

Construction phasing of a dam spillway: thermo- mechanical simulation

M. Azenha

R.M. Lameiras

J.A. Barros

A. Costa

isise



Universidade do Minho



SCOPE / MOTIVATION

- ❑ Mass concrete -> construction phasing issues;
- ❑ Compromise between cracking risk and economic feasibility;
- ❑ Thermo-mechanical simulation tools to allow sustained decisions increasing the casting layer thickness and anticipating the removal of formworks.

OBJECTIVES / OUTLINE

- ❑ Case study: thick central wall of a dam spillway;
- ❑ Extensive material characterization and in-situ monitoring;
- ❑ Air-cooling as a possibility to assist larger casting thicknesses.

THERMAL MODEL

Field equation

$$k \nabla \cdot (\nabla T) + \dot{Q} = \rho c \dot{T}$$

Thermal conductivity

Volumetric specific heat

Boundary conditions

$$q = h (T_b - T_{env})$$

Boundary flux

Boundary coefficient

Heat generation

$$\dot{Q} = A f(\alpha) e^{-E_a/(RT)}$$

Heat generation rate

Constant

Normalized heat generation function

Apparent activation energy

- ❑ 3D Finite Element implementation (MATLAB / DIANA)
- ❑ Non-linear algorithm based on the Newton-Raphson method;

MECHANICAL MODEL

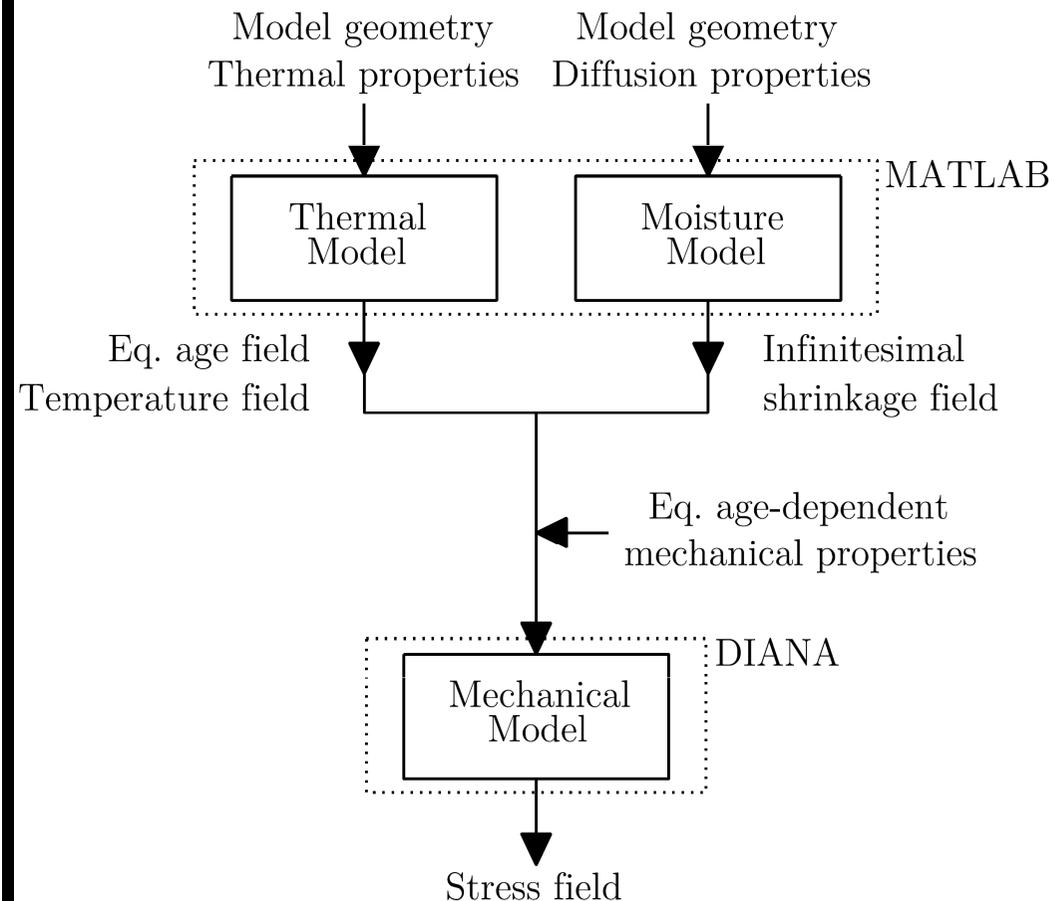
- Equivalent age concept for evolution of properties;

$$t_{eq} = \int_0^t e^{-\frac{E_a}{R} \left(\frac{1}{273.15+T(\tau)} - \frac{1}{273.15+T_{ref}} \right)} d\tau$$

- Creep according to the Double Power Law;

$$J(t, \tau) = \frac{1}{E_0(\tau)} + \frac{\phi_1}{E_0(\tau)} \tau^{-m} (t - \tau)^n$$

