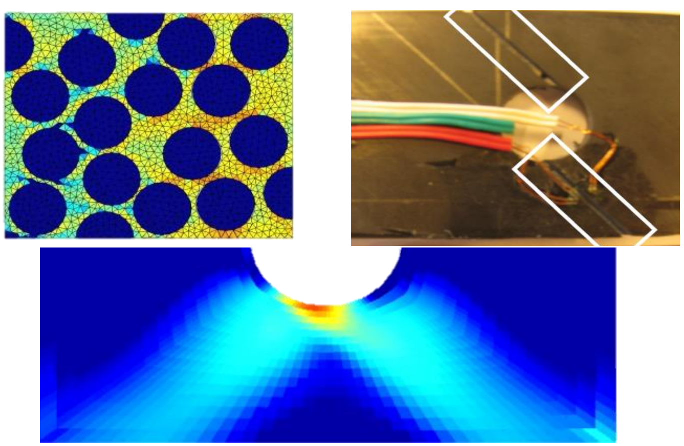
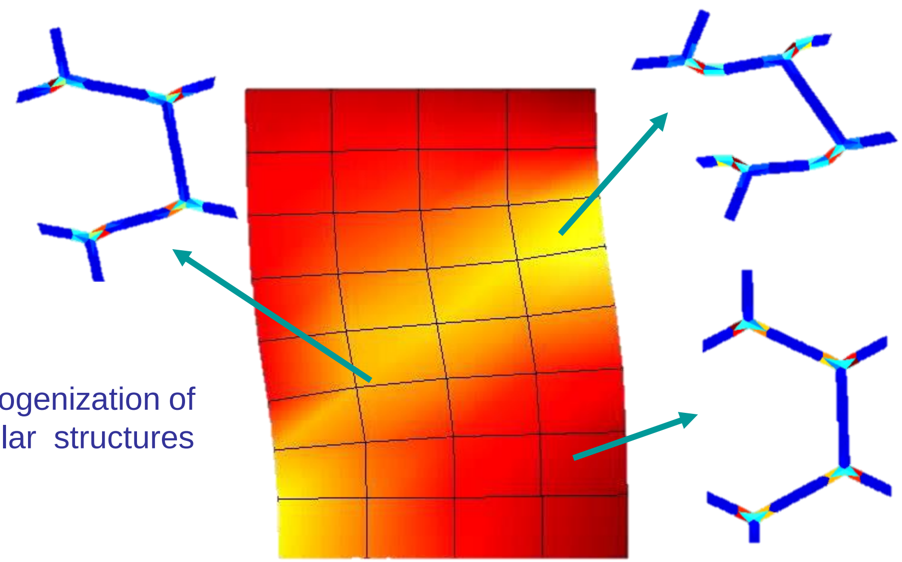
Muti-scale methods with strain-softening: damage-enhanced MFH for composite materials and computational homogenization for cellular materials with micro-buckling

L. Noels, G. Becker, V.-D. Nguyen,
L. Wu , L. Adam (x-Stream), I. Doghri (UCL)



Non-local damage mean-field-homogenization

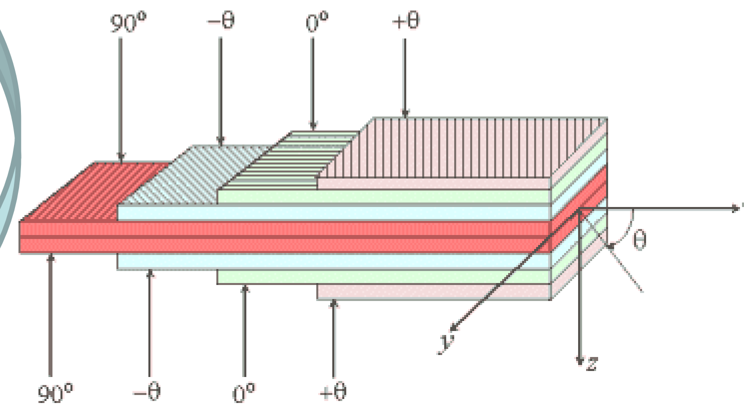


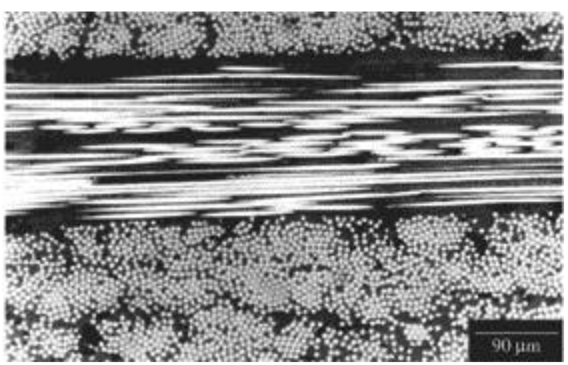
FE2 homogenization of cellular structures

Multi-scale modelling: Why?

- Materials in aeronautics
  - More and more engineered
  - Multi-scale in nature

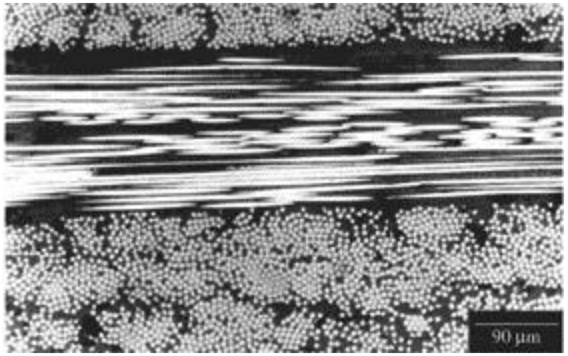
A350 wing lower cover

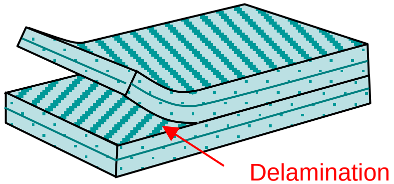


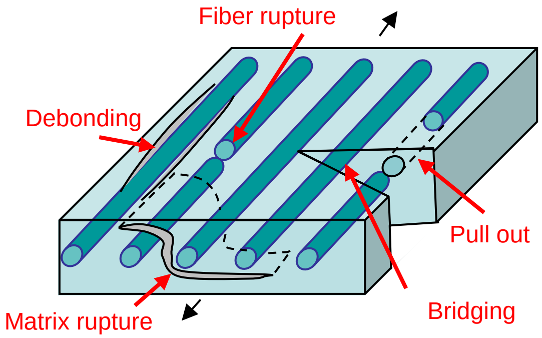


Multi-scale modelling: Why?

