Estimating rock mass effective elastic properties from a Discrete Fracture Network (DFN) approach

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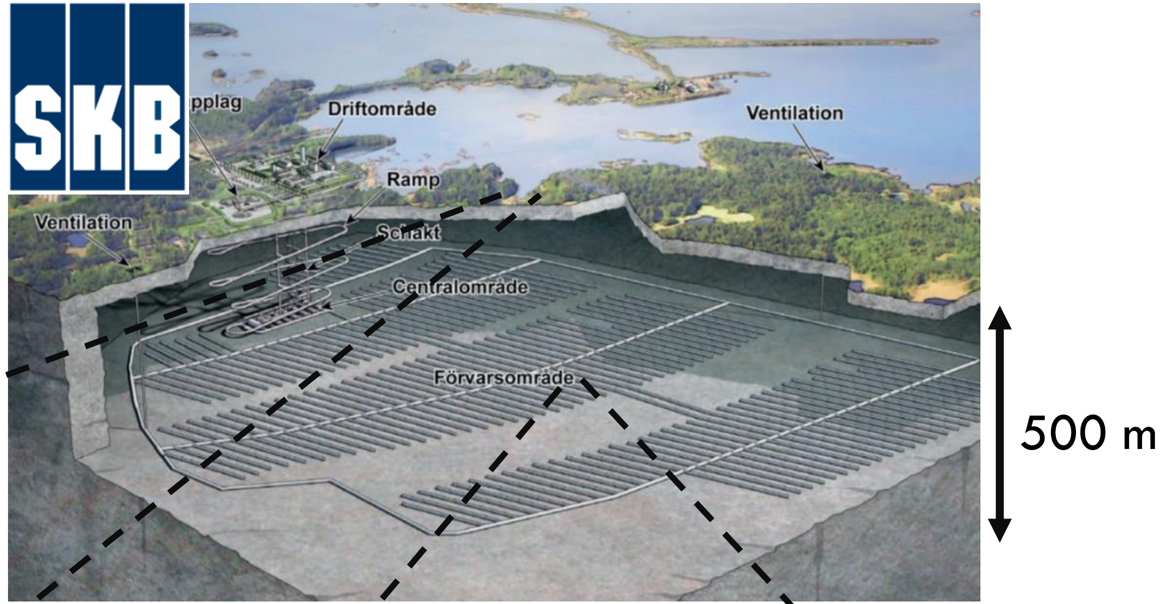
Joint laboratory

Introduction

Context

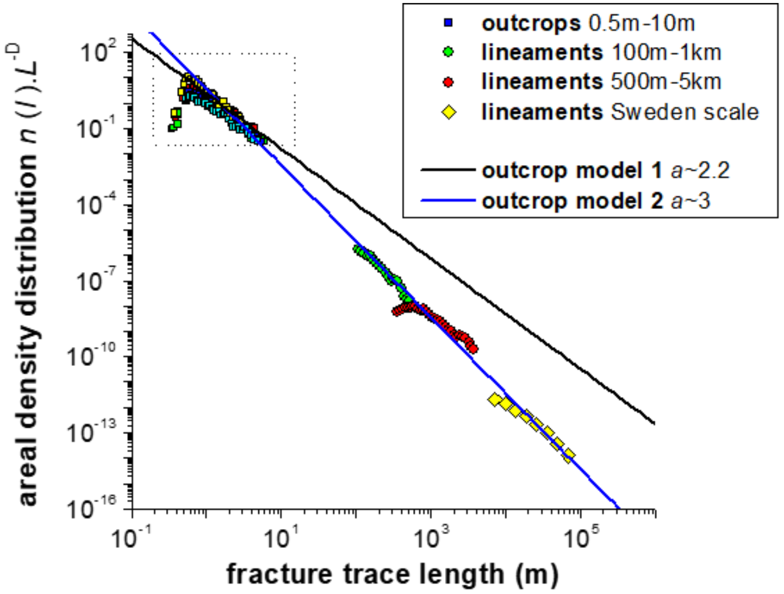
- Nuclear waste storage
- Crystalline rocks
- Fracture networks
- Hydrogeology
- Geomechanics



Introduction

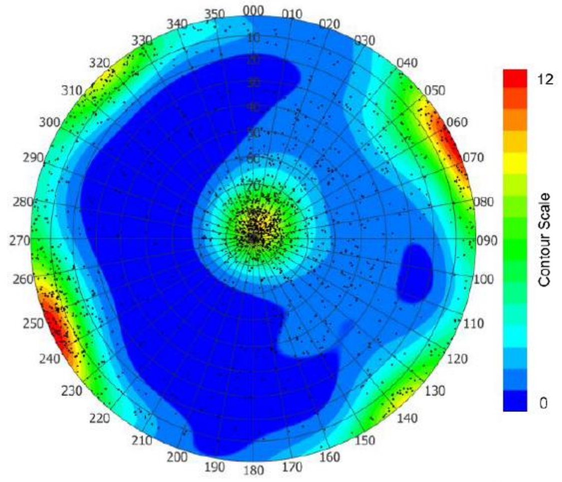
Challenges

- Scale
  - Multiscale fracture networks (cm → km)
  - REV ?



Fracture size distribution

- Anisotropy
  - Several fracture sets
  - Orientation distributions



Fracture stereonet

⇒ Fractures should be a central point of rock mass (RM) modelling

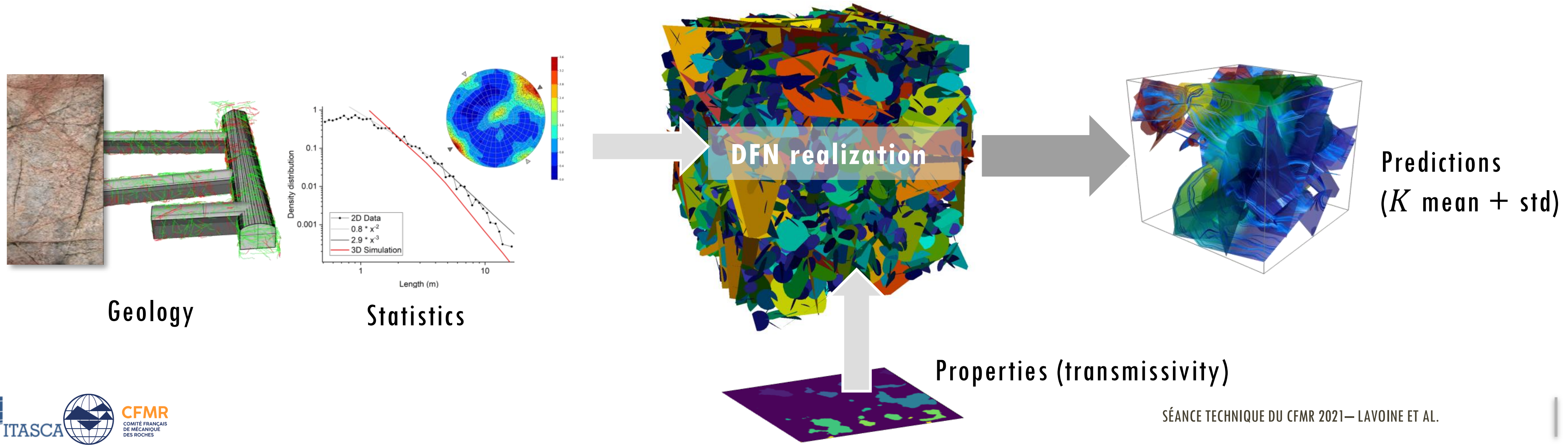
⇒ DFN methodology

Introduction

The Discrete Fracture Network (DFN) methodology *[Selroos et al., 2021]*

Fractured RM: population of deterministic and stochastic fracture-like objects embedded in an impervious elastic matrix

- Integrate geological, hydrogeological and mechanical data
- Valid regardless of fracture density
- Basis for simplification: effective properties, main hydro paths…
- And understanding: link with global indicators (percolation parameter…)