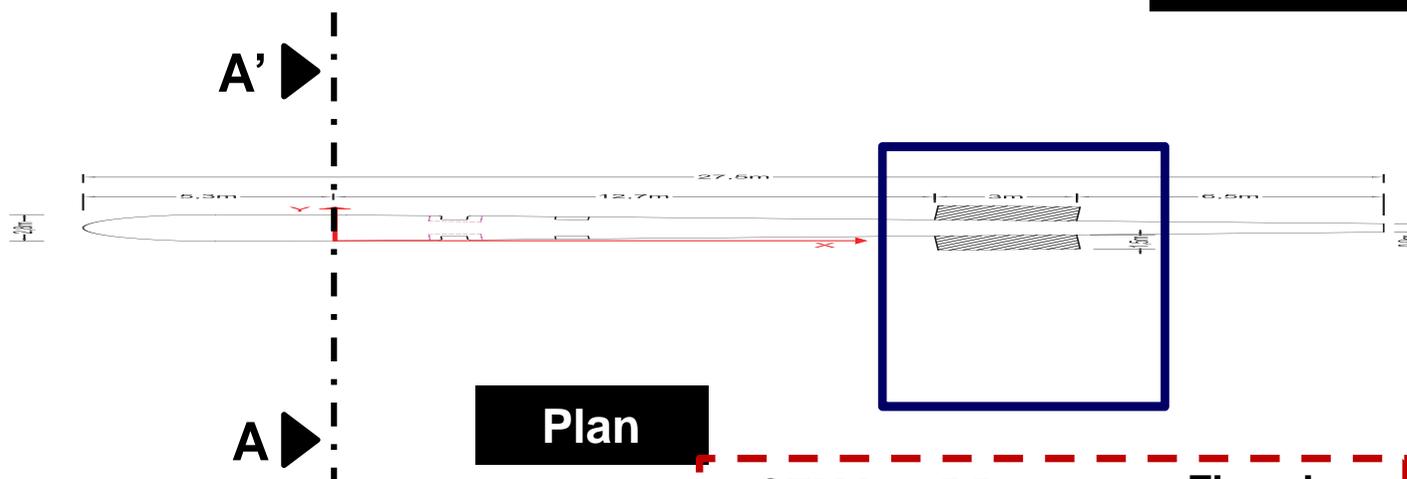
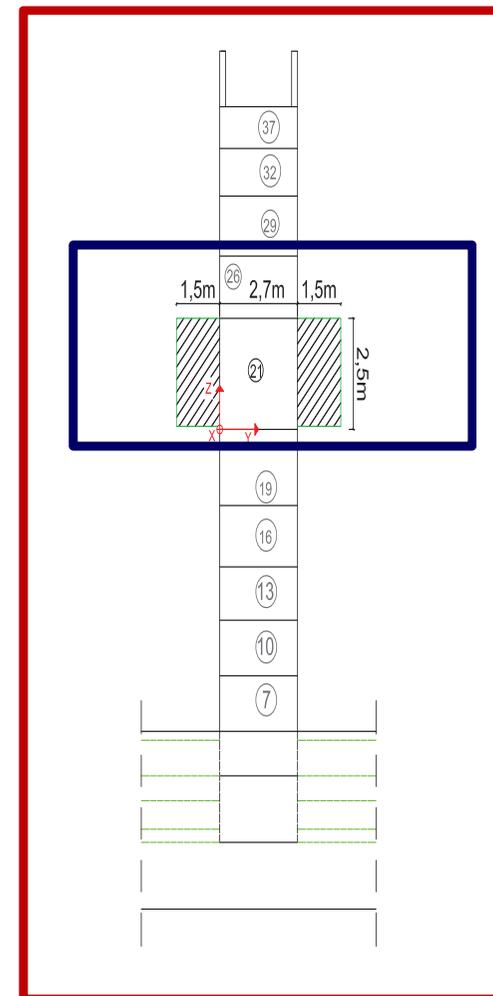
OVERAL FRAMEWORK



POST-COOLING OF CONCRETE TO REDUCE CRACKING RISK

- ❑ Usual strategies based on the circulation of water within pipes (steel, PVC or polyethylene) placed within concrete;
- ❑ Water cooling -> use of pumping equipment and pipes (not standard in concrete construction);
- ❑ Hedlund and Groth (1998) proposed the possibility of using vertically placed pre-stressing sheaths into which air is blown;
- ❑ Air-cooling has the interesting advantage of using pipes that construction is familiar with, as well as fans (used in tunnels).

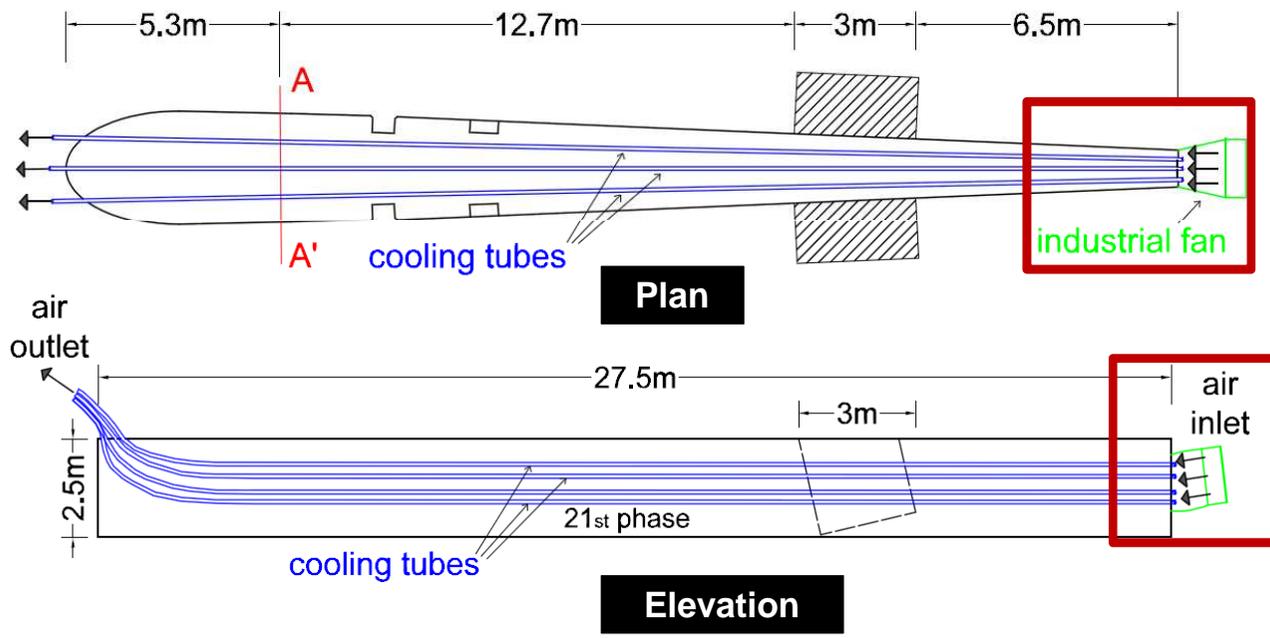
CENTRAL WALL OF THE SPILLWAY – GENERAL DESCRIPTION



CEM I 42.5 R
(224 kg/m³)

Fly ash:
(96 kg/m³)

