AMPHOS 21

SCIENTIFIC AND STRATEGIC ENVIRONMENTAL CONSULTING

COMSOL CONFERENCE
2018 LAUSANNE

Mechanical Damage Models for Concrete

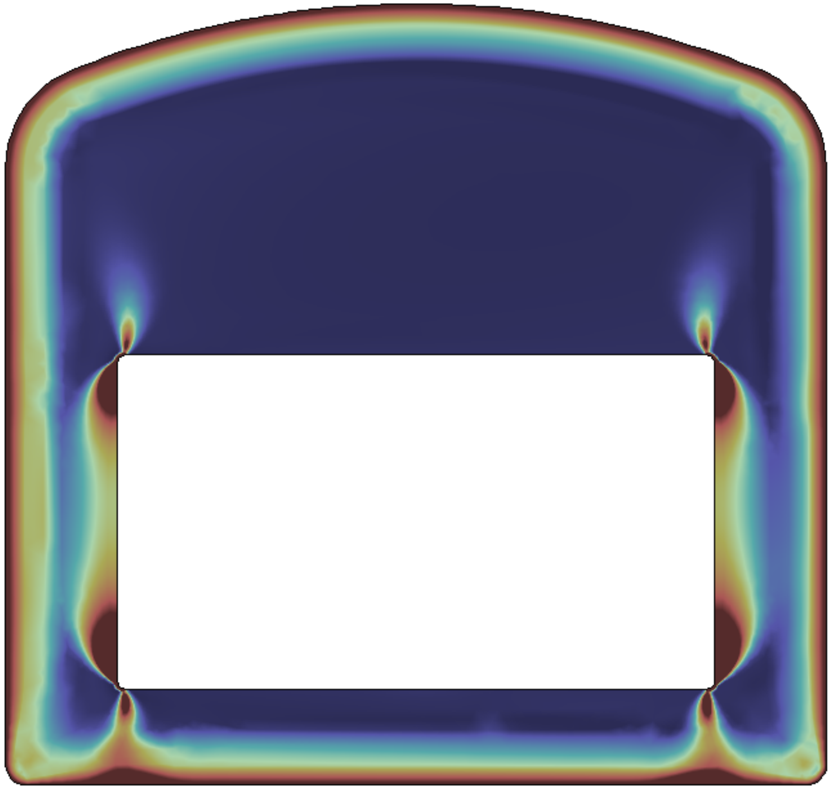
From Classical Mazars' model to fully integrated multiaxial regularized methods

24th October 2018
marcelo.lavina@amphos21.com

www.amphos21.com

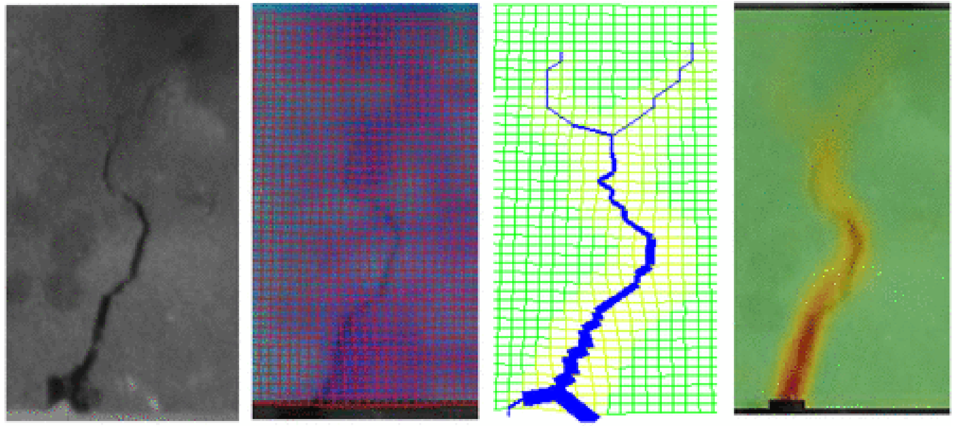
Outline

- Introduction
- Mazars' damage model
- External material vs built-in implementation
- Regularization
- μ damage model
- Conclusions
- Application case



Introduction

- Concrete structures
  - Damage mechanics
  - Quasi-brittle behaviour
  - Cracking representation
  - Various loading conditions
  - Load bearing capacity and post-peak behaviour
  - Accurate representation through a simple isotropic model



Concrete cracking representation with different approaches

Final goal:

Develop concrete mechanics model in the Comsol interface that allows its coupling with other processes, such as chemical degradation for durability assessment, or moisture and heat transport.

Non-mechanical process → Strain generation → Damage mech. model → Change in mech. properties

Mazars' damage model

- Damage mechanics theory [1]
  - Based on scalar damage variable affecting directly the stiffness tensor