Introduction

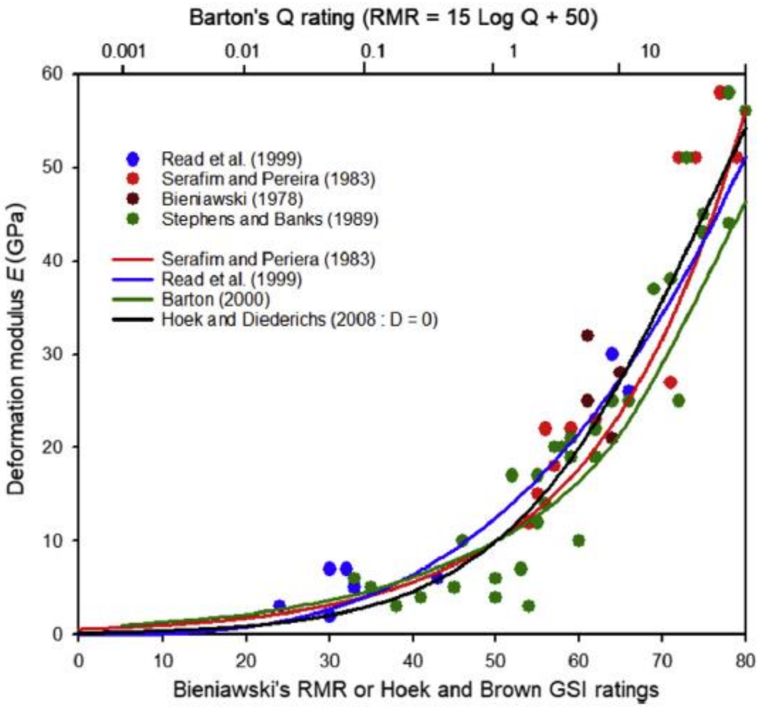
Applying the DFN methodology in geomechanics

To estimate fractured RM effective elastic properties

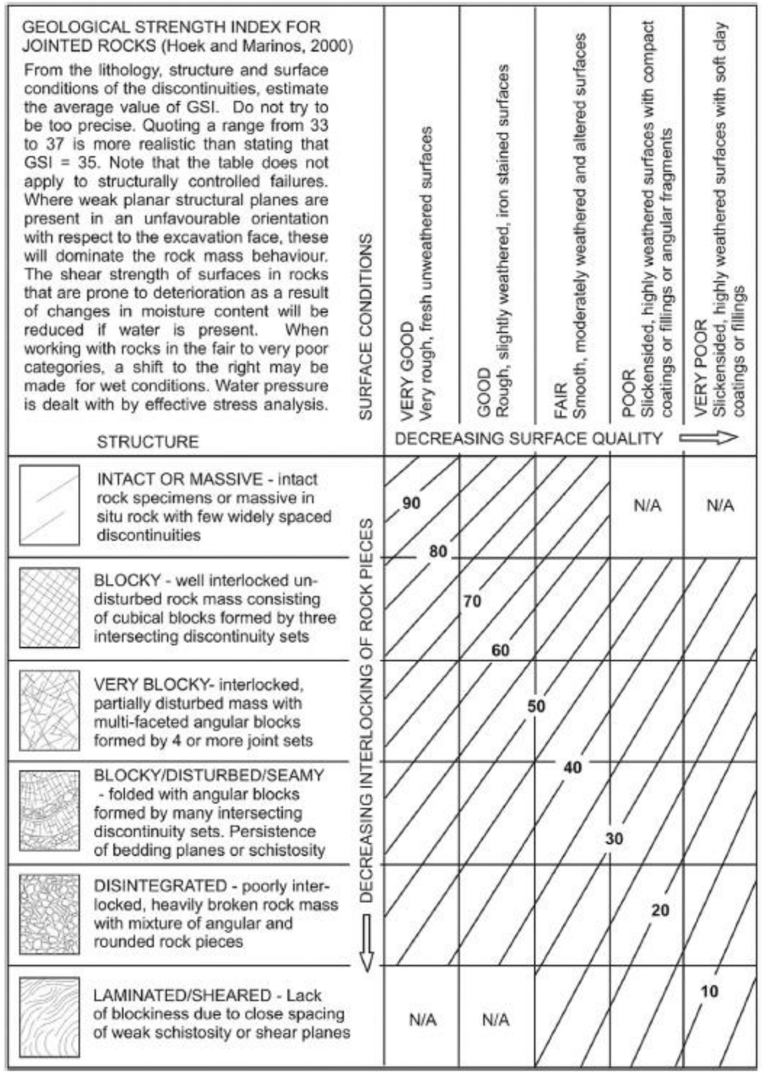
Introduction

Classically

- Rock Mass Classification (RMC) charts
- RQD, Q, RMR, GSI, D…
- Semi-empirical relationships



[Hoek and Brown (2018)]

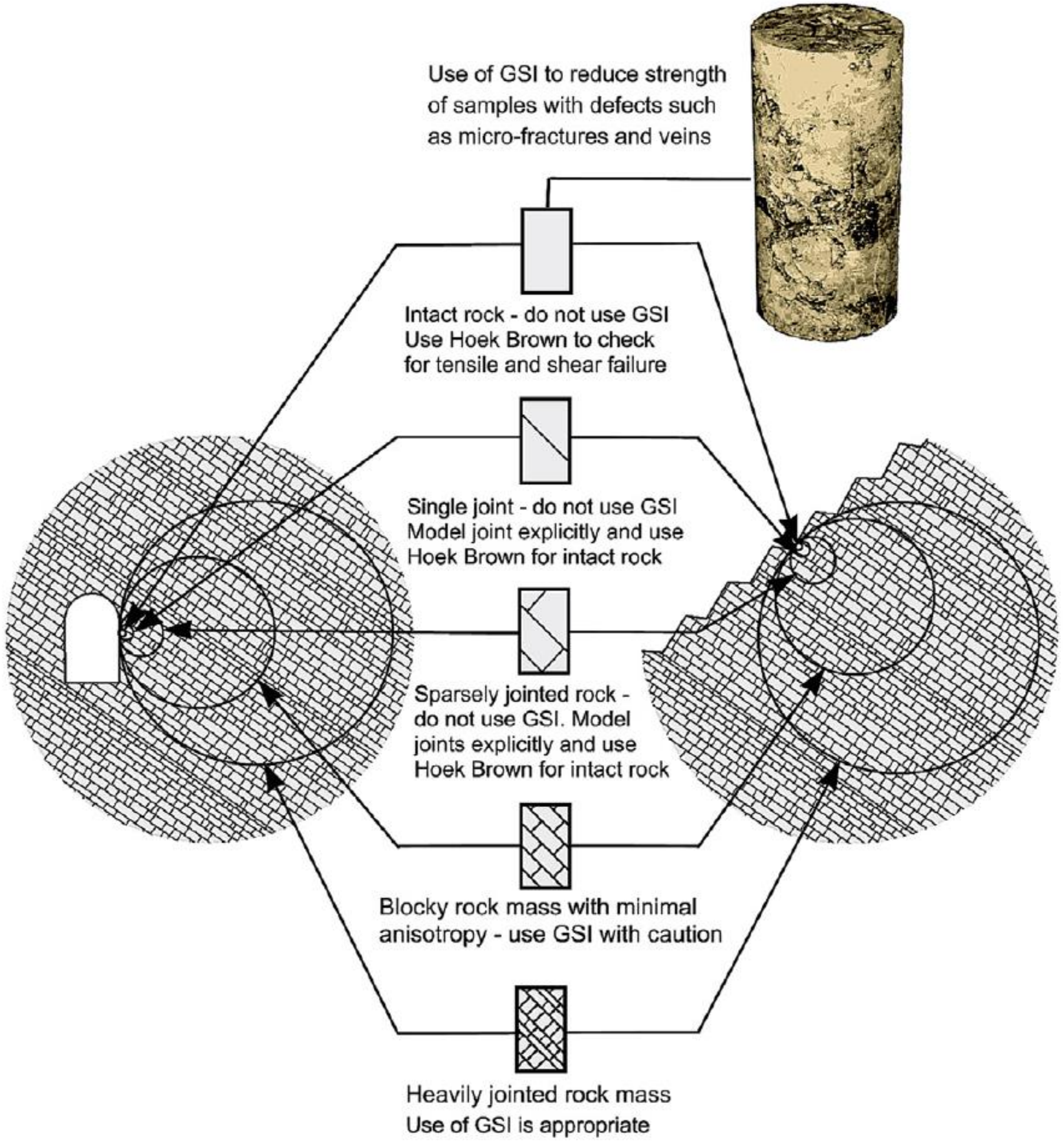


[Hoek and Marinos (2000)]

