Numerical Modeling Strategies for Sustainable Concrete Structures
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Microstructural Imaging to Produce Physically-Based Numerical Models of Concrete: Lattice Simulations

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Collaborative Research: An Integrated Microstructure-Based Approach to Property Prediction for Cement-Based Materials
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Outline of presentation

- Research objectives
  - Durability mechanics of structural concrete and repair technologies
- Rigid-Body-Spring Networks – Basic concepts
  - domain discretization
  - fracture modeling
- Effects of spatial distribution of material structure
  - split-cylinder testing of micro-concrete
  - tensile response of fiber-reinforced concrete
- Lattice modeling of transport processes
- Concluding remarks

Engineering: the activity of using scientific principals to solve problems with constraints

Newly recognized, evolving constraints on structural concrete use within the civil infrastructure

- scarcity of natural resources
- environmental loading
- increasing emphases on social and economic factors

New concrete technologies (e.g., alternative aggregates)

Recycled concrete aggregate

Lightweight aggregate produced from reservoir sediments (Tang et al., 2011)

How do new technologies affect the fresh and (long-term) hardened properties of structural concrete?

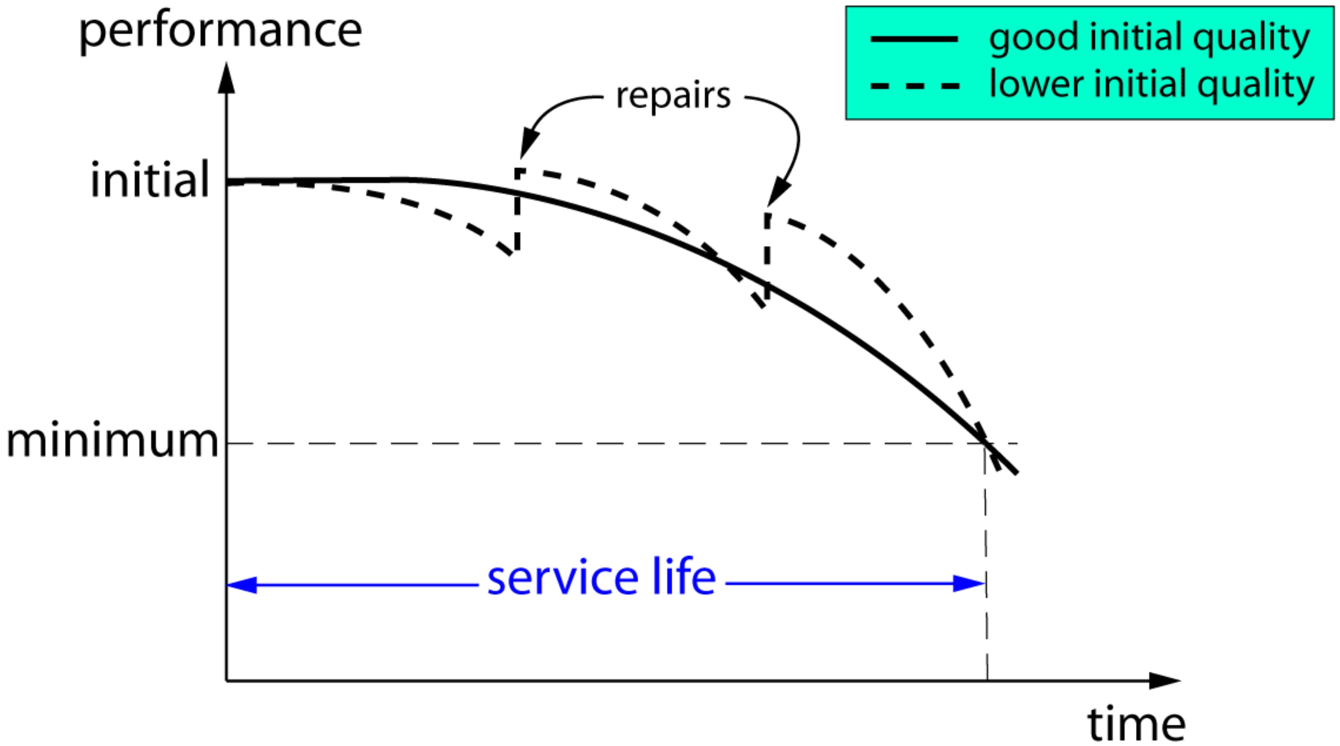
→

Strengthens the role of computational modeling in the development of concrete materials and structures!

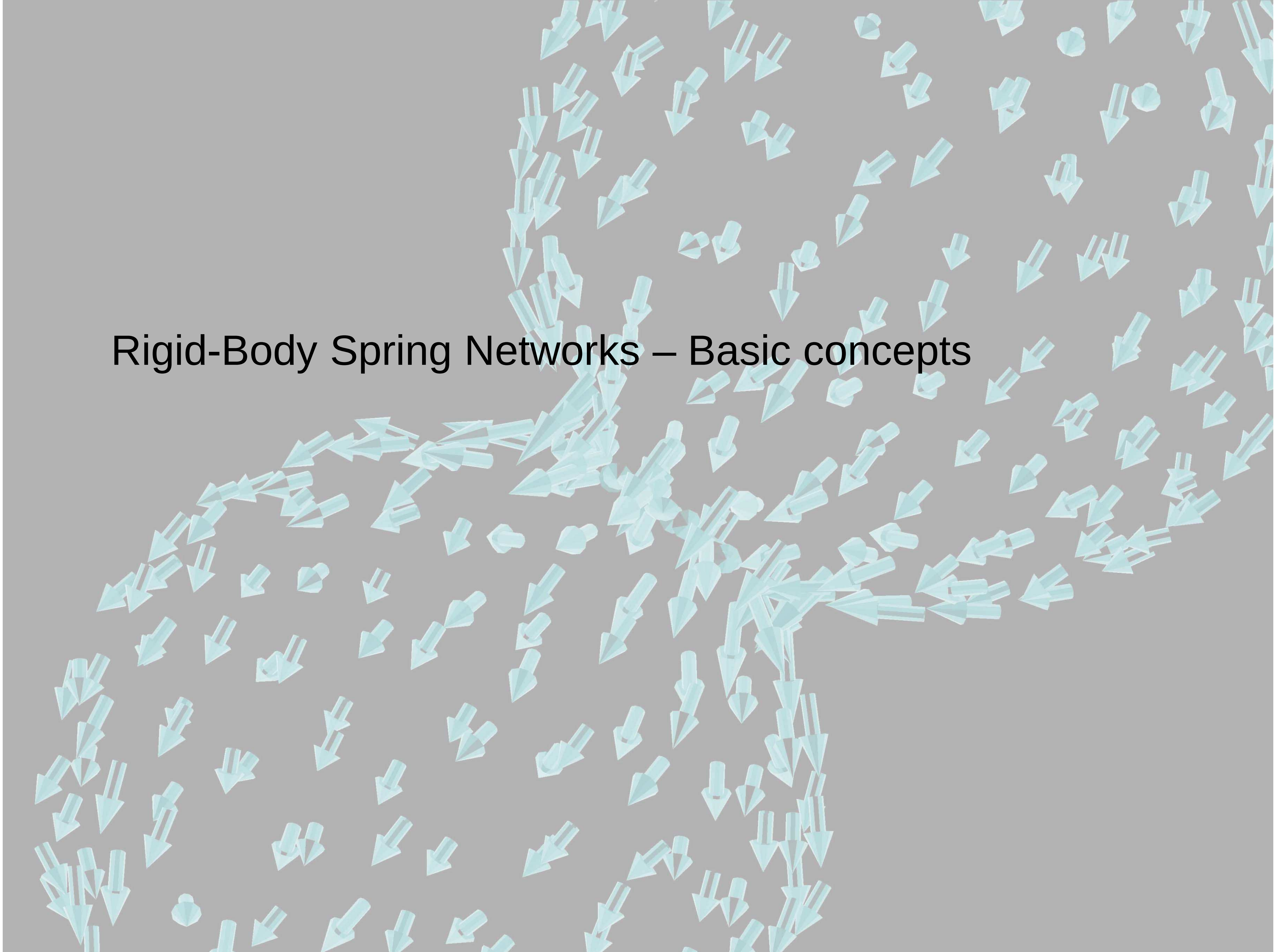
Durability design of structural concrete involves:

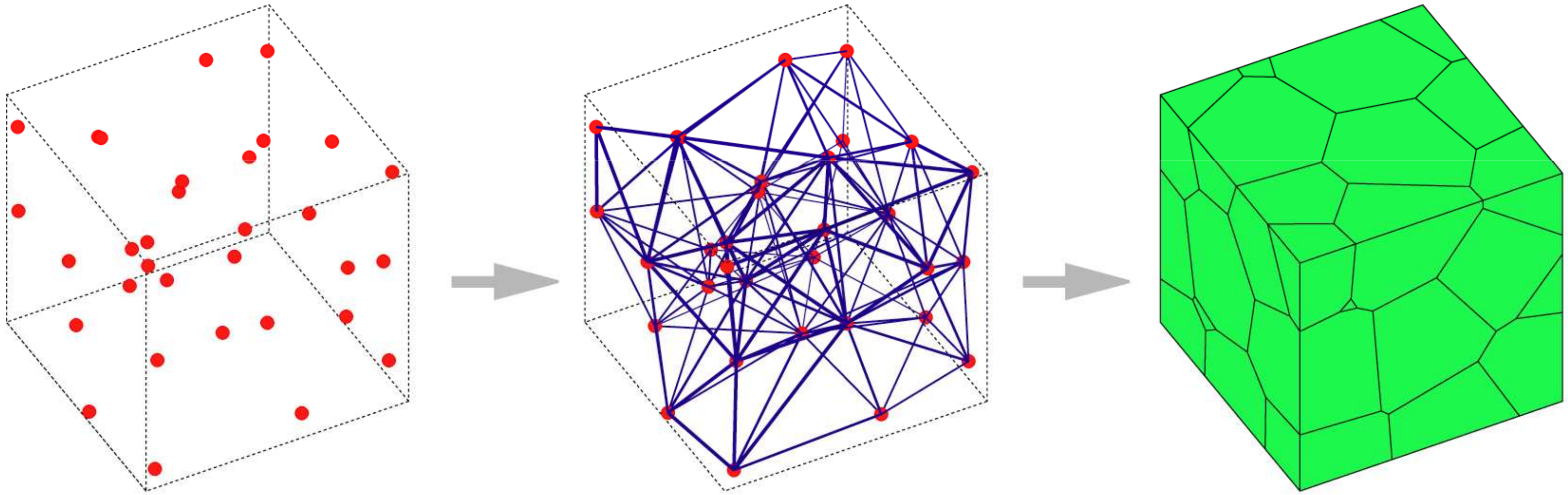
- forecasting of the exposure and load conditions
- material design
- elements of architecture and structural design
- processes of execution
- planned inspection and maintenance

Overall design objective: prevent deterioration of performance or ensure sufficiently slow rate of deterioration to meet service life requirements