$$E = E_0 \cdot (1 - d)$$

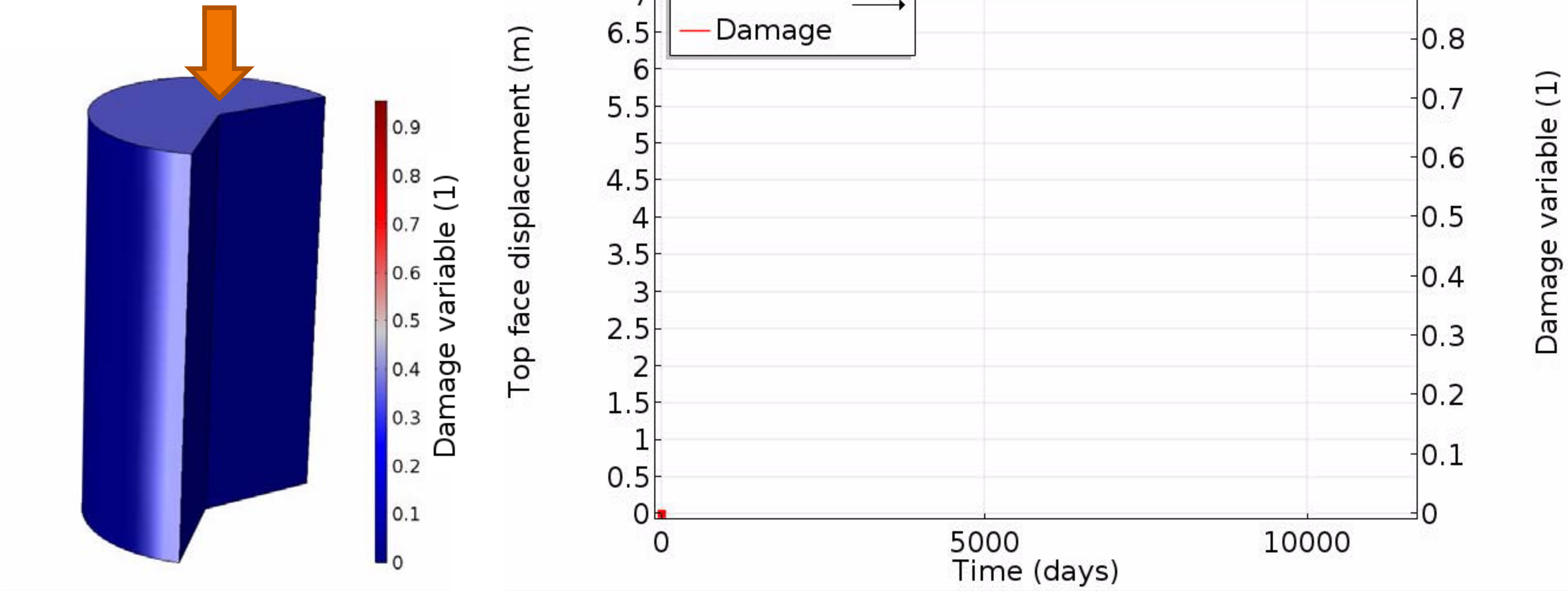
  - Stress – strain non-linear relation

$$\sigma = f(d) \cdot \varepsilon$$

$$d = f(\varepsilon)$$

- Mazars' formulation [2]
  - d is isotropic and scalar
  - Different laws for compression or tension stress state
  - Strain maximum values

History variable



Uniaxial cyclic loading test. Test representation, damage variable evolution and deformation (left); time evolution of the top face displacement in m (cyclic) and damage variable (monotonous increasing) on the right.

[1] Kachanov LM, 1958. Isv. Akad. Nauk. SSR, 8, 26–31.

[2] Mazars J, 1986. Engineering Fracture Mech., 25(5–6), 729-737.

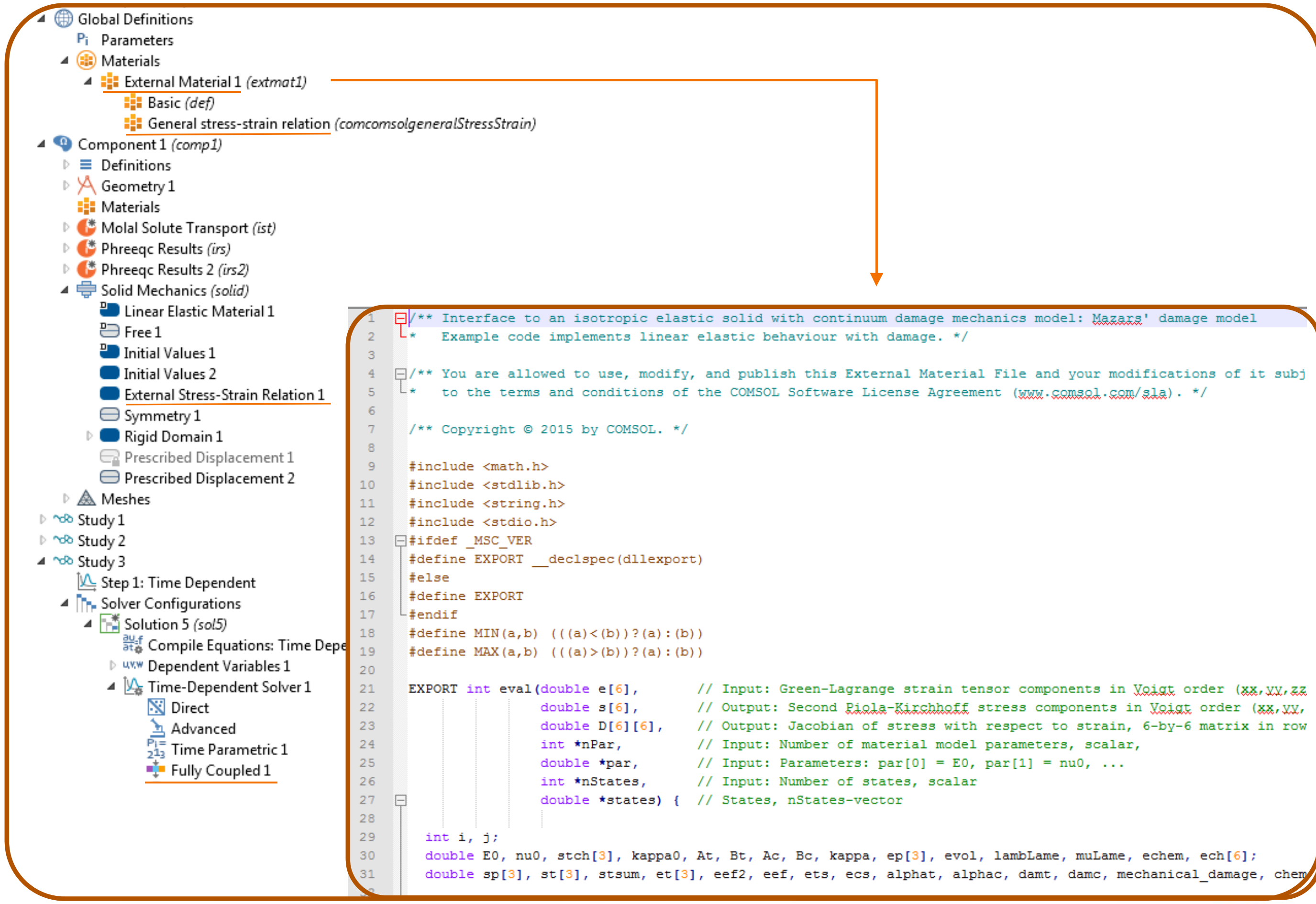
External material *vs.* built-in implementation

- External material model
  - Comsol post by Ed Gonzalez (2015) [1]
  - Any constitutive model can be programmed

- Built-in implementation
  - 2 History variables storage
    - Domain Ordinary Differential Equations
    - Specific solver configuration

2 additional degrees of freedom

Segregated step
+
Previous solution node



```c
/** Interface to an isotropic elastic solid with continuum damage mechanics model: Mazars' damage model
 *   Example code implements linear elastic behaviour with damage. */

/** You are allowed to use, modify, and publish this External Material File and your modifications of it subj
 *   to the terms and conditions of the COMSOL Software License Agreement (www.comsol.com/sla). */

/** Copyright © 2015 by COMSOL. */

#include <math.h>
#include <stdlib.h>
#include <string.h>
#include <stdio.h>
#ifdef _MSC_VER
#define EXPORT __declspec(dllexport)
#else
#define EXPORT
#endif
#define MIN(a,b)  (((a)<(b))?(a):(b))
#define MAX(a,b)  (((a)>(b))?(a):(b))

EXPORT int eval(double e[6],        // Input: Green-Lagrange strain tensor components in Voigt order (xx,yy,zz
                double s[6],        // Output: Second Piola-Kirchhoff stress components in Voigt order (xx,yy,
                double D[6][6],     // Output: Jacobian of stress with respect to strain, 6-by-6 matrix in row
                int *nPar,          // Input: Number of material model parameters, scalar,
                double *par,        // Input: Parameters: par[0] = E0, par[1] = nu0, ...
                int *nStates,       // Input: Number of states, scalar
                double *states) {   // States, nStates-vector

  int i, j;
  double E0, nu0, stch[3], kappa0, At, Bt, Ac, Bc, kappa, ep[3], evol, lambLame, muLame, echem, ech[6];
  double sp[3], st[3], stsum, et[3], eef2, eef, ets, ecs, alphat, alphac, damt, damc, mechanical_damage, chem
```