Introduction

Adapted to heavily jointed rock masses

- Assembly of blocks
- Several sets of potentially infinite fractures
- Defined by fracture spacing only
- Applicable when model resolution >> spacing



[Hoek and Brown (2018)]

Introduction

Adapted to heavily jointed rock masses

- Assembly of blocks
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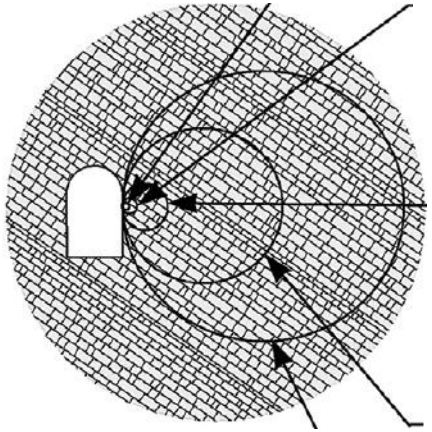
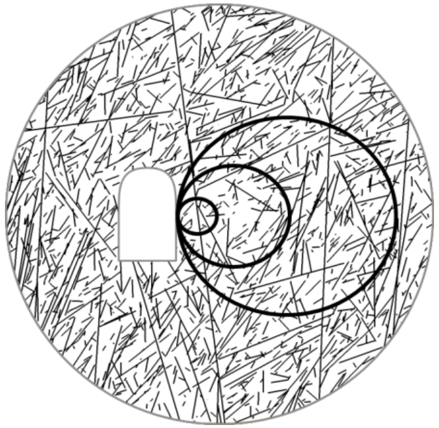
Lack of

- 3D representation
- Scale
- Anisotropy

⇒ DFN methodology



Block assembly



Population of individual fractures

Introduction

Objectives

- Overcome limitations of classical RMC approaches

- Using the DFN methodology to estimate RM effective elastic properties quantitatively

Effective compliance tensor $$\bar{\bar{\bar{\bar{C}}}} = \bar{\bar{\epsilon}} : \bar{\bar{\sigma}}^{-1}$$

Total rock mass deformation

- Define which DFN metric is the controlling factor

Fractures contribution to rock deformation

Total rock mass deformation : matrix deformation + contribution of all fractures

$$\epsilon_{ij} = C^0_{ijkl}\sigma^R_{ij} + \sum_f (\epsilon_{ij})_f$$

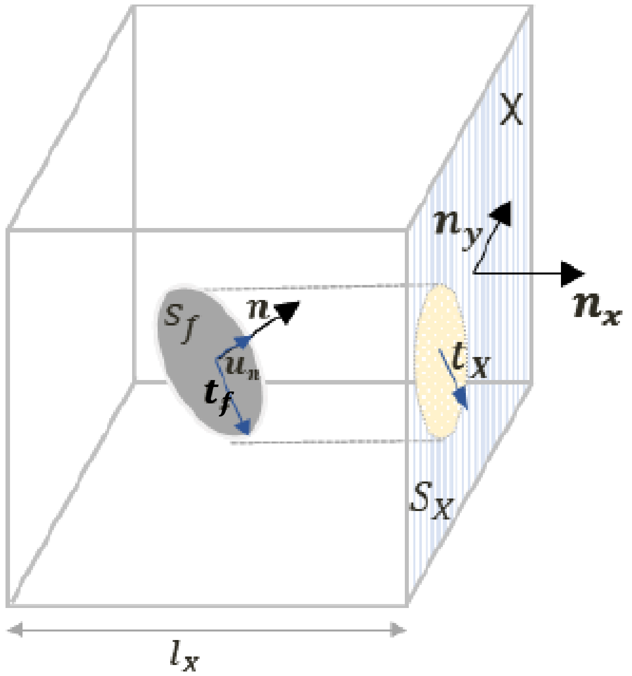
Contribution of fracture f to the deformation component ϵ_{xy}

$$(\epsilon_{xy})_f = \frac{\boldsymbol{t_X}.\boldsymbol{n_y}}{l_X}$$

Displacement / length

$$\boldsymbol{t_X} = (\boldsymbol{n}.\boldsymbol{n_x})\frac{\int_{S_f} \boldsymbol{t_f}.dS}{S_X}$$

contribution of the fracture f to the displacement to the x boundary is obtained by projecting and integrating the displacement field on the x boundary



Fractures contribution to rock deformation

Total rock mass deformation : matrix deformation + contribution of all fractures

$$\epsilon_{ij} = C^0_{ijkl}\sigma^R_{ij} + \sum_f (\epsilon_{ij})_f$$

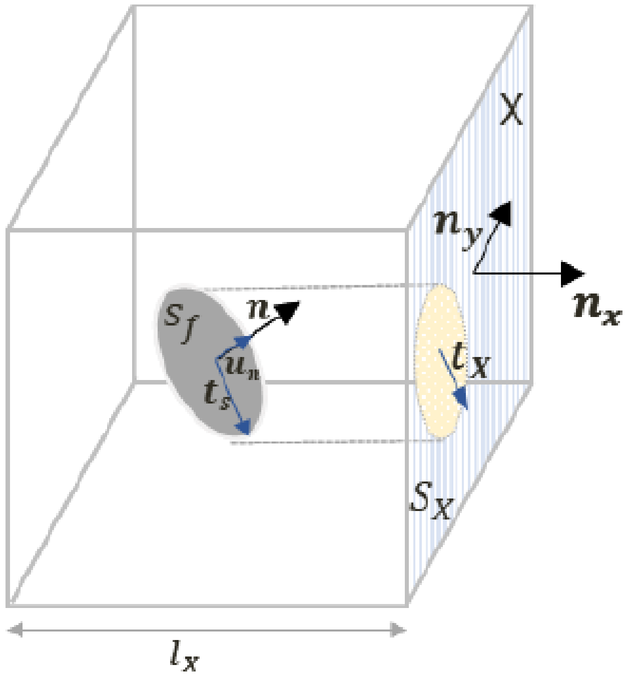
Contribution of fracture f to the deformation component ϵ_{xy}

$$(\epsilon_{xy})_f = (\mathbf{n}.\boldsymbol{n}_x)\frac{S_f}{V}(\overline{t_f}.\boldsymbol{n}_y)$$