- Limitations of one-scale models
  - Physics at the micro-scale is too complex to be modelled by a simple material law at the macro-scale
    - Engineered materials
    - Multi-physics/scale problems
    - ….
    - See next slides
  - Lack of information of the micro-scale state during macro-scale deformations
    - Required to predict failure
    - …..
  - Effect of the micro-structure on the macro-structure response
    - Fibres distribution …
    - …
- Solution: multi-scale models





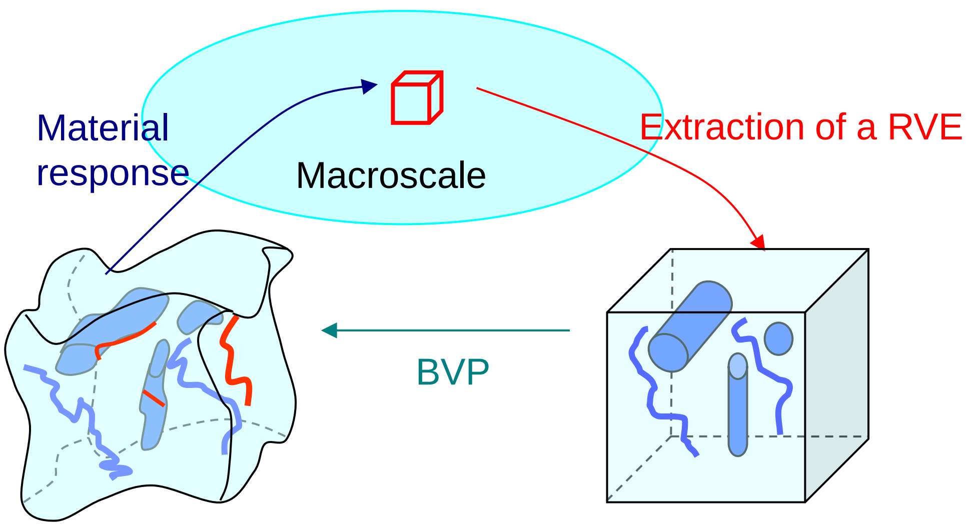


Content

- Introduction
  - Multi-scale modelling: How?
  - Strain softening issues
- Non-local damage-enhanced mean-field-homogenization
- Computational homogenization for cellular materials
- Other researches
  - DG-based fracture mechanics: blast, fragmentation, …
- Conclusions

Multi-scale modelling: How?

- Principle
  - 2 problems are solved concurrently
    - The macro-scale problem
    - The micro-scale problem (Representative Volume Element)
  - Scale transitions coupling the two scales
    - Downscaling: transfer of macro-scale quantities (e.g. strain) to the micro-scale to determine the equilibrium state of the Boundary Value Problem
    - Upscaling: constitutive law (e.g. stress) for the macro-scale problem is determined from the micro-scale problem resolution

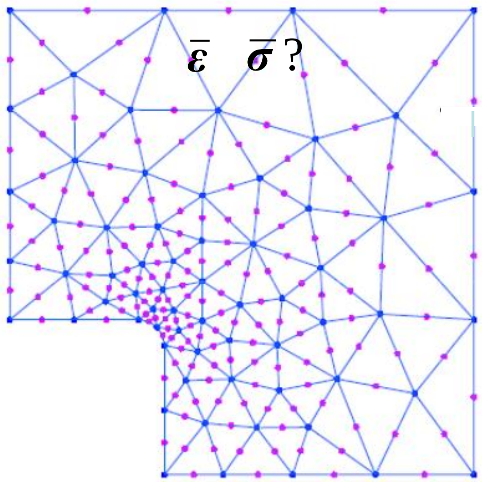


Assumptions:

$L_{macro} >> L_{RVE} >> L_{micro}$

Multi-scale modelling: How?

- Computational technique: FE^2
  - Macro-scale
    - FE model
    - At one integration point $\bar{\boldsymbol{\varepsilon}}$ is know, $\bar{\boldsymbol{\sigma}}$ is sought



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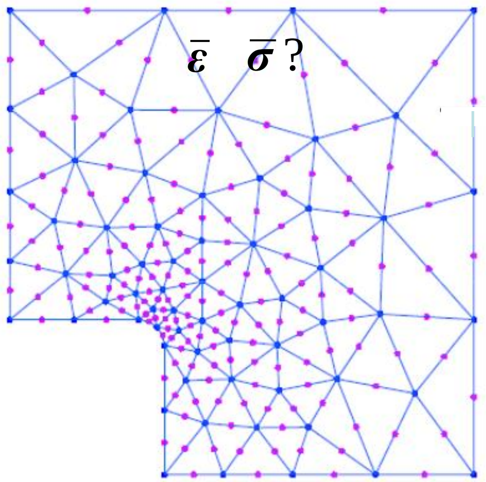
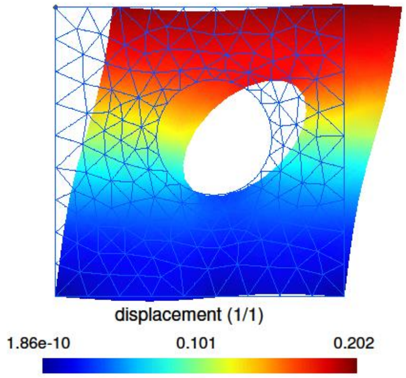