[1] Gonzalez E, 2015. *Accessing External Material Models for Structural Mechanics. COMSOL Blog December 2015.*

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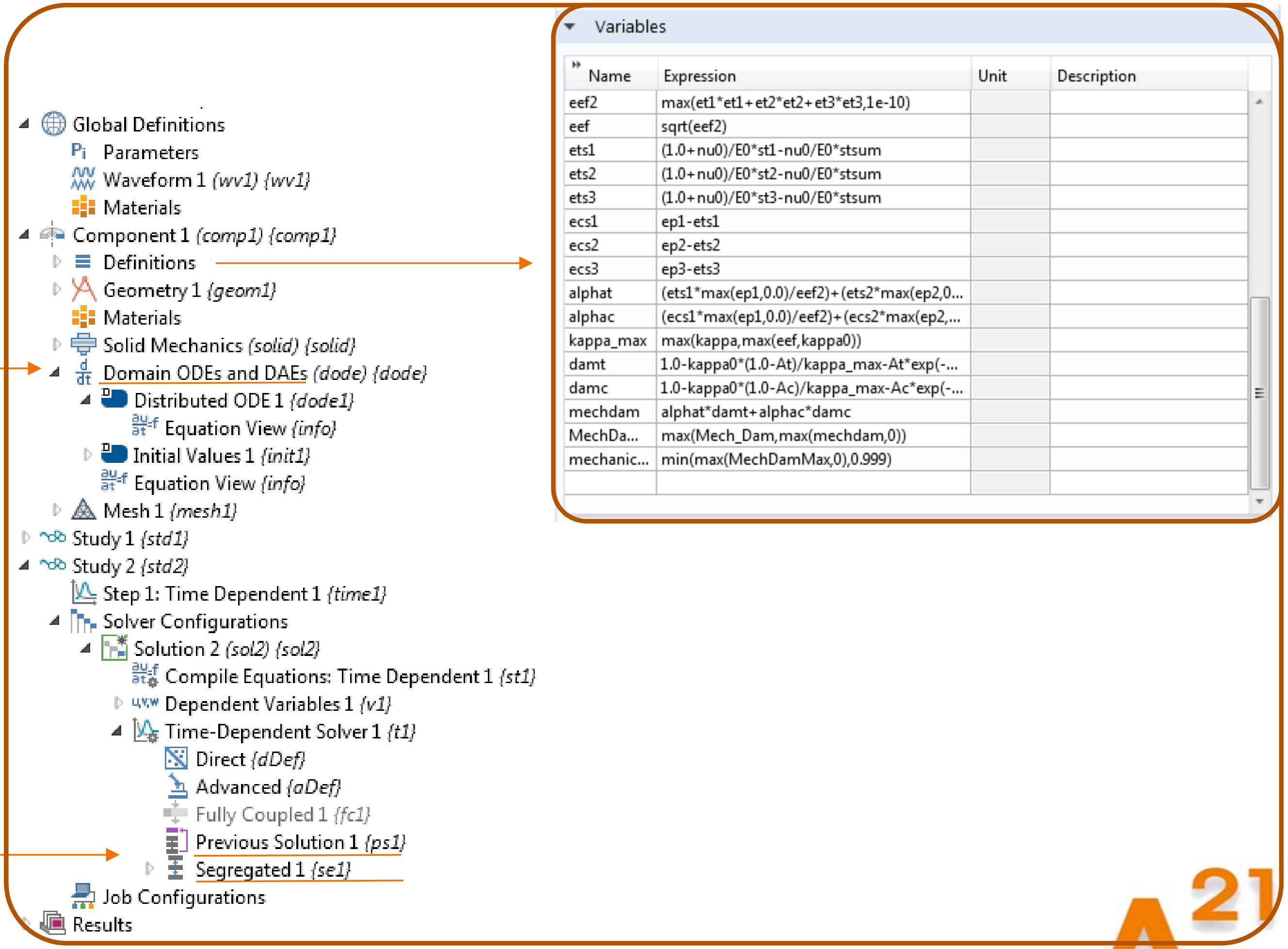
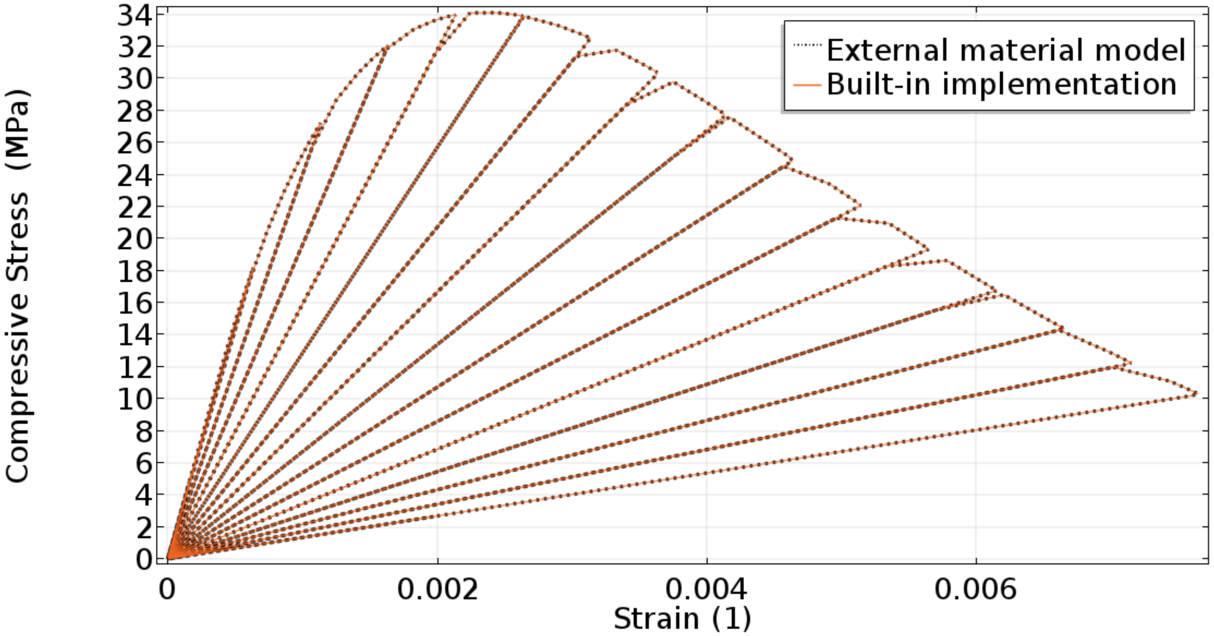