Fracture surface

mean shear fracture displacement

Rock volume



Fractures contribution to rock deformation

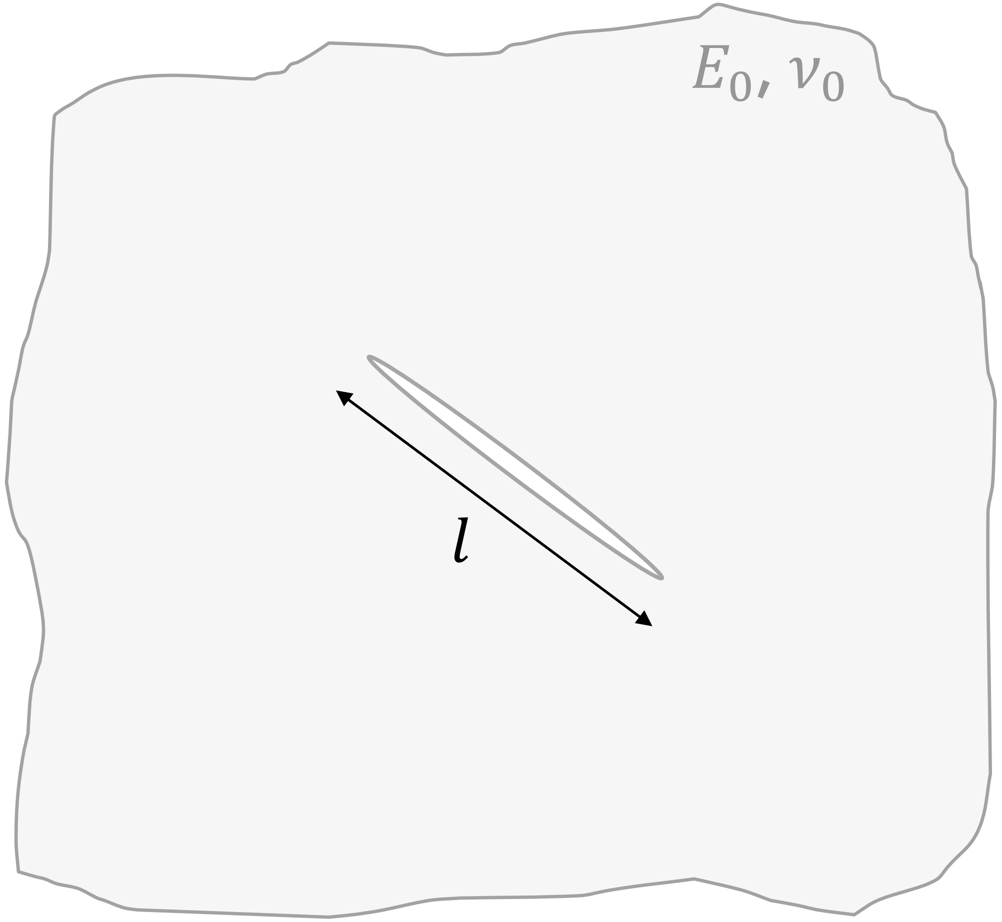
Mean shear displacement

Fracture of size l

Elastic matrix

Intact Young modulus E_0

Intact Poisson ratio ν_0



Fractures contribution to rock deformation

Mean shear displacement

Matrix resistance to deformation

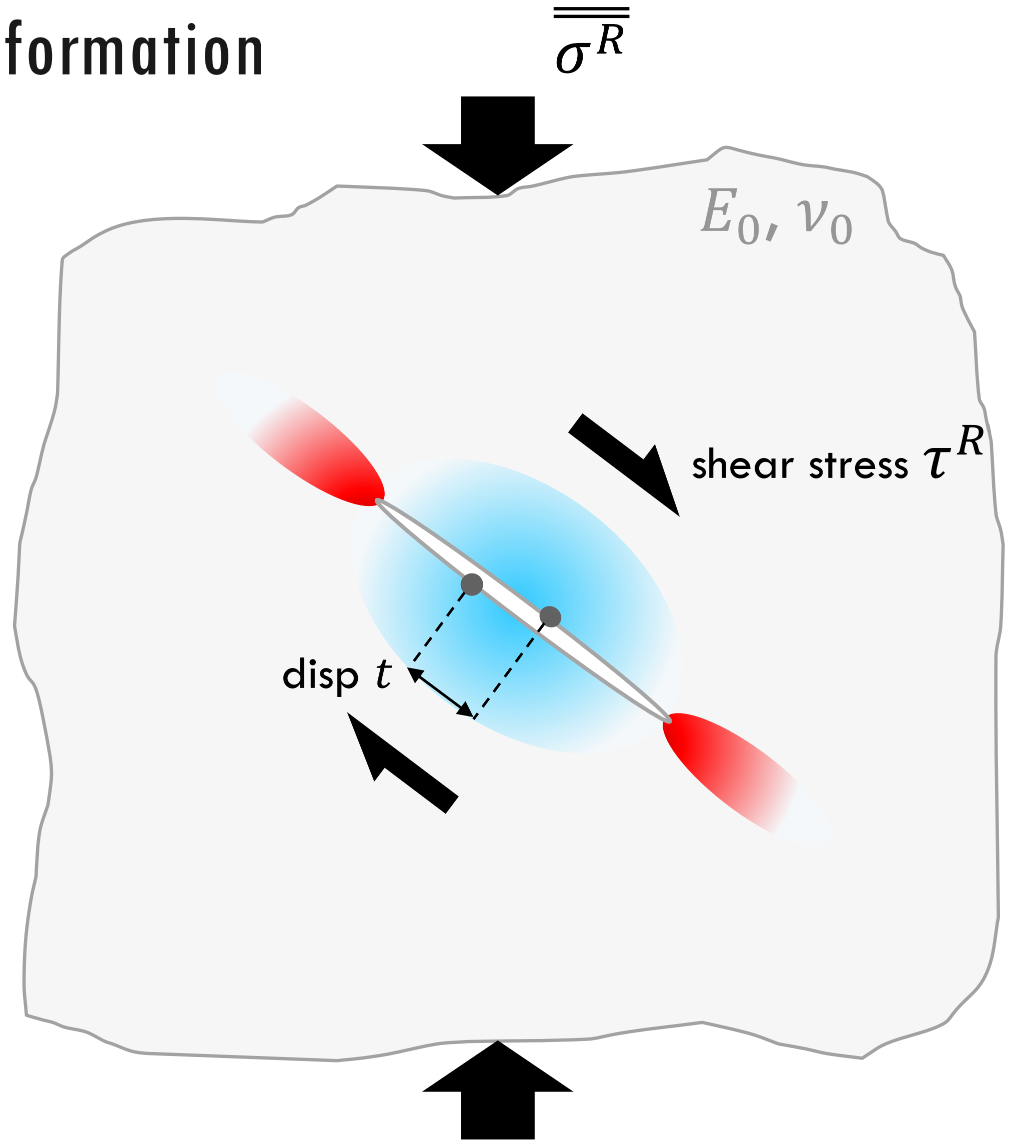
$$\tau_m = k_m . t$$

Intact rock modulus

Poisson ratio

$$k_m = \frac{3\pi}{8} \cdot \frac{1 - \nu_o/2}{1 - \nu_0^2} \cdot \frac{E_0}{l} = \frac{E_m^*}{l}$$

