma_{eff} = \bar{E}\mathbf{D_V}\left(\Delta\varepsilon - \Delta\varepsilon'' - \Delta\varepsilon_{sh,aut} - \Delta\varepsilon_{\mathbf{T}}\right)$$
$$\sigma = (1-\omega)\sigma_{eff}$$

Preliminary validation – Nové spojení, Prague

- 4-track railway bridge (12 spans, total length 443 m)
- Construction 2004-2008, bridge ~10 mil. €, *a posteriori* analysis

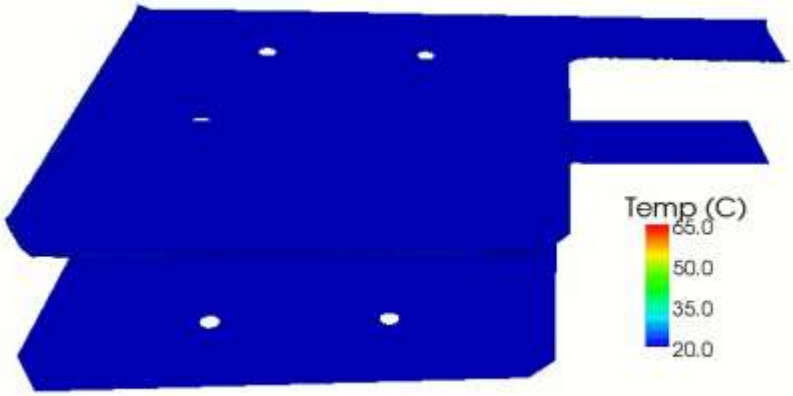


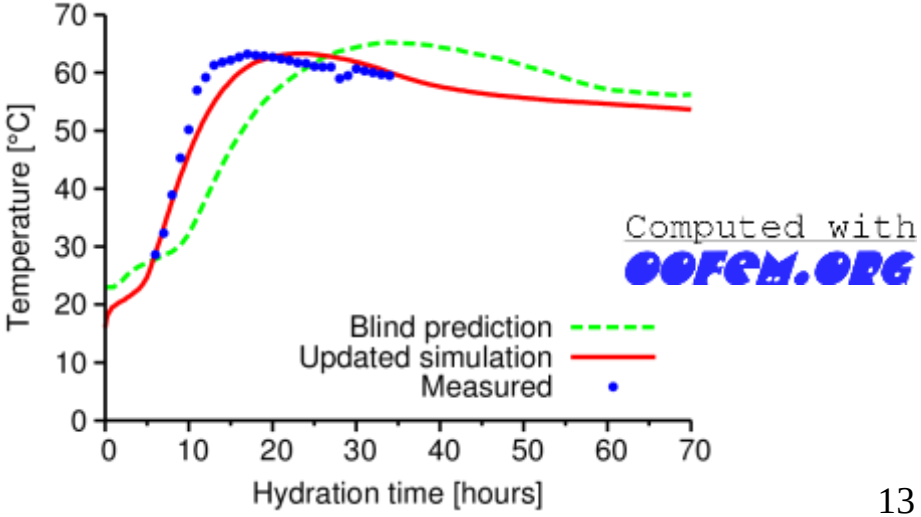




Design of concrete cooling – Bridge over Opárno valley

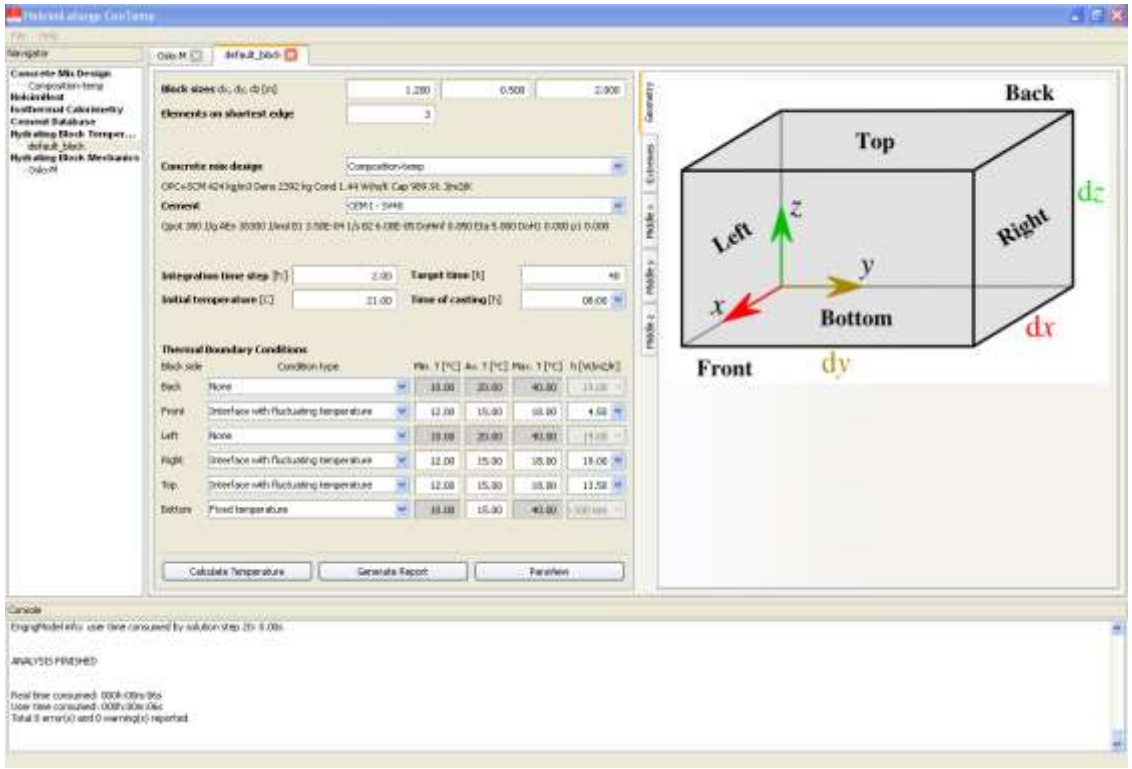