  - Micro-scale
    - Usual 3D finite elements
    - Periodic boundary conditions



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    - Upscaling: $\bar{\sigma}$ is known from the reaction forces
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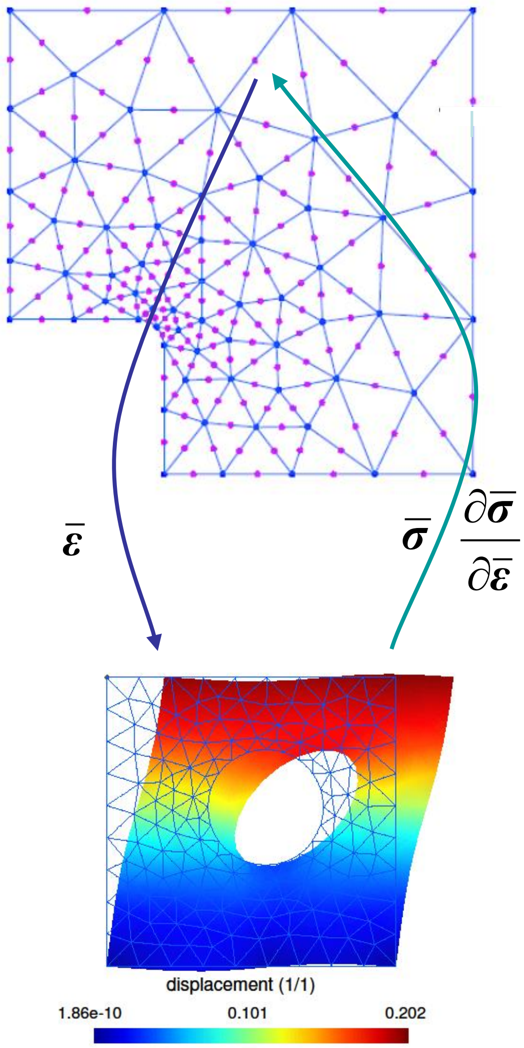

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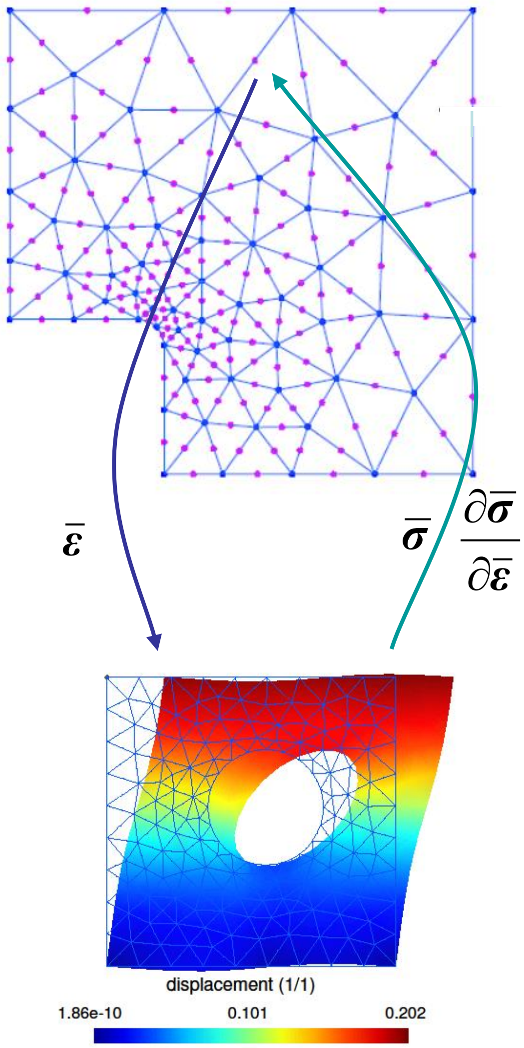
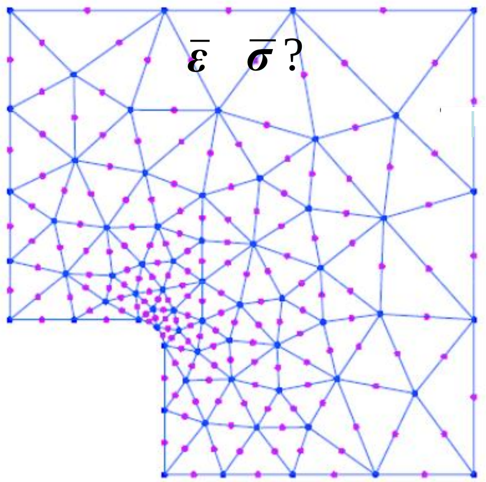
  - Micro-scale
    - Usual 3D finite elements
    - Periodic boundary conditions
  - Advantages
    - Accuracy
    - Generality
  - Drawback
    - Computational time



Ghosh S et al. 95, Kouznetsova et al. 2002, Geers et al. 2010, …

- Mean-Field Homogenization
  - Macro-scale
    - FE model
    - At one integration point $\bar{\varepsilon}$ is know, $\bar{\sigma}$ is sought



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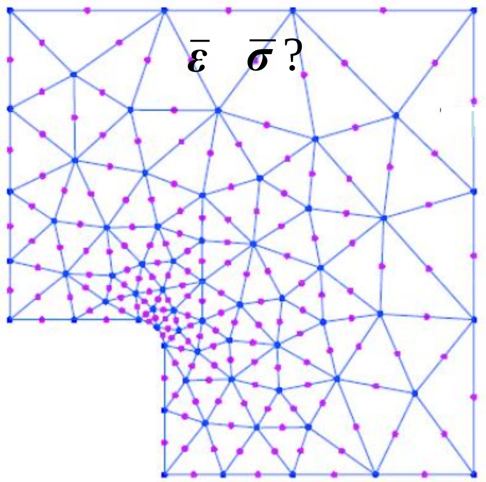
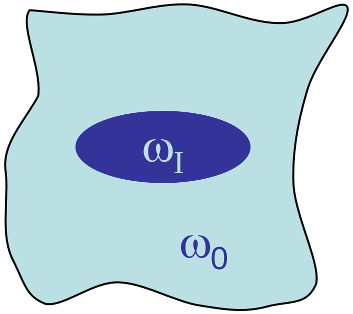


  - Micro-scale
    - Semi-analytical model
    - Predict composite meso-scale response
    - From components material models



Multi-scale modelling: How?

