INTEGRATING 3D MODELLING AND NON-LINEAR NUMERICAL SIMULATIONS IN CONCRETE ADDITIVE MANUFACTURING

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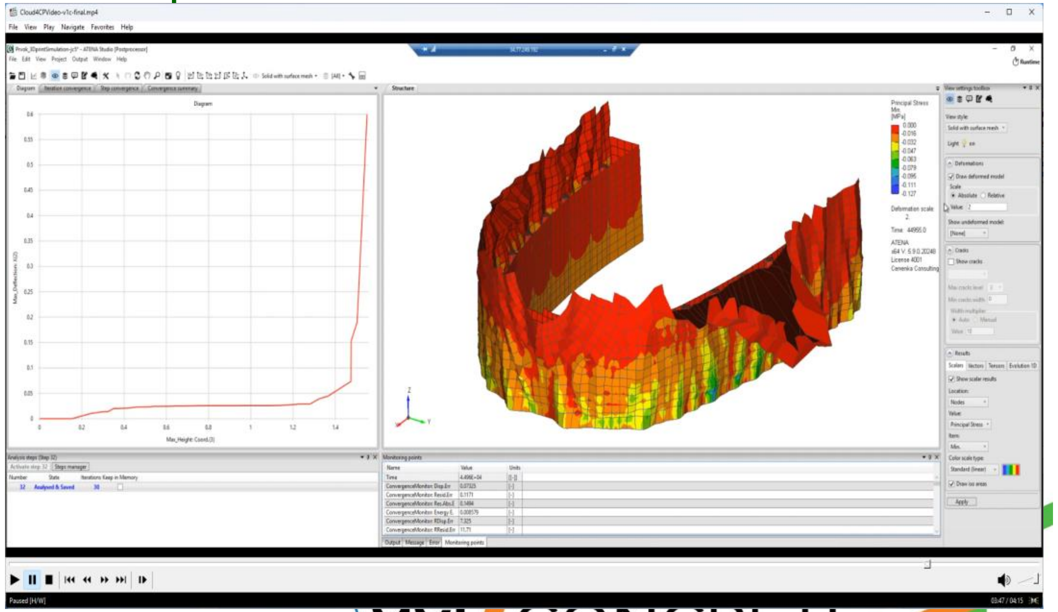
- **Simulation of additive manufacturing using FEA**
- **Material model for concrete 3D printing**
- **Examples: From the Lab to the Field**
  - Simulation of material tests
  - 3D-printed wall and column
  - Prvok House



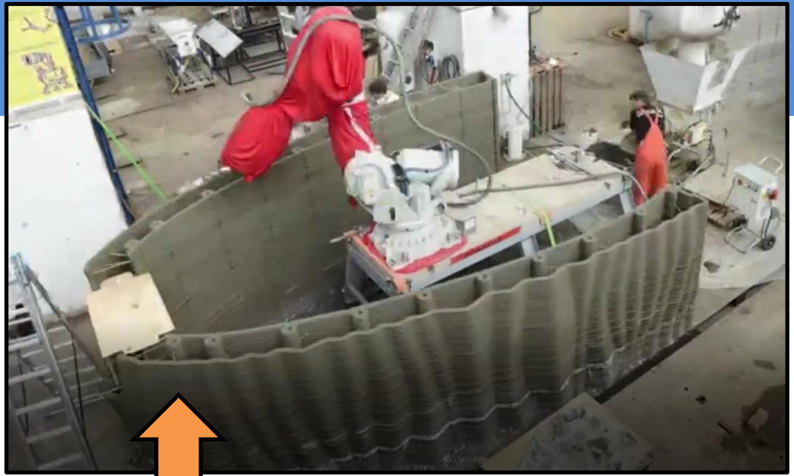
Concrete 3D printing

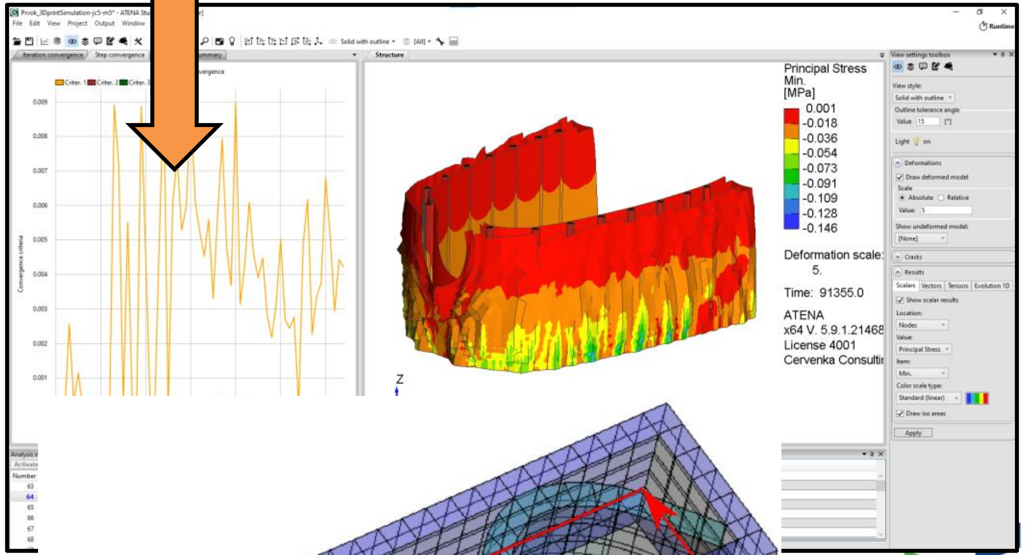
Advantages of numerical simulation:

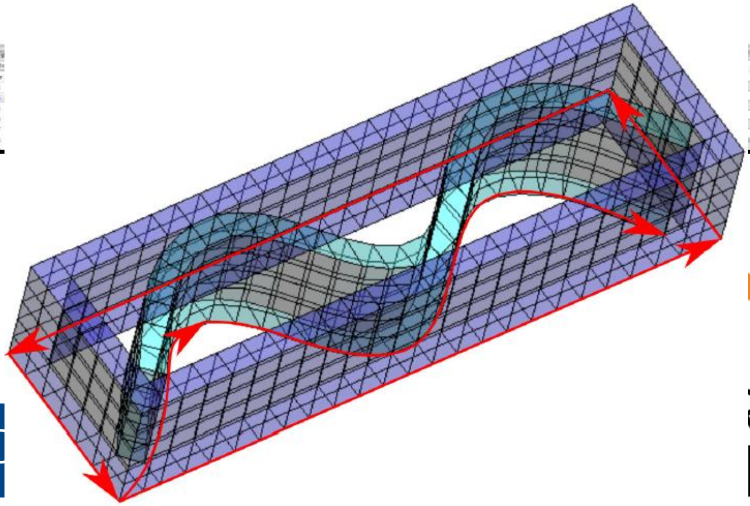
- upscaling laboratory experiments
- speed and shapes optimisations
- predicting construction interruptions in real time
- environmental conditions: humidity, temperature, wind

Simulation approach:

- gradual activation of finite elements along the printing track
- time-dependent (maturing) non-linear material model
- time-dependent loads (self-weight, shrinkage)
- updated Lagrangian formulation (i.e., nodal coordinates are updated every step)







Creating model based on G-code

Standard G-code input generation → **Import & visualization** → **Finite element model with inclined shapes**

```
( Layer 1, Z= 60.000000 )
G00 X3436.860661  Y1674.281556 Z60.000000
M40
G01 X3346.913203  Y1742.862717 Z60.000000
G01 X3329.520742  Y1751.019088 Z60.000000
G01 X3310.503950  Y1753.736754 Z60.000000
G01 X3271.720657  Y1740.362567 Z60.000000
G01 X3115.574342  Y1666.599599 Z60.000000
G01 X3097.000923  Y1663.242901 Z60.000000
G01 X3069.182515  Y1667.734186 Z60.000000
G01 X3041.838507  Y1674.995193 Z60.000000
G01 X3004.087825  Y1667.963098 Z60.000000