Rigid-Body Spring Networks – Basic concepts



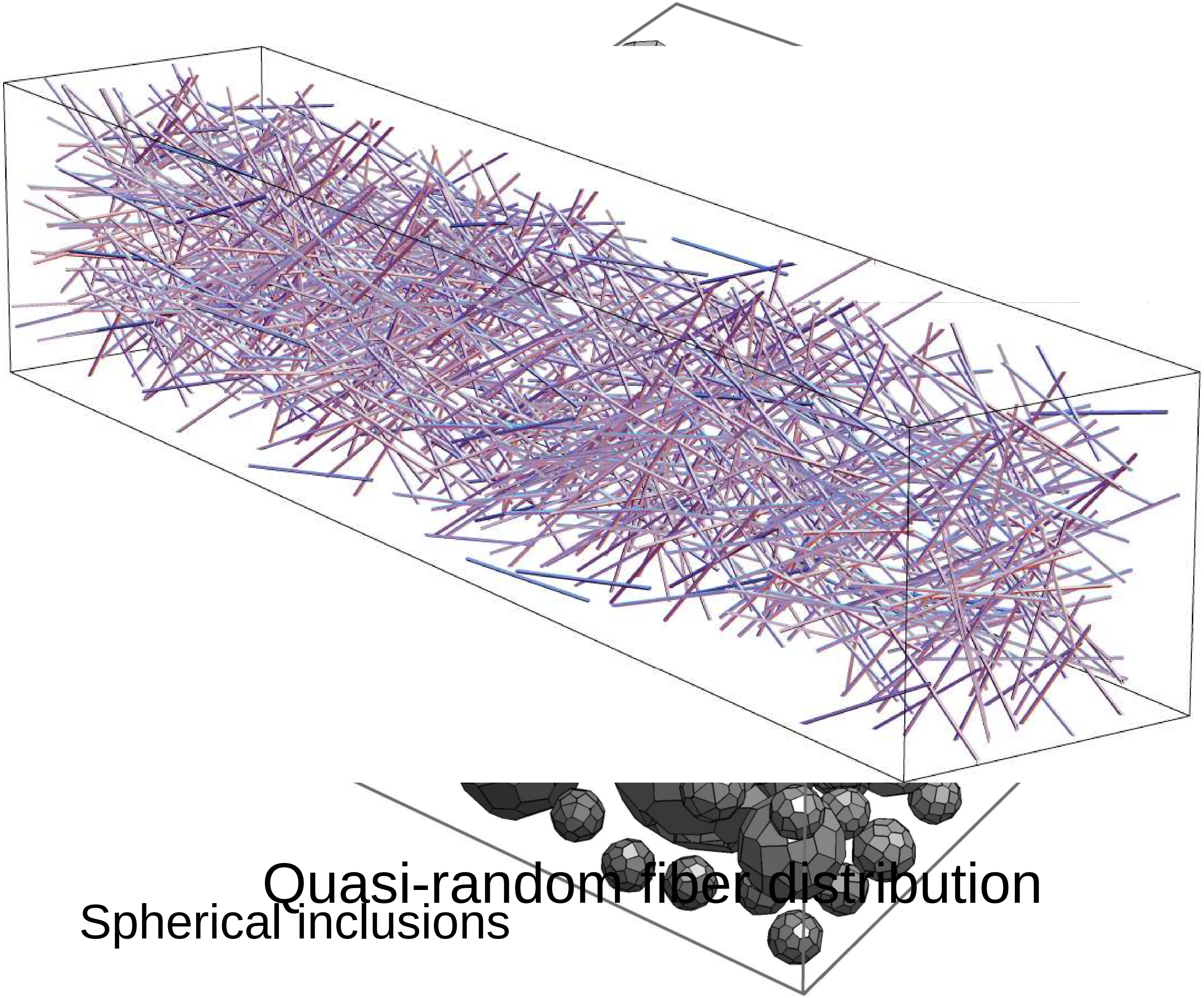


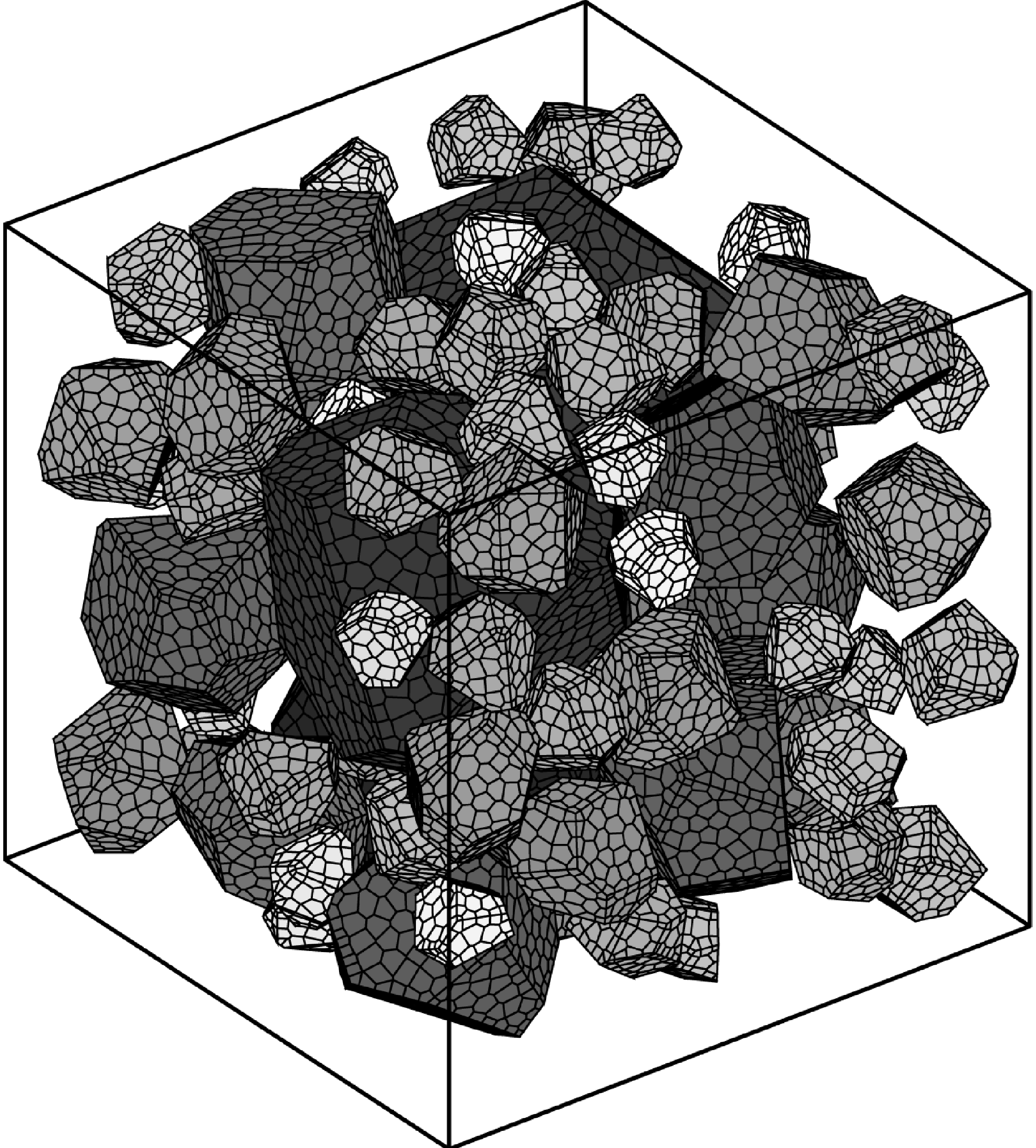
irregular point set
Random Sequential Addition - RSA
(Widom, 1966)

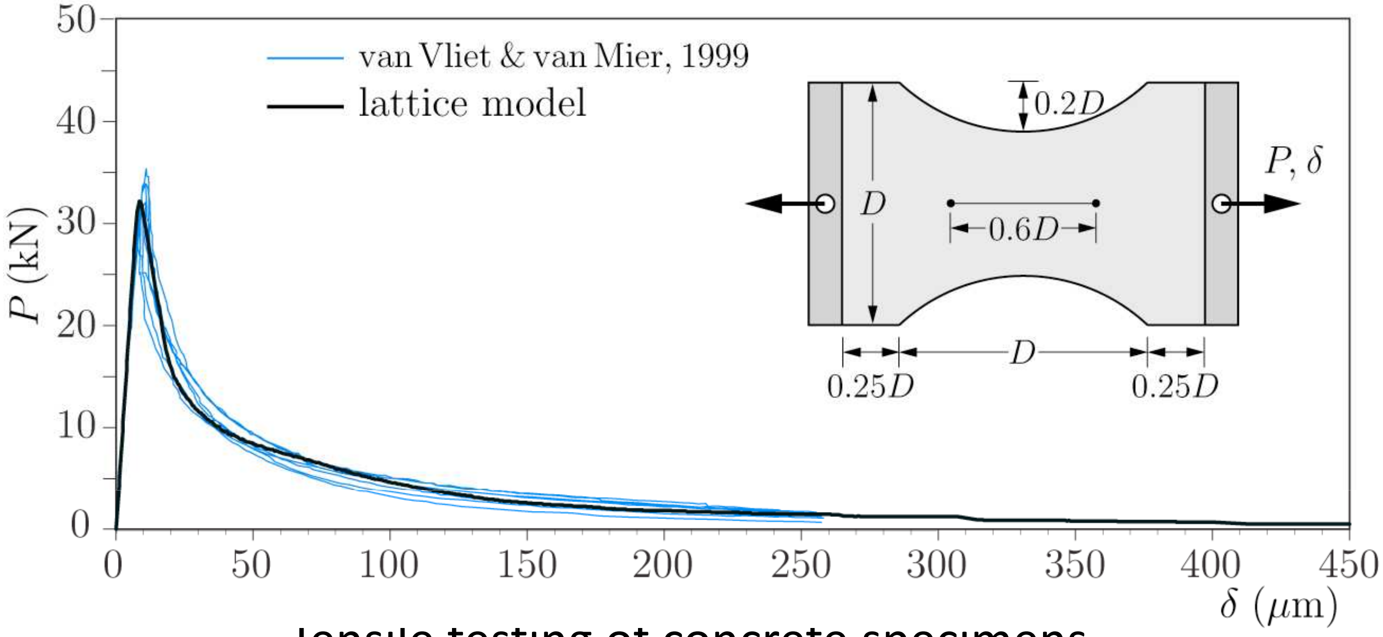
Delaunay tessellation

Voronoi tessellation

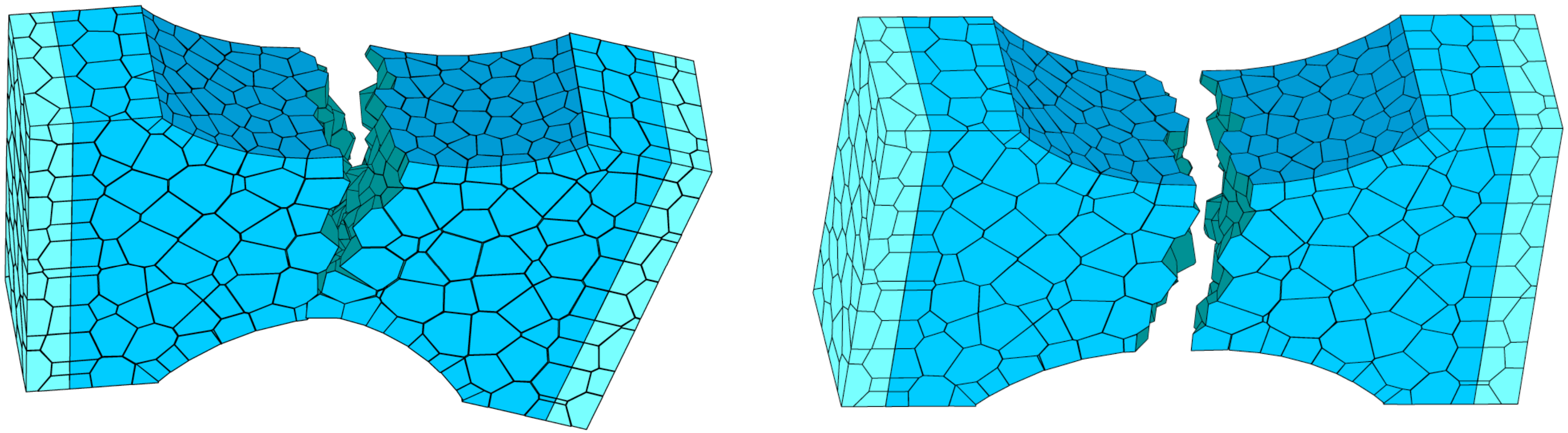
Domain discretization


Quasi-random fiber distribution
Spherical inclusions





Tensile testing of concrete specimens

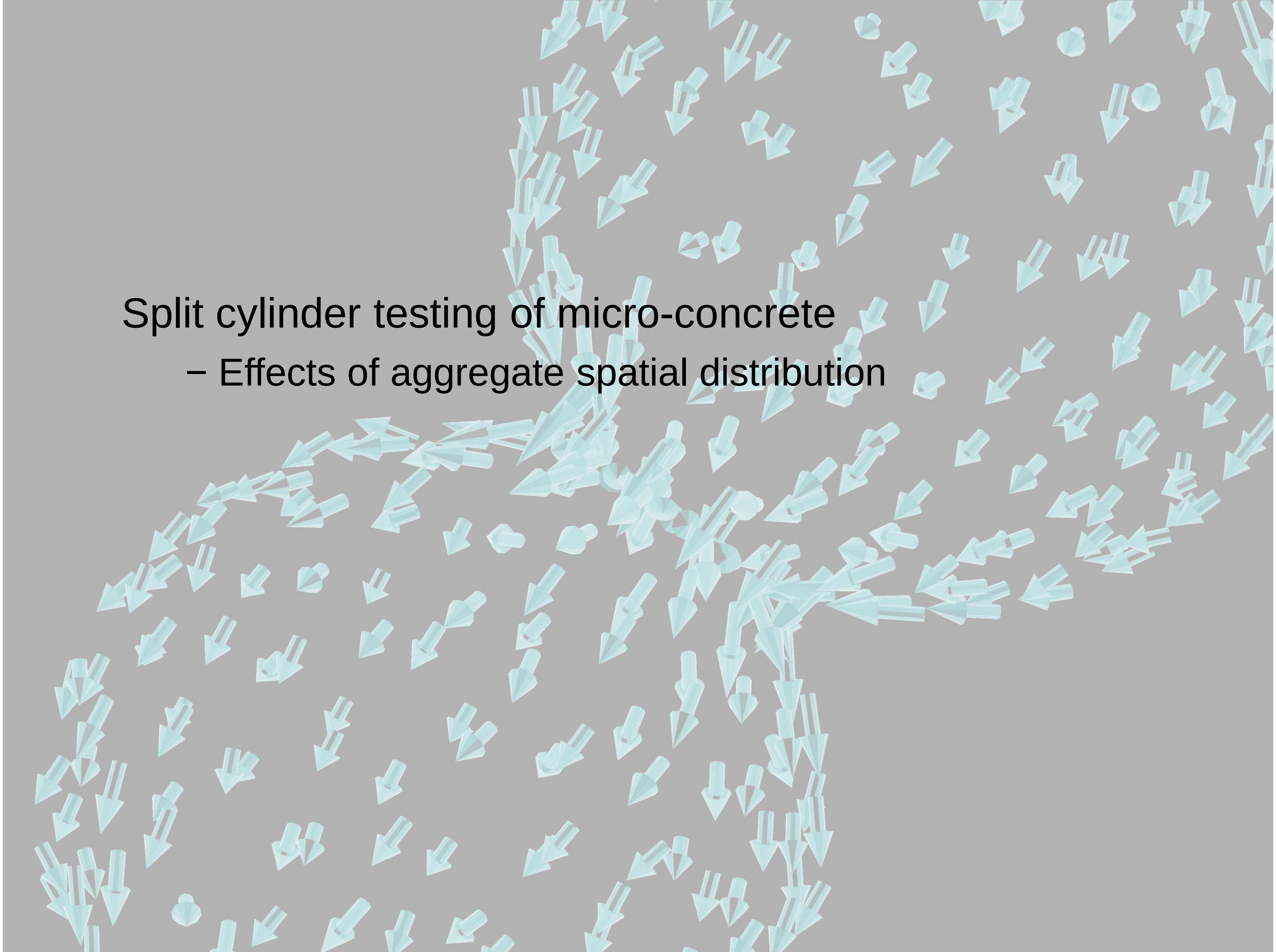


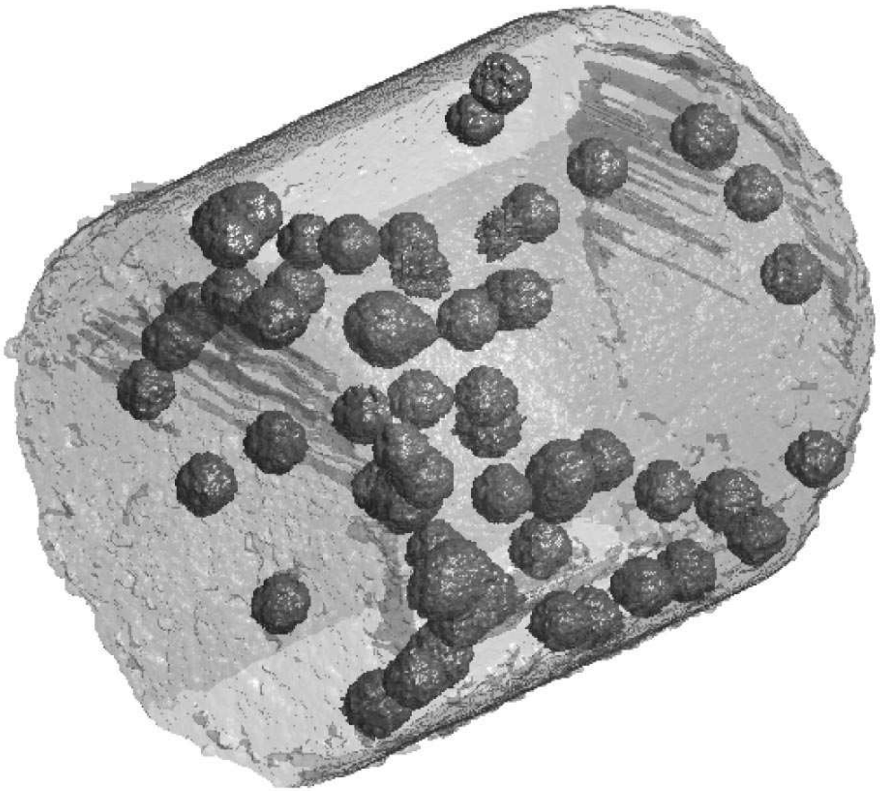
Fracture pattern for differing boundary conditions

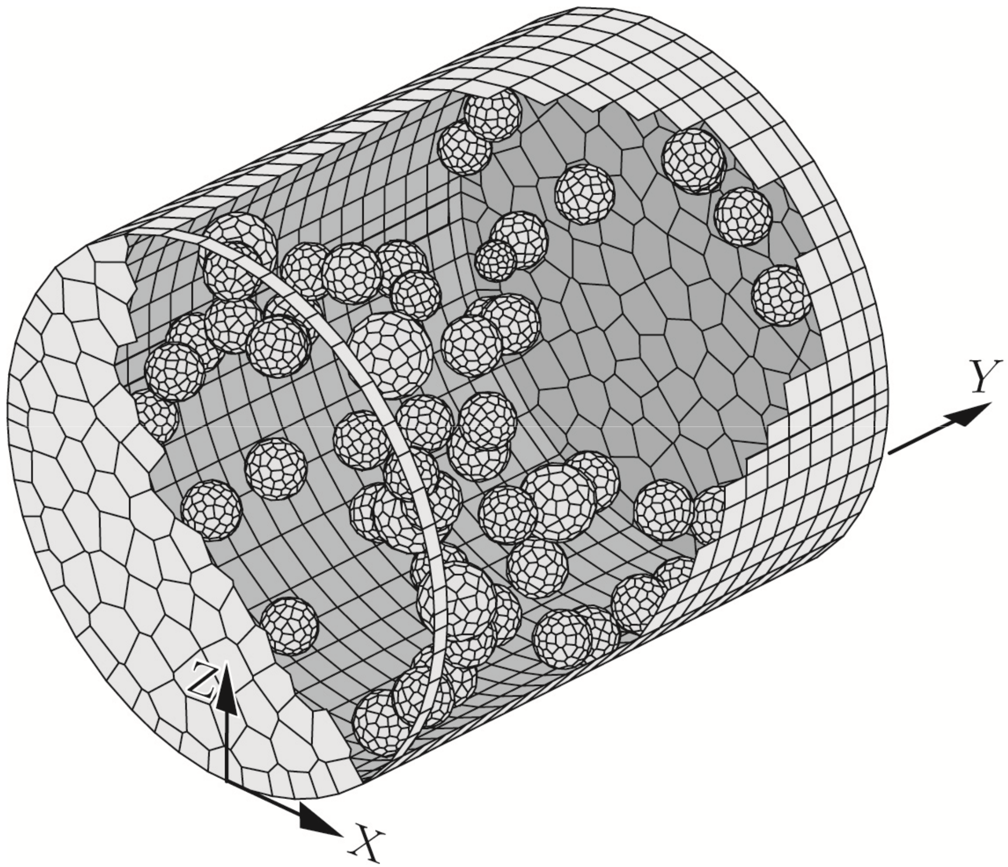
Berton and Bolander, Crack band model of fracture in irregular lattices, *Computer Methods in Applied Mechanics and Engineering* 2006; 195(52): 7172-7181