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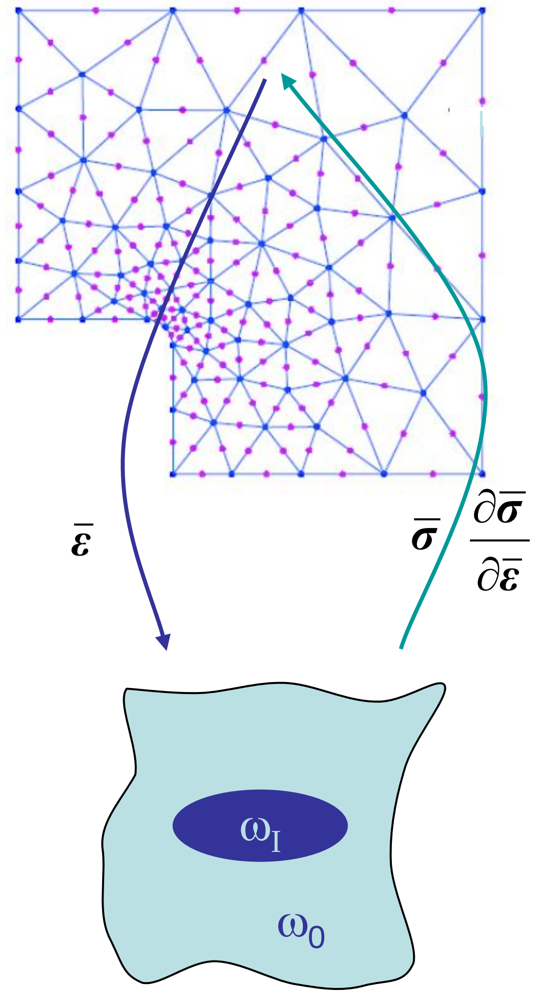

Mori and Tanaka 73, Hill 65, Ponte Castañeda 91, Suquet 95, Doghri et al 03, Lahellec et al. 11, Brassart et al. 12, …

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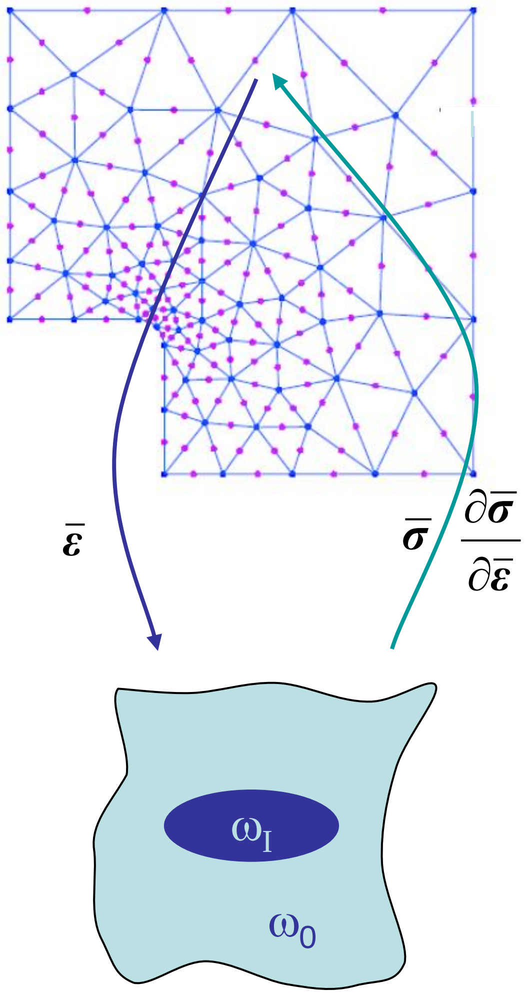
  - Micro-scale
    - Semi-analytical model
    - Predict composite meso-scale response
    - From components material models
  - Advantages
    - Computationally efficient
    - Easy to integrate in a FE code (material model)
  - Drawbacks
    - Difficult to formulate in an accurate way
      - Geometry complexity
      - Material behaviours complexity



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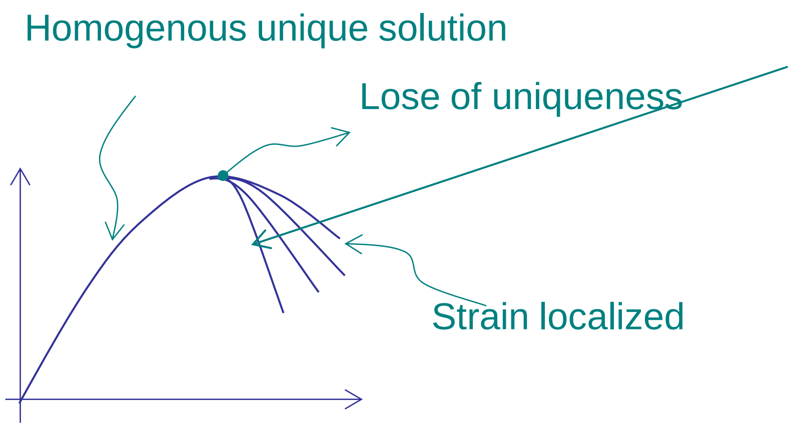
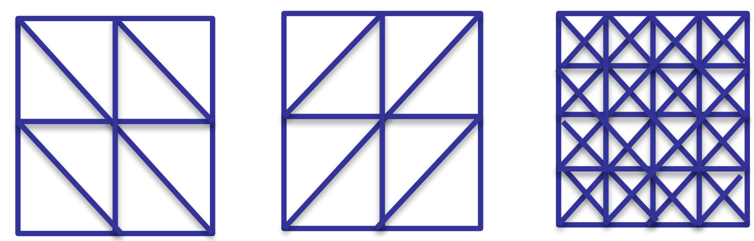
Strain softening of the microscopic response

- Finite element solutions for strain softening problems suffer from:
  - The loss the uniqueness and strain localization
  - Mesh dependence