Name	Expression	Unit	Description
eef2	max(et1*et1+et2*et2+et3*et3,1e-10)		
eef	sqrt(eef2)		
ets1	(1.0+nu0)/E0*st1-nu0/E0*stsum		
ets2	(1.0+nu0)/E0*st2-nu0/E0*stsum		
ets3	(1.0+nu0)/E0*st3-nu0/E0*stsum		
ecs1	ep1-ets1		
ecs2	ep2-ets2		
ecs3	ep3-ets3		
alphat	(ets1*max(ep1,0.0)/eef2)+(ets2*max(ep2,0...		
alphac	(ecs1*max(ep1,0.0)/eef2)+(ecs2*max(ep2,...		
kappa_max	max(kappa,max(eef,kappa0))		
damt	1.0-kappa0*(1.0-At)/kappa_max-At*exp(-...		
damc	1.0-kappa0*(1.0-Ac)/kappa_max-Ac*exp(-...		
mechdam	alphat*damt+alphac*damc		
MechDa...	max(Mech_Dam,max(mechdam,0))		
mechanic...	min(max(MechDamMax,0),0.999)		

[1] Gonzalez E, 2015. *Accessing External Material Models for Structural Mechanics. COMSOL Blog December 2015.*

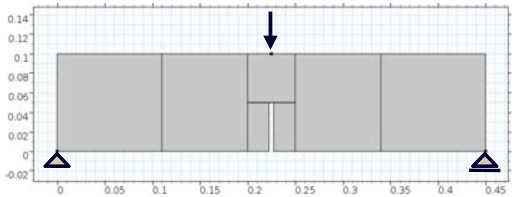
External material vs built-in implementation

- External material model
  - Comsol post by Ed Gonzalez (2015) [1]
  - Any constitutive model can be programmed
- Built-in implementation
  - 2 History variables storage
    - Domain Ordinary Differential Equations
    - Specific solver configuration
- Advantages
  - Fully coupling with other constitutive models
  - Fully coupling with other physics
  - Variables availability (pre/post-process)
  - Easier adjustment or reformulation (compilation avoided)
- Drawback
  - Increased model complexity (DOF's and solvers)



Results of the verification (uniaxial compression) test in terms of stress-strain curves using two different damage model implementations.

[1] Gonzalez E, 2015. Accessing External Material Models for Structural Mechanics. COMSOL Blog December 2015.



Regularization method – Gradient enhanced formulation

- Implicit gradient formulation [1 ; 2]:
  - Implemented as a Helmholtz differential equation

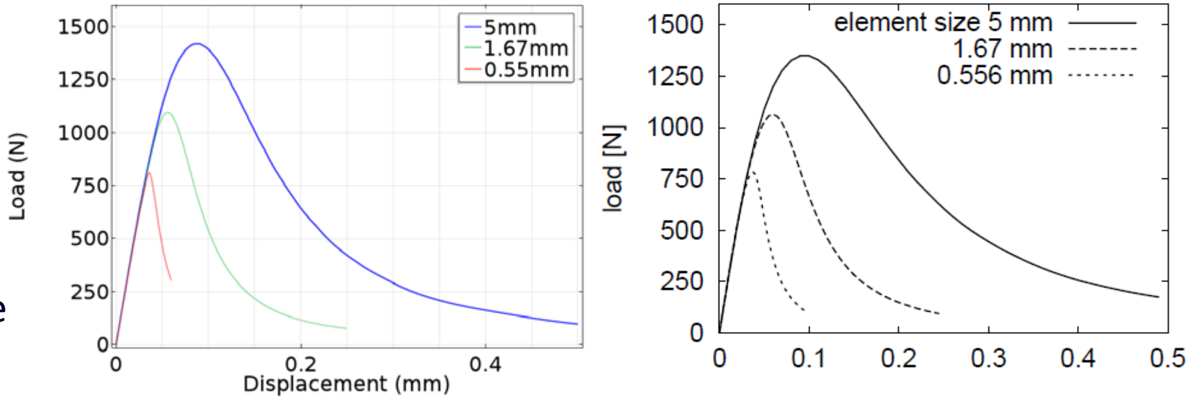
$$\bar{\varepsilon} - l^2 \nabla^2 \bar{\varepsilon} = \tilde{\varepsilon}$$

- *Local equivalent strain* $\tilde{\varepsilon}$
- *Non-local equiv. strain* $\bar{\varepsilon}$
- *characteristic length* l *(m)*

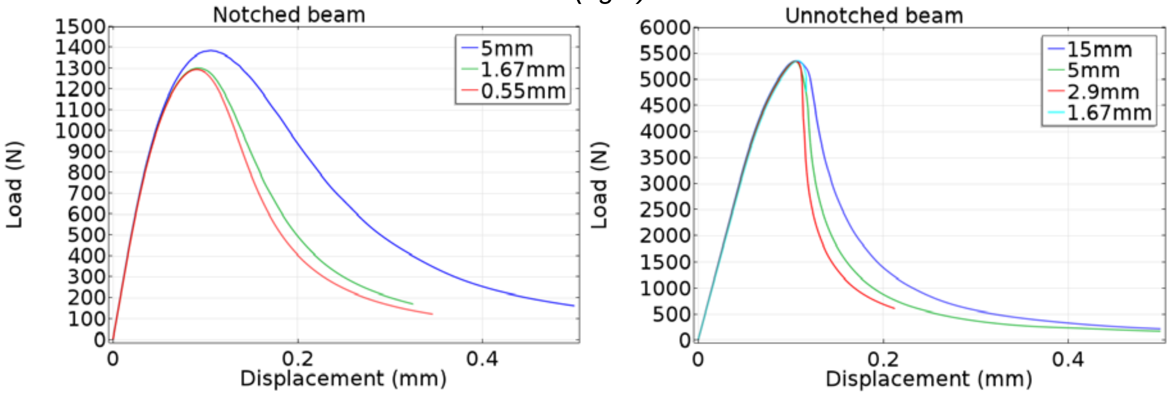
- Three-point bending tests of notched and unnotched concrete beams modelled with the regularized and non-regularized models

Mechanical parameters and damage model parameters

Parameters	**Notched**	**Unnotched**
E_0 (GPa)	20	
ν_0	0.2	
ε_0	$1.2{\cdot}10^{-4}$	$0.9{\cdot}10^{-4}$
ε_f^*	0.007	0.003
A_c	1.09	
B_c	1500	
l (mm)	0.6	1.0



Results of the Comsol model for different mesh refinements (left) , results from [3] (right).