- Construction 2008-2010, arch span 135 m, budget ~20 mil. €
- Design of water cooling during summer casting





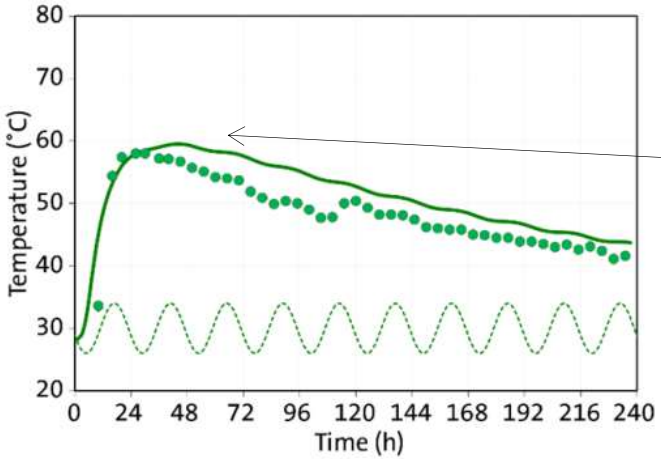
ConTemp – a thermomechanical simulator

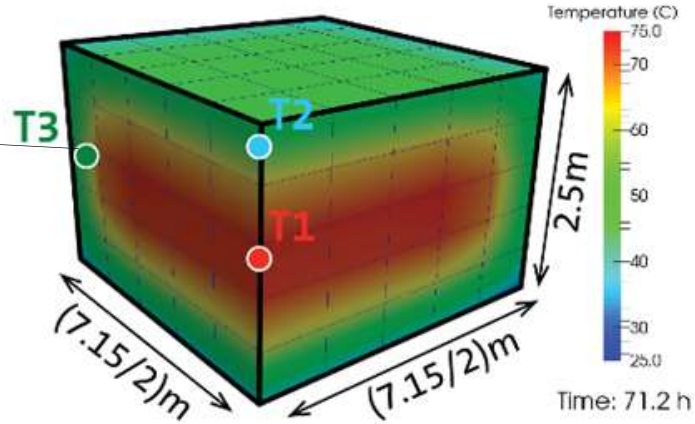
- Graphical user interface
- Simple tool for designers/consultants, massive block concrete
- Contract with LafargeHolcim, license holder
- CTU owns background technology
- Qt5 for GUI, OOFEM C++ for computation, ParaView for postprocessing
- Developed since 2013, ~2000 working hours, 4 developers
- Used during workshops in 20+ countries, 40+ licenses