Split cylinder testing of micro-concrete

− Effects of aggregate spatial distribution





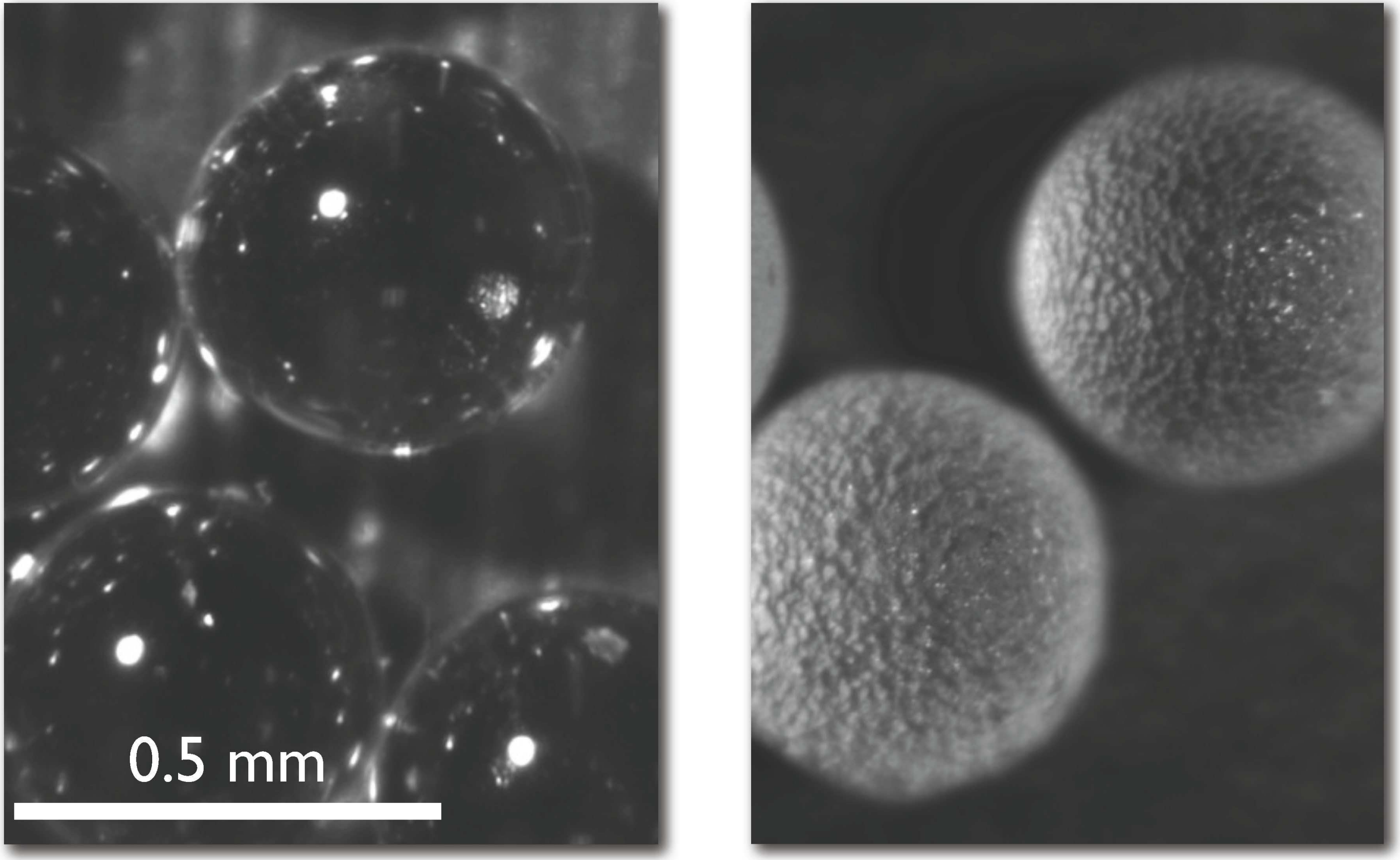


Segmented tomographic image

Lattice model discretization

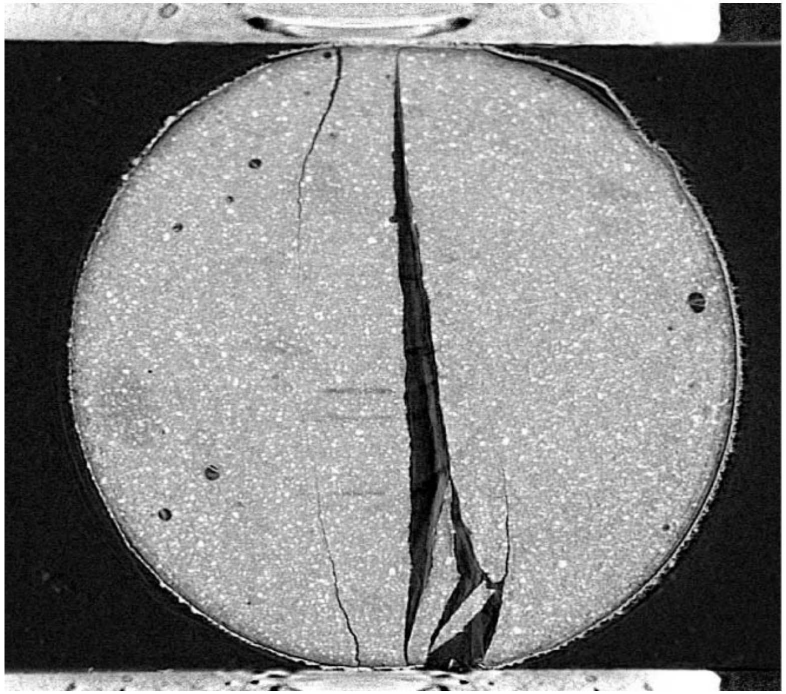
Split-cylinder testing of glass bead-mortar composites

Asahina et al., Modeling of phase interfaces during pre-critical crack growth in concrete, *Cement and Concrete Composites* 2011; 33(9): 966-977