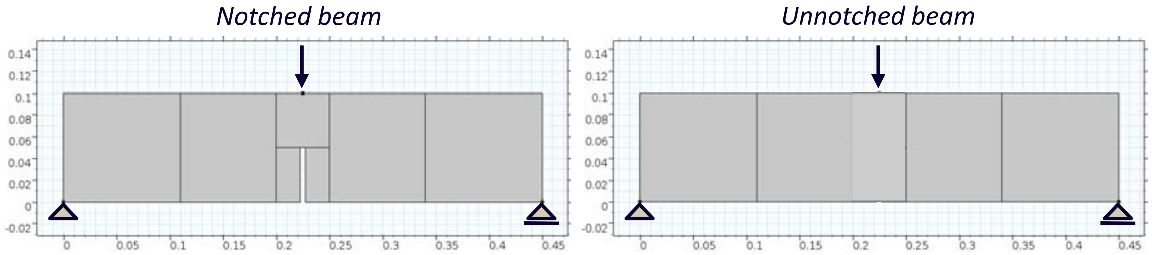


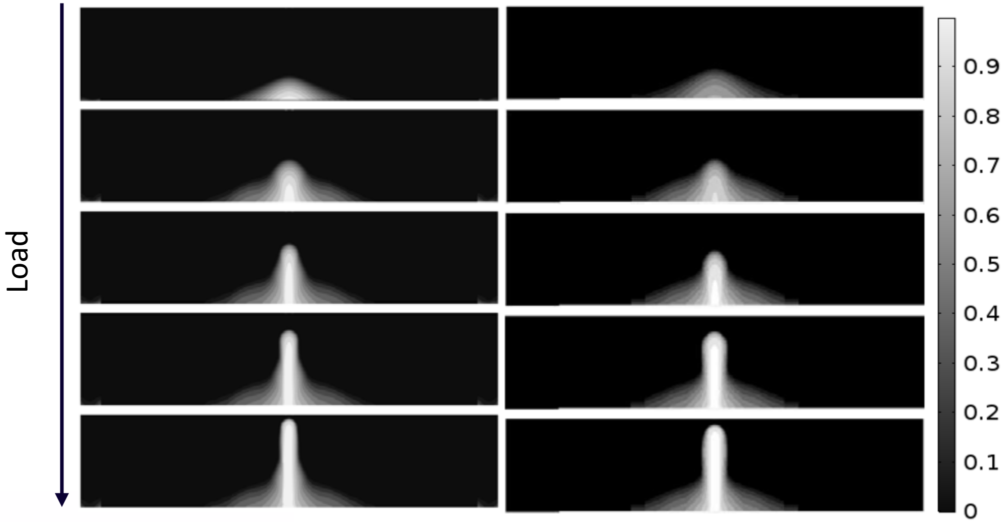
Results of the Comsol regularized damage model for different mesh refinements.

[1] Peerlings R H J et al., 1996. Int. J. for Num. Meth. Engng., 39, 3391-3403.
[2] Simone A, 2007. Revue Européenne de Génie Civil, 11(7-8), 1023-1044.
[3] Jirásek M, 2011. In Numerical Modeling of Concrete Cracking. Eds.: G Hofstetter, G Meschke, 1-49.

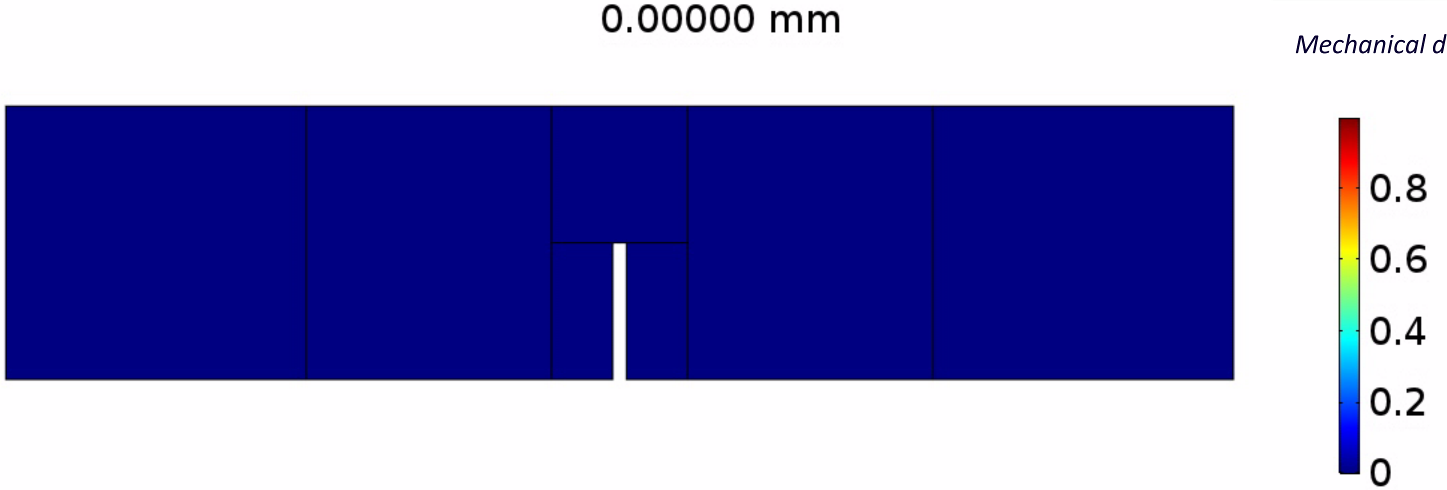
Regularization method – Gradient enhanced formulation

- Comparison with results presented in [1]
  - Damage variable evolution


Notched beam *Unnotched beam*



Mechanical damage evolution in Comsol (left) and results from [1] (right).