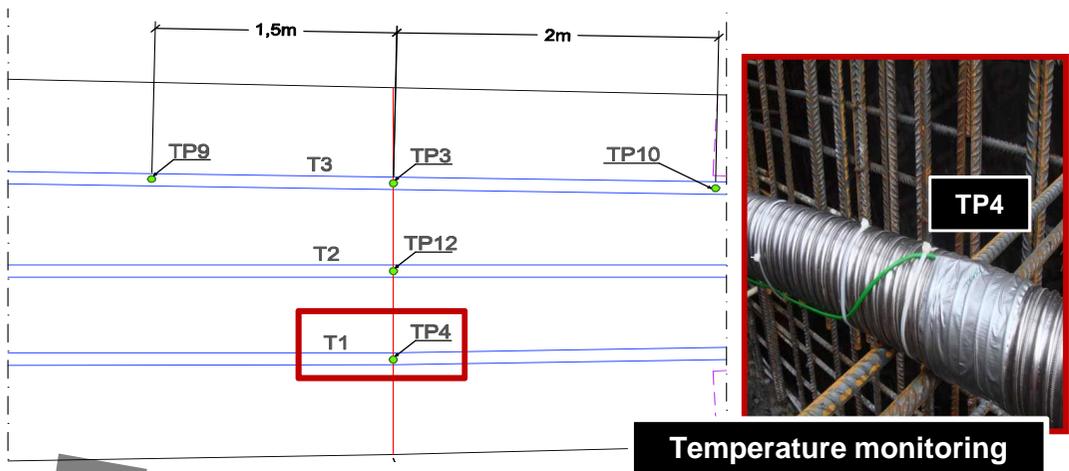
CENTRAL WALL OF THE SPILLWAY – COOLING SYSTEM



Cooling sheaths after placement



Fan

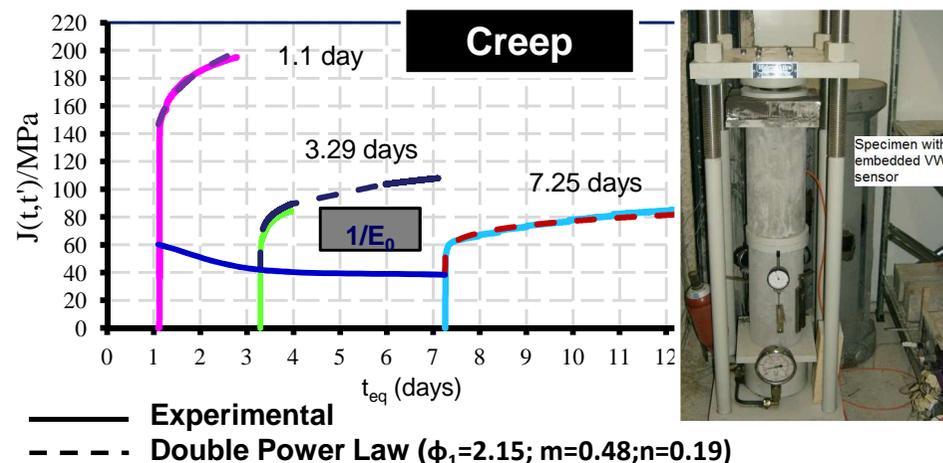
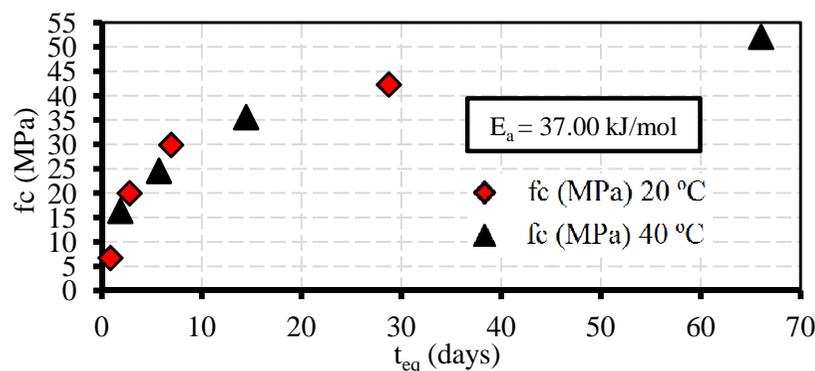
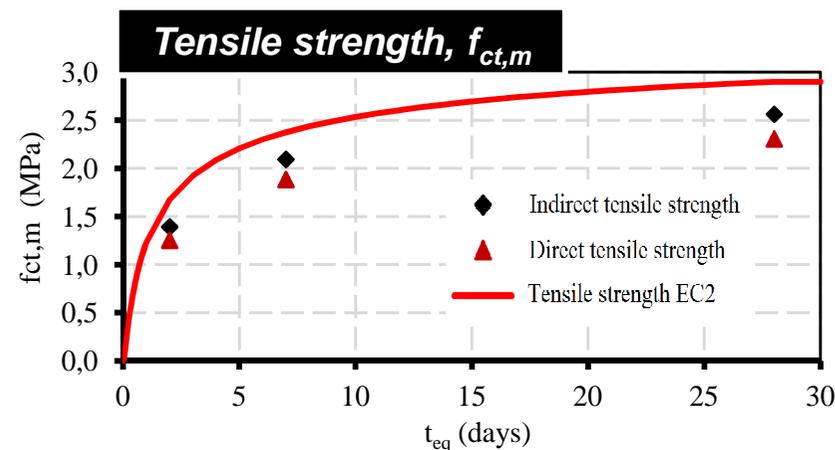
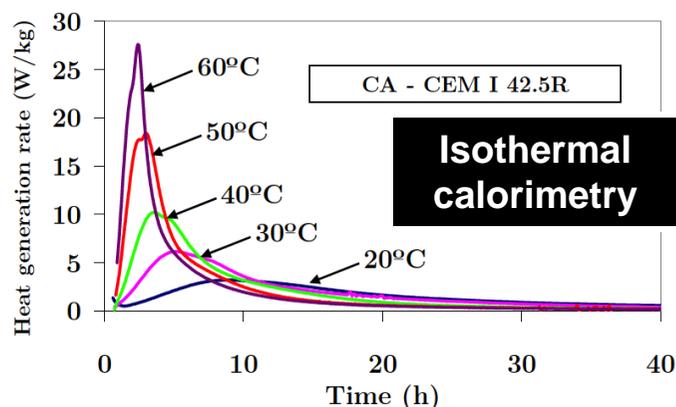


Temperature monitoring

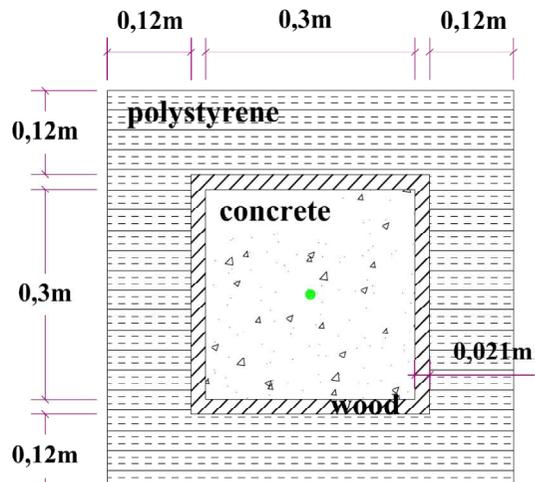


MODELLING PARAMETERS AND MATERIAL CHARACTERIZATION

□ $k=2.4 \text{ W/m}^2 \text{ K}$ and $\rho c=2.4 \times 10^6 \text{ J/m}^3 \text{ K}$ obtained through pondered average of mix constituents;