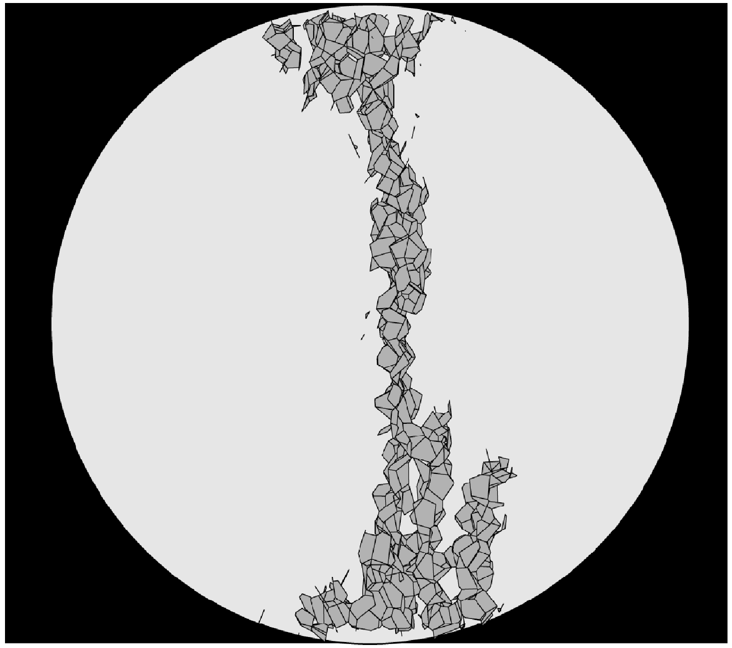


untreated acid-etched

Glass bead inclusions used in micro-concrete specimens

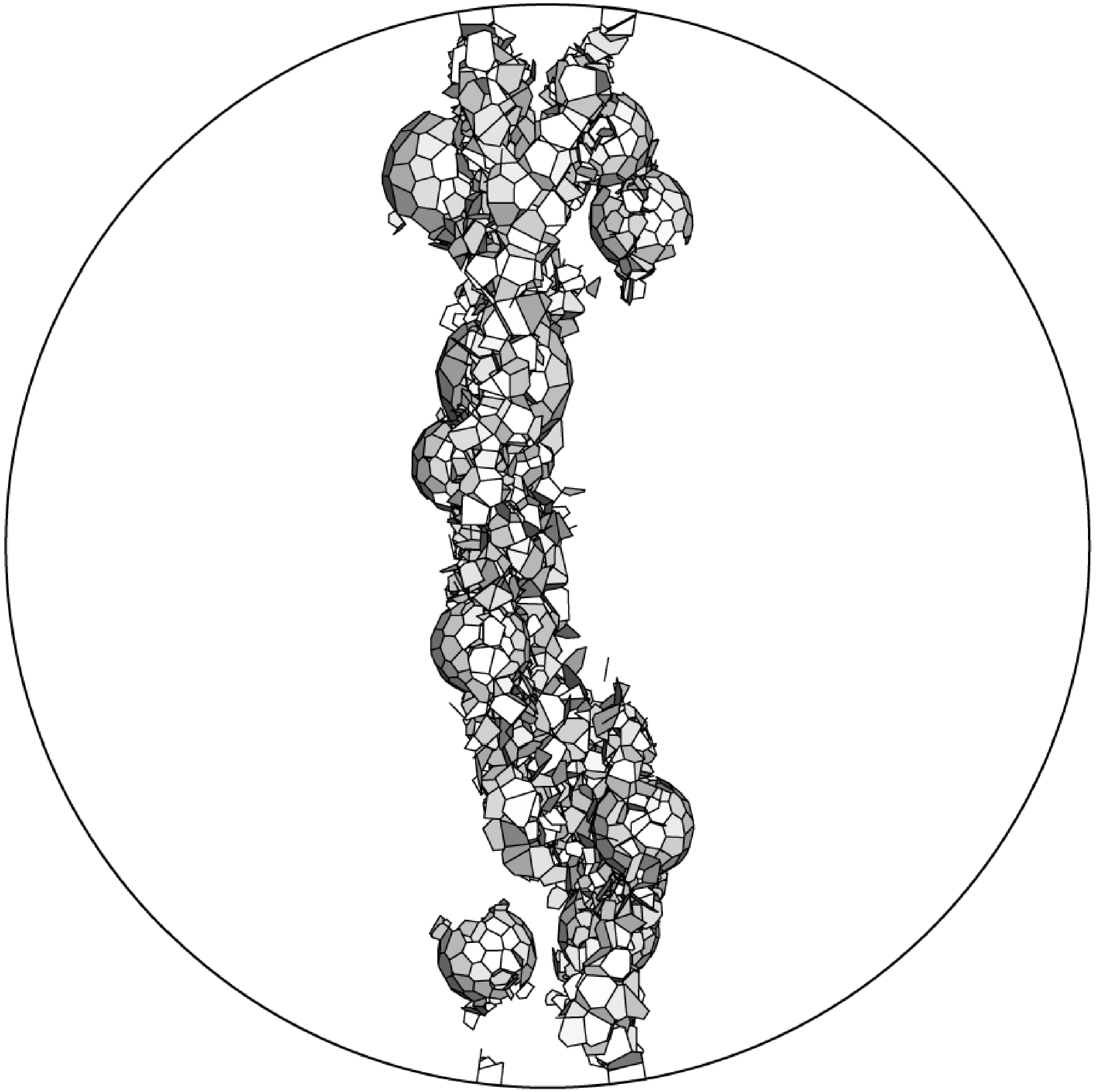


Physical test

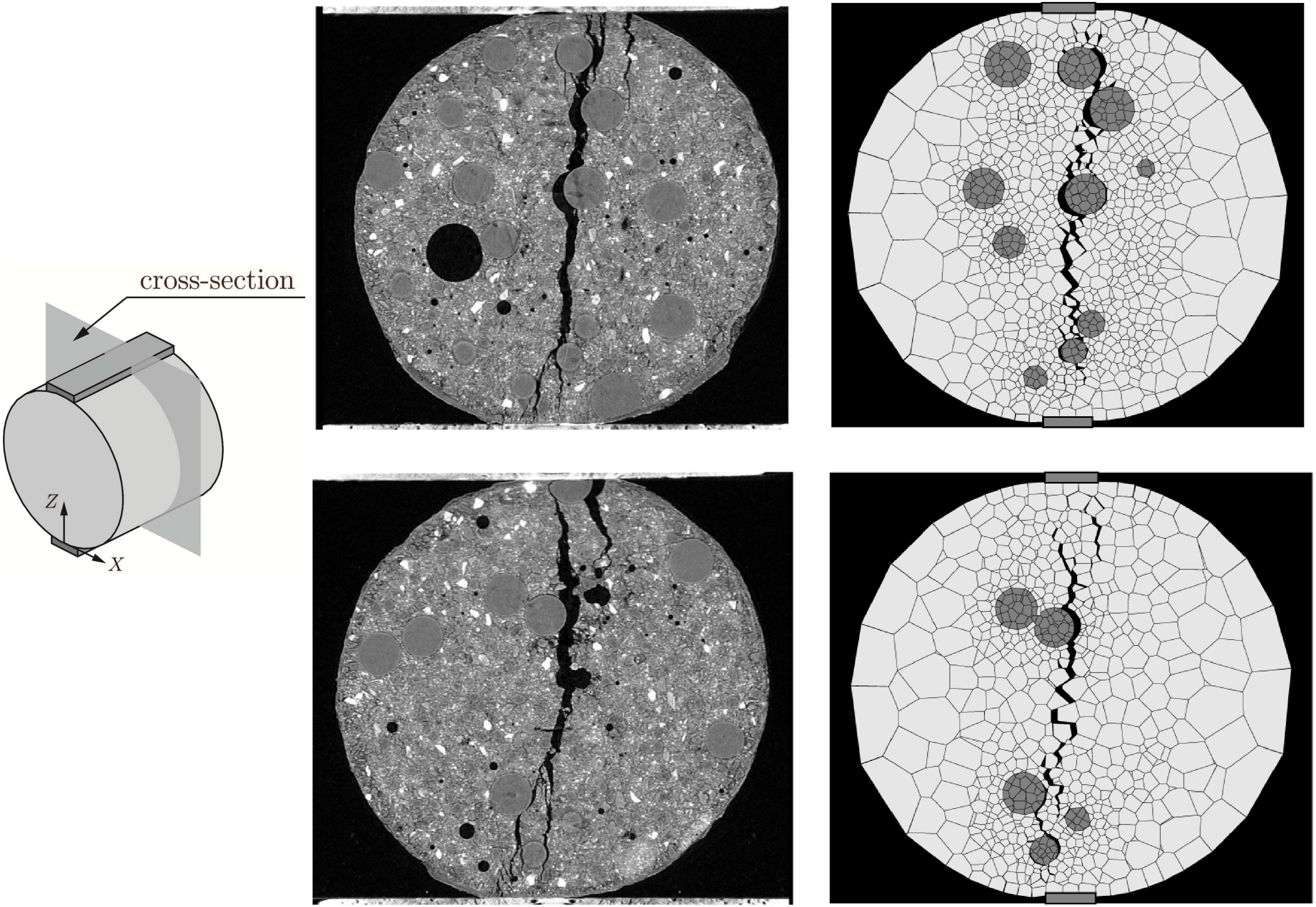


Numerical test

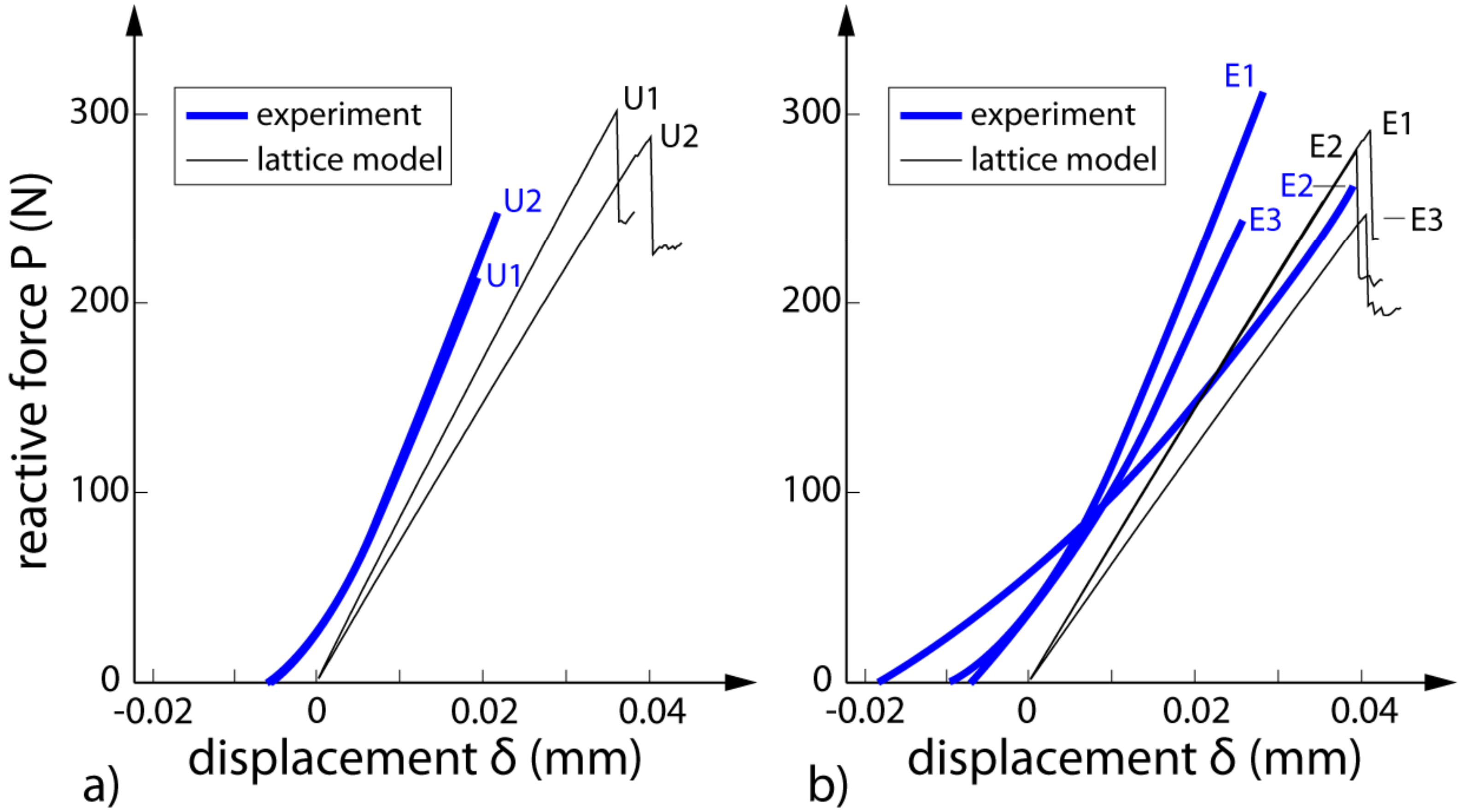
Calibration of matrix strength through simulation of split cylinder test



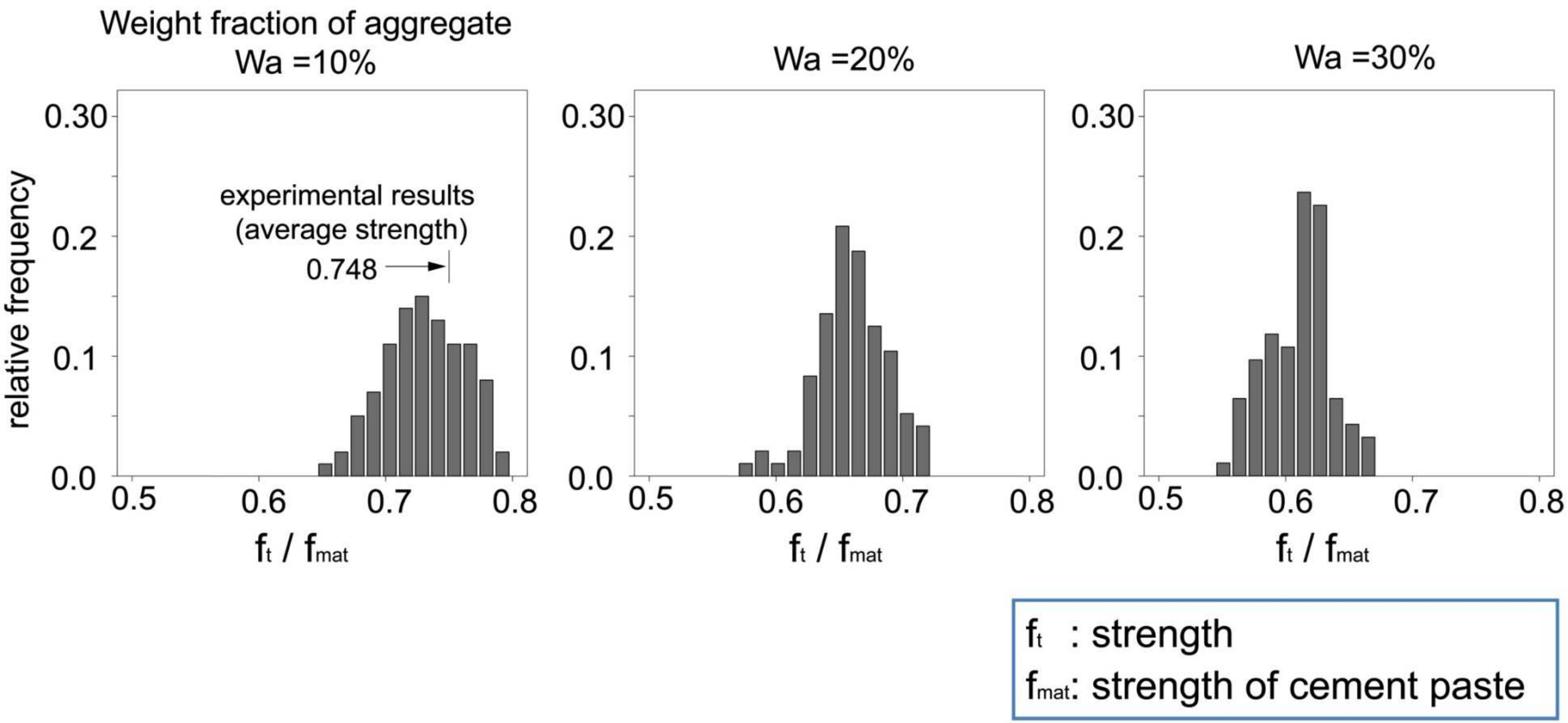
Frontal view of 3-D fracture process



Typical damage patterns after peak load

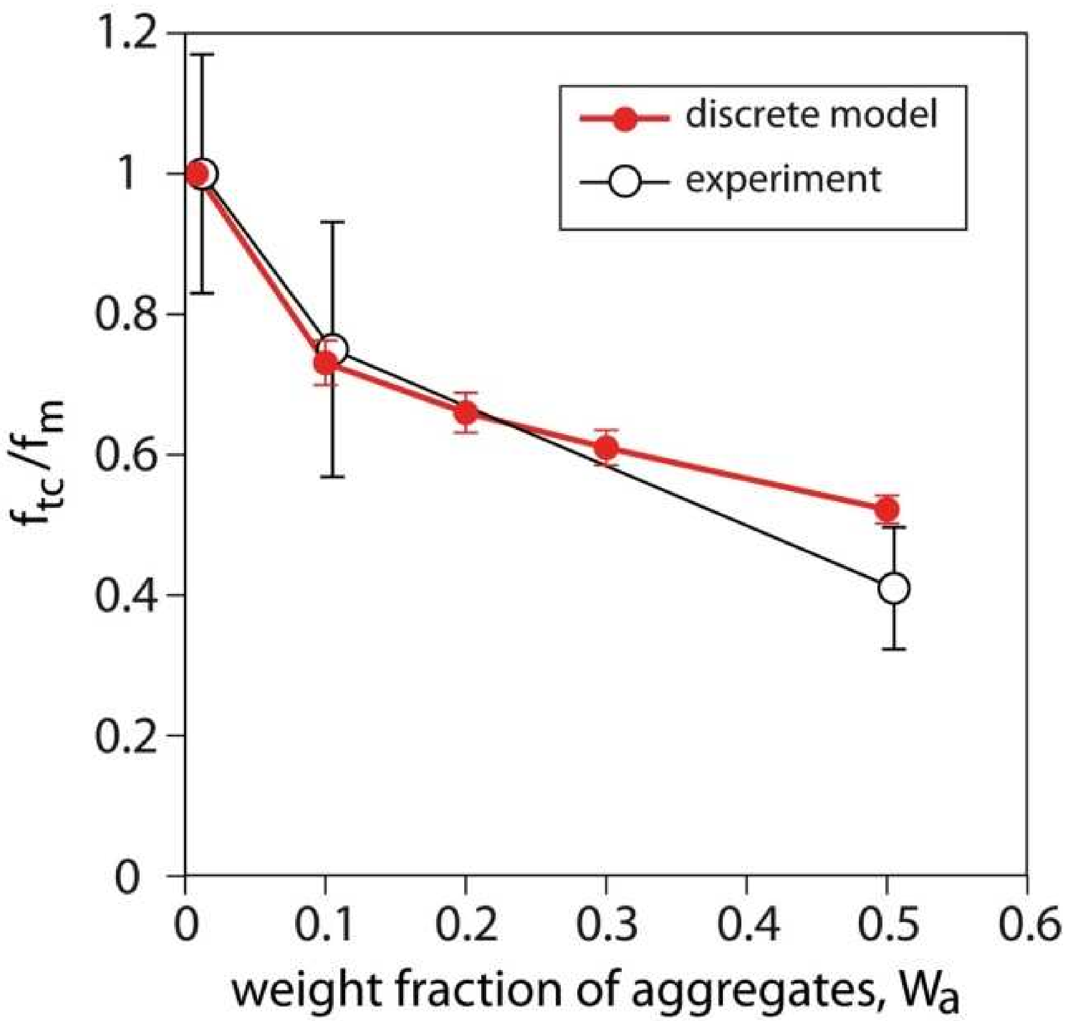


Load-displacement response of split-cylinder specimens containing:
a) unetched glass beads; and b) etched glass beads

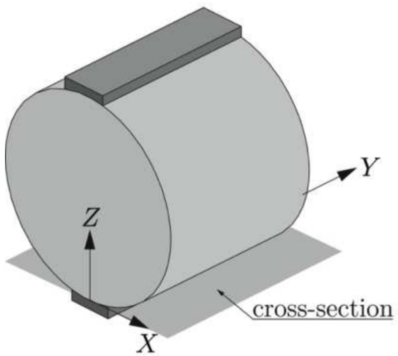


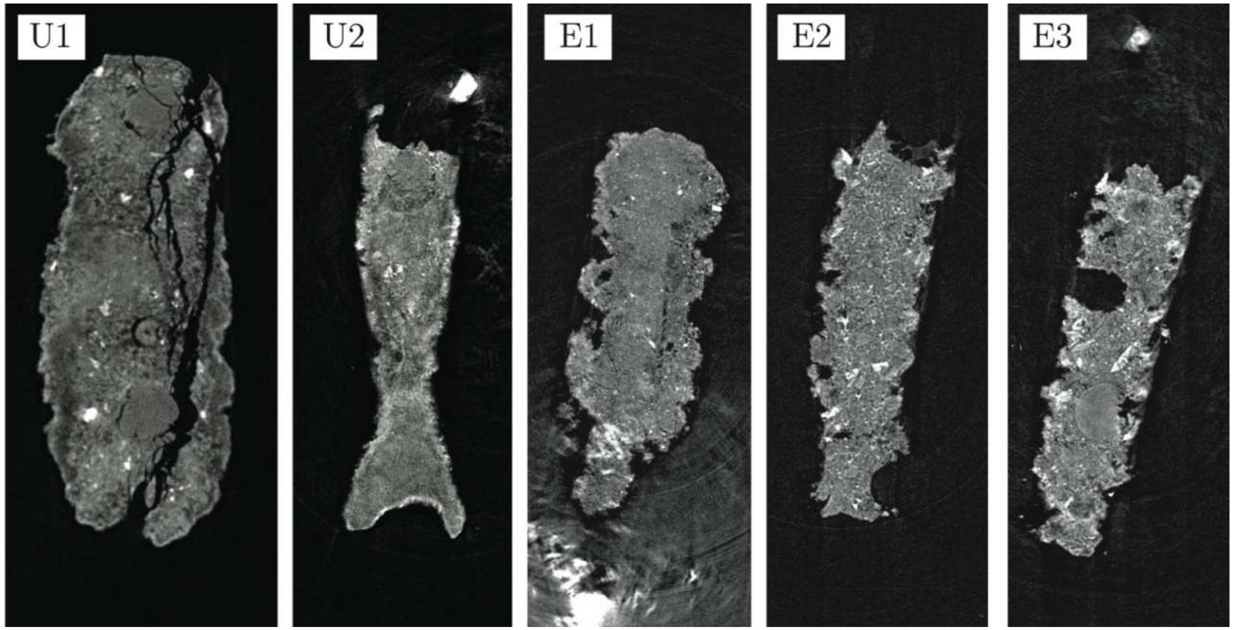
Variation of specimen strength

(100 models differing only in aggregate spatial distribution)