The numerical results change with the size of mesh and direction of mesh

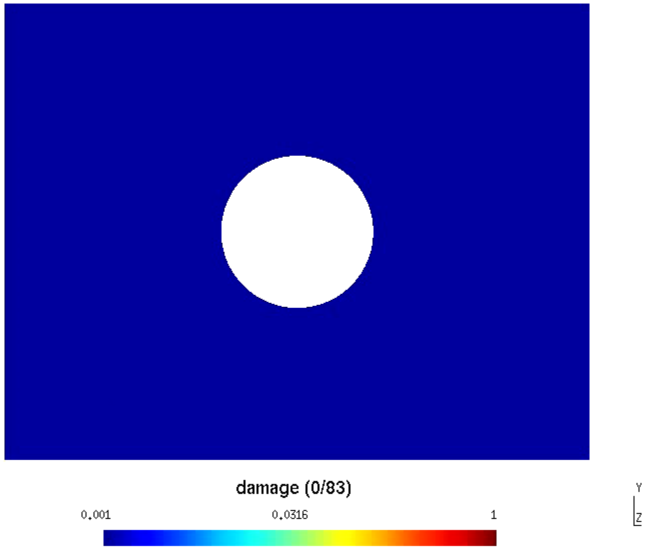


The numerical results change without convergence

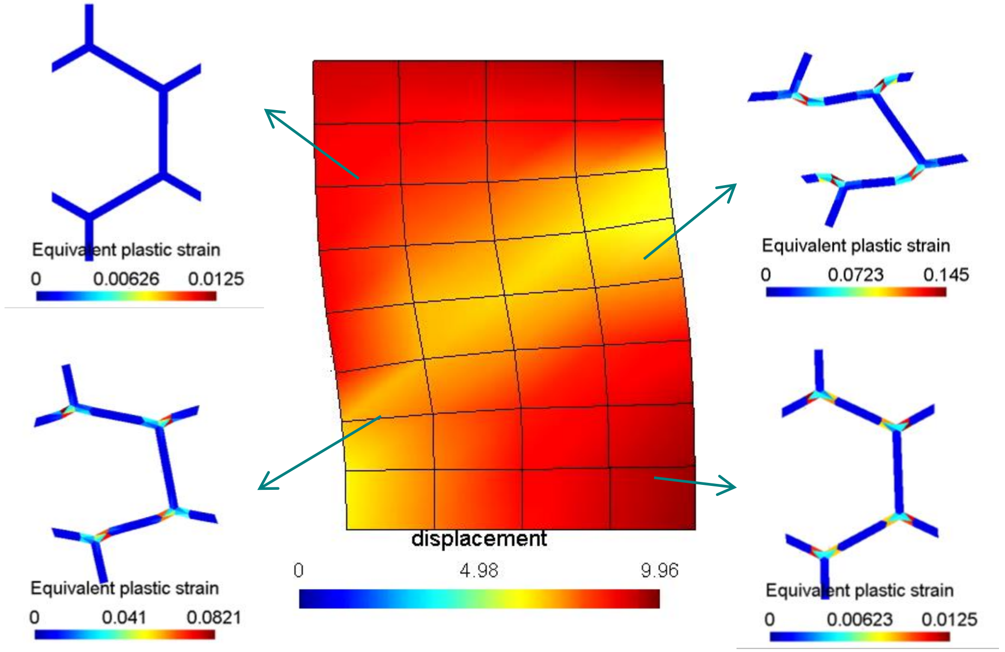
- Requires a non-local formulation of the macro-scale problem

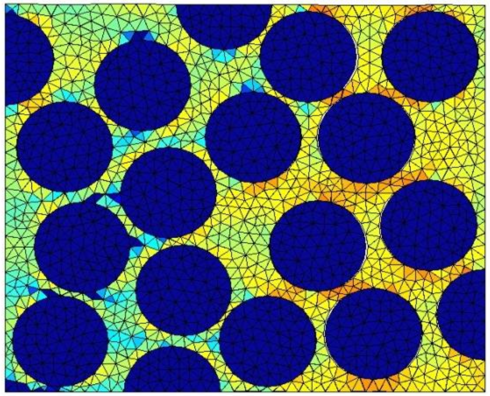
Multi-scale simulations with strain softening

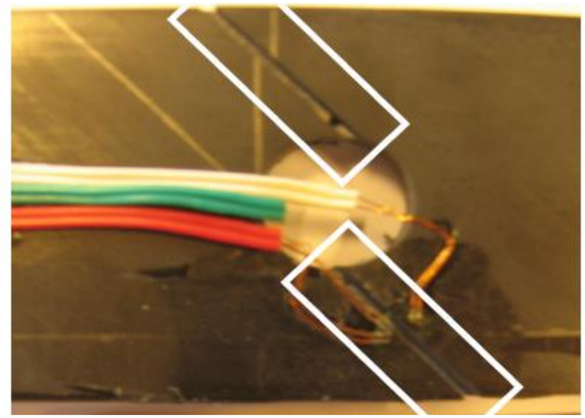
- Two cases considered
  - Composite materials
    - Mean-field homogenization
    - Non-local damage formulation

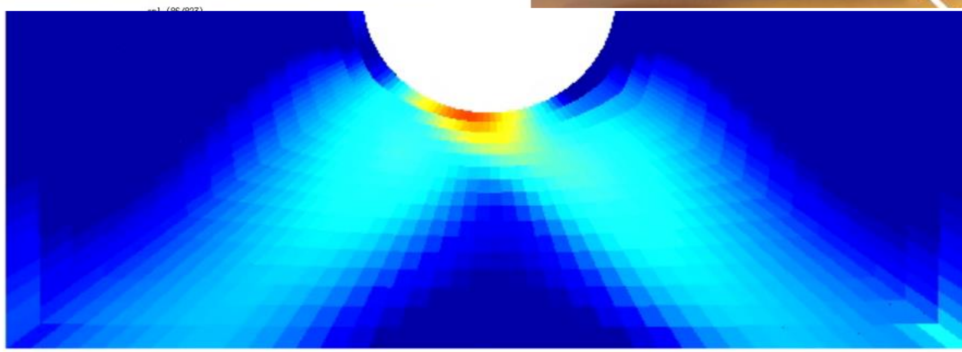


  - Honeycomb structures
    - Computational homogenization
    - Second-order FE2
    - Micro-buckling