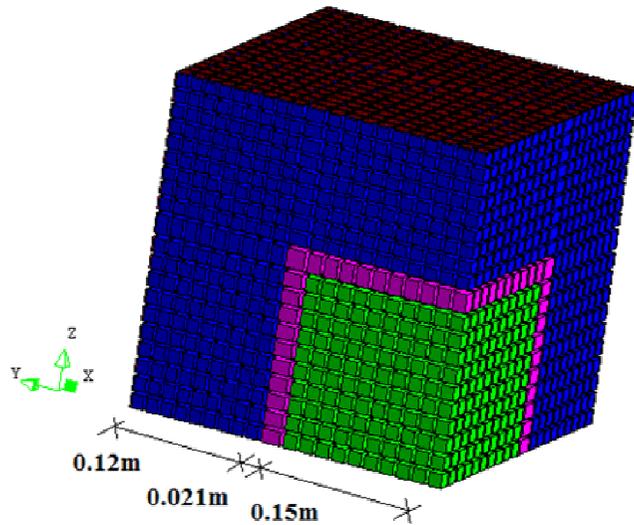
IN-SITU VERIFICATION OF HEAT GENERATION



Scheme of calorimeter

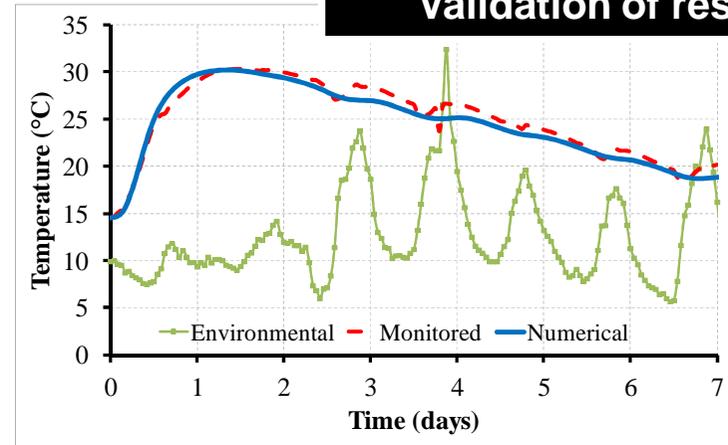


Photo of calorimeter

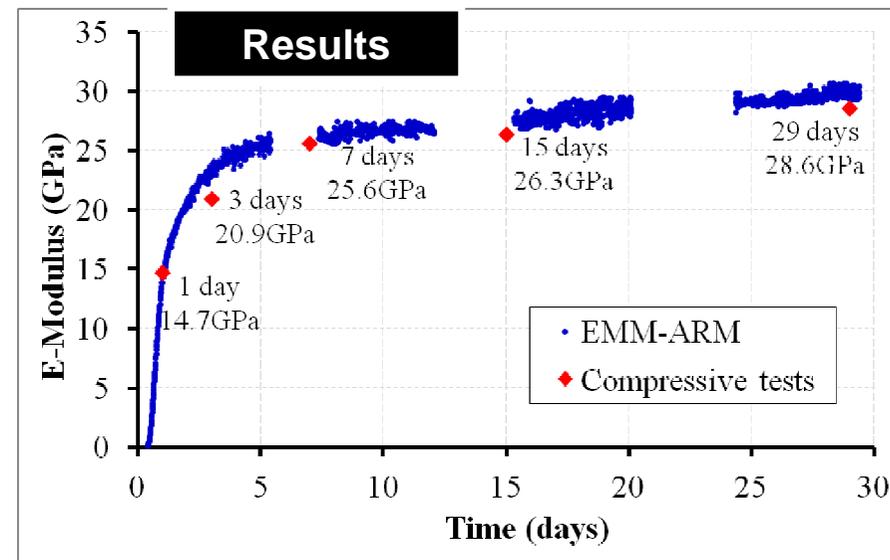
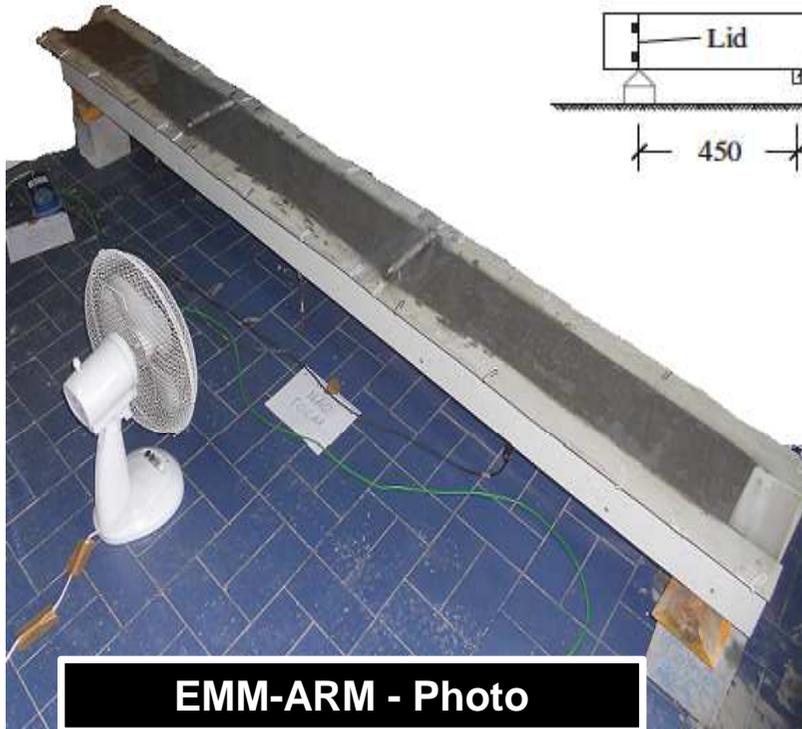
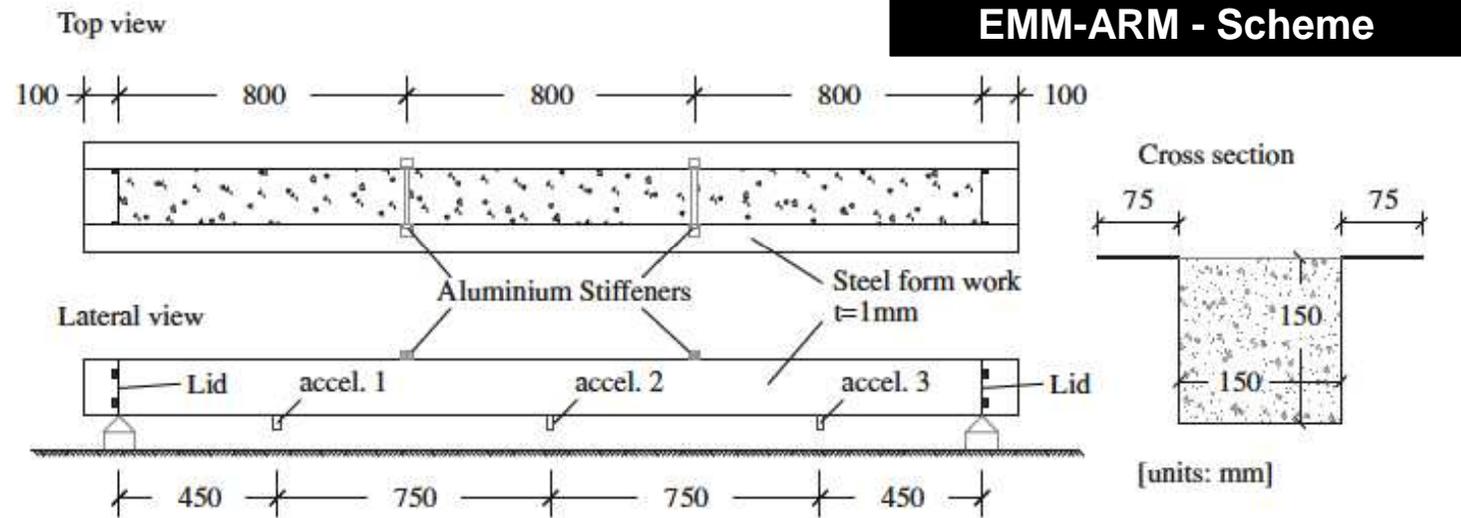