G01 X2967.614590  Y1677.167756 Z60.000000
G01 X2893.342895  Y1677.792611 Z60.000000
G01 X2856.848915  Y1687.353553 Z60.000000
G01 X2819.234442  Y1679.751165 Z60.000000
G01 X2791.329354  Y1687.568590 Z60.000000
G01 X2720.601619  Y1731.628112 Z60.000000
G01 X2710.768915  Y1734.637643 Z60.000000
G01 X2691.458443  Y1733.954091 Z60.000000
G01 X2653.867456  Y1717.769582 Z60.000000
G01 X2607.472545  Y1692.737785 Z60.000000
G01 X2597.339911  Y1690.451132 Z60.000000
G01 X2569.232759  Y1696.502184 Z60.000000
G01 X2497.596258  Y1738.862123 Z60.000000
G01 X2477.407566  Y1739.681121 Z60.000000
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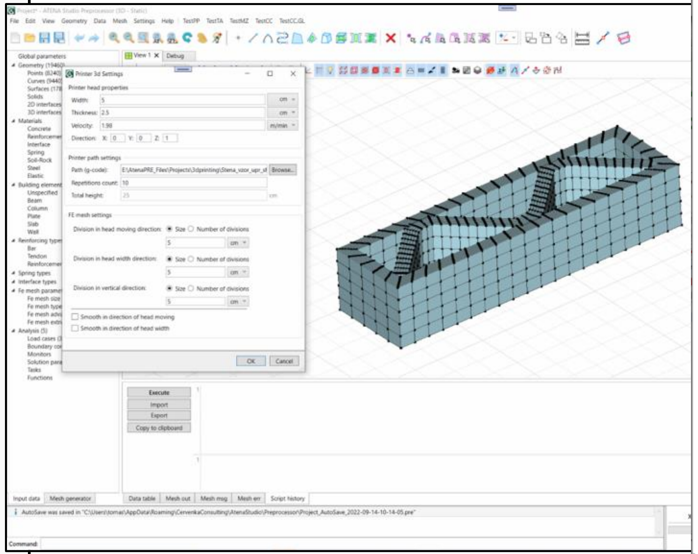
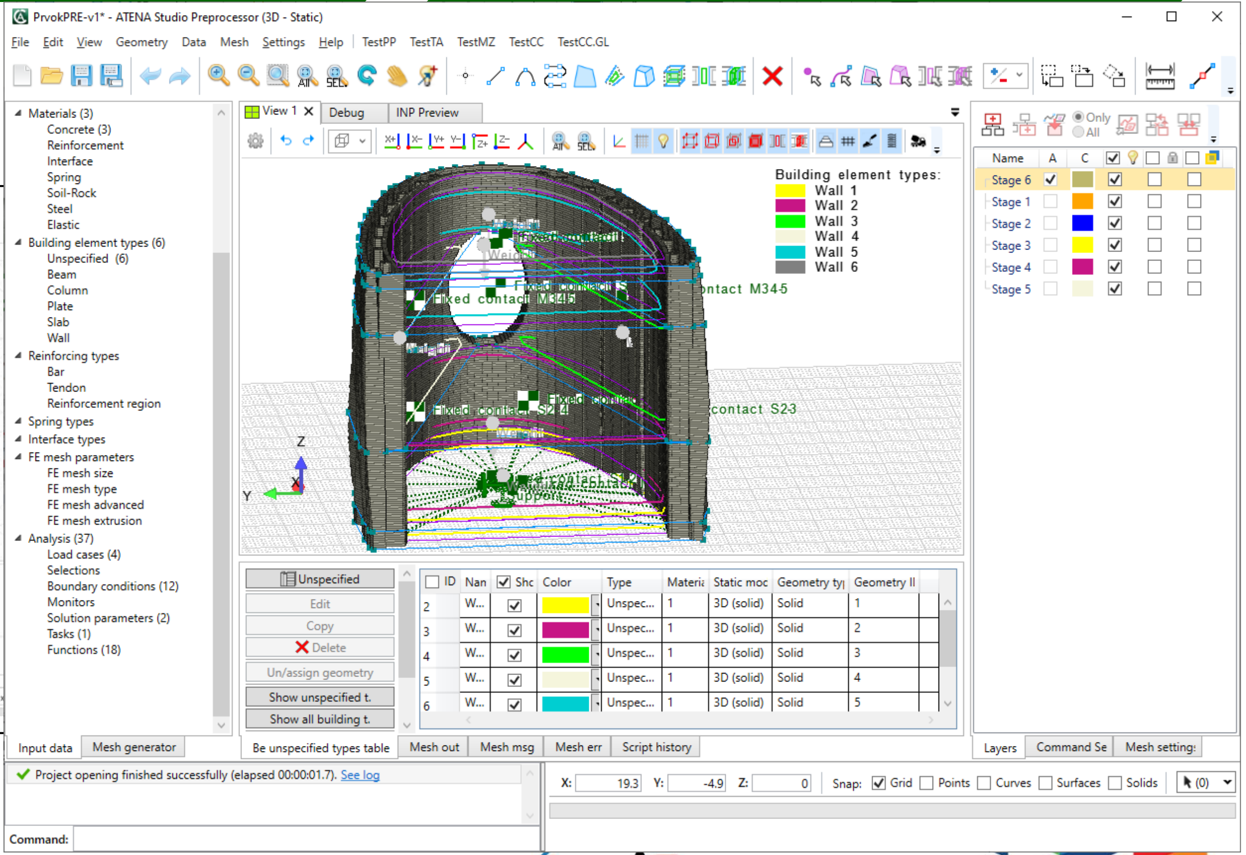


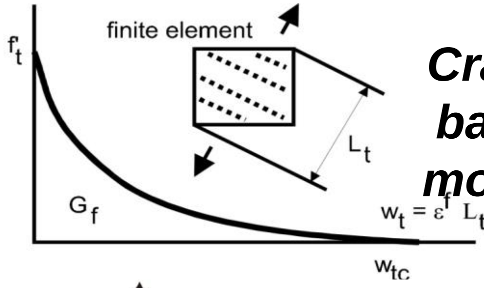


Nonlinear material model

Strain decomposition: $\dot{\sigma}_{ij} = D_{ijkl} \cdot (\dot{\varepsilon}_{kl} - \dot{\varepsilon}^{p}_{kl} - \dot{\varepsilon}^{f}_{kl})$

Concrete cracking in tension:

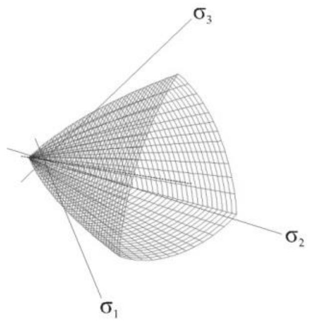
- fracture energy approach with smeared crack model
- Rankine criterion and Hordijk's softening law

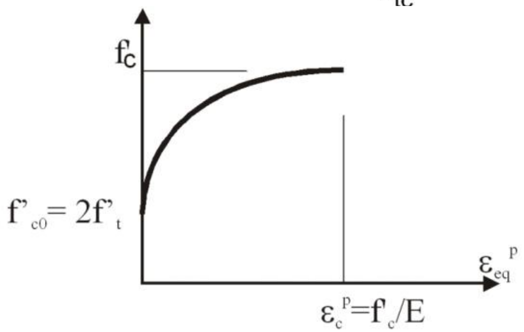


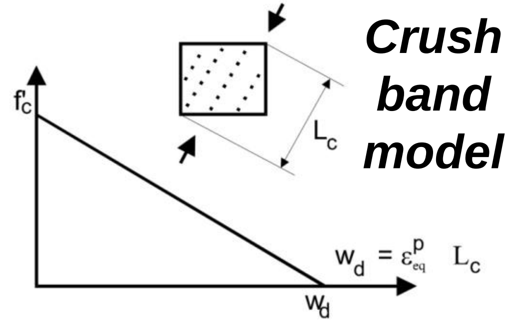
Crack band model

Concrete crushing in compression:

- based on plasticity
- Willam & Menetrey 3 par. surface







Crush band model

Reinforcement:

- yielding and rupture based on multilinear stress-strain relationship

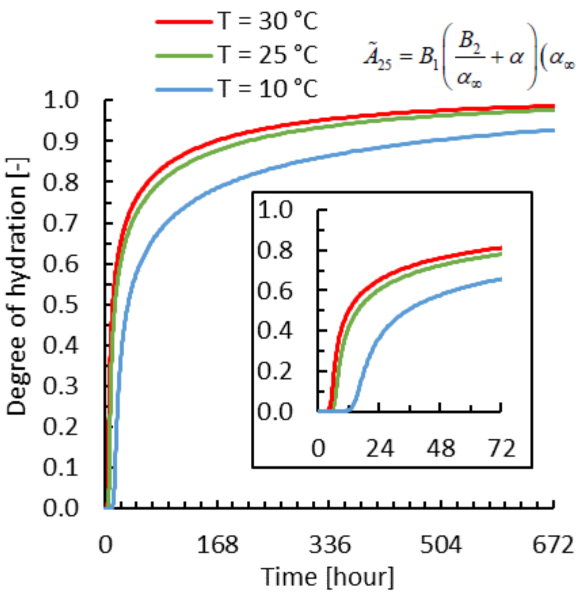
J. Cervenka, V. Cervenka, R. Eligehausen, Fracture-plastic material model for concrete, application to analysis of powder actuated anchors, in: Proc. FraMCoS., 1998: pp. 1107–1116.