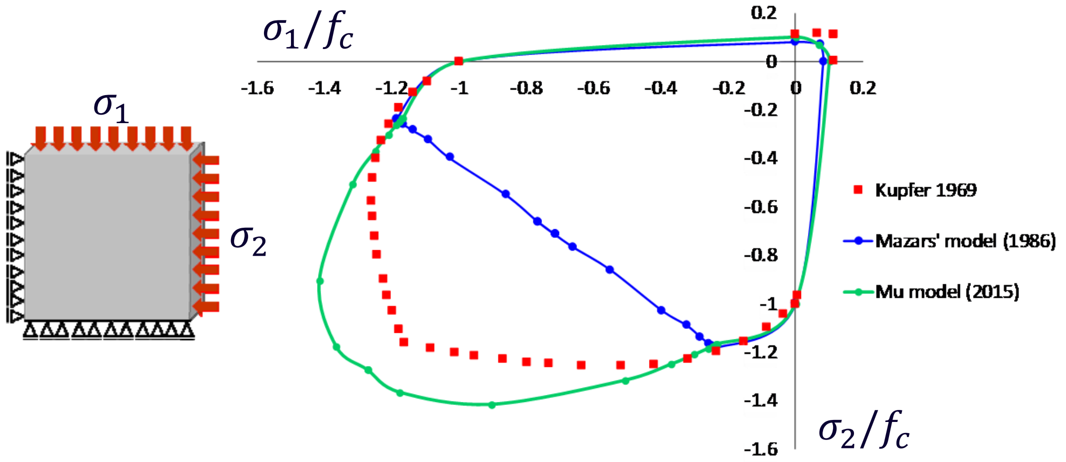


Evolution of mechanical damage as a function of the imposed displacement in the top face center point

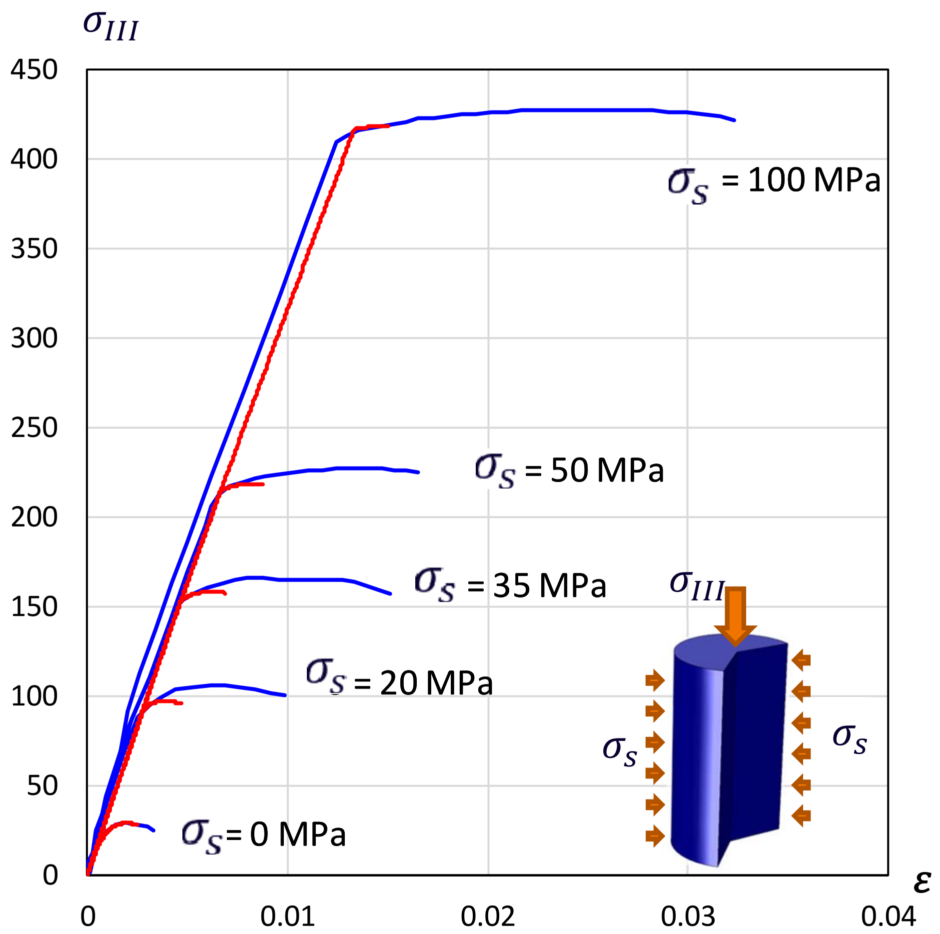
[1] Jirásek M, 2011. In Numerical Modeling of Concrete Cracking. Eds.: G Hofstetter, G Meschke, 1-49.

μ damage model

- Improvements of the formulation presented in [1]:
  - Two principal models:
    - Cracking in tensile state
    - Crushing in compressive state
  - Good representation of cyclic loading paths
  - Behaviour under biaxial compression
  - Behaviour under triaxial (EA) compression



Biaxial loading tests from [2], model results for classical and μ damage models



Triaxial test modelled in [1] (blue) and Comsol results (red)

[1] Mazars J, Hamon F, Grange S, 2015. Materials and Structures, 48, 3779–3793.

Conclusions

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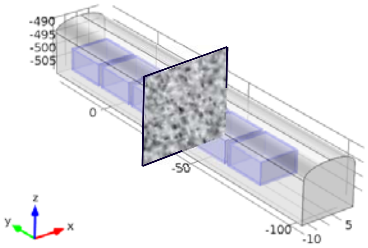
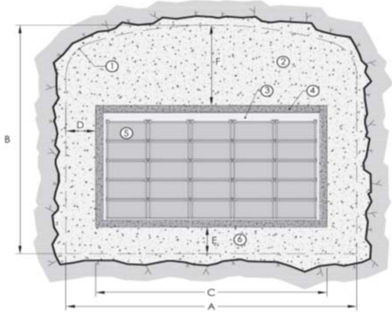
Acknowle

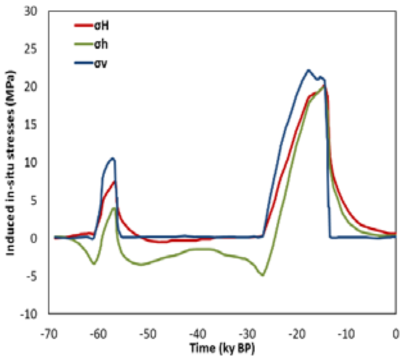
This work ha
Community (H2020-NFRP-2014/2015) under grant agreement n° 662147 (CEBAMA) and from the Swedish Nuclear Fuel and Waste Management Company (SKB), which are gratefully acknowledged.