FE MESH

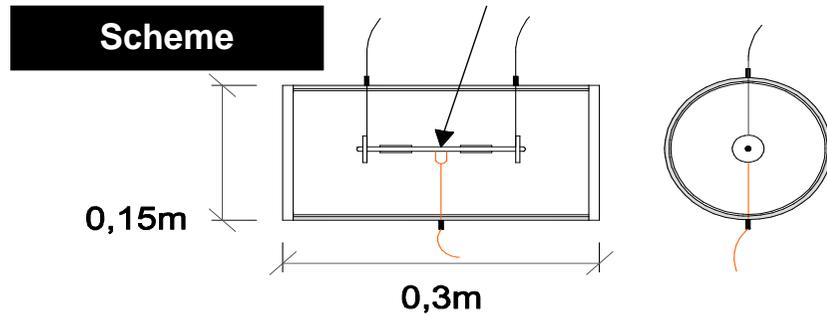
Validation of results



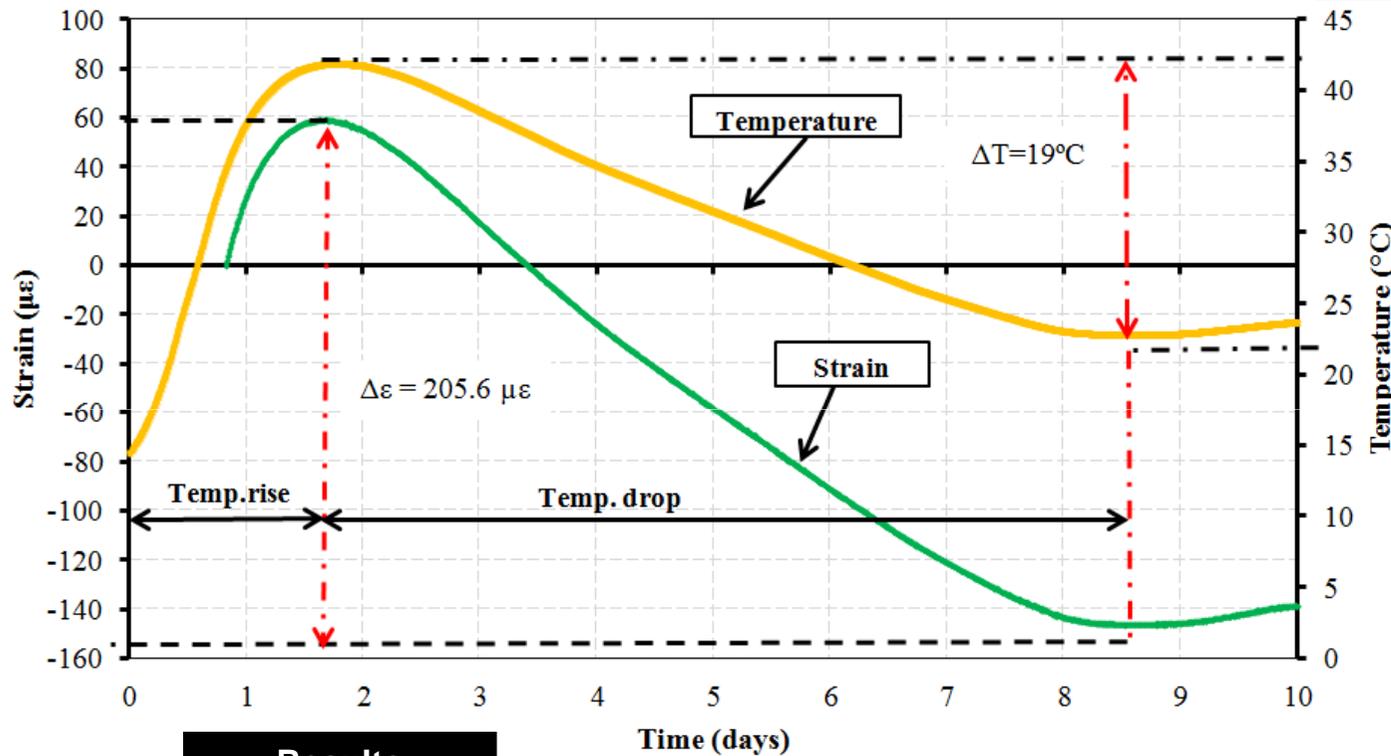
STIFFNESS MONITORING THROUGH EMM-ARM METHODOLOGY



IN-SITU ASSESSMENT OF THERMAL DILATION COEFFICIENT



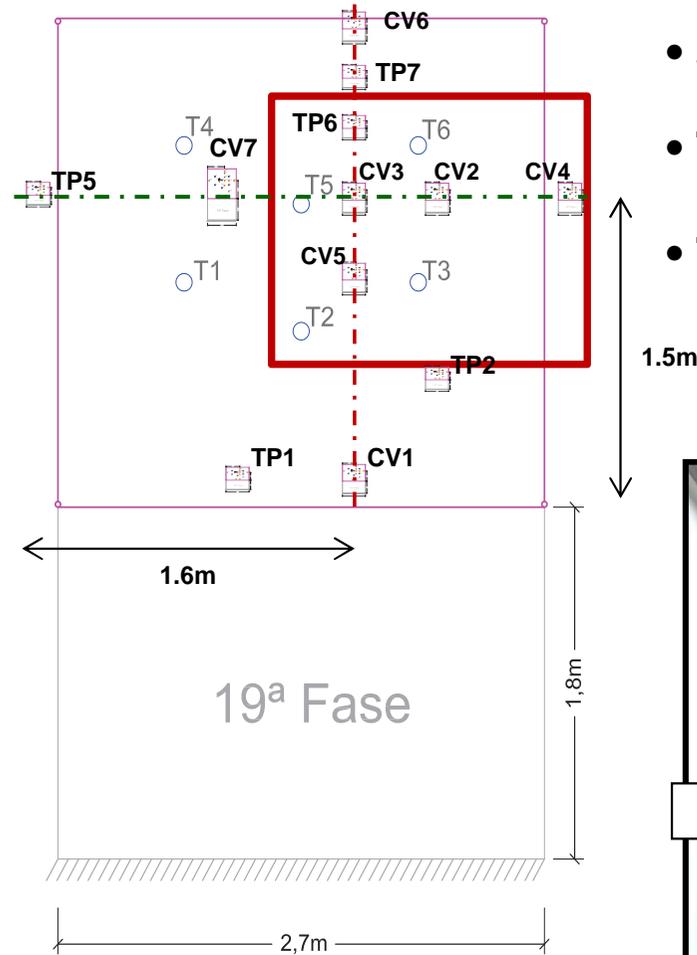
Photo



Results

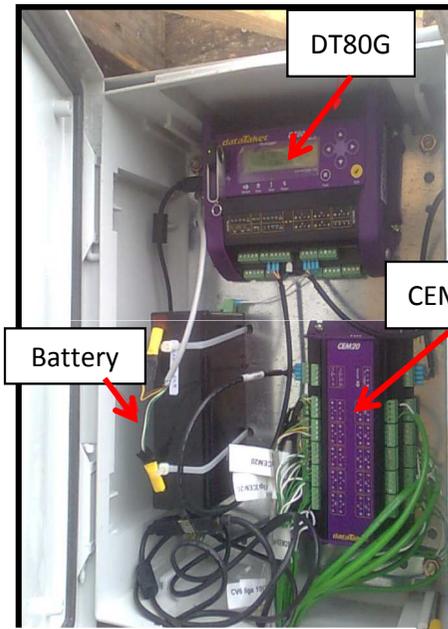