Validation – Pile caps

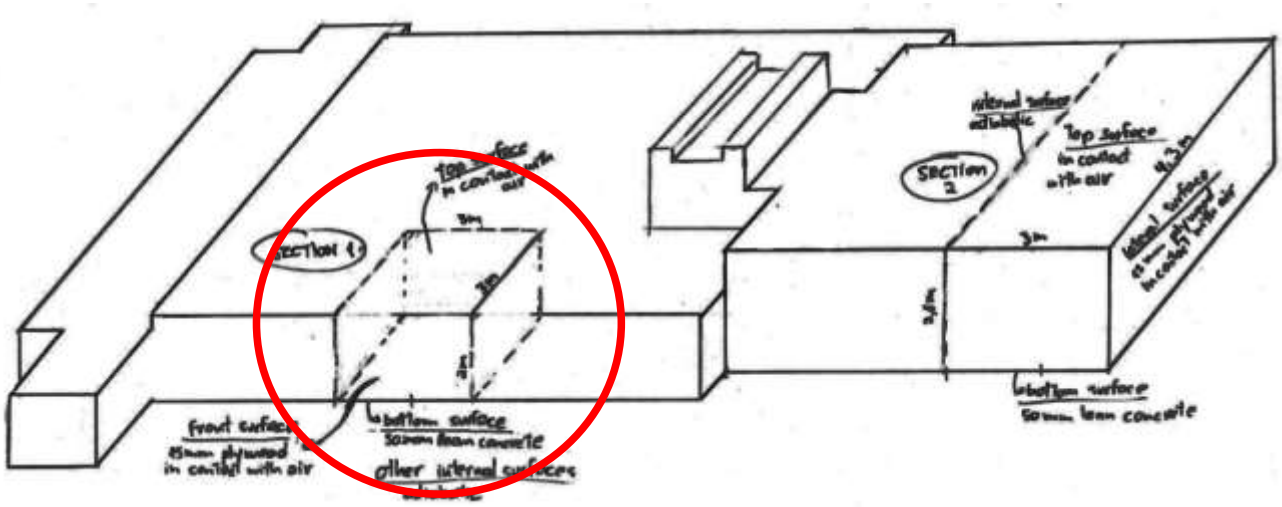
- Access Tower II, Colombo, Sri Lanka
- 28 floors, ~110 m
- Construction 2014-2016
- Pile caps 7.15 x 7.15 x 2.5 m