J. Cervenka, V.K. Papanikolaou, Three dimensional combined fracture–plastic material model for concrete, Int. J. Plast. 24 (2008) 2192–2220.

Kinetic material model for 3D printing

Increase of degree of hydration in time → **Gain of compressive strength in time** → **Development of material model parameters in time**

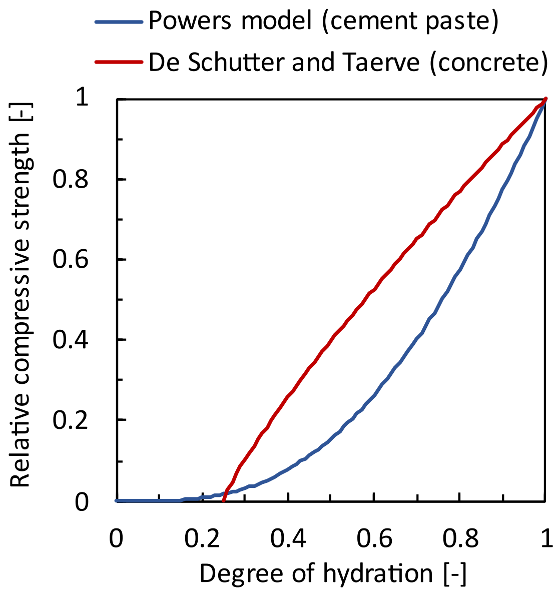
Function for hydration:



$$\tilde{A}_{25} = B_1\left(\frac{B_2}{\alpha_\infty} + \alpha\right)(\alpha_\infty - \alpha)\exp\left(-\bar{\eta}\frac{\alpha}{\alpha_\infty}\right)$$

Arrhenius law: $\frac{\partial \alpha_T}{\partial t} = \frac{\partial \alpha}{\partial t} k_T = \frac{\partial \alpha}{\partial t} \exp\left[\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$

Relating hydration and strength:



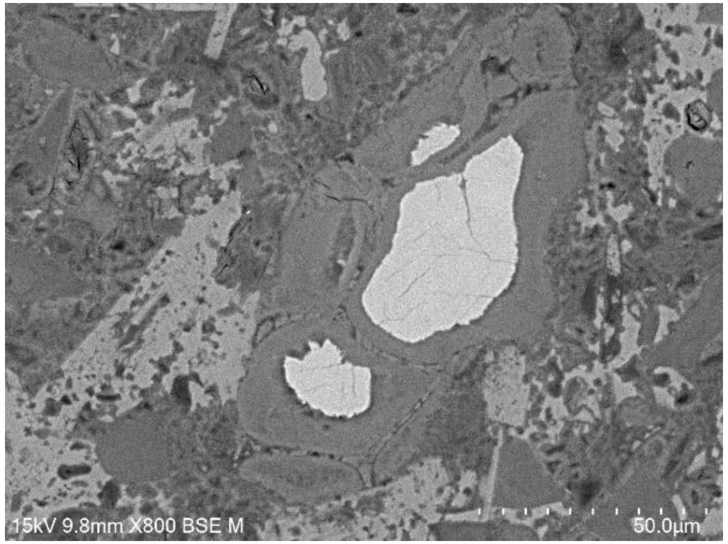
Parameters of the Fracture Model:

Parameter	Value
Compression strength [MPa]	INPUT: *fc*
Poisson ratio [-]	0.2
Young's modulus [MPa]	$(6000 - 15.5\, fc_{28})\sqrt{fc}$
Tensile strength [MPa]	$0.3\, fc^{2/3}$
Specific fracture energy [N/m]	$73(fc^{0.18})10^{-6}$
Critical compr. displacement [m]	0.0005
Onset of non-linear behaviour in compression [MPa]	$\frac{2}{3} fc$
Plastic strain at compressive strength	$fc\ / E_{28}$

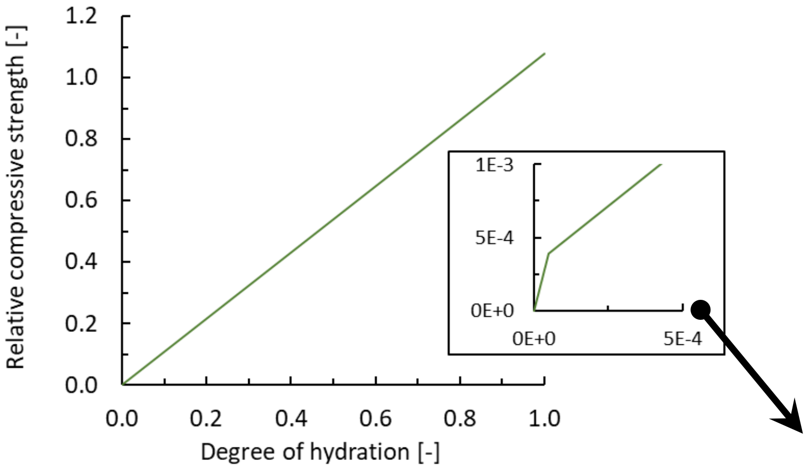
Kinetic material model for 3D printing: early age thixotropy

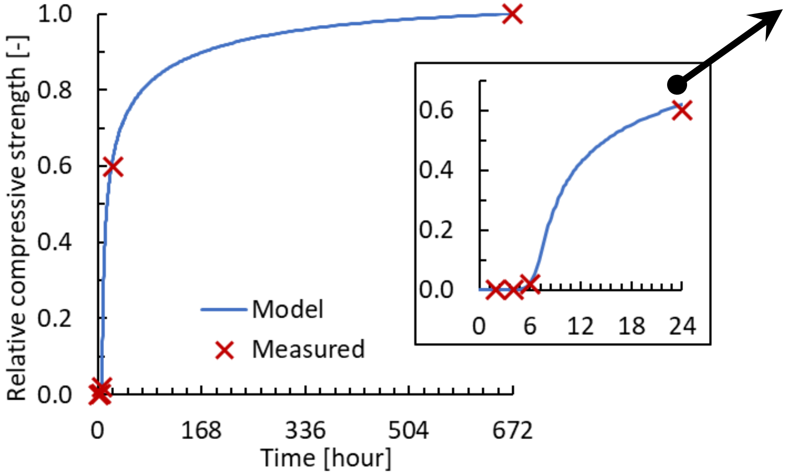
Hardened paste:

- material performance depends on the filling of the microstructure with hydrates
- increase in compressive strength is proportional to increase of DoH

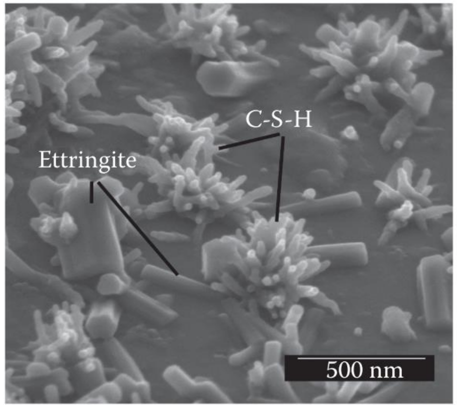


Microstructure after 10 years:





Microstructure after 4 hours:

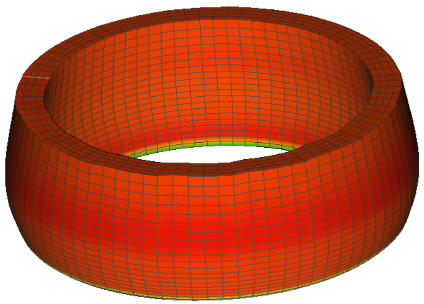
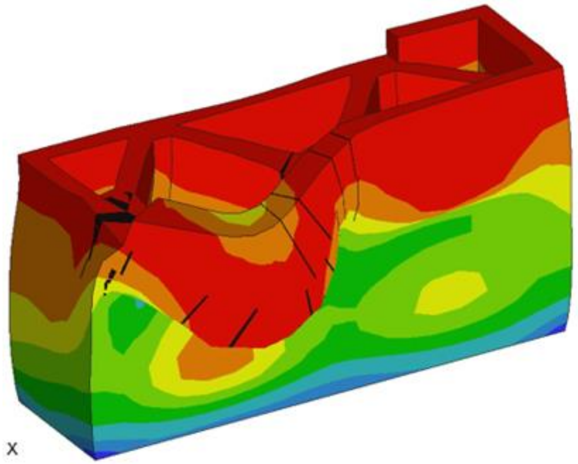


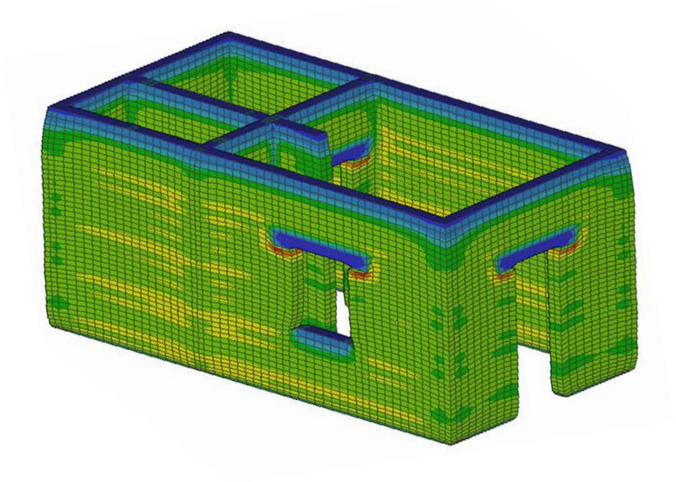
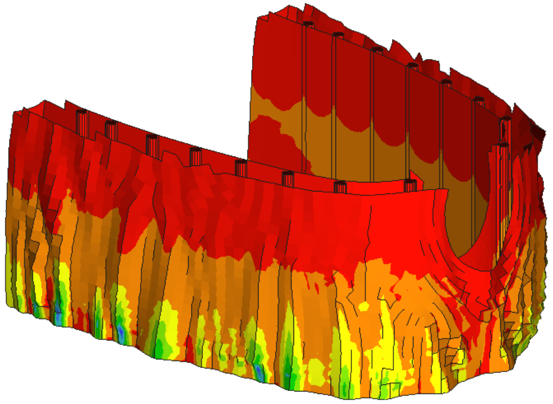
non-Newtonian fluid:

- material performance origins from the thixotropic state
- **up to a few minutes**: re-creation of inter-particle bonds after placing
- **up to a few hours:** structuration phase due to early hydration products
- can be also simulated by non-zero origin of compressive strength

EXAMPLES:
FROM THE LAB TO THE FIELD

- Simulation of material tests
- 3D-printed wall and column
- Printing of building structures
- Prvok House

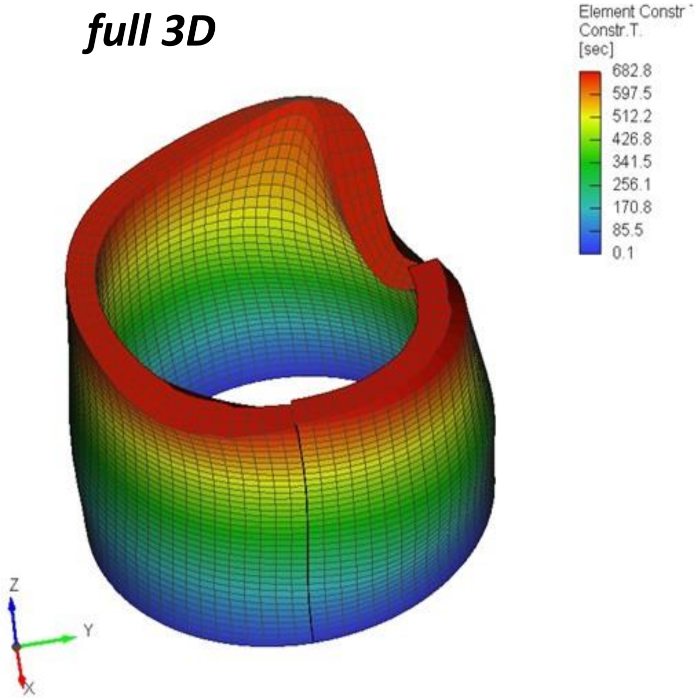



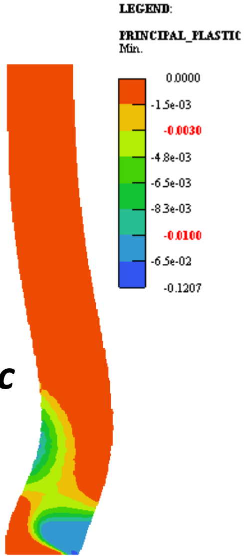



From the Lab to the Field: Wolfs' cylinder

- printing of cylindrical specimen from fresh concrete
- typical material and printing method test set-up
- **height at collapse:** experiment - 29 cm
  analysis - 33 cm

full 3D

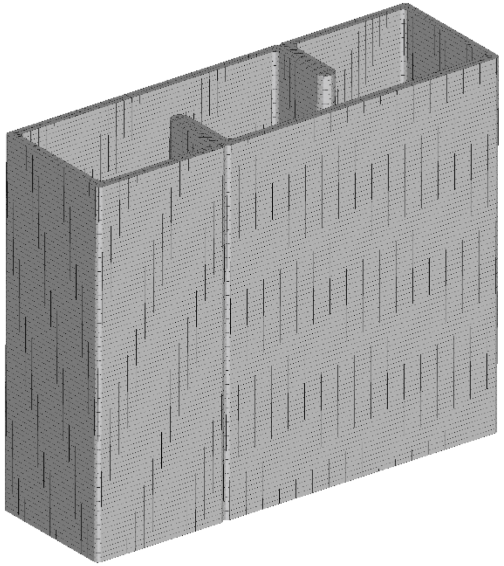


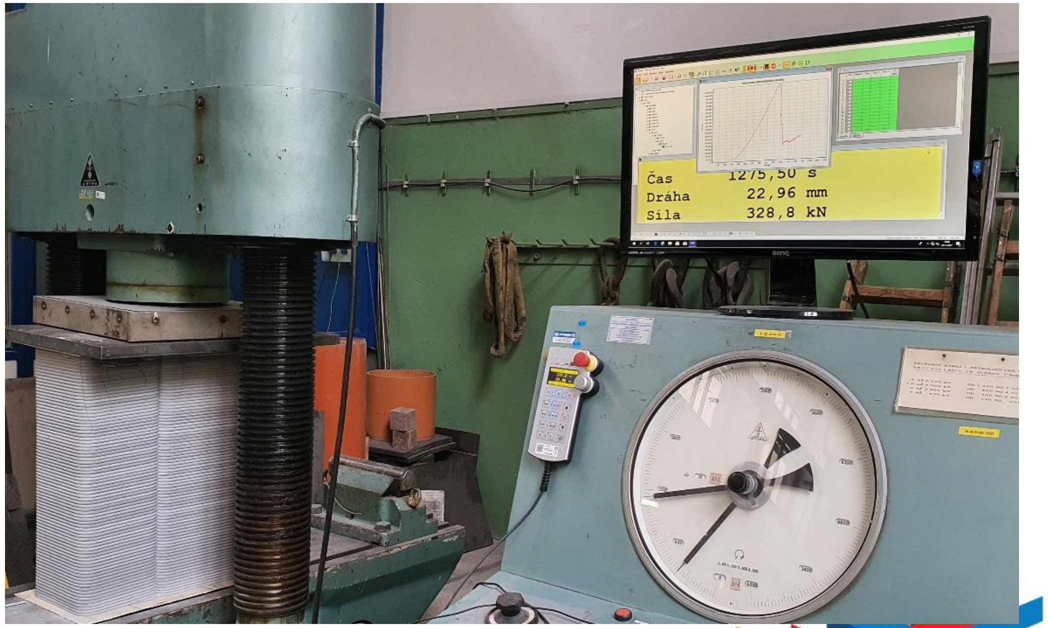


axisymmetric simulation

Wolfs, R. J. M., F. P. Bos, and T. A. M. Salet. "Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing." Cement and Concrete Research, 106 (2018): 103-116.