Fracture size



$$\boxed{\tau_R = \tau_m}$$

Fractures contribution to rock deformation

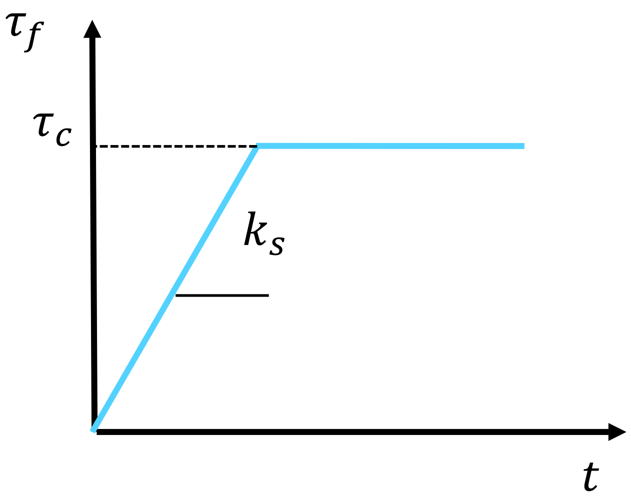
Mean shear displacement

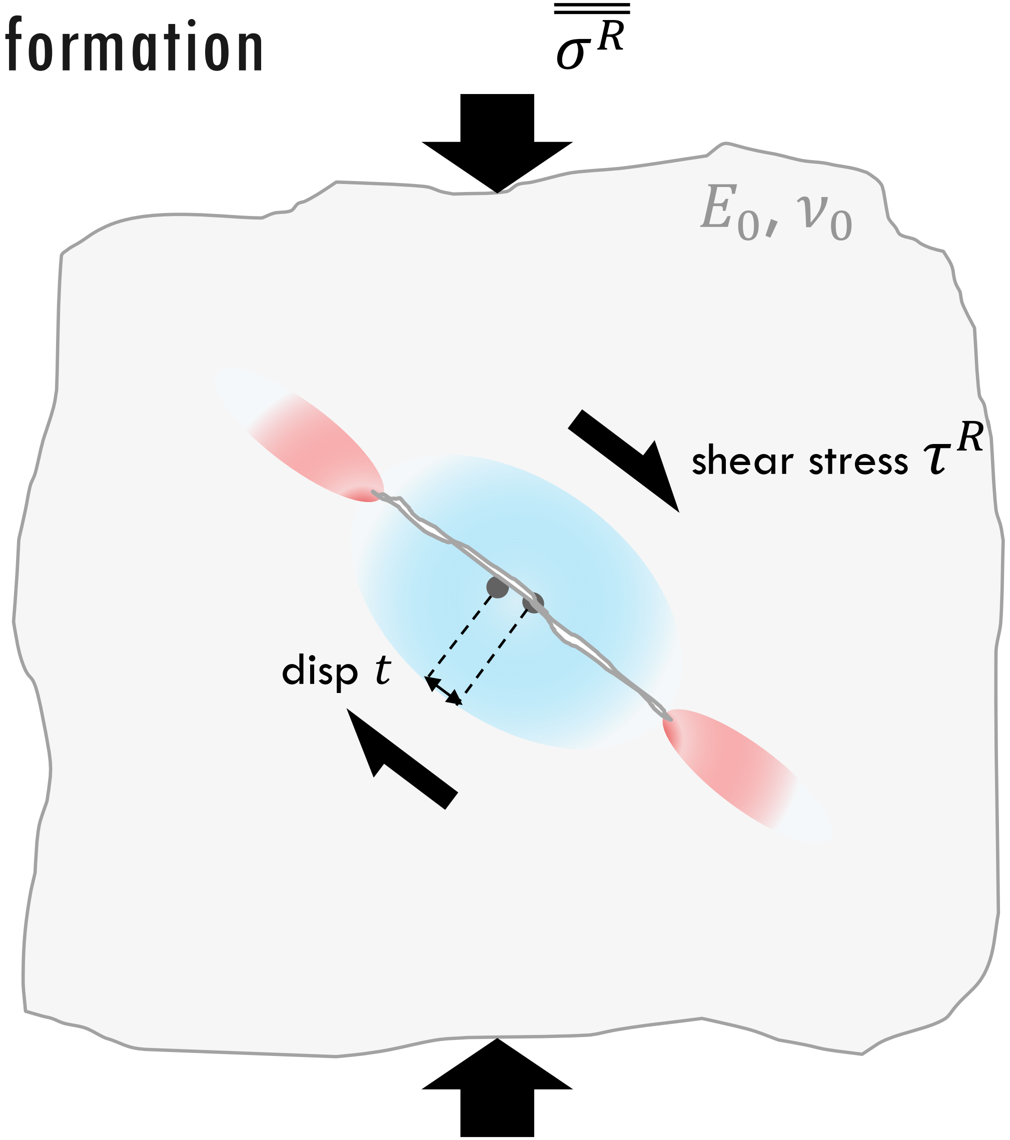
Fracture plane resistance

$$\tau_f = \min(k_s . t, \tau_c)$$

Fracture shear stiffness

Coulomb stress limit (if critically stressed)





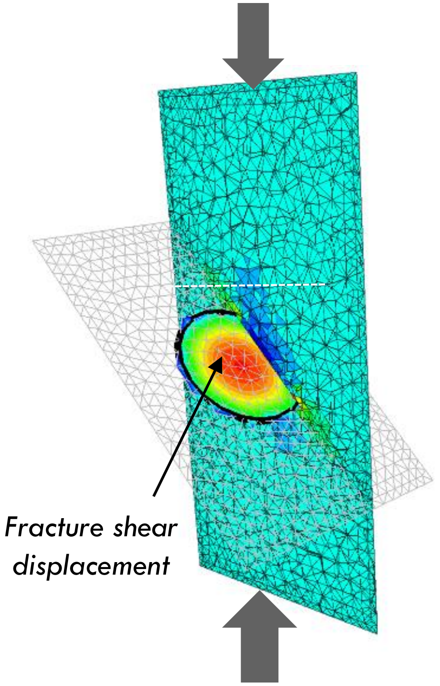
$$\boxed{\tau_R = \tau_m + \tau_f}$$

Stress partitioning

Fractures contribution to rock deformation

Mean shear displacement

Stress $\overline{\overline{\sigma^R}}$

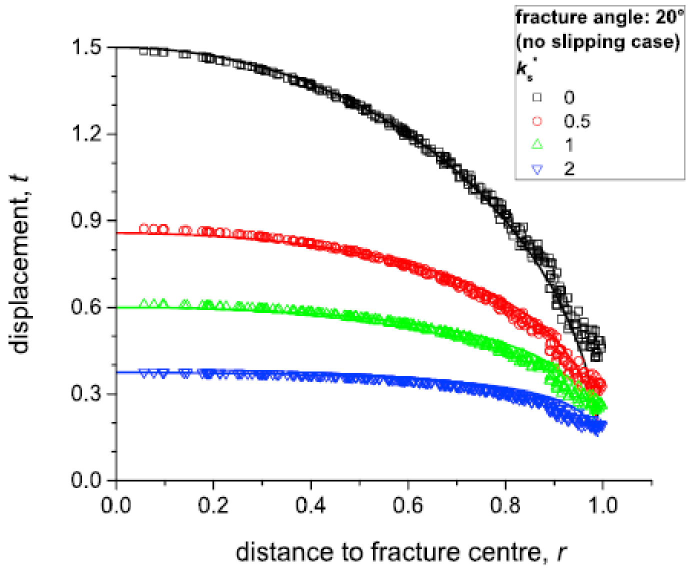


3DEC™

average

If not critically stressed

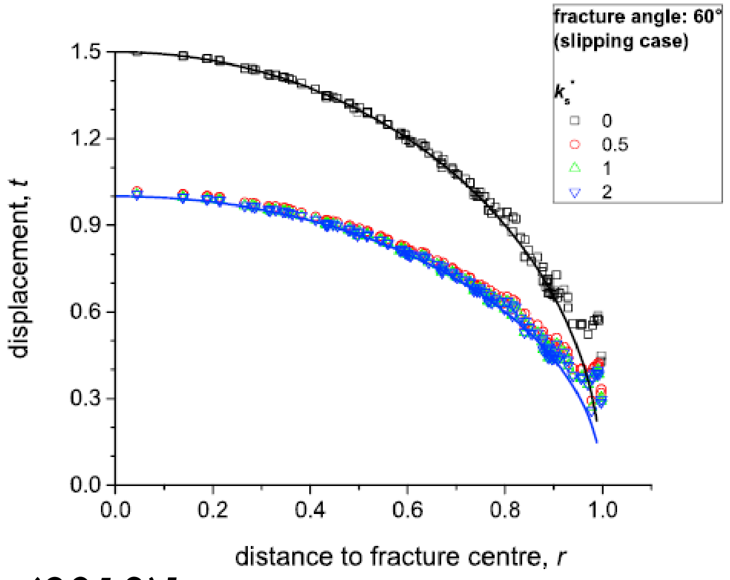
$$\frac{\tau^R}{t(r)} = \frac{\frac{2}{3}k_m}{\sqrt{1-\left(\frac{2r}{l}\right)^2}} + k_s$$



$$\bar{t} = \frac{\tau^R}{k_m+k_s}$$

If critically stressed

$$\frac{\tau^R - \tau_c}{t(r)} = \frac{\frac{2}{3}k_m}{\sqrt{1-\left(\frac{2r}{l}\right)^2}}$$



[Davy et al. (2018)]

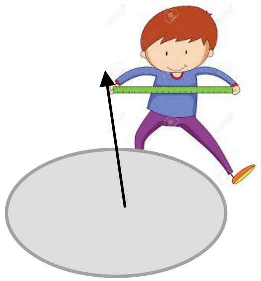
$$\bar{t} = \frac{\tau^R - \tau_c}{k_m}$$

Fractures contribution to rock deformation

Scale dependency

With $l_s = \frac{E_m^*}{k_s}$, the fracture size so that $k_m = k_s$

$l \ll l_s \Rightarrow \bar{t} = \frac{\tau^R}{k_s + k_m} \approx \frac{\tau^R}{k_m} \propto l$



If k_s is negligible, fracture size defines the shear displacement

$l \gg l_s \Rightarrow \bar{t} = \frac{\tau^R}{k_s + k_m} \approx \frac{\tau^R}{k_s}$

If k_s is dominant, shear displacement is independent from fracture size

Effective rock mass elastic properties

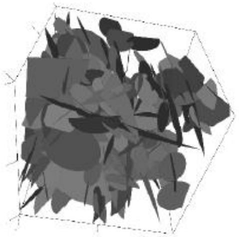
Remote stress field

$\overline{\overline{\sigma_R}}$

Intact rock mass properties

$\overline{\overline{\overline{\overline{C^0}}}}(E_0, \nu_0)$

DFN



Potentially anisotropic

$$\bar{\bar{\epsilon}} = \overline{\overline{\overline{\overline{C^0}}}} : \overline{\overline{\sigma_R}} + \sum_f \bar{\bar{\epsilon_f}}$$