Application case – Glaciation

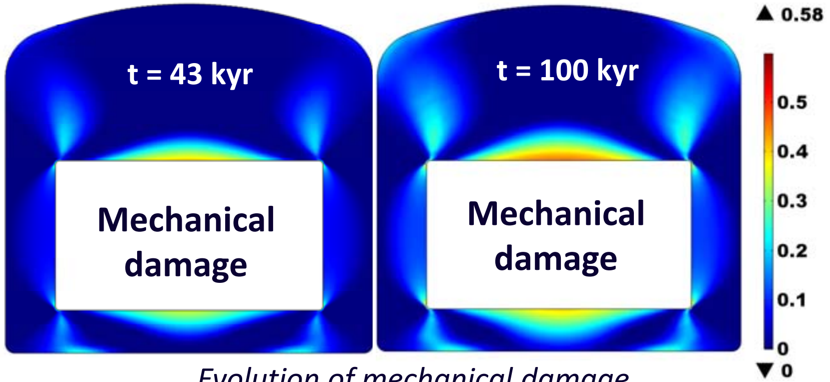
- Deep geological repository for nuclear waste



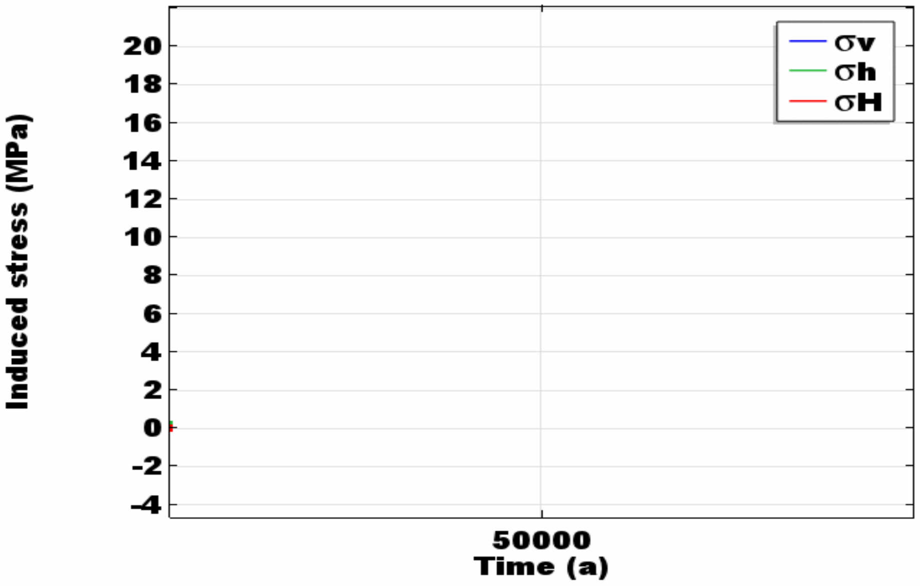


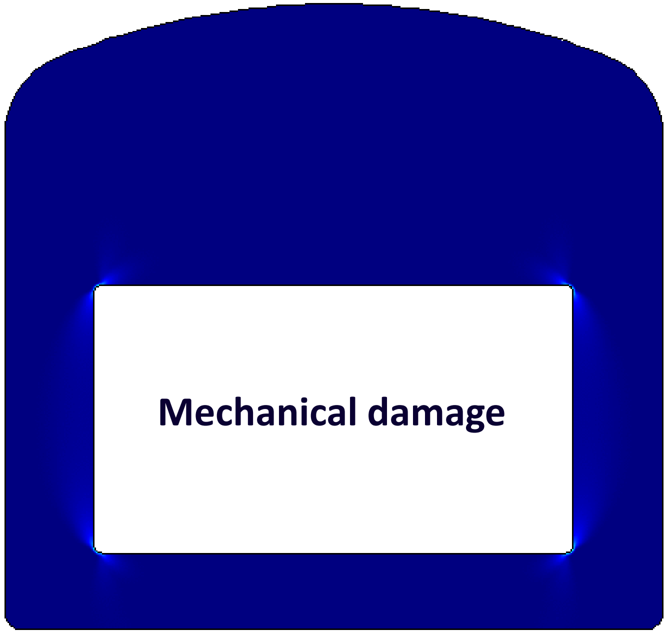


Evolution of in-situ stresses



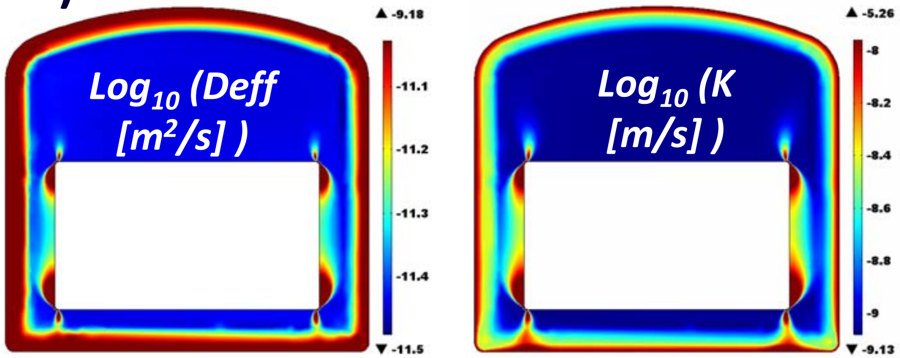
Evolution of mechanical damage





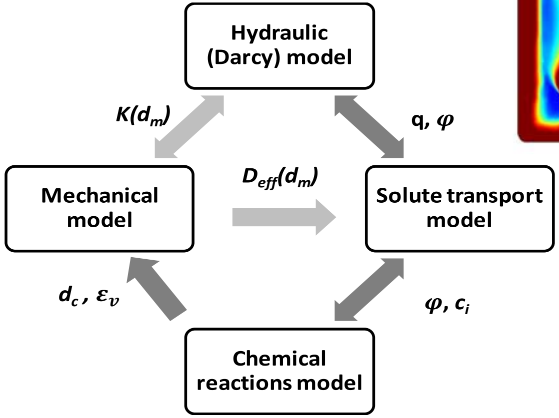
Application case – Sulphate attack (HCM)