Non-local damage-enhanced mean-field-homogenization

L. Wu (ULg), L. Noels (ULg), L. Adam (e-Xstream), I. Doghri (UCL)

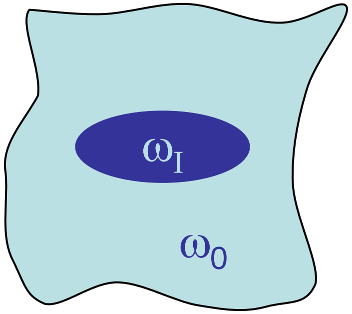
SIMUCOMP The research has been funded by the Walloon Region under the agreement no 1017232 (CT-EUC 2010-10-12) in the context of the ERA-NET +, Matera + framework.

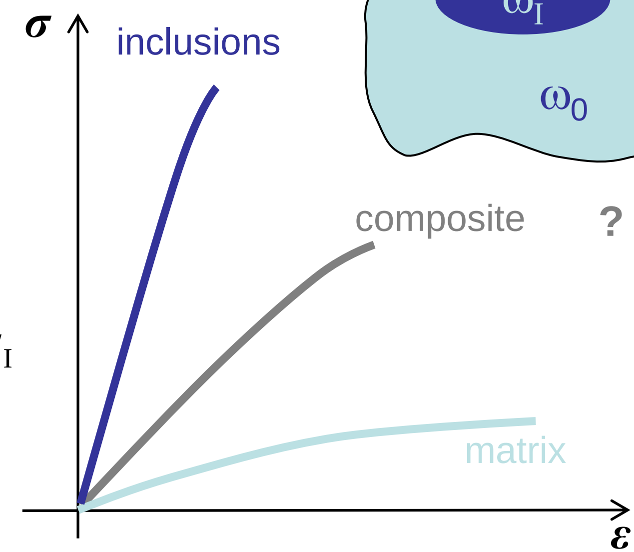
- Semi analytical Mean-Field Homogenization
  - Based on the averaging of the fields

$$\langle a \rangle = \frac{1}{V}\int_V a(\boldsymbol{X})\mathrm{d}V$$

  - Meso-response
    - From the volume ratios ($v_0 + v_\mathrm{I} = 1$)

$$\begin{cases} \bar{\boldsymbol{\sigma}} = \langle \boldsymbol{\sigma} \rangle = v_0 \langle \boldsymbol{\sigma} \rangle_{\omega_0} + v_\mathrm{I} \langle \boldsymbol{\sigma} \rangle_{\omega_\mathrm{I}} = v_0 \boldsymbol{\sigma}_0 + v_\mathrm{I} \boldsymbol{\sigma}_\mathrm{I} \\ \bar{\boldsymbol{\varepsilon}} = \langle \boldsymbol{\varepsilon} \rangle = v_0 \langle \boldsymbol{\varepsilon} \rangle_{\omega_0} + v_\mathrm{I} \langle \boldsymbol{\varepsilon} \rangle_{\omega_\mathrm{I}} = v_0 \boldsymbol{\varepsilon}_0 + v_\mathrm{I} \boldsymbol{\varepsilon}_\mathrm{I} \end{cases}$$





    - One more equation required

$$\boldsymbol{\varepsilon}_\mathrm{I} = \boldsymbol{B}^{\varepsilon} : \boldsymbol{\varepsilon}_0$$

  - Difficulty: find the adequate relations

$$\begin{cases} \boldsymbol{\sigma}_\mathrm{I} = f(\boldsymbol{\varepsilon}_\mathrm{I}) \\ \boldsymbol{\sigma}_0 = f(\boldsymbol{\varepsilon}_0) \\ \boldsymbol{\varepsilon}_\mathrm{I} = \boldsymbol{B}^{\varepsilon} : \boldsymbol{\varepsilon}_0 \end{cases} \qquad \boldsymbol{B}^{\varepsilon}\ ?$$

- Mean-Field Homogenization for different materials
  - Linear materials
    - Materials behaviours

$$\begin{cases} \boldsymbol{\sigma}_\mathrm{I} = \overline{\boldsymbol{C}}_\mathrm{I} : \boldsymbol{\varepsilon}_\mathrm{I} \\ \boldsymbol{\sigma}_0 = \overline{\boldsymbol{C}}_0 : \boldsymbol{\varepsilon}_0 \end{cases}$$

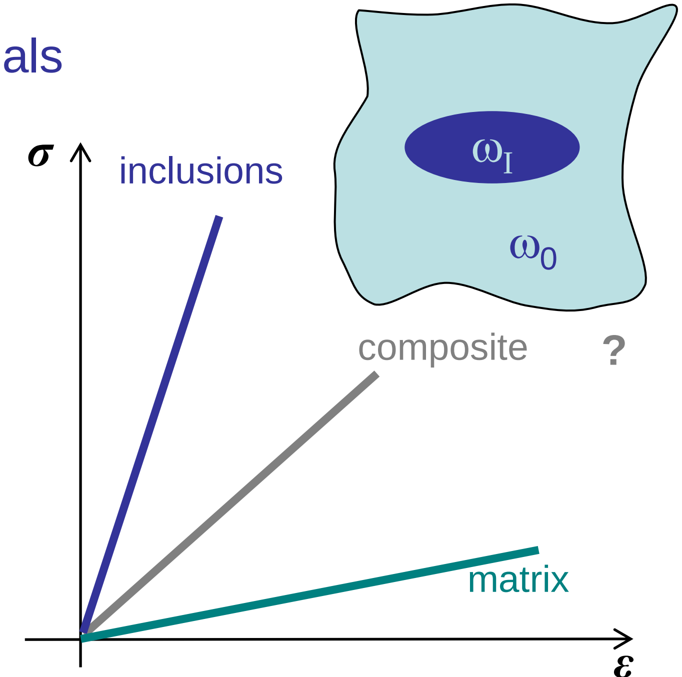
    - Mori-Tanaka assumption $\boldsymbol{\varepsilon}^\infty = \boldsymbol{\varepsilon}_0$
    - Use Eshelby tensor