Dependence of composite strength on weight fraction of aggregates



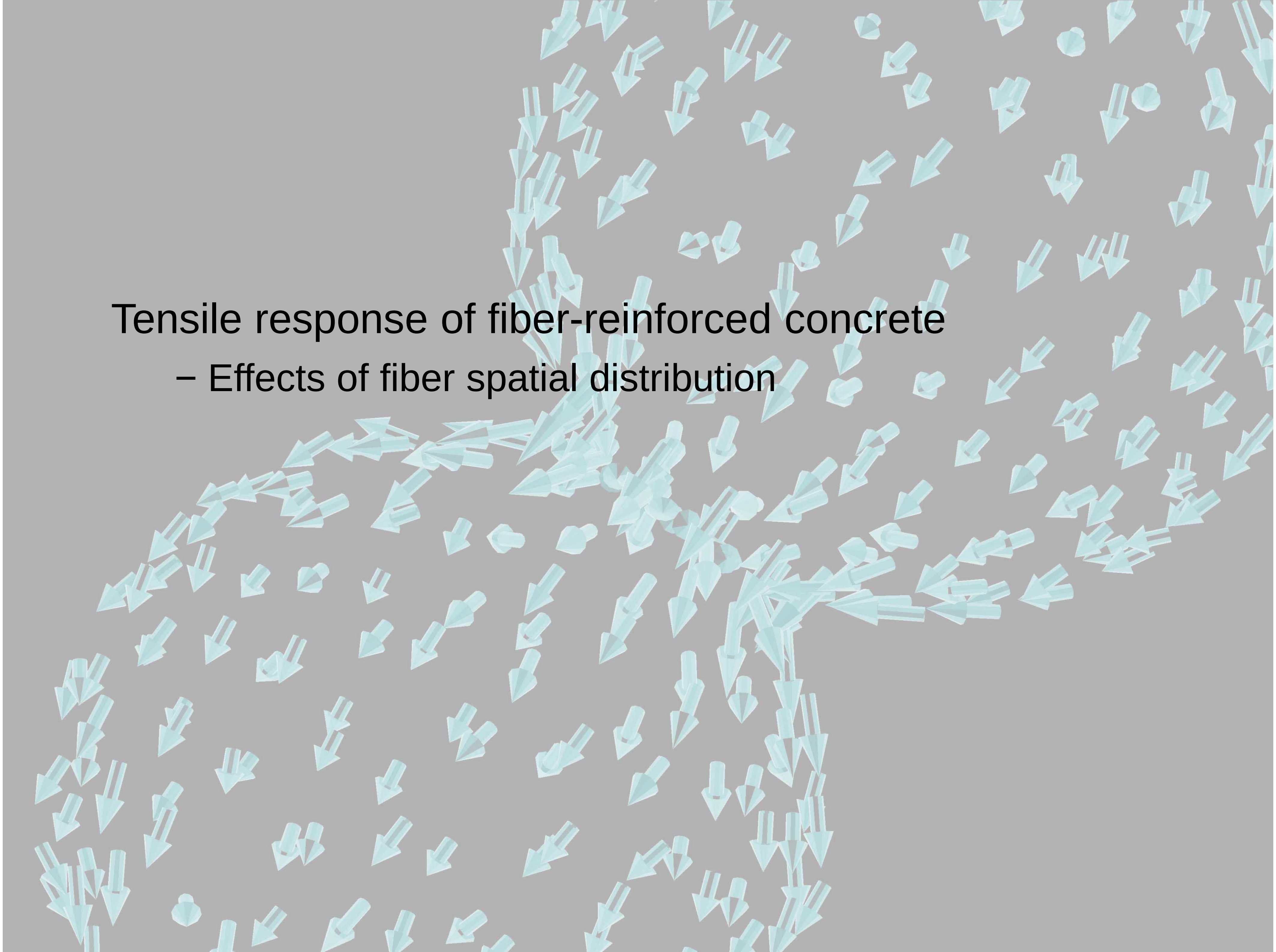


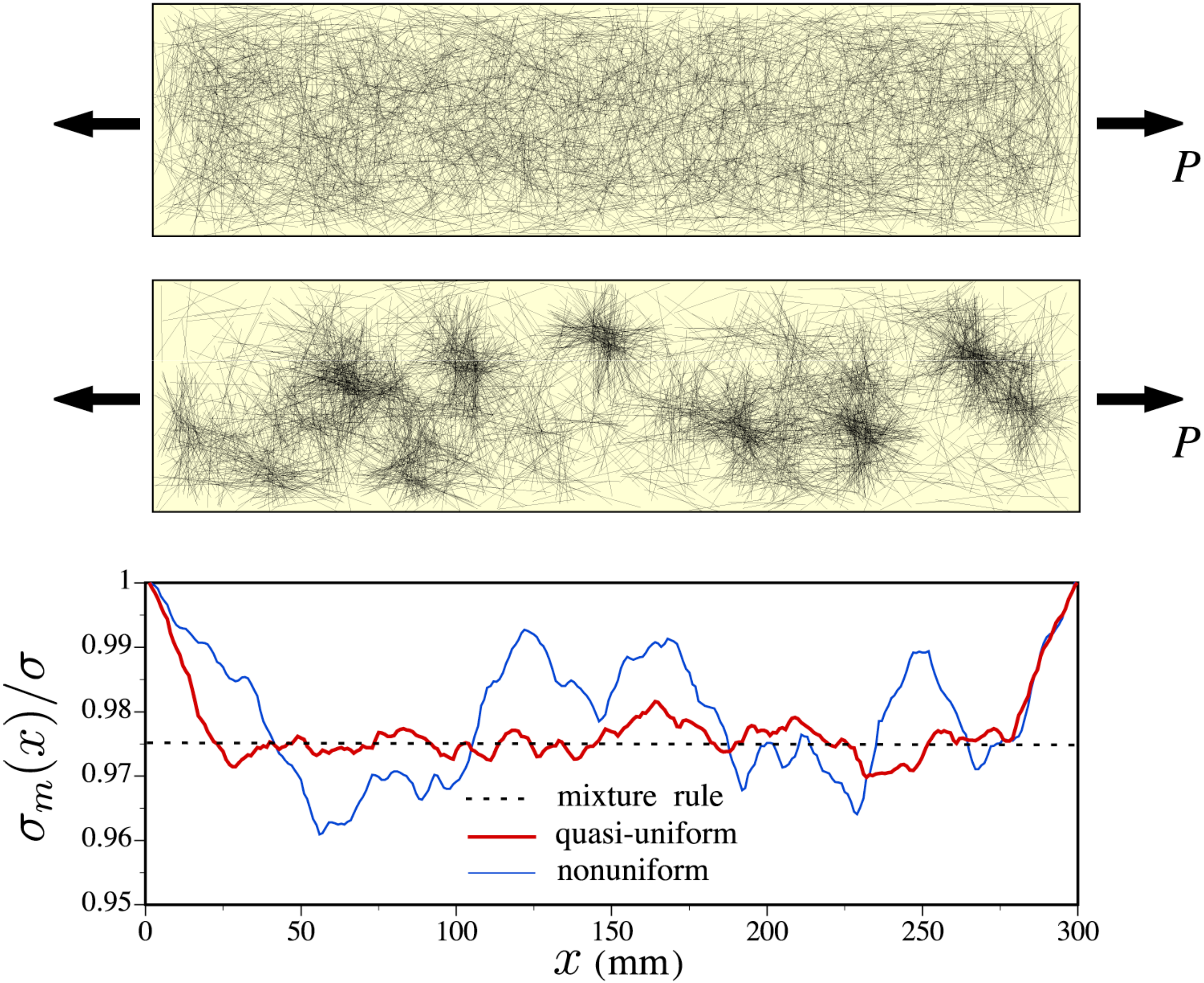
Other potential sources of variability

- differences in specimen size and geometry
- unevenness along the loading surfaces
- presence of large air voids

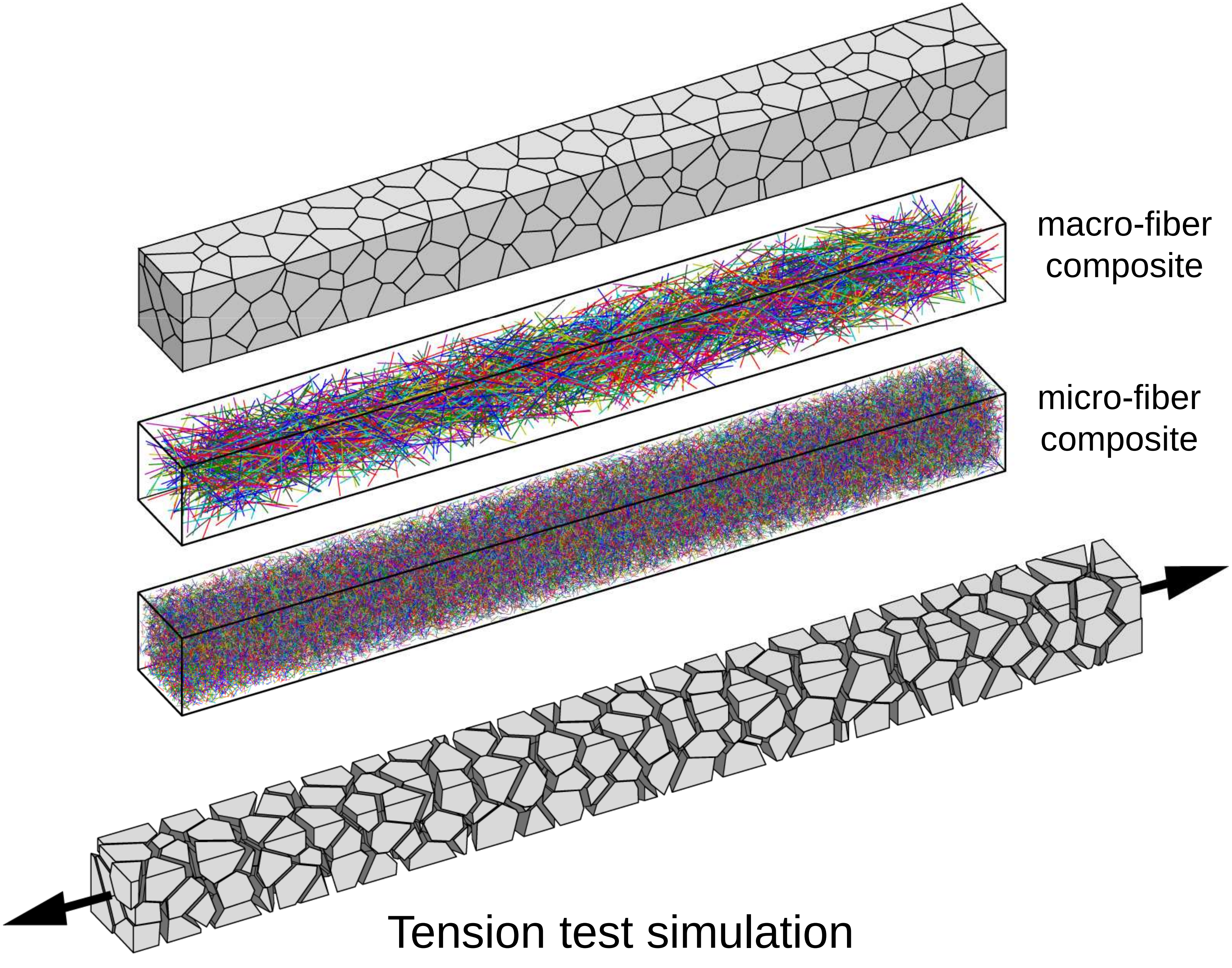
Tensile response of fiber-reinforced concrete

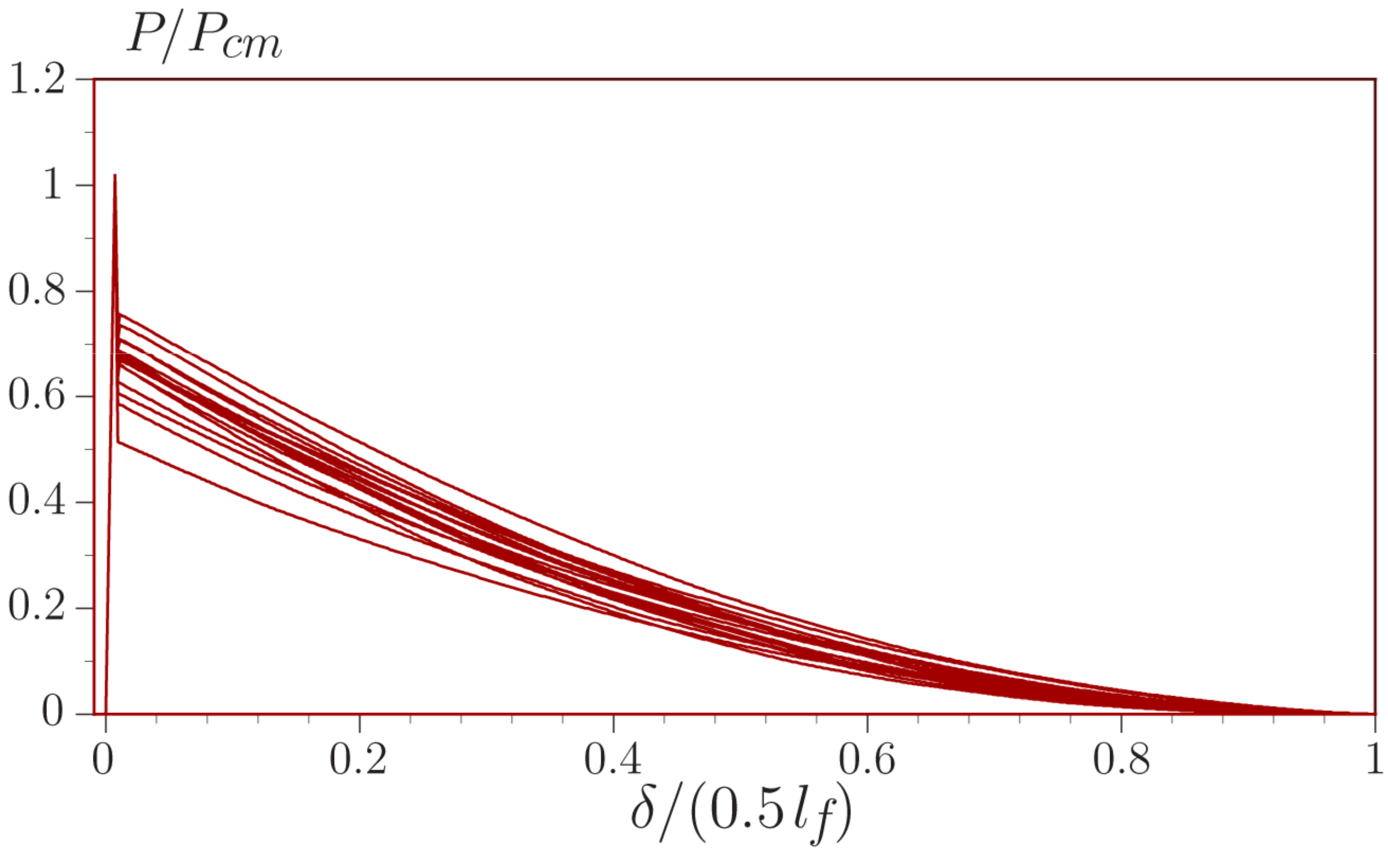
– Effects of fiber spatial distribution





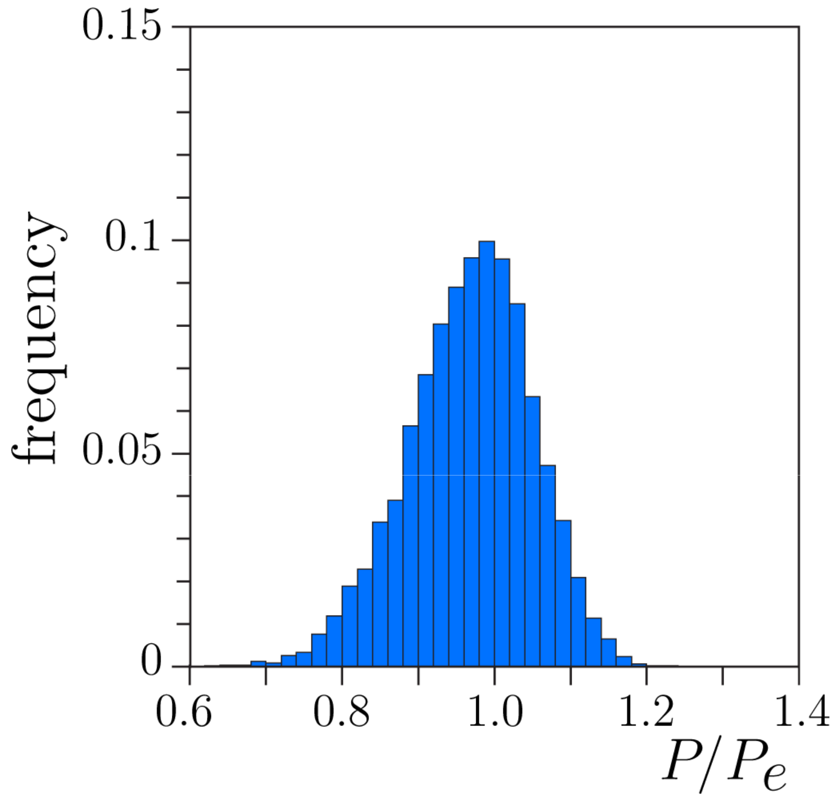
Matrix stress as affected by fiber distribution nonuniformity


macro-fiber
composite
micro-fiber
composite
Tension test simulation



Effect of fiber distribution non-uniformity on tensile response
(20 random realizations of the macrofiber distribution)

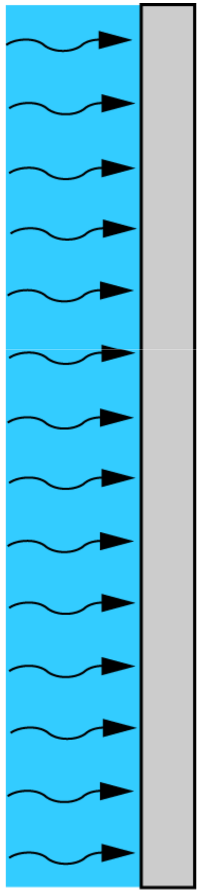
Bolander et al., Fracture of fiber-reinforced cement composites: effects of fiber distribution, *International Journal of Fracture* 2008; 154(1), 73-86