ATENA Analysis of the Load Capacity of a 3D-printed Wall Segment

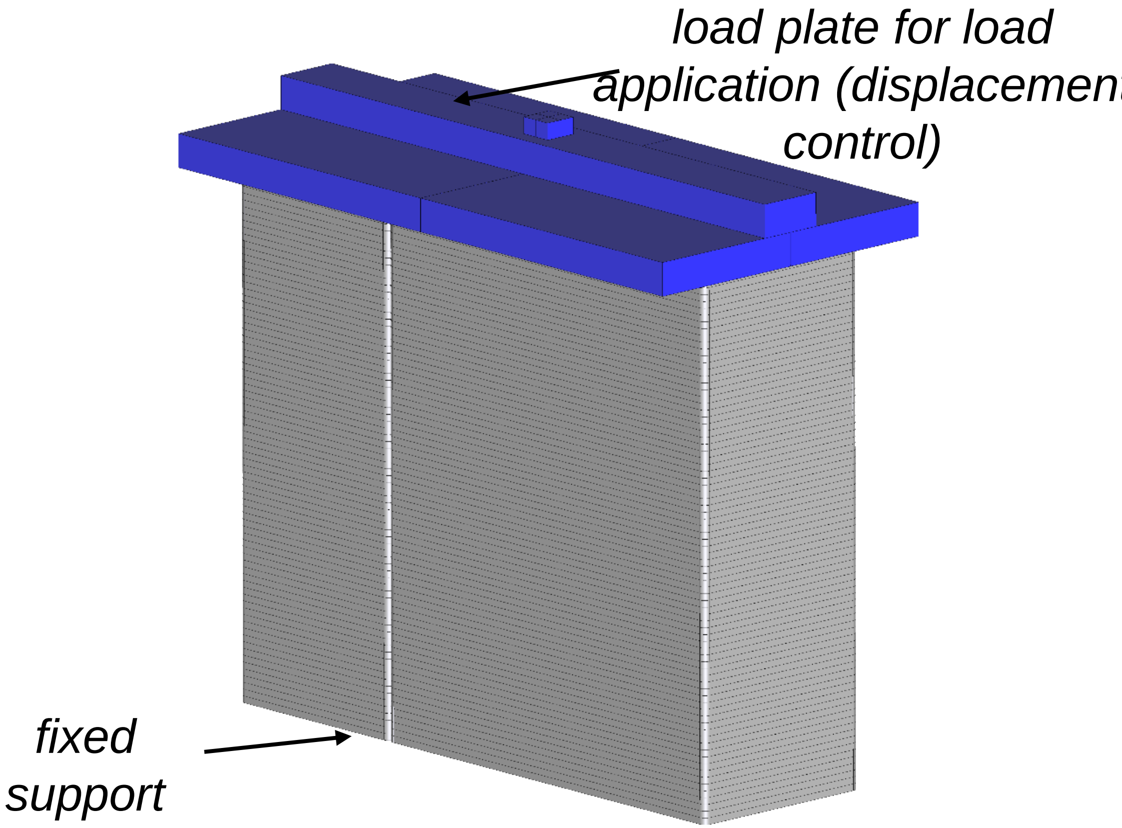


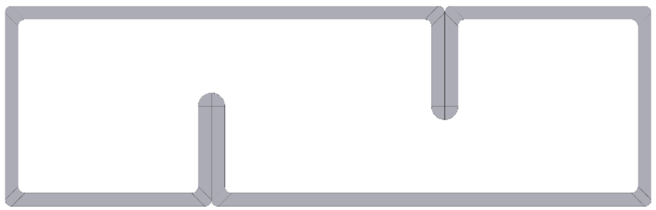


MODEL 1: "IDEALIZED MODEL"

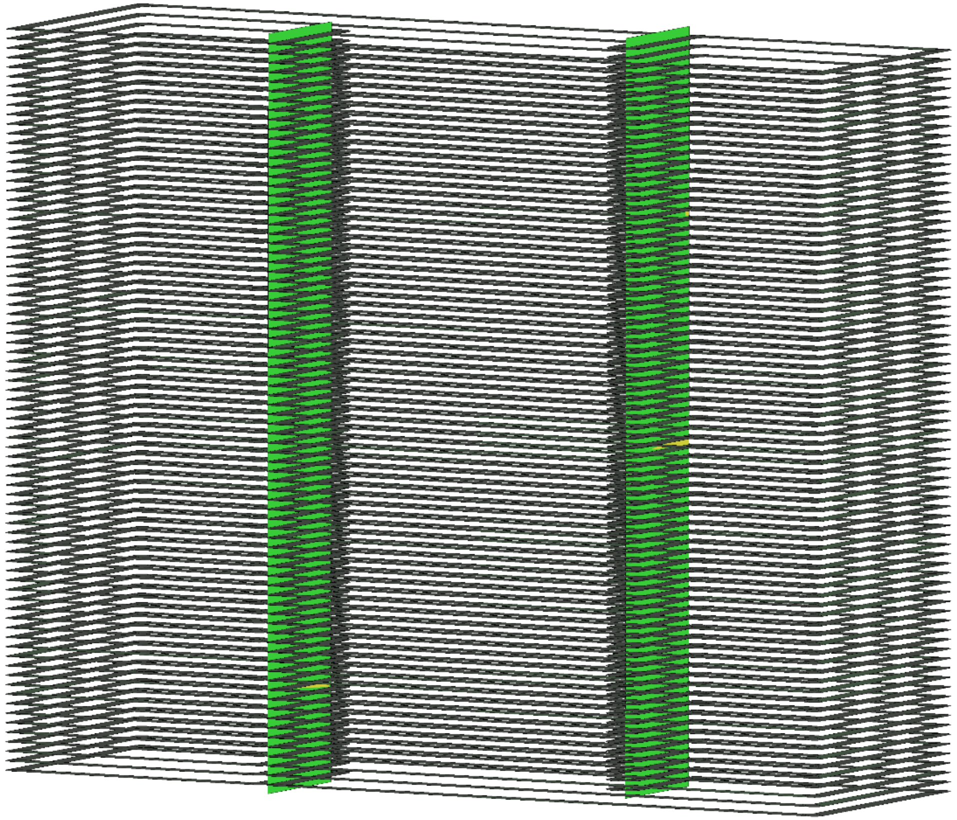
- ideal bond between layers (i.e., homogenous material properties)
- ideal geometry
- additional compliance simulated at the bottom support to match the stiffness in the experiment

Material properties	
Compressive strength	49.6 MPa
Tensile strength	3.5 MPa
Young's modulus	36.85 GPa

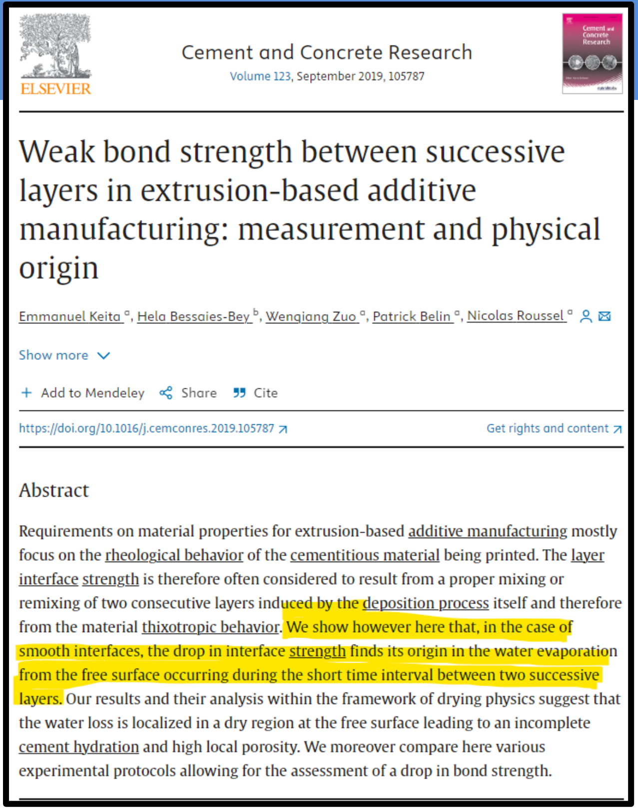




Model 2: Modelling 3DCP



- interface elements inserted between printed layers to simulate weaker bond
- both interlayer (i.e., between horizontal layers) and vertical (in the stiffeners) interfaces



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Volume 123, September 2019, 105787

Weak bond strength between successive layers in extrusion-based additive manufacturing: measurement and physical origin

Emmanuel Keita [a], Hela Bessaies-Bey [b], Wenqiang Zuo [a], Patrick Belin [a], Nicolas Roussel [a]

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Abstract

Requirements on material properties for extrusion-based additive manufacturing mostly focus on the rheological behavior of the cementitious material being printed. The layer interface strength is therefore often considered to result from a proper mixing or remixing of two consecutive layers induced by the deposition process itself and therefore from the material thixotropic behavior. We show however here that, in the case of smooth interfaces, the drop in interface strength finds its origin in the water evaporation from the free surface occurring during the short time interval between two successive layers. Our results and their analysis within the framework of drying physics suggest that the water loss is localized in a dry region at the free surface leading to an incomplete cement hydration and high local porosity. We moreover compare here various experimental protocols allowing for the assessment of a drop in bond strength.