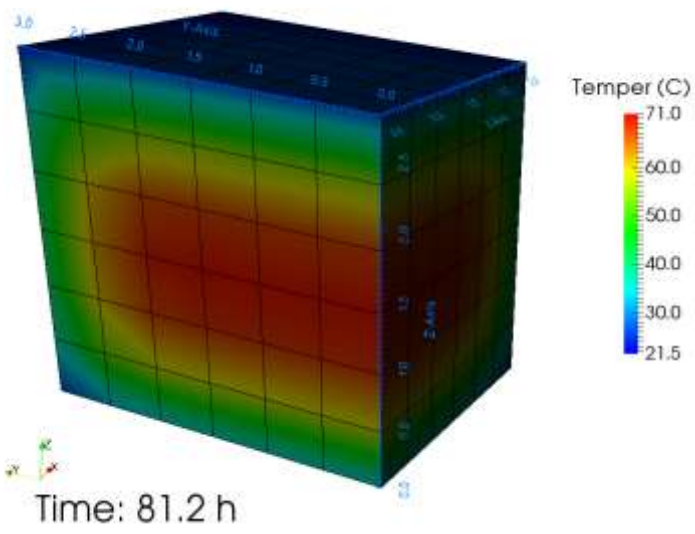


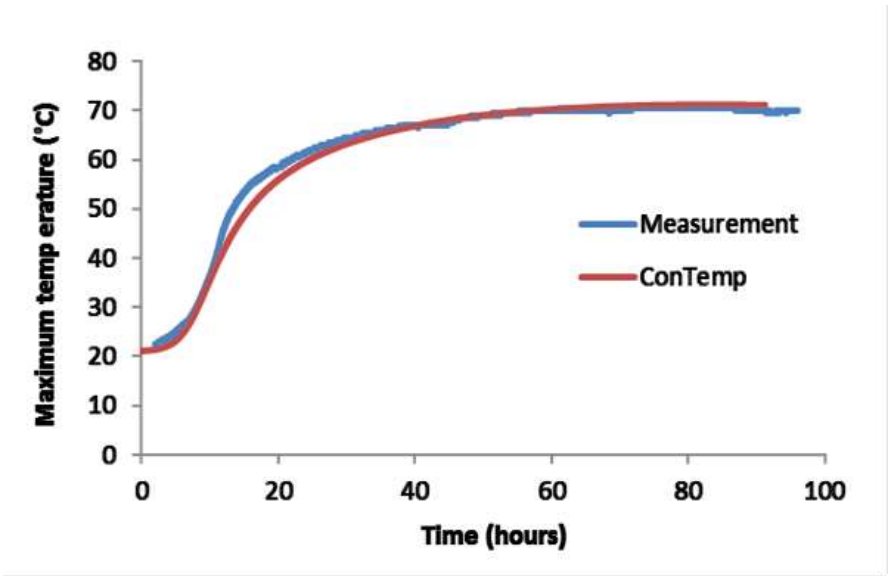


Validation – gas turbine foundation

- Massive concrete slab 20 x 6 x 2.0-2.8 m in Ecuador
- Original mix design 403 kg/m^3 ® 85.5^{o}C
- New mix design 350 kg/m^3 + ice ® 71°C