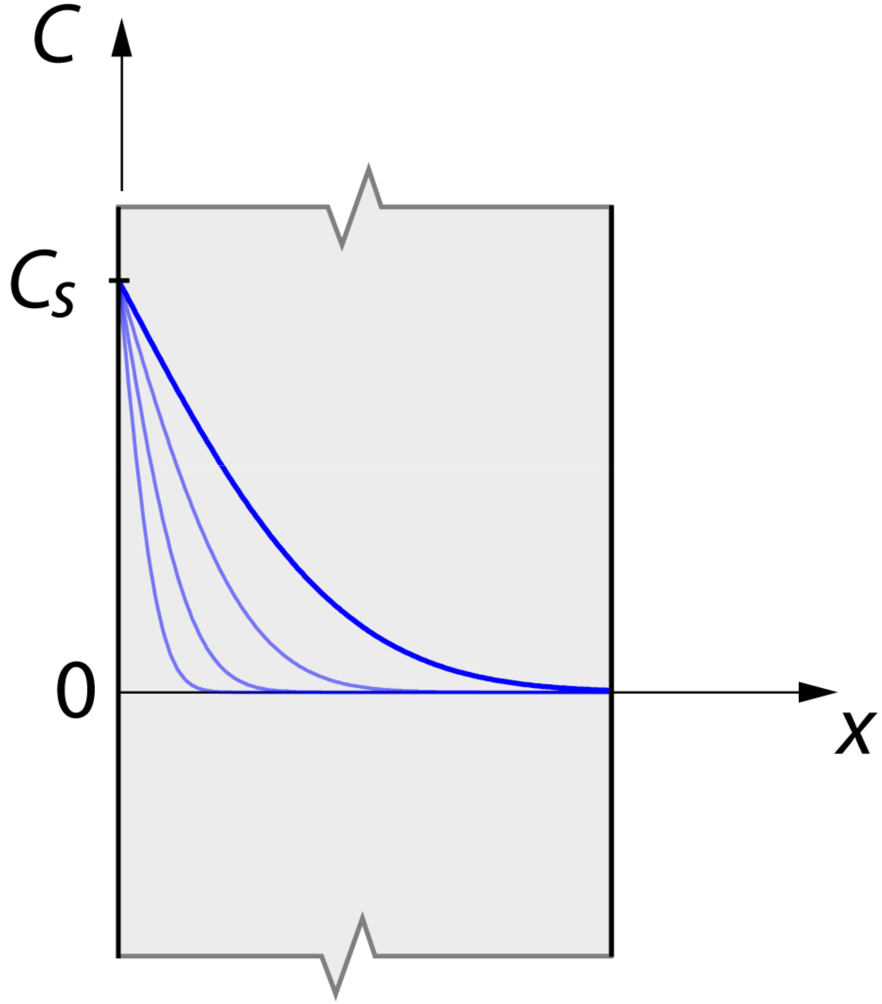
Frequency distribution of post-cracking strength
(10,000 random realizations of the macrofiber distribution)

$$P_e = n\pi\phi\frac{l}{4}\tau$$

where:
- n = number of fibers crossing fracture plane
- ϕ = fiber diameter
- l = fiber length
- τ = fiber-matrix bond strength

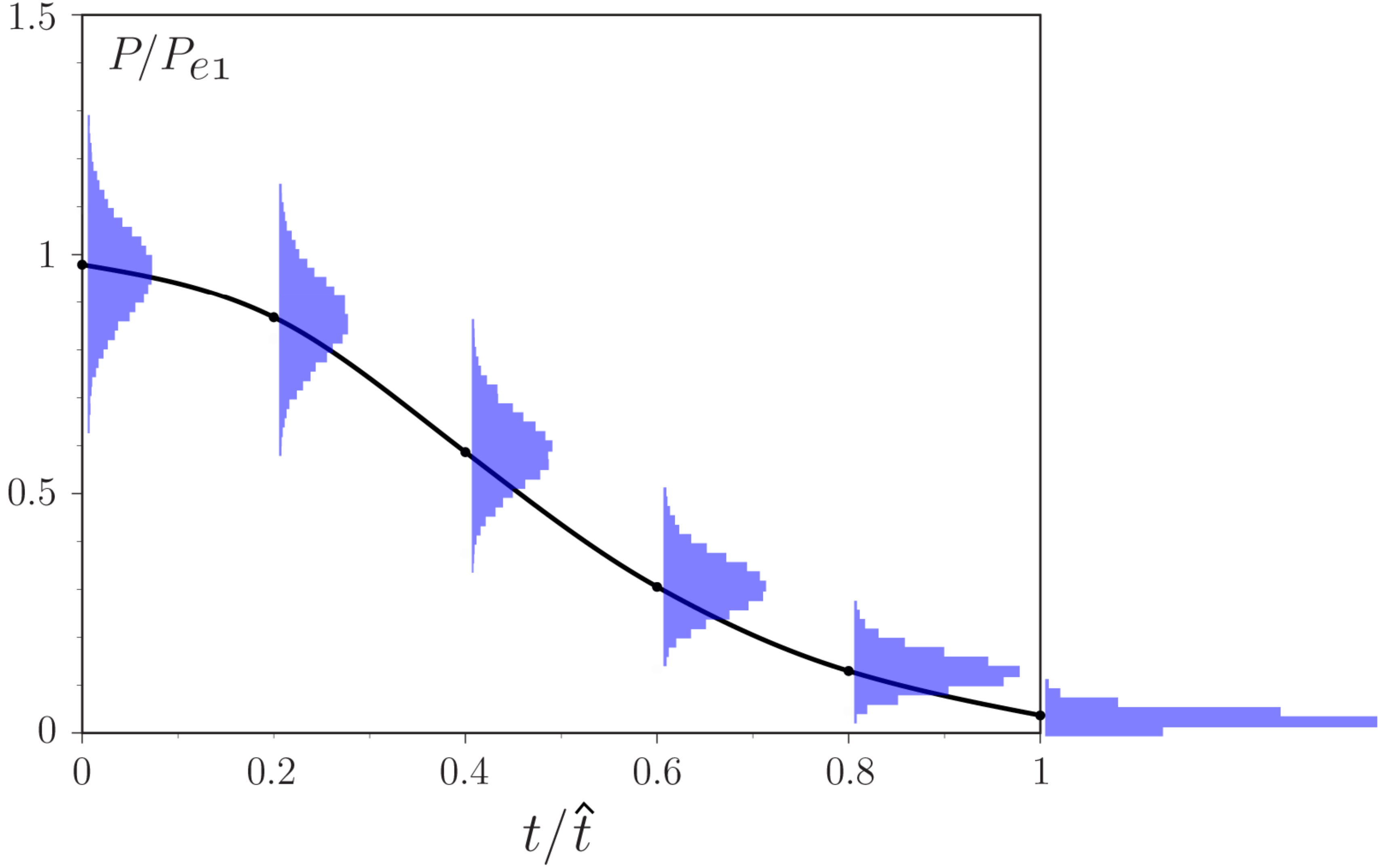


one-sided exposure of panel
to an aggressive environment

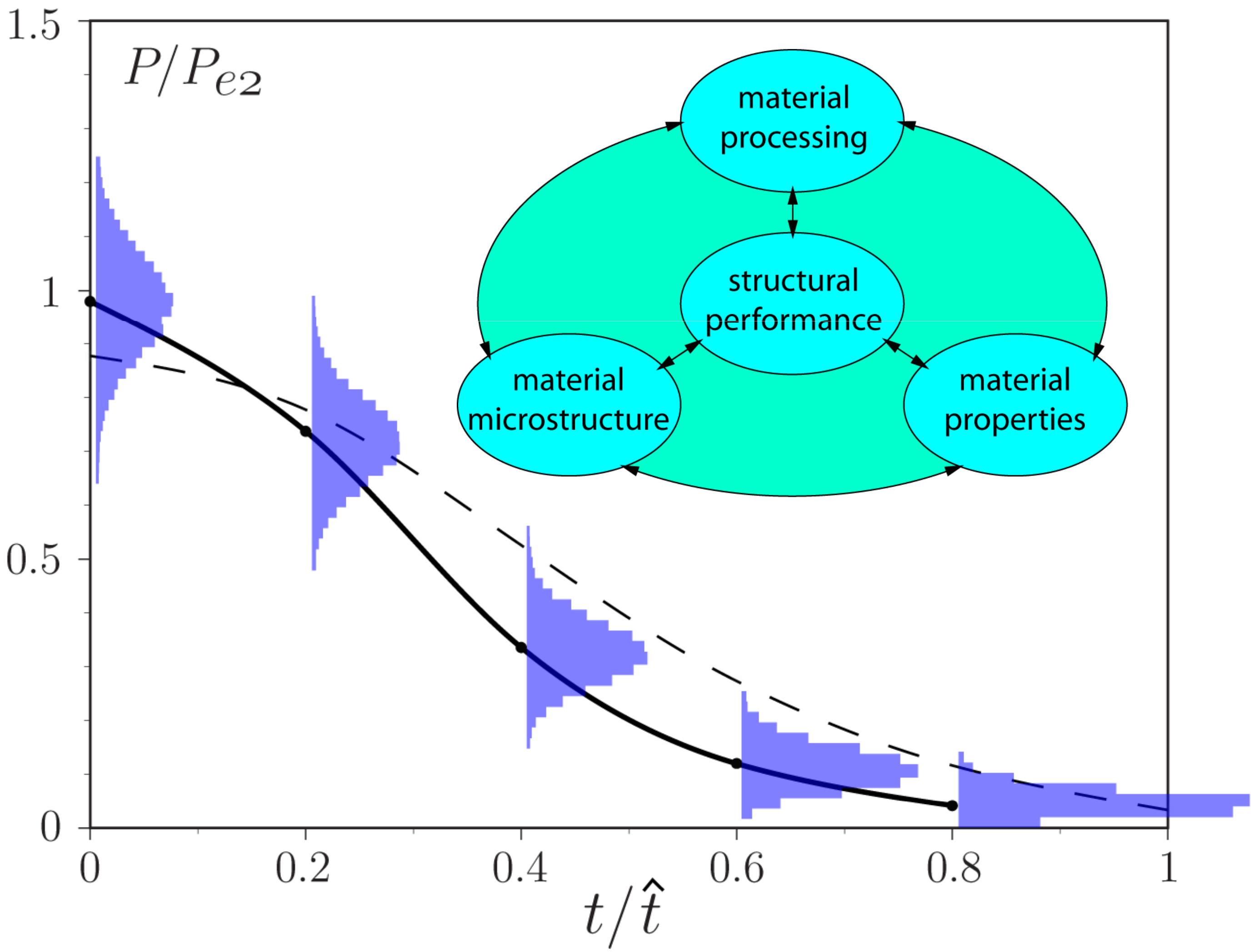


substance ingress profiles

Nam et al., Strength degradation of fiber reinforced cement composites exposed to simulated environments, *American Concrete Institute SP-272-10* 2010

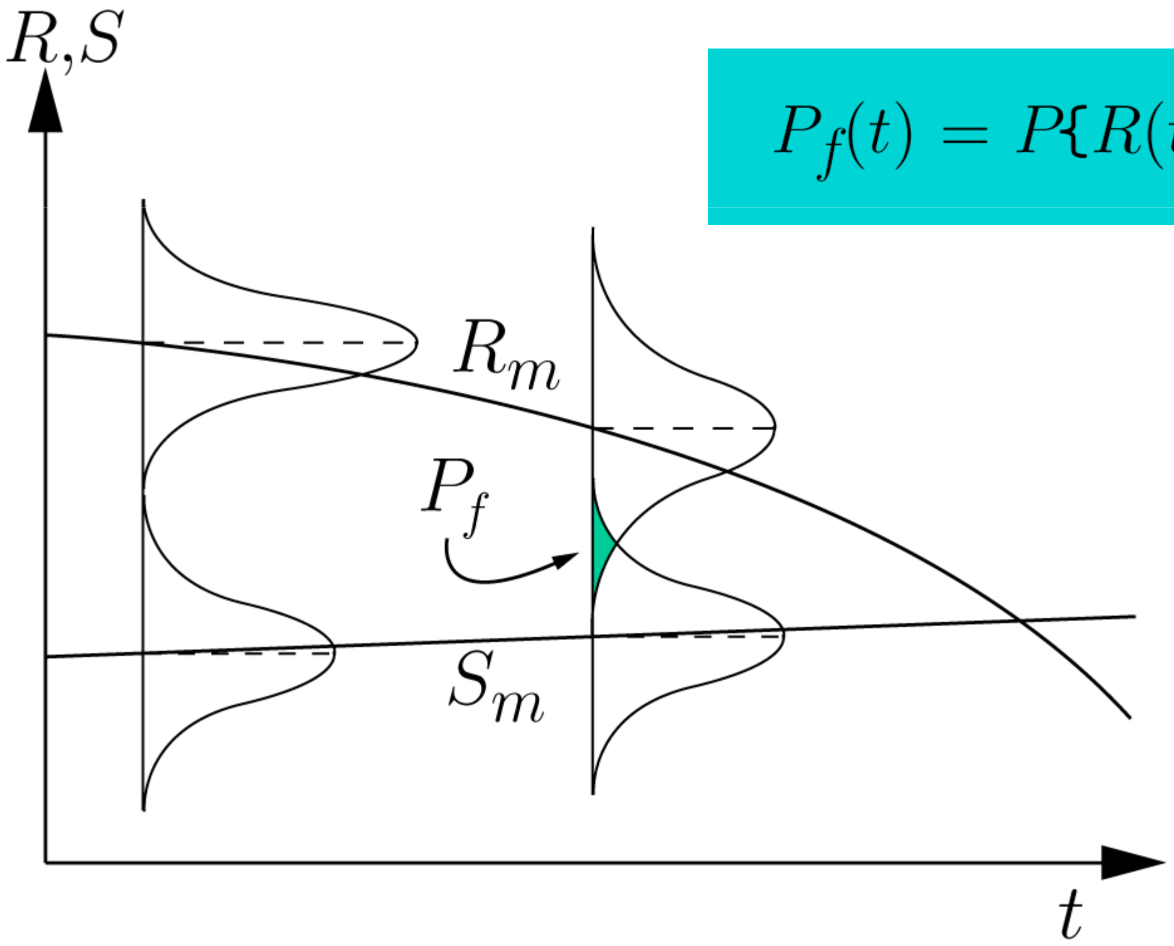


Time-dependent variation in post-cracking strength
(processing technique 1)