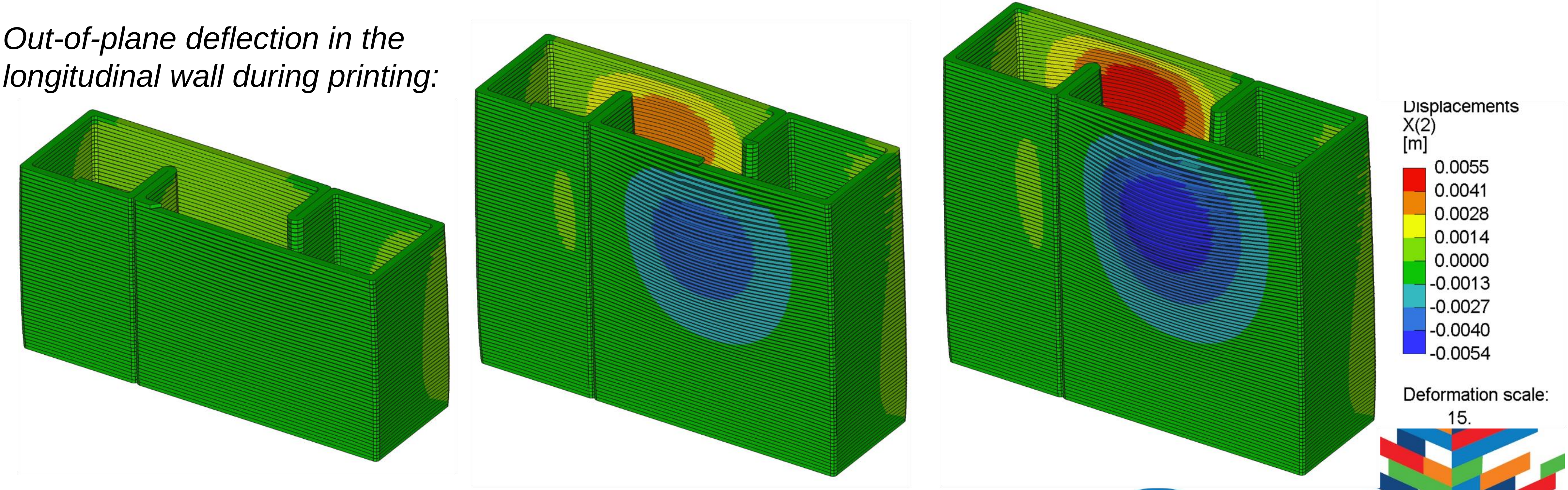
Parameter: symbol [unit]	Horizontal interface (interlayer)	Vertical interface (in the inner stiffener)
Tensile strength: $f_{t,int}$ [MPa]	0.50	0.25
Cohesion: c [MPa]	0.50	0.25
Friction coefficient: μ [-]	0.5	0.5

Model 2: Modelling 3DCP

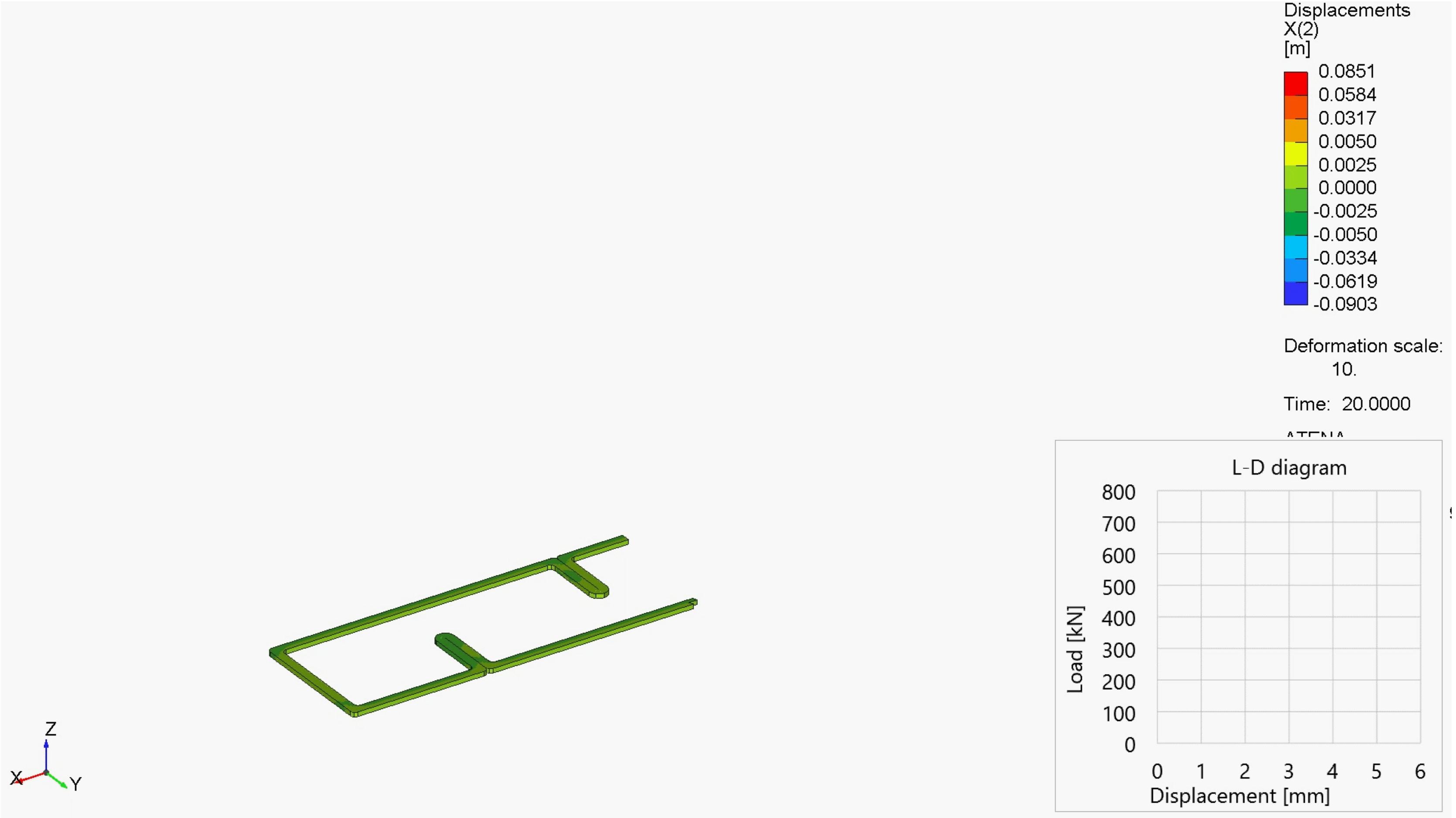
printing — *maturing* — *loading*

0 min — 35 min — 28 days

Out-of-plane deflection in the longitudinal wall during printing:



MODEL 2: MODELLING 3DCP

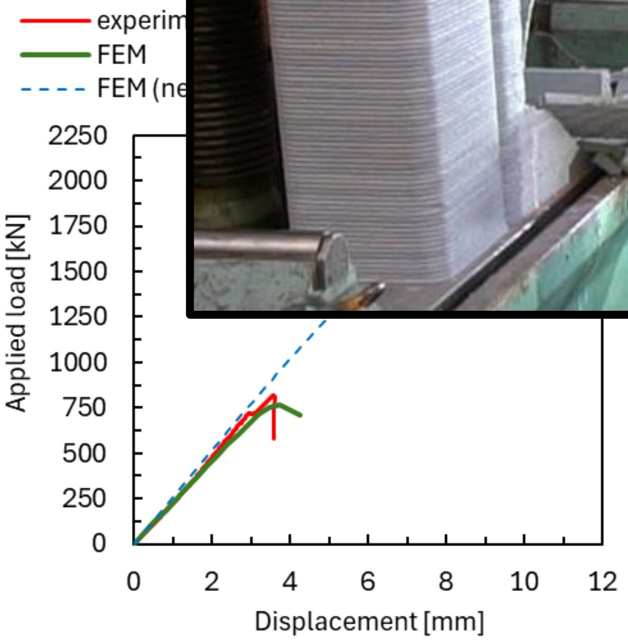


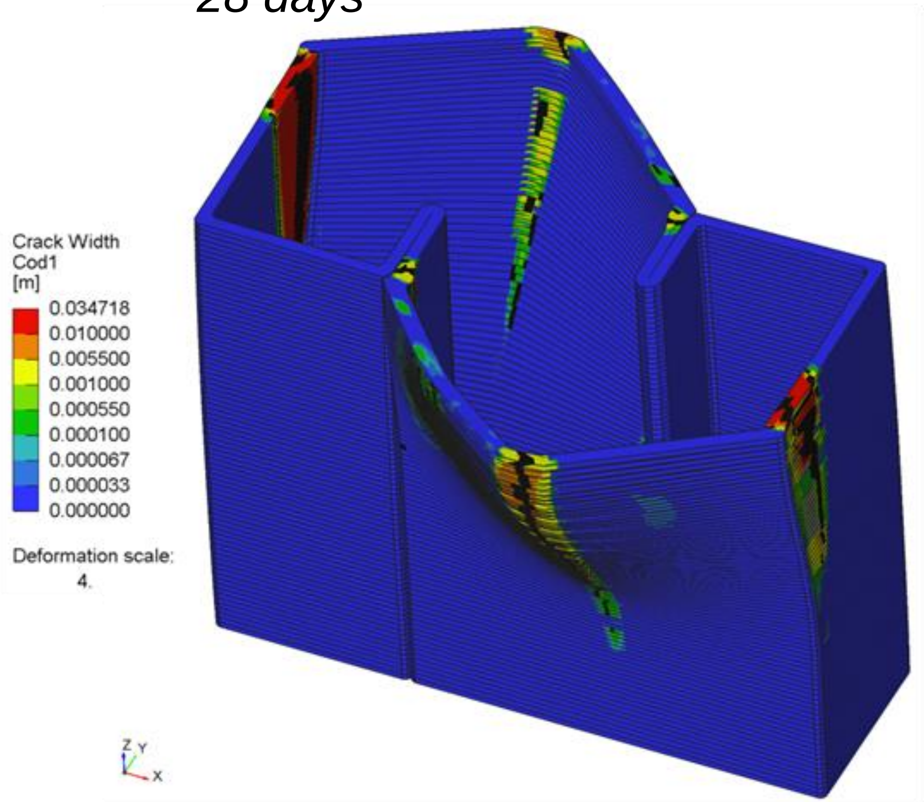
Model 2: Modelling 3DCP

printing — *loading*

0 min — 35 min — 28 days

- results were reproduced when considering geometrical imperfection (circa 5 mm) and interfaces between printed layers