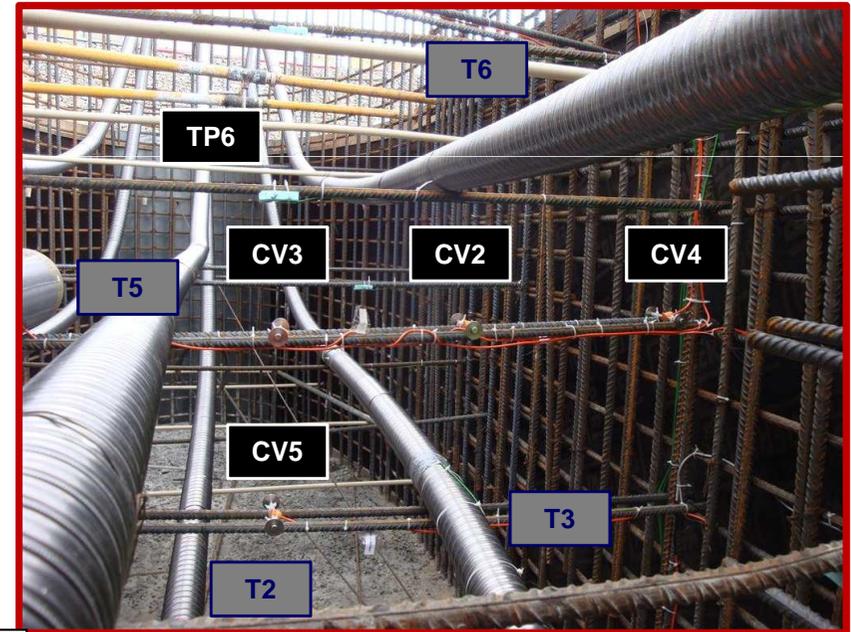
Necessary compensation for autogenous shrinkage effects!

MONITORING OF TEMPERATURES AND STRAINS

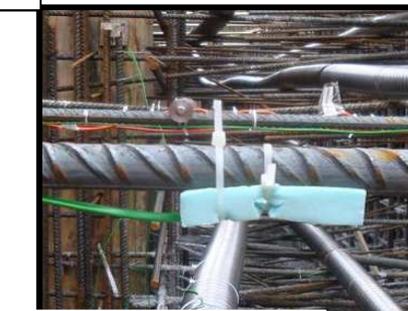


Monitored section

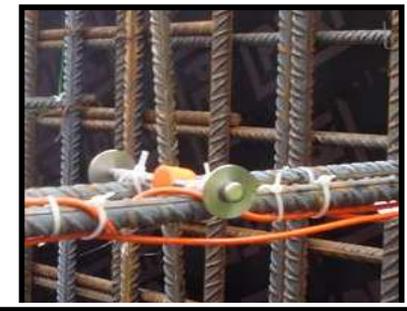
- 5 thermocoules “pipes”
- 7 V.Wire Str. gages
- 7 thermocouples concrete