Effective compliance tensor

$$\bar{\bar{\bar{\bar{C}}}} = \bar{\bar{\epsilon}} : \bar{\bar{\sigma}}^{-1}$$

Potentially anisotropic

Loop for all fractures

$$E_{f-1} = \frac{1}{3}\left(\frac{1}{E_{xx,f-1}} + \frac{1}{E_{xx,f-1}} + \frac{1}{E_{xx,f-1}}\right)$$

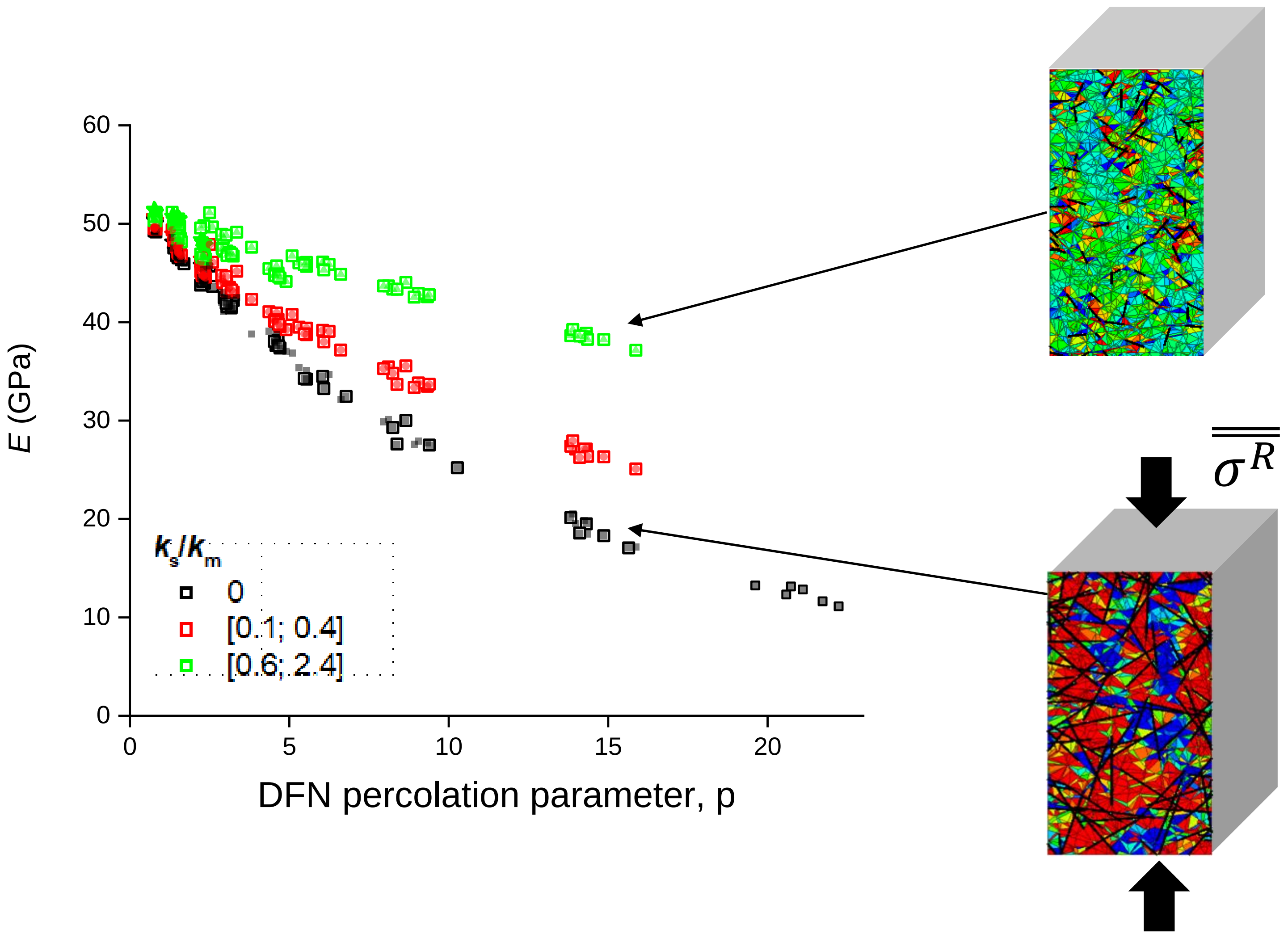
$$t_f = \frac{\tau}{k_s + \frac{E^*_{f-1}}{l_f}}$$

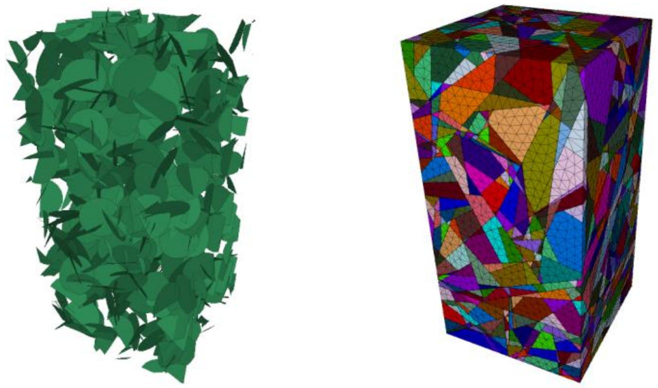
$$E_{xx,f}, E_{yy,f}, E_{zz,f}$$

Effective Theory:

Fracture f « sees » a matrix damaged by $[1, (f-1)]$ fractures

Effective rock mass elastic properties

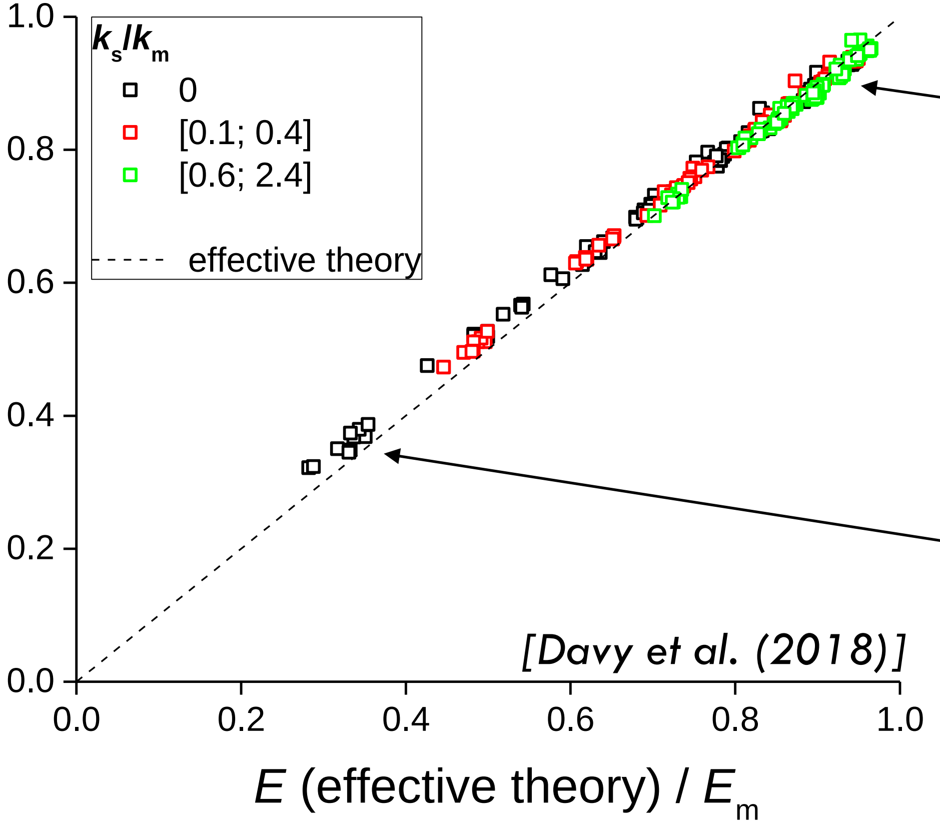




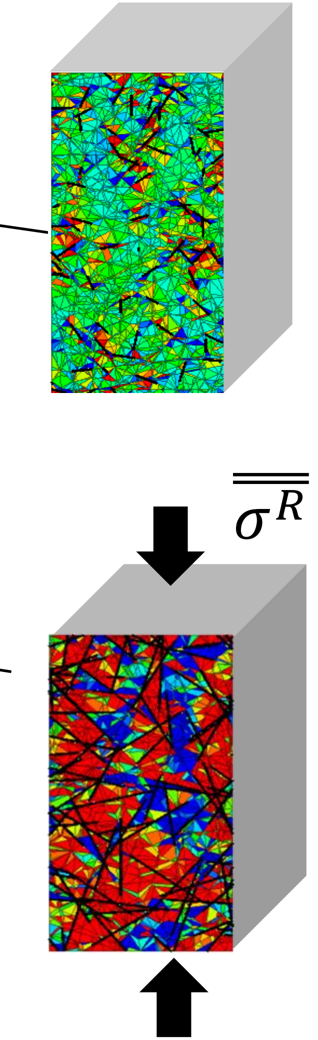
Effective rock mass elastic properties

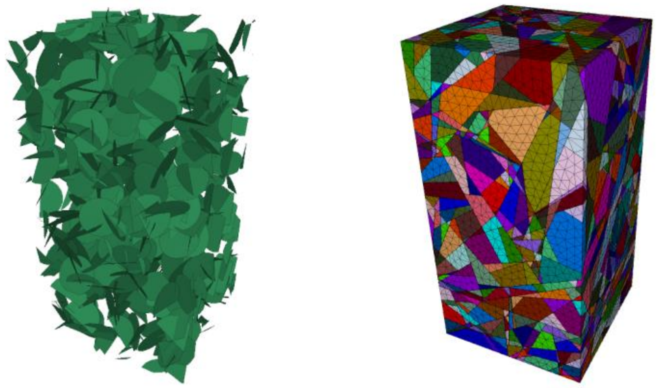
$E \,/\, E_m$

Numerical simulations



Theoretical calculations





Effective rock mass elastic properties

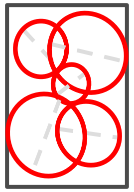
Analytical solutions for simple cases

- If $k_s \ll k_m$ $(l \ll l_s)$

$$E_{eff} = E_m \exp(-c(\theta)p)$$

$$p = \frac{1}{V}\sum_f l_f^3$$

So-called percolation parameter



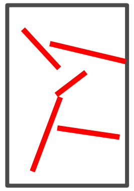
Potential size effect since p is scale dependent

- If $k_s \gg k_m$ $(l \gg l_s)$

$$E_{eff} \sim \frac{k_s}{P_{32} + k_s/E_m}$$

$$P_{32} = \frac{1}{V}\sum_f l_f^2$$

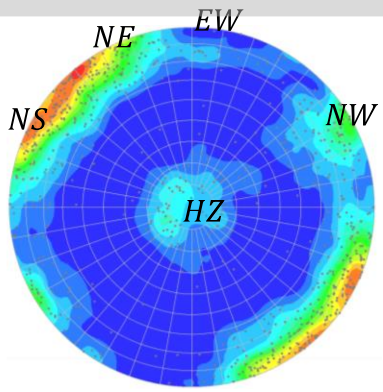
Total fracture surface per unit volume

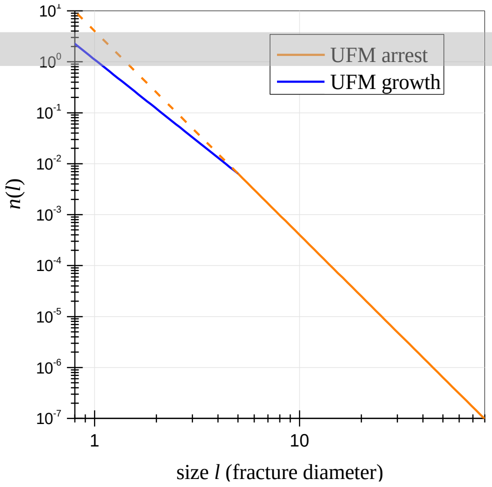


No size effect since P_{32} is scale independent

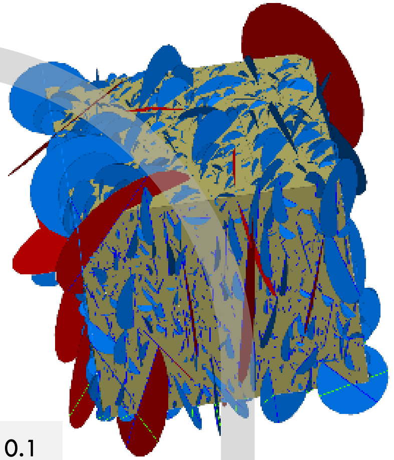
Application to Forsmark FFM01 deformation zone

DFN (FFM01 unit)

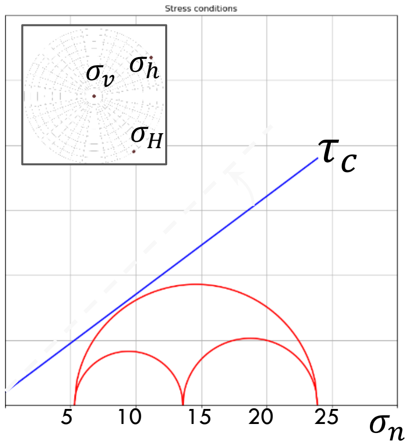




$l_{min} = 0.1$
$L = 20$



Mechanical properties



No critically stressed fractures

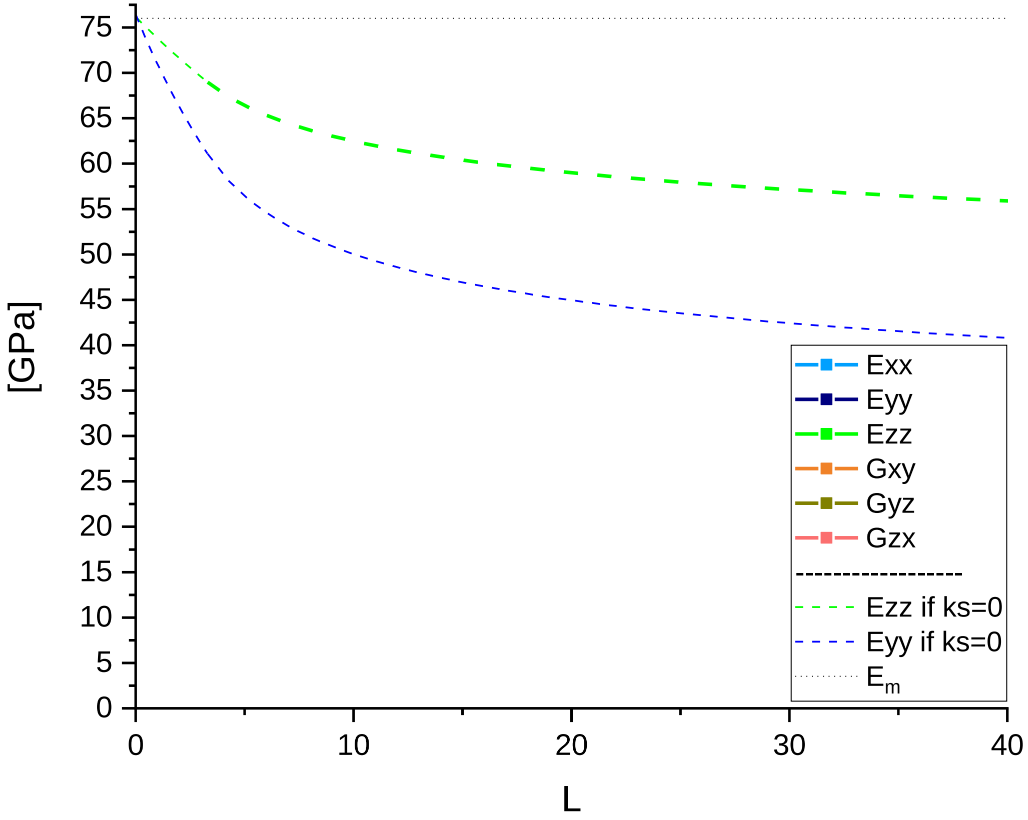
Intact Rock
$E_m = 76\ GPa$
$\nu_m = 0.23$