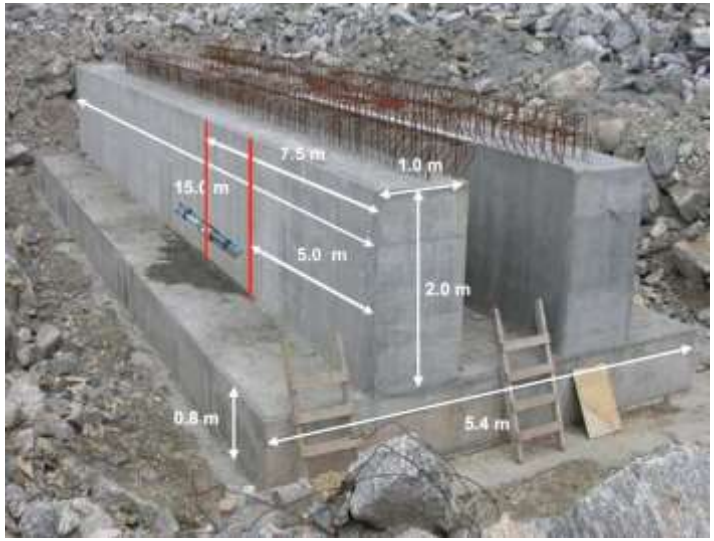


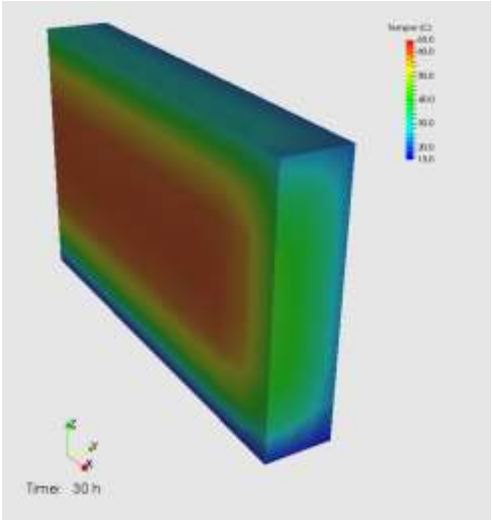


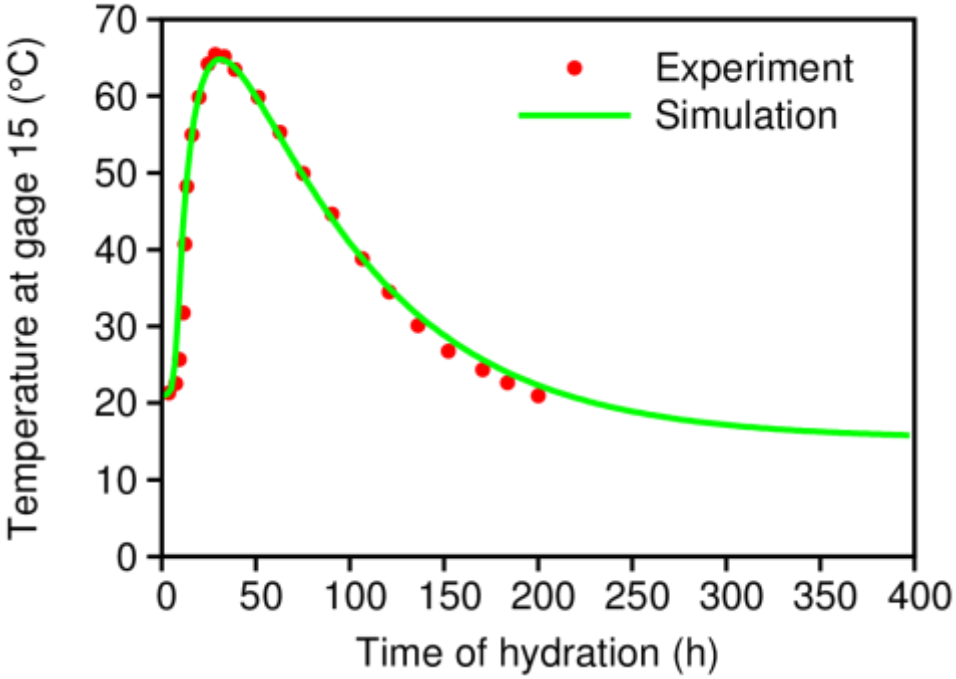


Validation – restrained wall

- Forerunner experiment for Bjørvika submerged tunnel project 2005-2012
- Restrained wall constructed in Oslo, Norway
- Reference concrete CEM I 52.5 404 kg/m^3 + 20 kg/m^3 silica fume