- The concrete damage model presented:
  - Completely built-in Comsol interface



Changes in transport properties due to mechanical effects

Affected material



Hydraulic (Darcy) model

$K(d_m)$

q, φ

Mechanical model

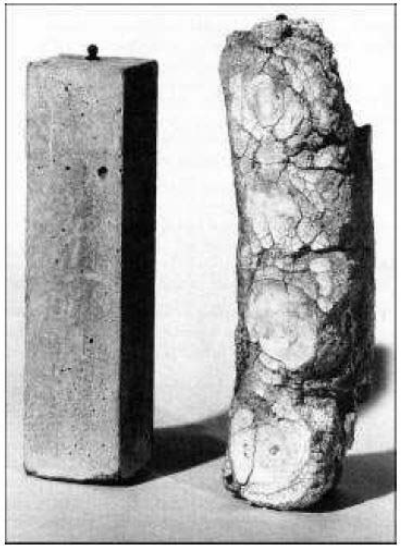
$D_{eff}(d_m)$

Solute transport model

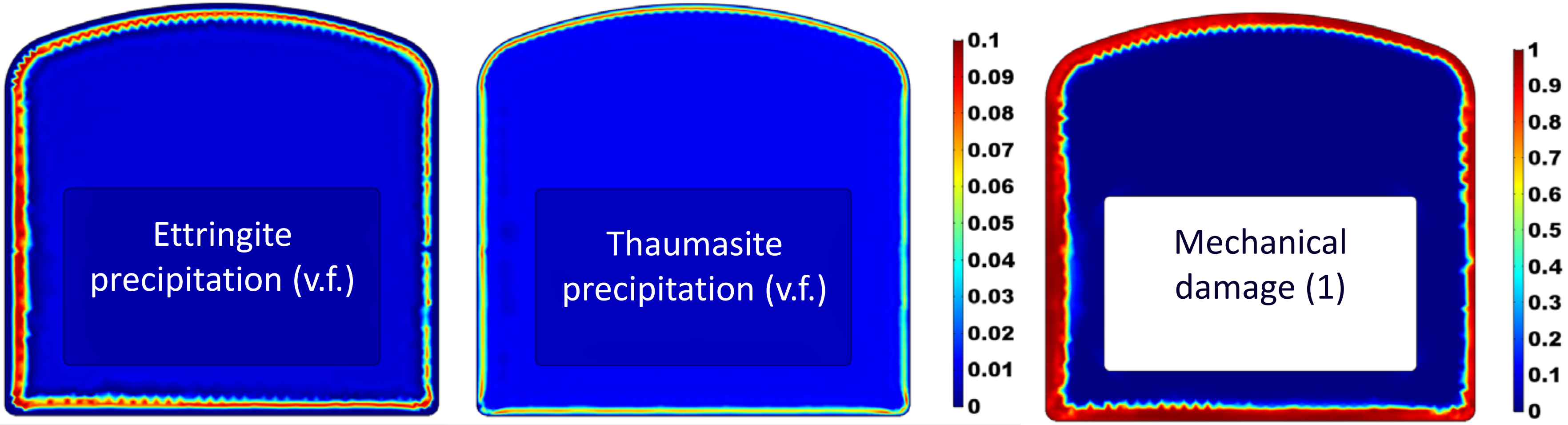
d_c, ε_v

φ, c_i

Chemical reactions model



4.1 Conventional sulfate attack associated with expansive ettringit in a concrete prism (RHS) and non-degraded control prism (LHS). I reproduced from CEB Design Guide, *Durable Concrete Structure* Thomas Telford, 1989.



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SCIENTIFIC AND STRATEGIC ENVIRONMENTAL CONSULTING

ESPAÑA
Paseo de García Faria, 49-51
08019 Barcelona
Tel.: +34 93 583 05 00

Paseo de la Castellana 40, 8ª Planta
28046 Madrid
Tel.: +34 620634729

CHILE
Avda. Nueva Tajamar, 481
WTC – Torre Sur – Of 1005
Las Condes, Santiago
Tel.: +562 2 7991630

PERÚ
Jr. Pietro Torrigiano 396
San Borja, Lima 41
Tel.: +51 1 592 1275

FRANCE
14, Avenue de l'Opéra
75001 Paris
Tel.: +33 645 766 322

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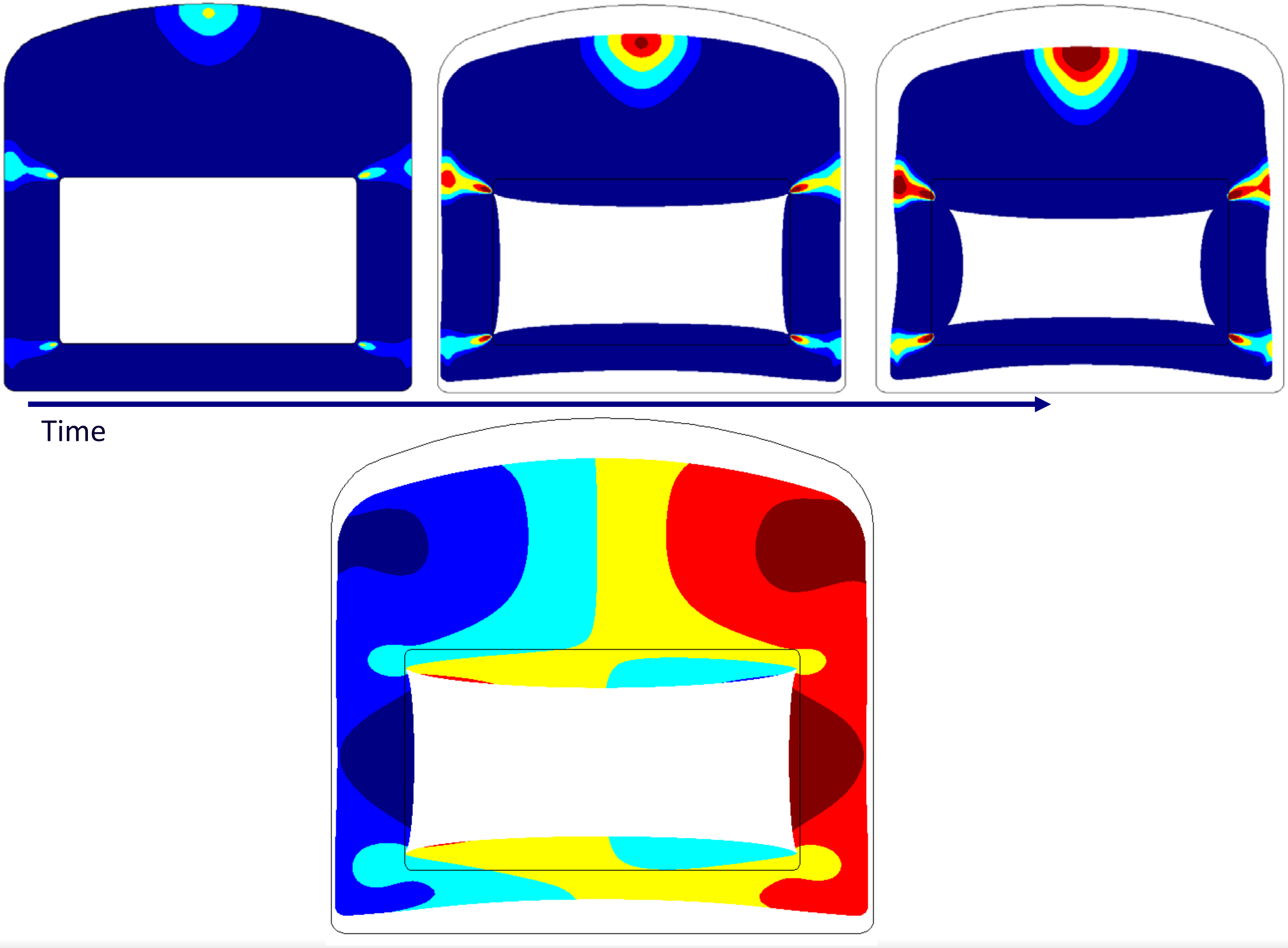
http://www.amphos21.com   *amphos21@amphos21.com*


Time