Fractures
$k_s(\sigma_n) = 46.55 \times \sigma_n^{0.4039} \times 10^6$
$k_n > 100 k_s$

$$
\begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \epsilon_{yz} \\ \epsilon_{xz} \\ \epsilon_{xy} \end{bmatrix}
=
\begin{bmatrix}
\frac{1}{E_{xx}} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\
-\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\
-\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{2G_{yz}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{2G_{xz}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{xy}}
\end{bmatrix}
\times
\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix}
$$

Compliance tensor $\overline{\overline{C}}$

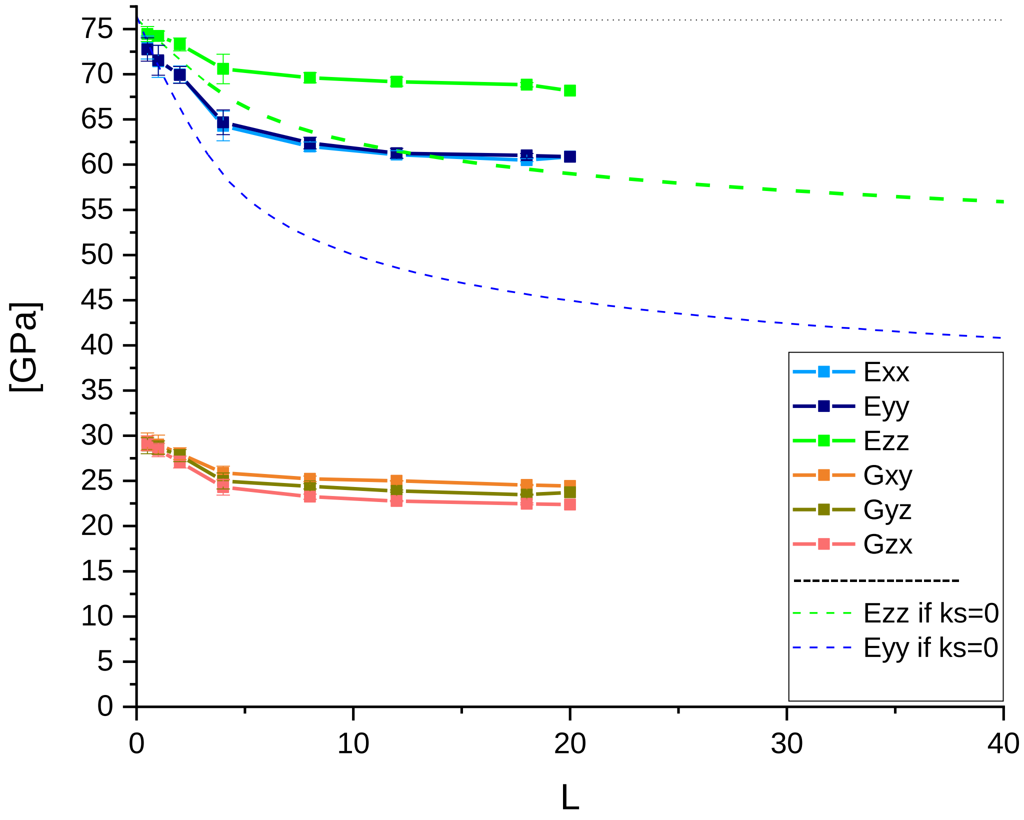
Application to Forsmark FFM01 deformation zone



Given the DFN conditions:

- If $k_s = 0 \rightarrow$ maximise the scaling effect

Application to Forsmark FFM01 deformation zone



Given the DFN conditions:

- If $k_s = 0 \rightarrow$ maximise the scaling effect

With current mechanical properties

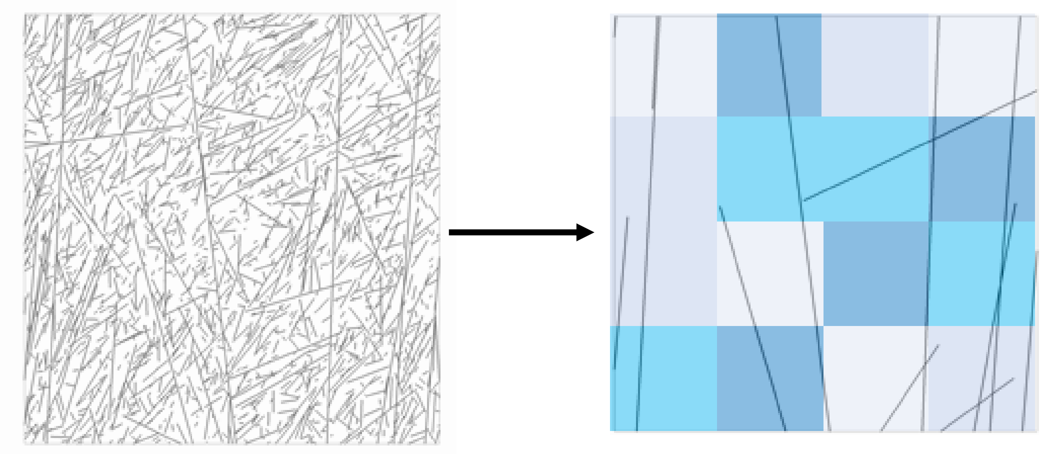
- $1.5 \text{ m} \leq l_s \leq 3.5 \text{ m}$
- Decrease of E_{ii} with L up to ~10m.
- E_{xx} decrease from 76 Gpa to about 62 GPa, i.e. about 25%.

Conclusion

- DFN methodology: integrate multiscale anisotropic fracture distributions
- Effective elastic properties of fractured RM can be assessed quantitatively by a method combining individual fractures contributions
- The developed method can be applied to large DFN (million of fractures)
- Fracture frictional properties introduce scales effects
- Depending on fracture frictional properties (ratio l/l_s) the effective properties are driven either by p or P_{32}

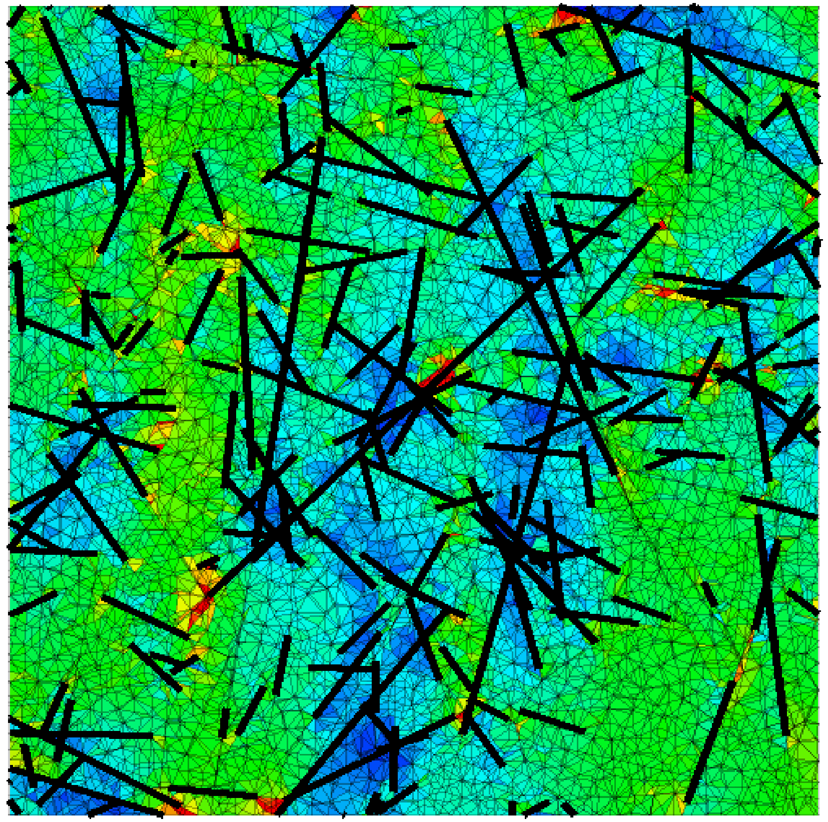
Perspective

- Comparison with predictions based on RMC charts
- Characterization of stress fluctuations, and associated scale dependence
- Semi-effective medium representation
- Extend the methodology to strength properties



Full DFN *Semi-effective medium*

Thanks for your attention



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