- failure occurs through crack formation in the longer portion of the longitudinal wall and its subsequent brittle buckling
- failure mode in the analysis is similar as in the experiment



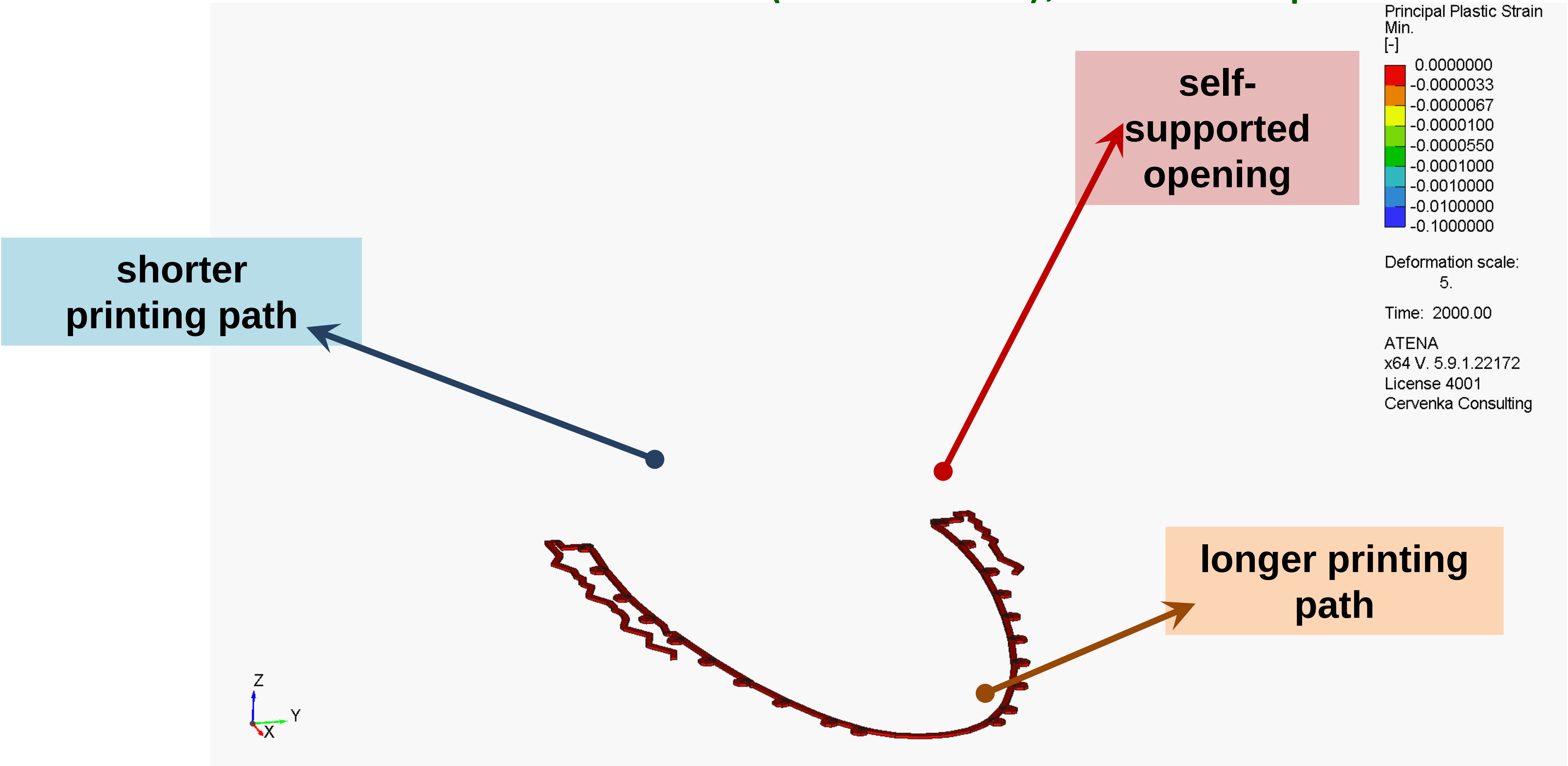


From the Lab to the Field: Prvok (Protozoan) House, Czech Republic

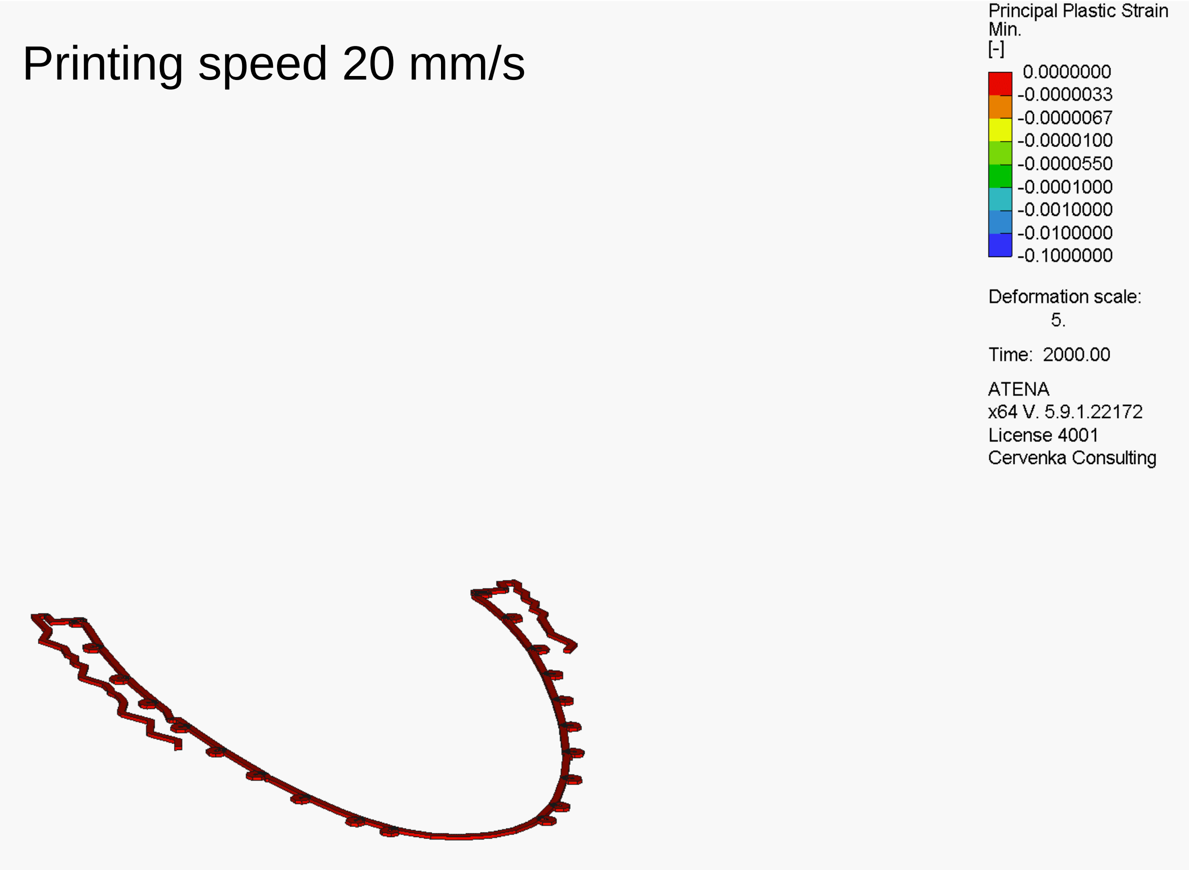
- first 3D printed house in the Czech Republic
- printed on a pontoon on the Vltava River in the city center of Prague
- wavy outer wall fo
- inner wall with Ω-
- layer thickness 45

s.r.o., www.scoolpt.com, Czech Republic

From the Lab to the Field: Prvok (Protozoan), Czech Republic