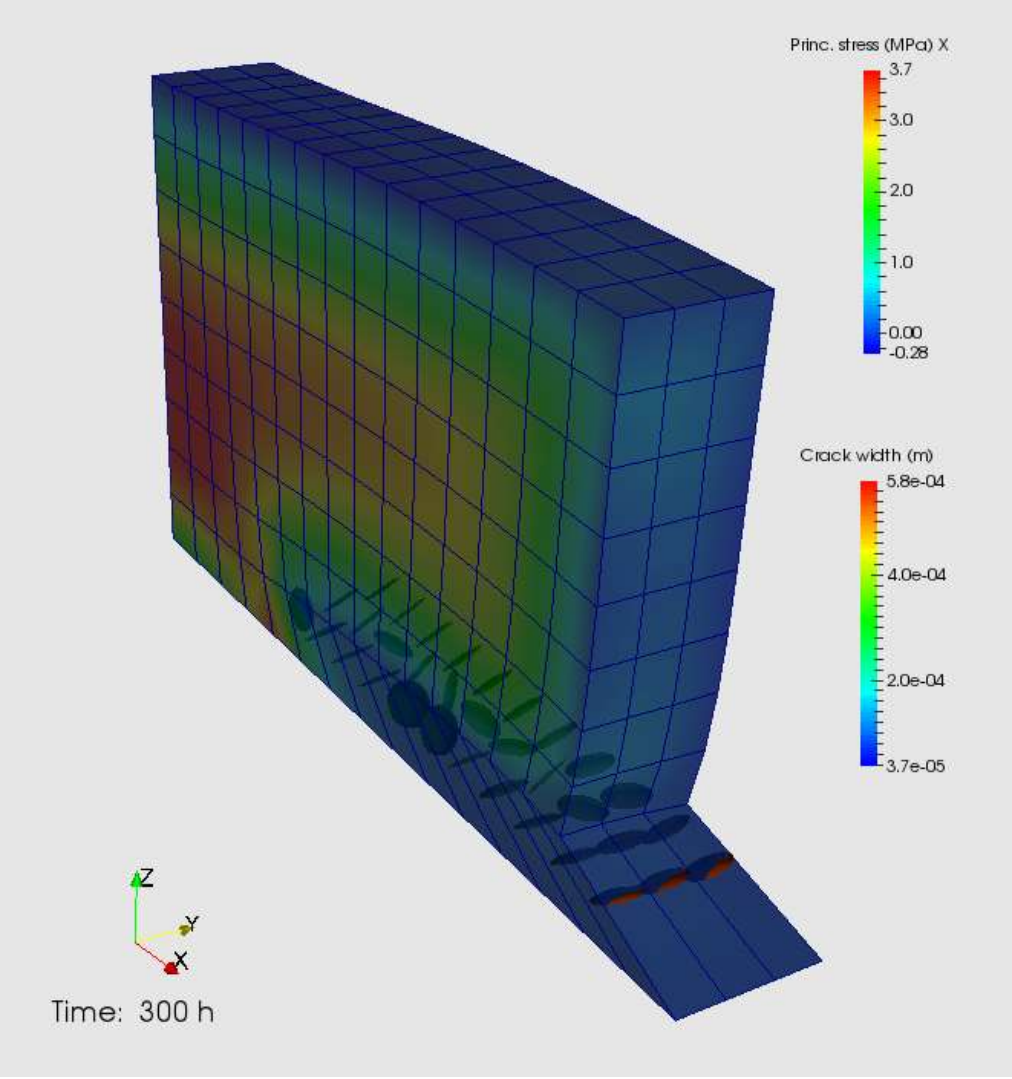


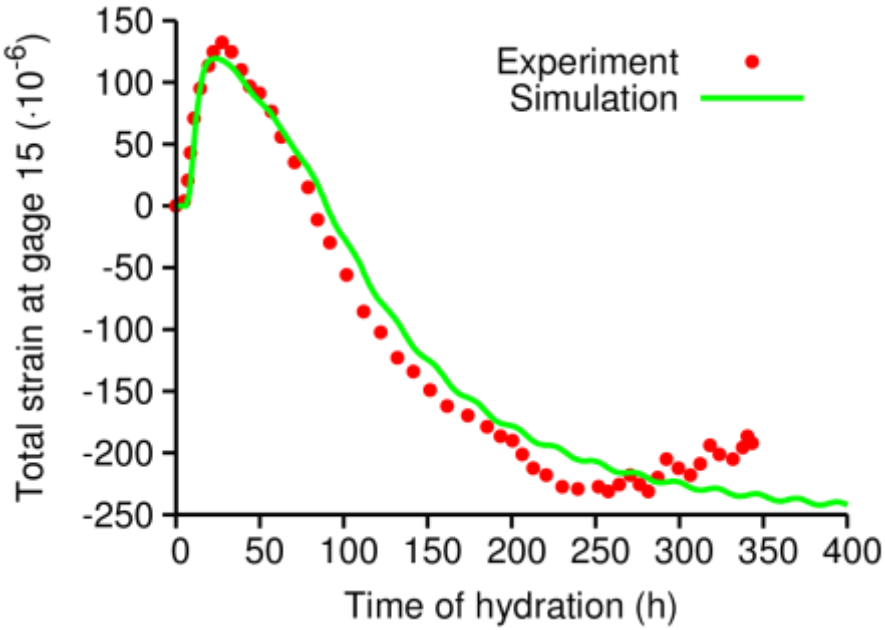




Validation – restrained wall

- Horizontal strain at gage 15 (1.2 m from bottom)
- Cracks up to 0.58 mm (simulation only)





Conclusions

- ConTemp lessons
  - Gap in concrete process modeling
  - Interdisciplinary approach needed
  - Definition of target group – academician, modeler, engineer
  - Industry prefers *preventing problem* than finding *optimal solution*
- The Bloomberg innovation index 2015
  - South Korea, Japan, Germany, Finland, Israel, USA, Sweden,...
  - Czech Republic – 19. R&D, 20. manufacturing, 43. high-tech
- Research and development
  - Parent/holding companies often abroad, willing to keep R&D there
  - Academia has unexploited knowledge for transfer to industry
  - Industry may largely benefit if common language found
- Open for further collaboration in mechanics of brittle materials