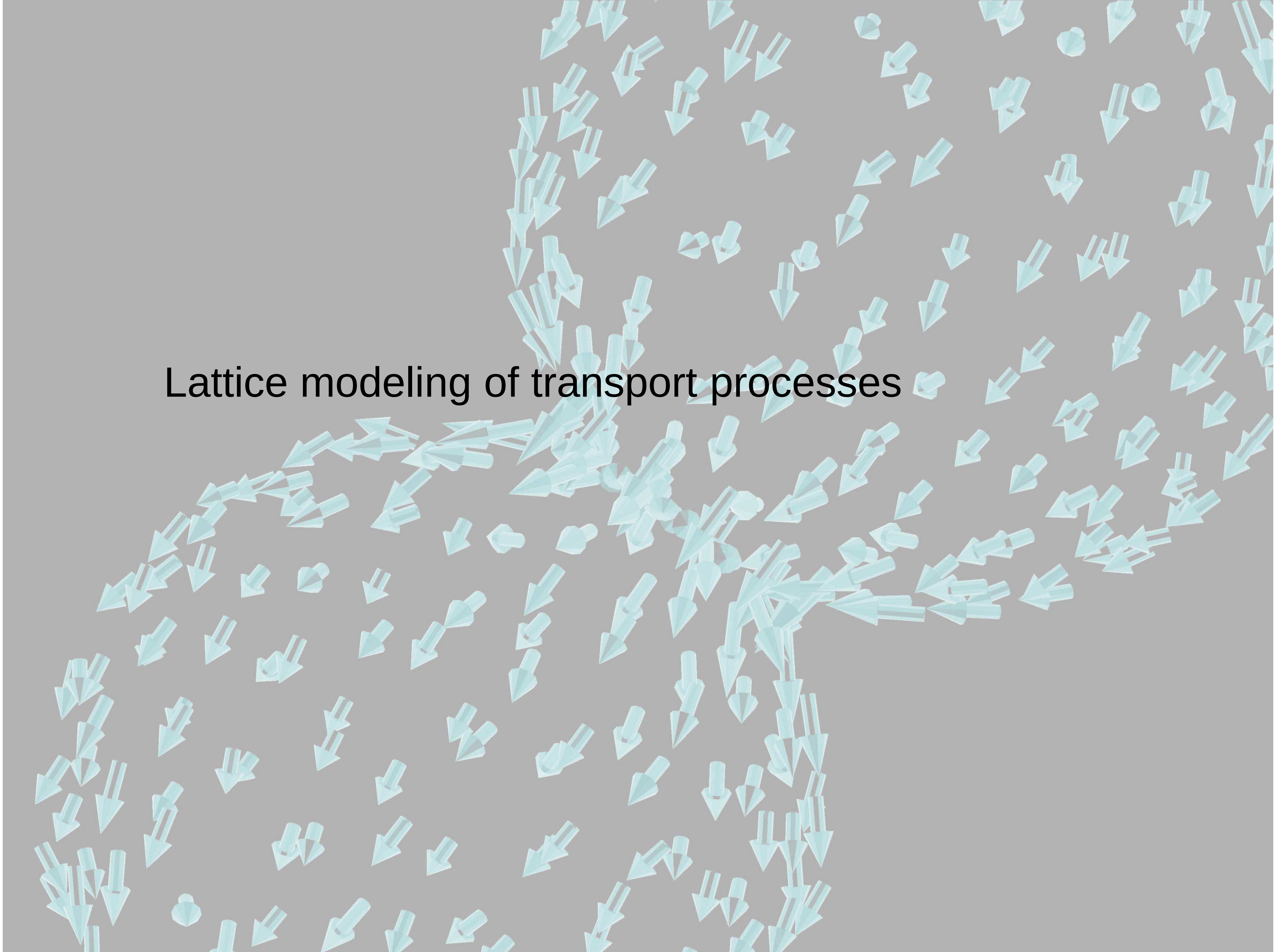
Time-dependent variation in post-cracking strength
(processing technique 2)

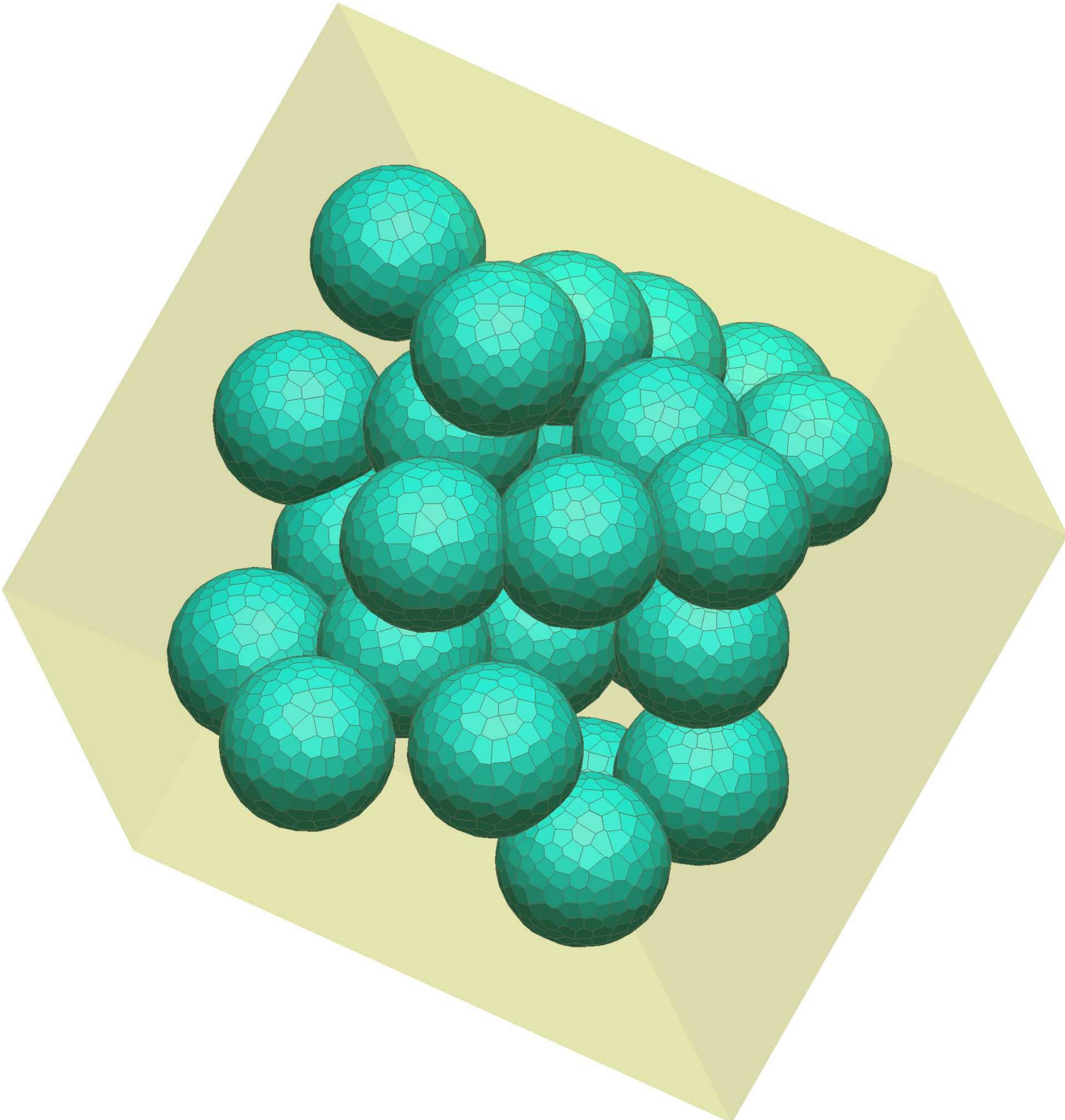
$$P_f(t) = P\{R(t) < S(t)\}$$

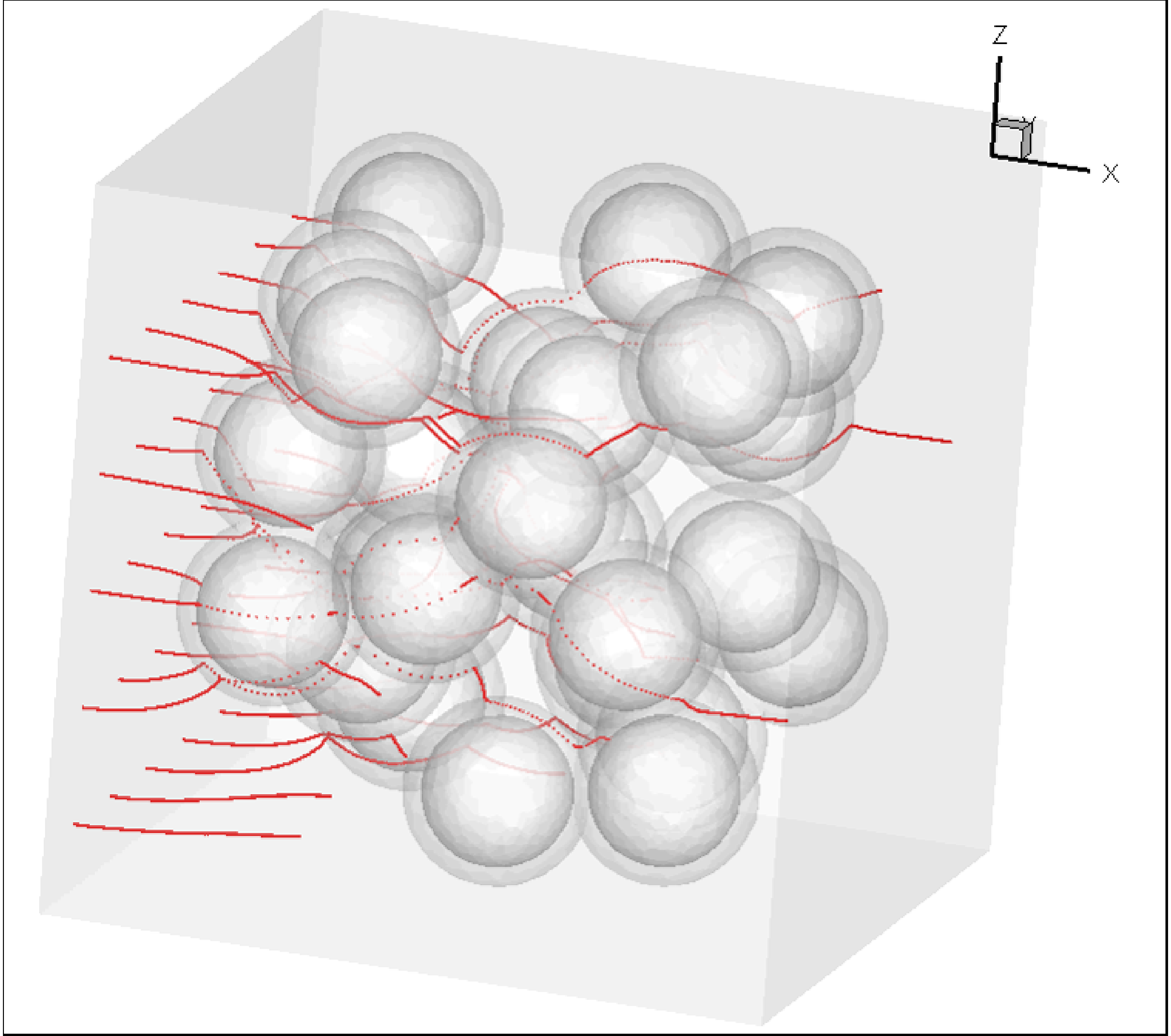


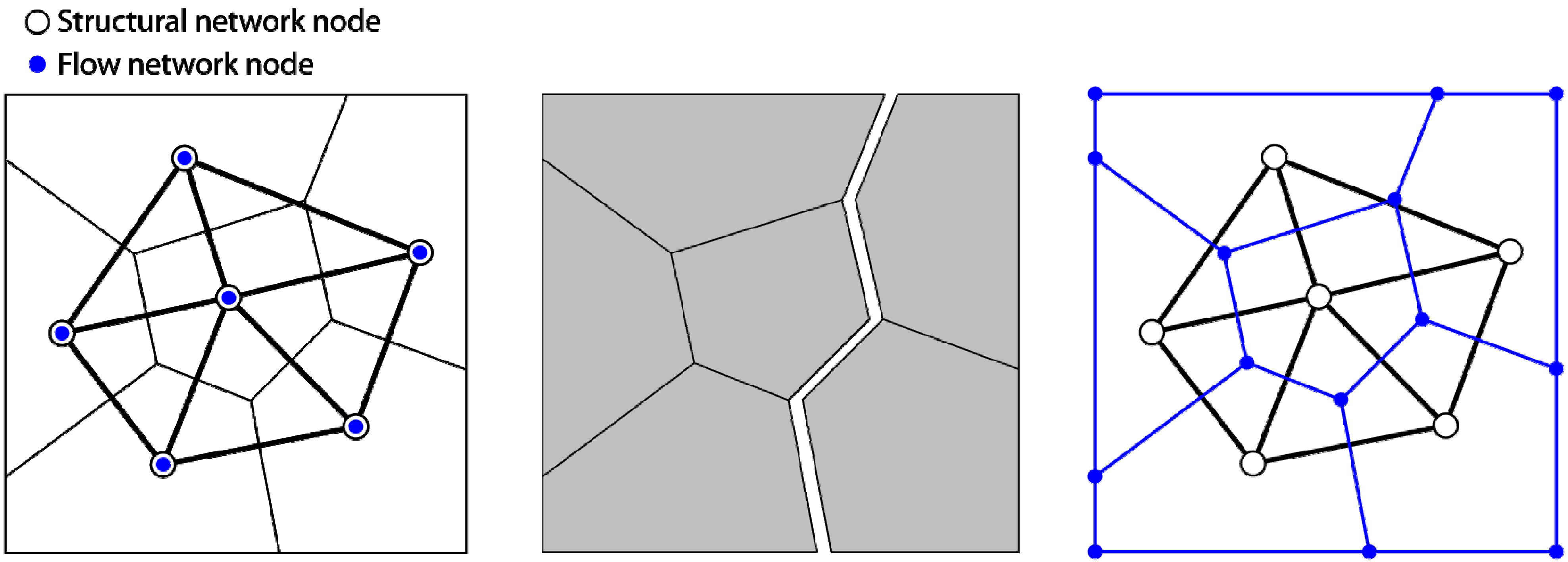
Time variant model of failure probability

Lattice modeling of transport processes






Z
X



Structural and flow network nodes are coincident

Semi-vertical crack in structural network

Flow elements are on the Voronoi edges (Grassl, 2009)

Lattice models for coupled simulations

Discrete form of the flow equation

$$\boldsymbol{\alpha}_{\mathrm{e}}\mathbf{P}_{\mathrm{c}} + \mathbf{C}_{\mathrm{e}}\frac{\partial \mathbf{P}_{\mathrm{c}}}{\partial t} = \mathbf{f}$$

where

$\mathbf{P}_c$ = vector of nodal values of capillary pressure

α_e = conductivity matrix

$\mathbf{C}_e$ = capacity matrix

$\mathbf{f}$ = nodal flow vector

$$\boldsymbol{\alpha}_{\mathrm{e}} = \frac{A}{\ell}\alpha \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}$$

$$\alpha(\kappa_{\mathrm{r}}) = \alpha_0(\kappa_{\mathrm{r}}) + \alpha_{\mathrm{c}} = \frac{\rho}{\mu}\kappa\kappa_{\mathrm{r}} + \xi\frac{\rho}{\mu}\frac{w_{\mathrm{c}}^3}{12h}$$

$\alpha_0(\kappa_{\mathrm{r}})$: uncracked material; α_{c}: crack

ρ = density of water

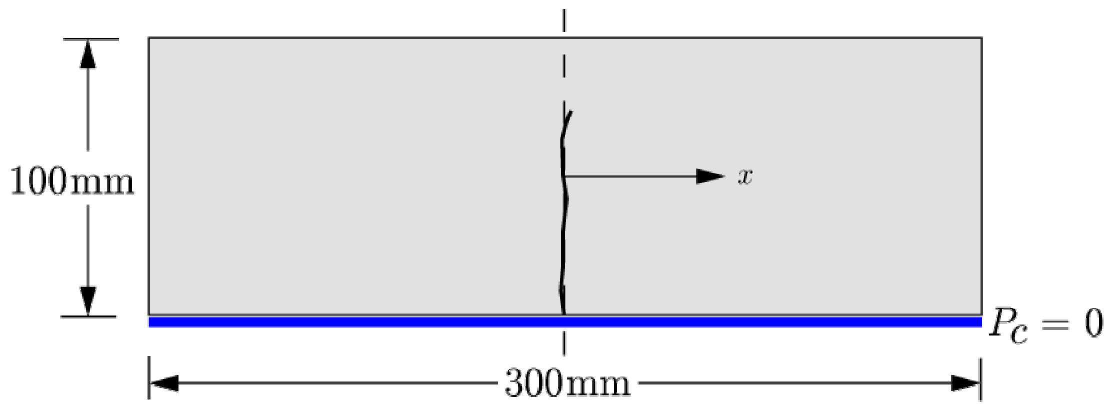
μ = viscosity of water

κ = intrinsic permeability of concrete

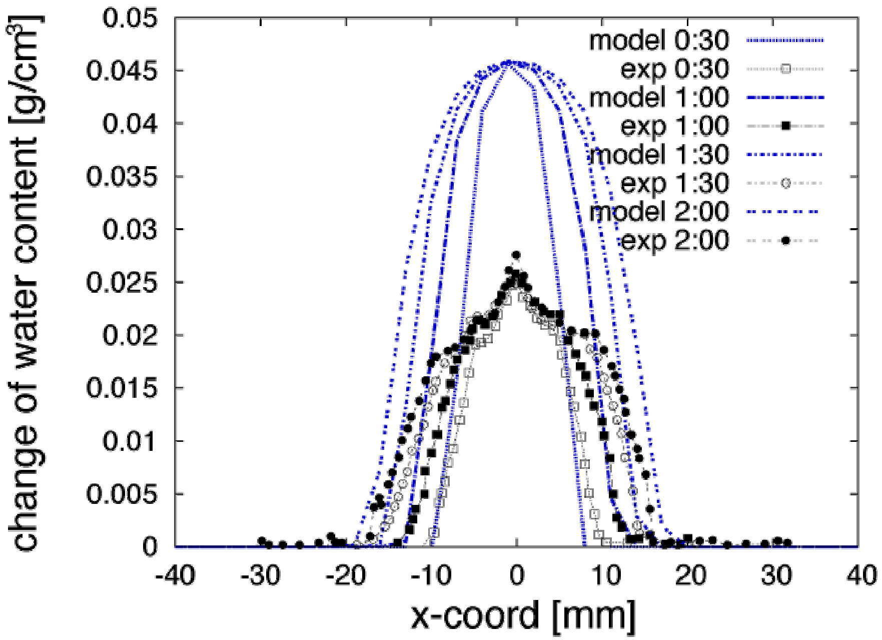
κ_r = relative permeability (depends on degree of saturation)