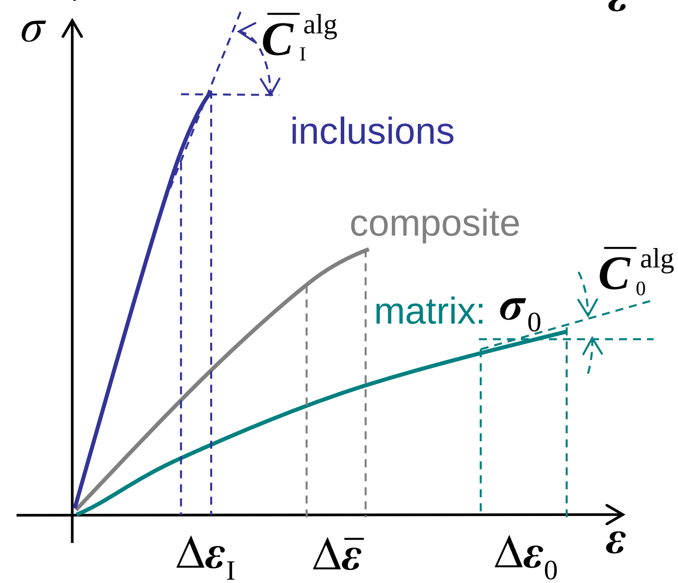
$$\boldsymbol{\varepsilon}_\mathrm{I} = \boldsymbol{B}^\varepsilon\left(\mathrm{I}, \overline{\boldsymbol{C}}_0, \overline{\boldsymbol{C}}_\mathrm{I}\right) : \boldsymbol{\varepsilon}_0$$

with $\boldsymbol{B}^\varepsilon = [\boldsymbol{I} + \boldsymbol{S} : \overline{\boldsymbol{C}}_0^{-1} : (\overline{\boldsymbol{C}}_1 - \overline{\boldsymbol{C}}_0)]^{-1}$

  - Non-linear materials
    - Define a Linear Comparison Composite
    - Common approach: incremental tangent

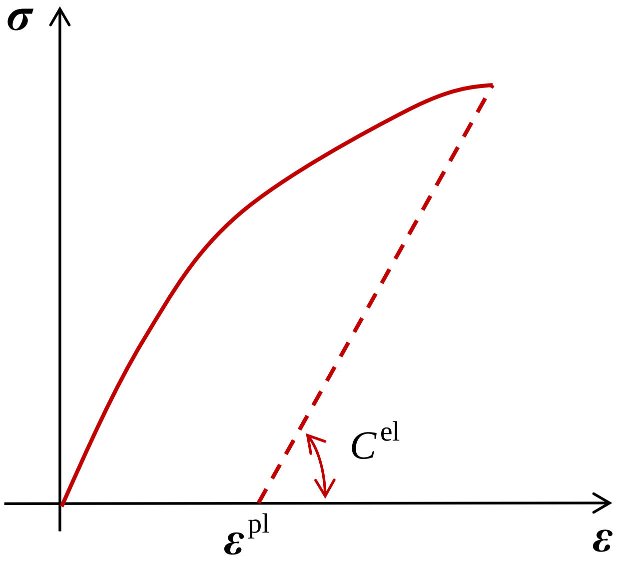
$$\Delta\boldsymbol{\varepsilon}_\mathrm{I} = \boldsymbol{B}^\varepsilon\left(\mathrm{I}, \overline{\boldsymbol{C}}_0^{\mathrm{alg}}, \overline{\boldsymbol{C}}_\mathrm{I}^{\mathrm{alg}}\right) : \Delta\boldsymbol{\varepsilon}_0$$





Non-local damage-enhanced mean-field-homogenization

- Material models
  - Elasto-plastic material
    - Stress tensor $\boldsymbol{\sigma} = \boldsymbol{C}^{\text{el}} : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{\text{pl}})$
    - Yield surface $f(\boldsymbol{\sigma}, p) = \boldsymbol{\sigma}^{\text{eq}} - \sigma^{Y} - R(p) \leq 0$
    - Plastic flow $\Delta\boldsymbol{\varepsilon}^{\text{pl}} = \Delta p \boldsymbol{N}$ & $\boldsymbol{N} = \frac{\partial f}{\partial \boldsymbol{\sigma}}$
    - Linearization $\delta\boldsymbol{\sigma} = \boldsymbol{C}^{\text{alg}} : \delta\boldsymbol{\varepsilon}$



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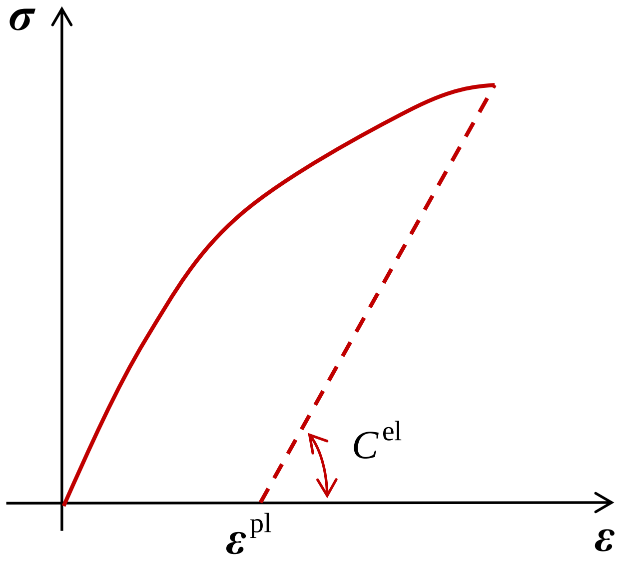
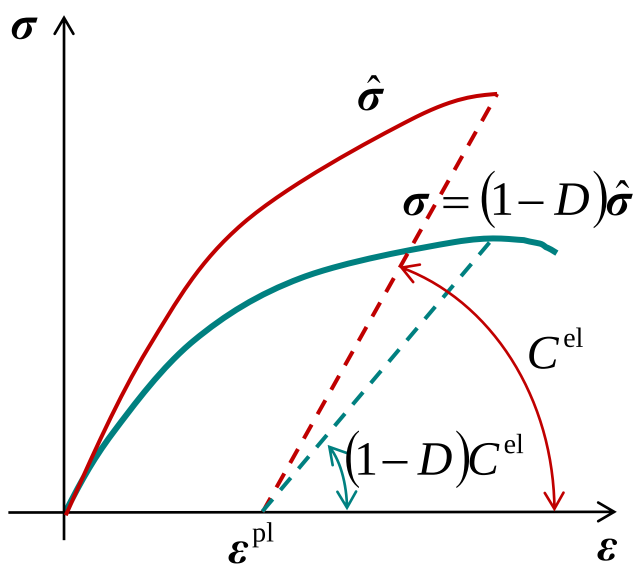
  - Local damage model
    - Apparent-effective stress tensors $\boldsymbol{\sigma} = (1-D)\hat{\boldsymbol{\sigma}}$
    - Plastic flow in the effective stress space
    - Damage evolution $\Delta D = F_D(\boldsymbol{\varepsilon}, \Delta p)$