Data logger

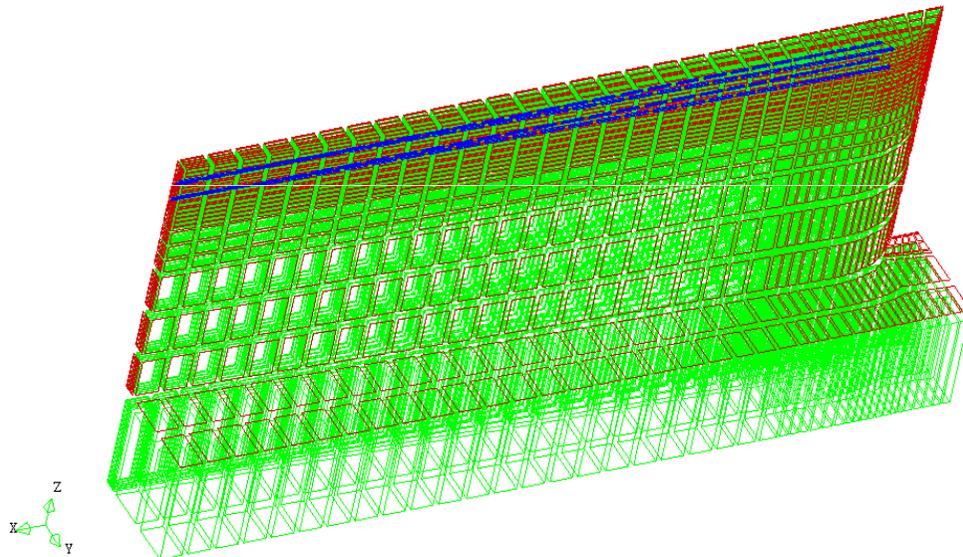


Thermocouple K

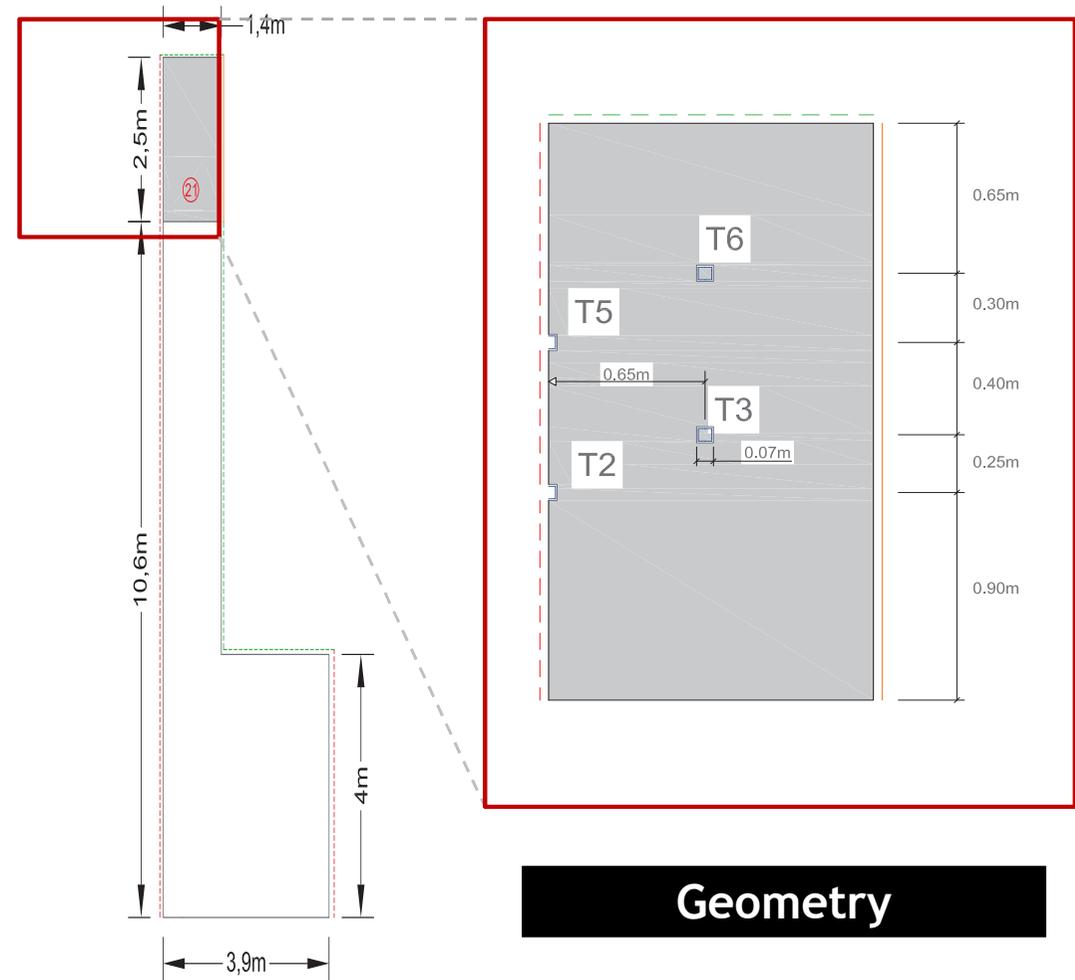


V. Wire Strain Gage

FINITE ELEMENT SIMULATION



FE mesh

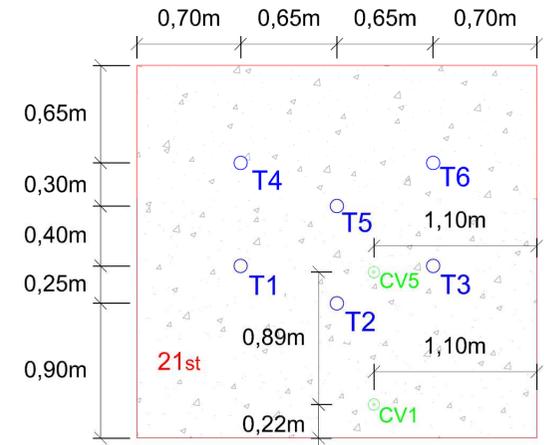
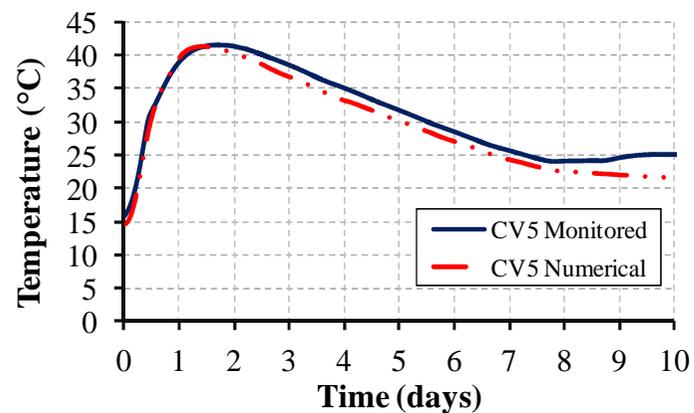
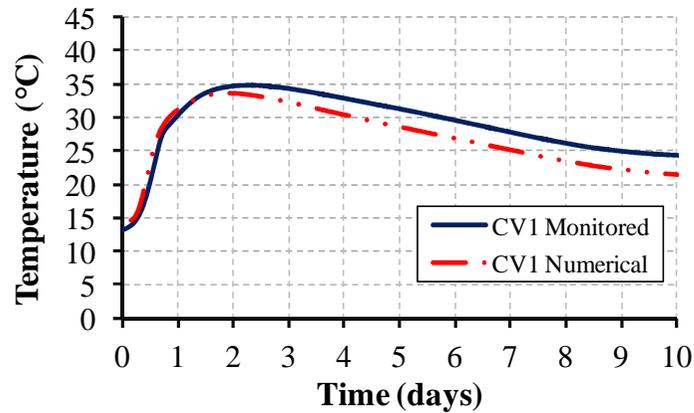