ξ = crack tortuosity factor

w_c = crack opening (supplied by structural lattice)



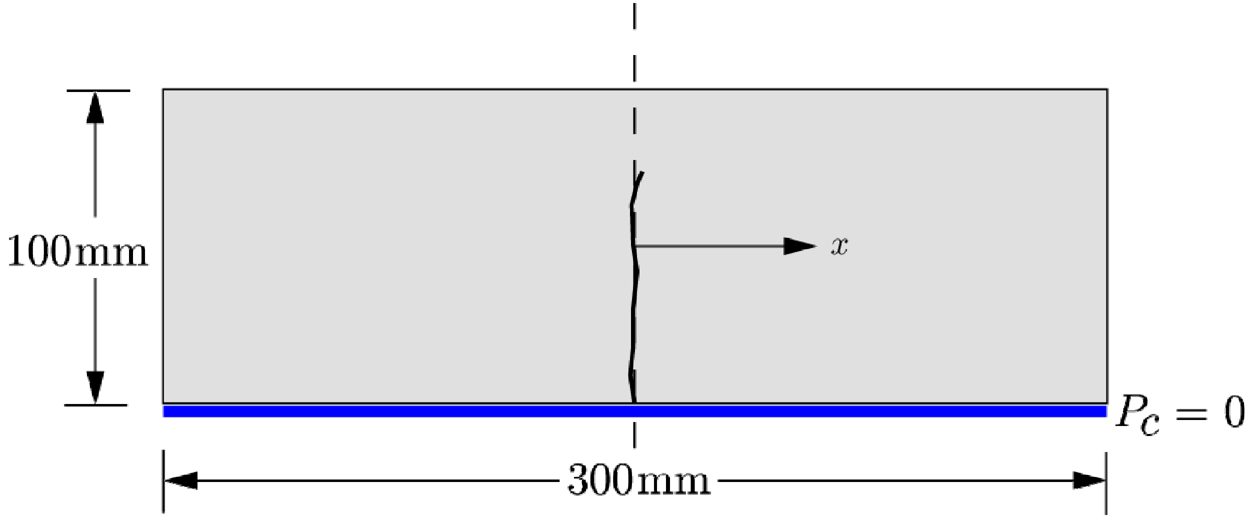
Cracked beam in contact with water



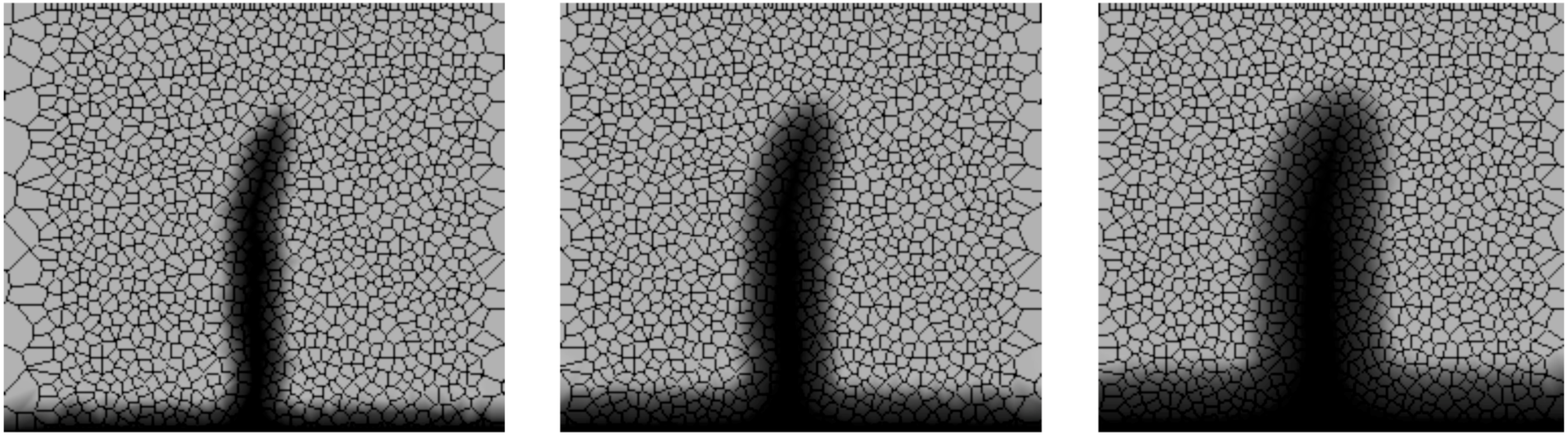
Grassl et al., 2012

Change in water content with distance from central crack

(moisture profiles measured by neutron radiography by Wittmann et al., 2008)



Cracked beam in contact with water



(a) t = 30 min (b) t = 1 h (c) t = 2 h

Simulated distributions of capillary pressure (Grassl et al., 2012)

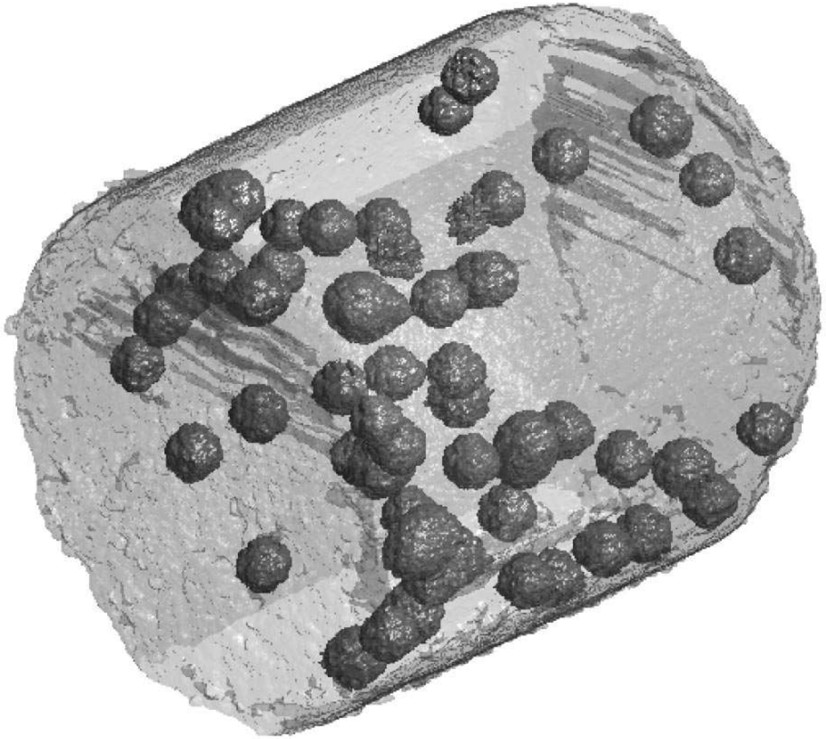
Concluding remarks

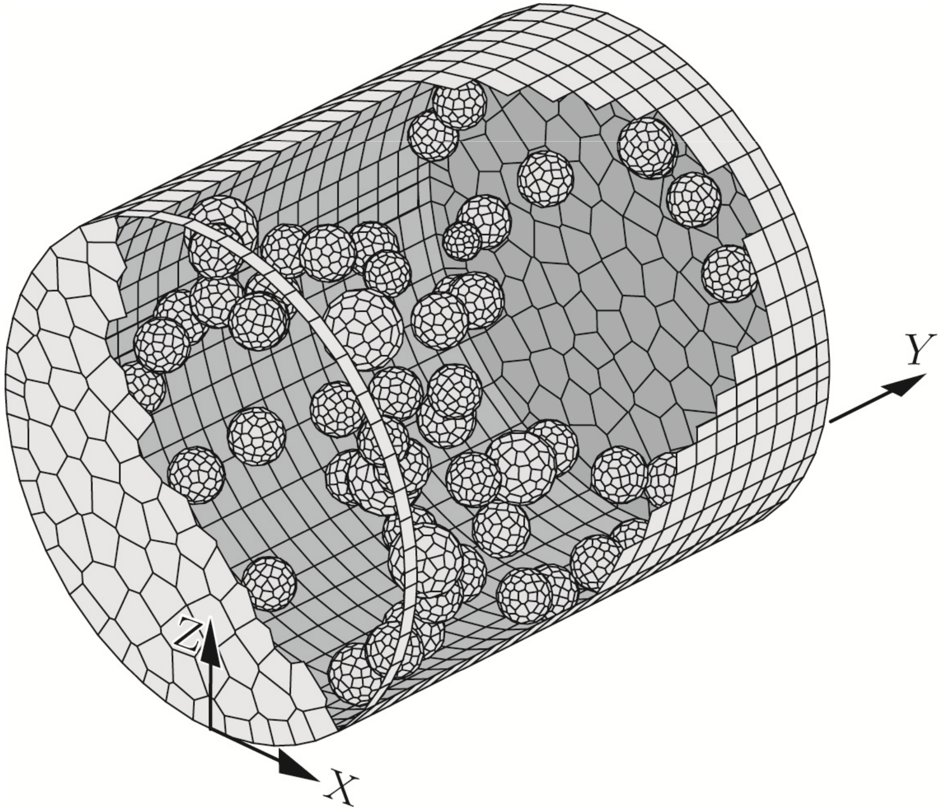
"A model is a lie that helps you see the truth"
- Howard Skipper (pharmacologist, cancer researcher)

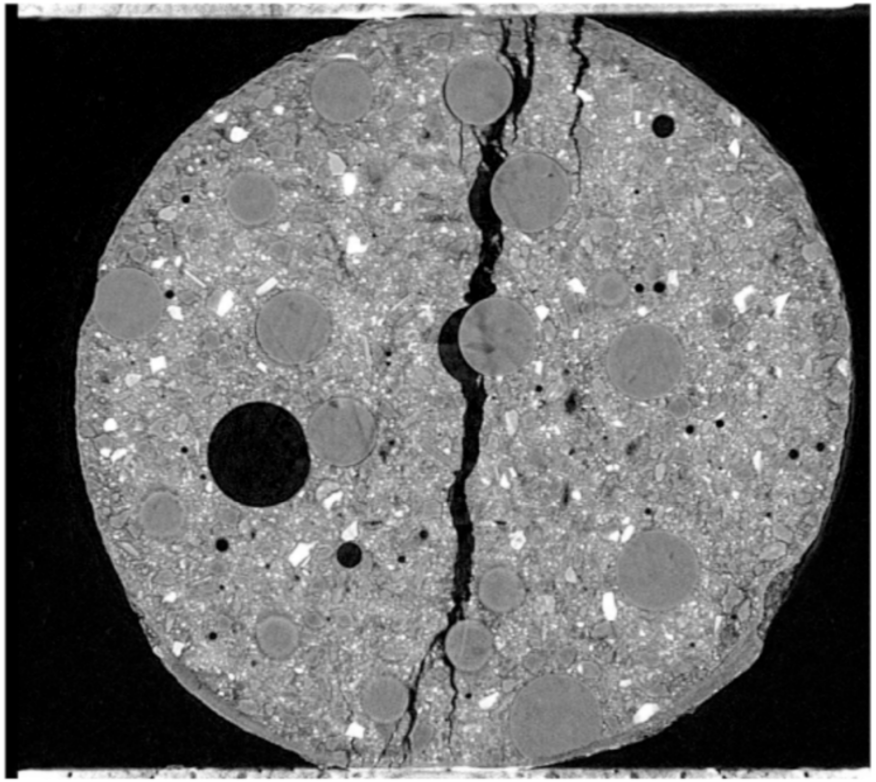
Improvements in structural concrete modeling through

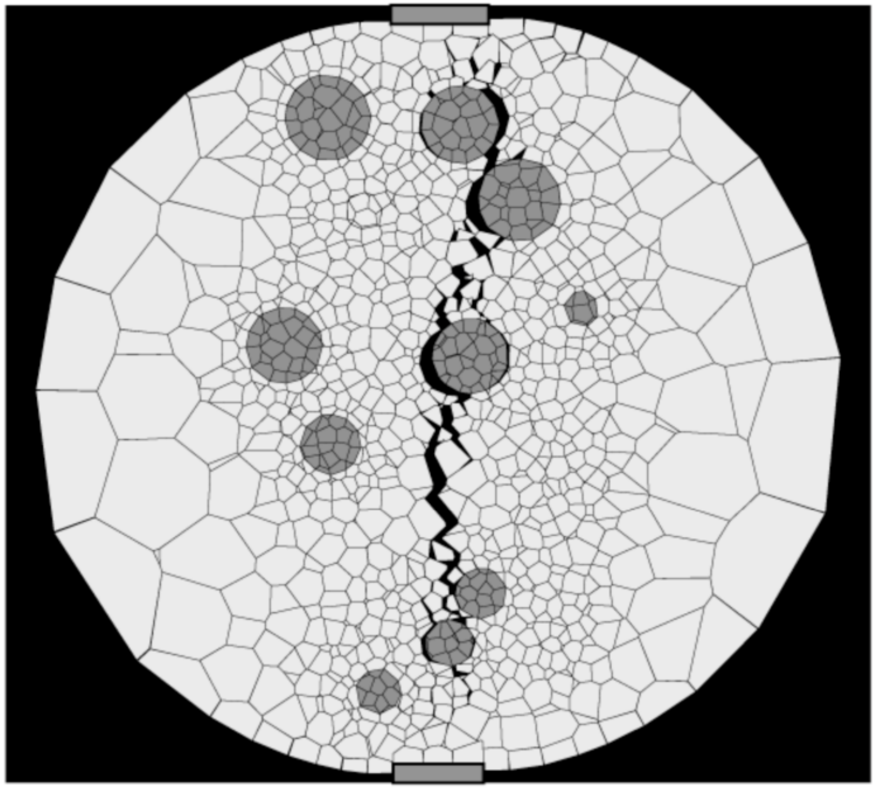
- increased physical bases
- accounting of probabilistic aspects of constituent materials and evolutionary processes
- recognition of the multi-scale nature of concrete materials
- collaboration with experimentalists at all relevant scales

Complementary nature of computed tomography and computational models that mimic material structure and evolutionary processes









Computed tomography

- High resolution images
- Results amenable to digitally-based methods of interrogation
- Quantitative linking of micromechanical phenomena and bulk material properties
- CT scans made at distinct stages of the loading history
- Depends on mismatch between phase radiodensities

Lattice-type models

- Relatively coarse discretization of material features (due to computing cost)
- 3D meshing limitations
- Quantitative linking of multi-field phenomena over multiple length and time scales
- Event-by-event tracking of fracture and related phenomena
- Uncertainty quantification through Monte Carlo-type simulations