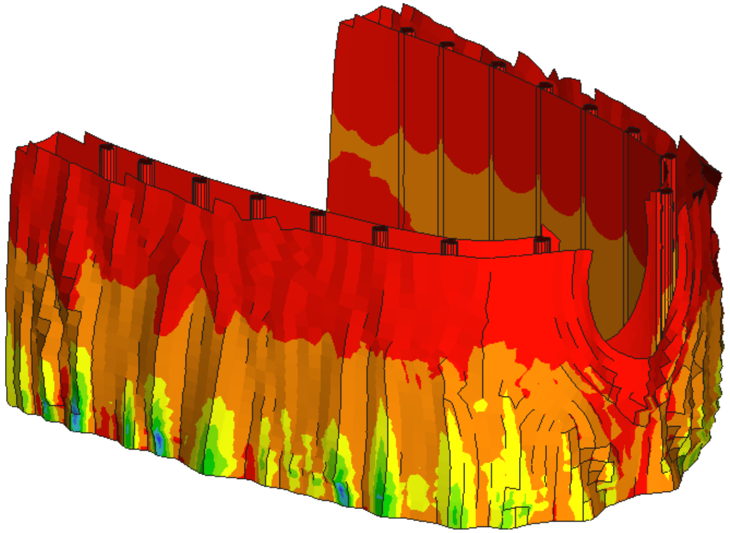


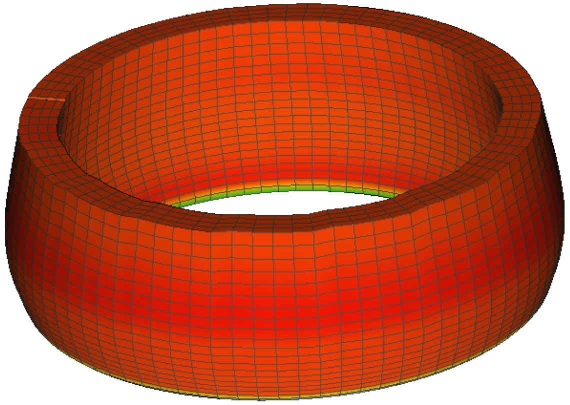
From the Lab to the Field: Prvok (Protozoan), Czech Republic

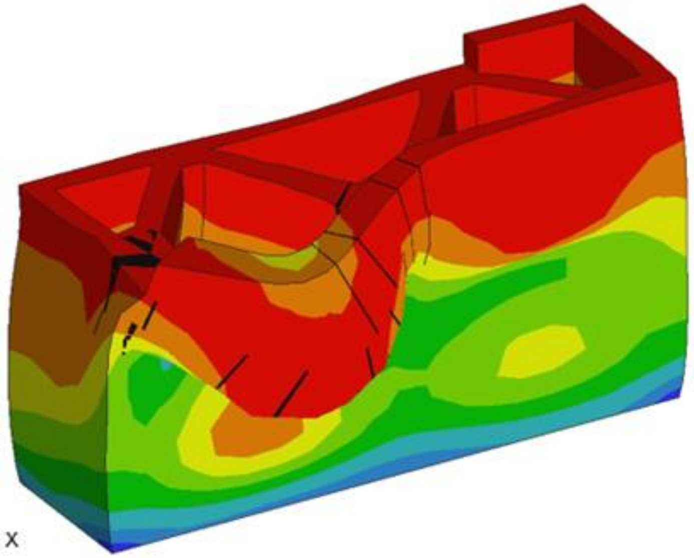


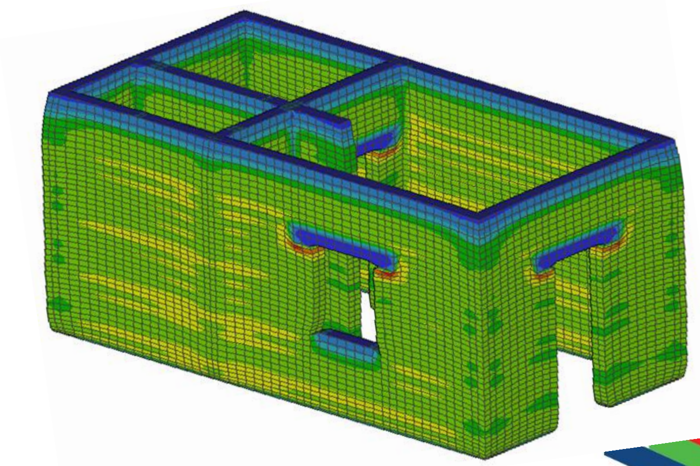
Summary

- module for analysis of digitally fabricated concrete structures through 3D extrusion
- extension of the ATENA FEM package
- application from laboratory to structural scale
- available for research and civil engineering practice
- issues remain in modelling strength of printed structures









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“Test your structure
before you print it.”

Thank you for your attention

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