Geometry

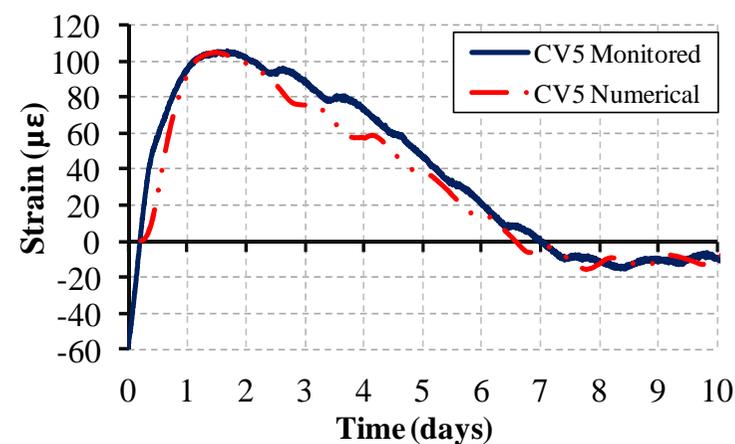
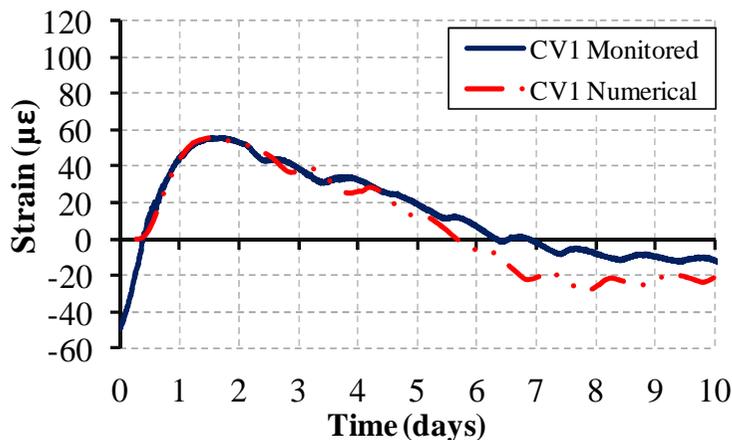
- ~25000 nodes; 7200 finite elements
- 8 node brick elements; 4 node planar elements for surfaces
- Cooling pipes as hollow “equivalent squares”
- Analysis of 10 days with 1h time increments

RESULTS OF SIMULATION AND COMPARISON WITH MONITORING

Temperature at the location of sensors CV1 and CV5

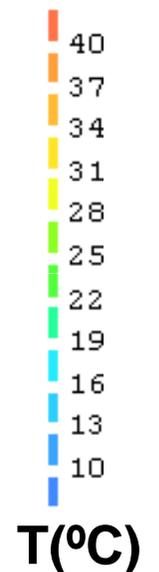
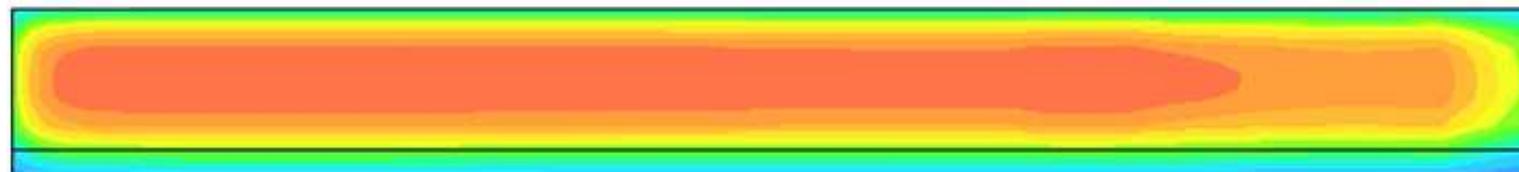
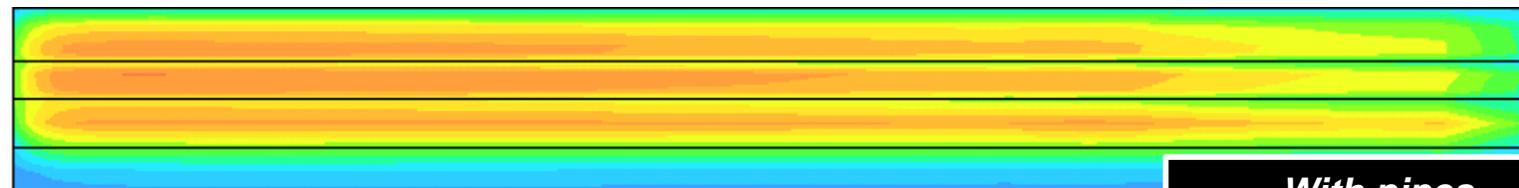
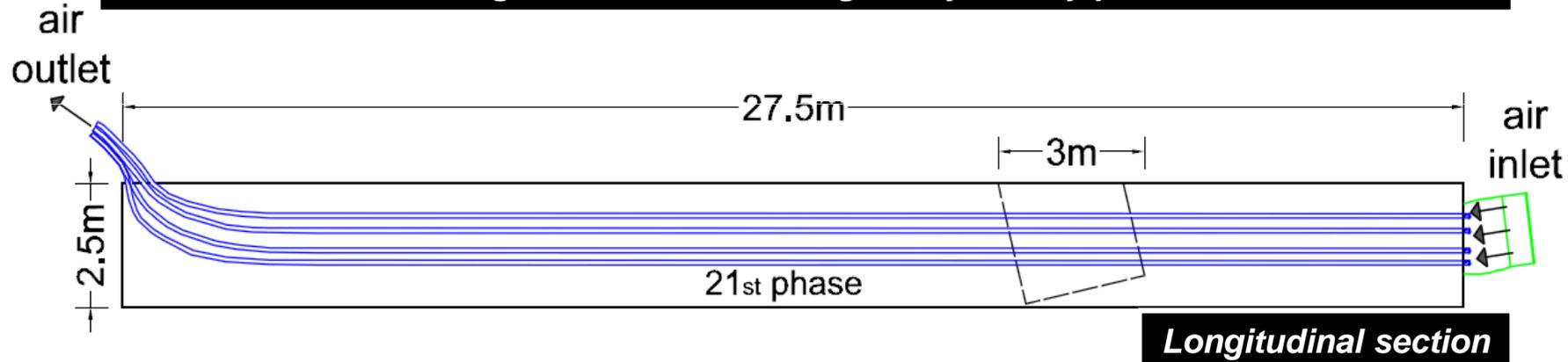


Strain at the location of sensors CV1 and CV5



PARAMETRIC ANALYSIS: WITH AND WITHOUT COOLING

Calculated temperatures for the instant at which the maximum temperature is reached
 Longitudinal section along the symmetry plane



CONCLUSIONS

- ❑ Numerical simulation of a thick concrete wall;
- ❑ Simulation backed by extensive material characterization;
- ❑ Simulation compared to monitoring results (T and ε);
- ❑ Good choice of parameters -> adequate predictions of T and ε ;
- ❑ Accurate simulation of stresses not necessarily assured;
- ❑ Feasibility of air cooling pipes was demonstrated but limitations exist due to the temperature increase along the pipes.

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