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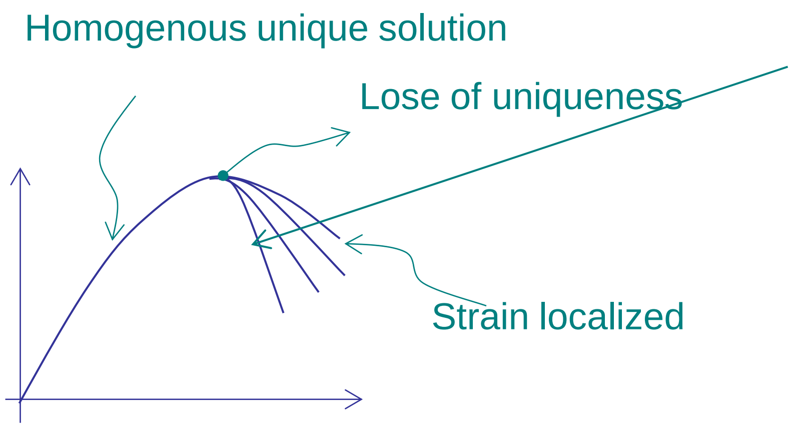

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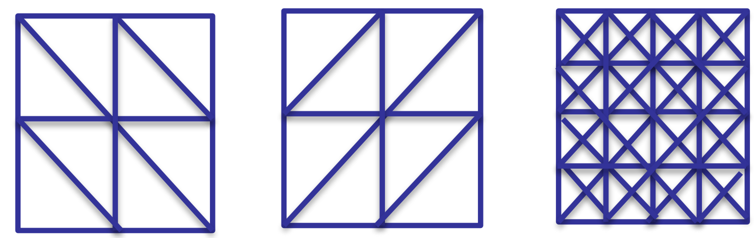

The numerical results change without convergence

- Implicit non-local approach [Peerlings et al 96, Geers et al 97, …]
  - A state variable is replaced by a non-local value reflecting the interaction between neighboring material points

$$\tilde{a}(\boldsymbol{x}) = \frac{1}{V_C} \int_{V_C} a(\boldsymbol{y}) w(\boldsymbol{y}; \boldsymbol{x}) \mathrm{d}V$$

  - Use Green functions as weight $w(y; x)$

$$\Rightarrow \quad \tilde{a} - c\nabla^2 \tilde{a} = a \quad \Rightarrow$$ New degrees of freedom

Non-local damage-enhanced mean-field-homogenization

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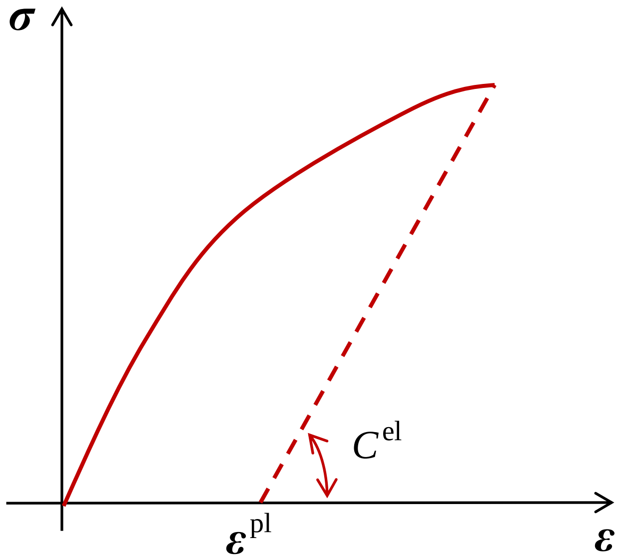
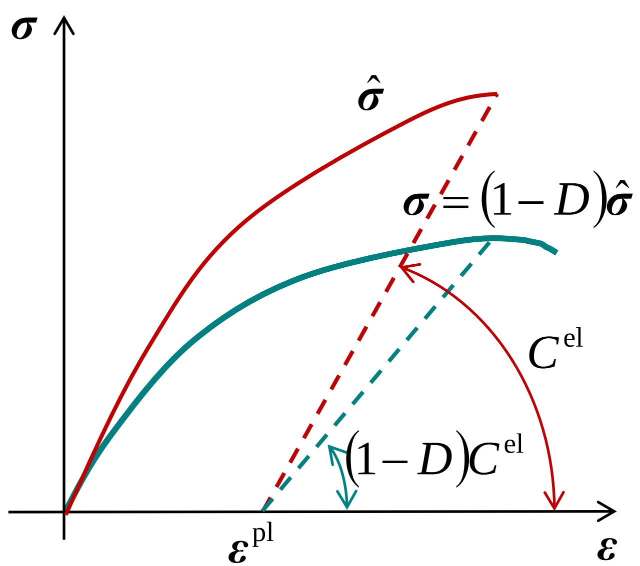


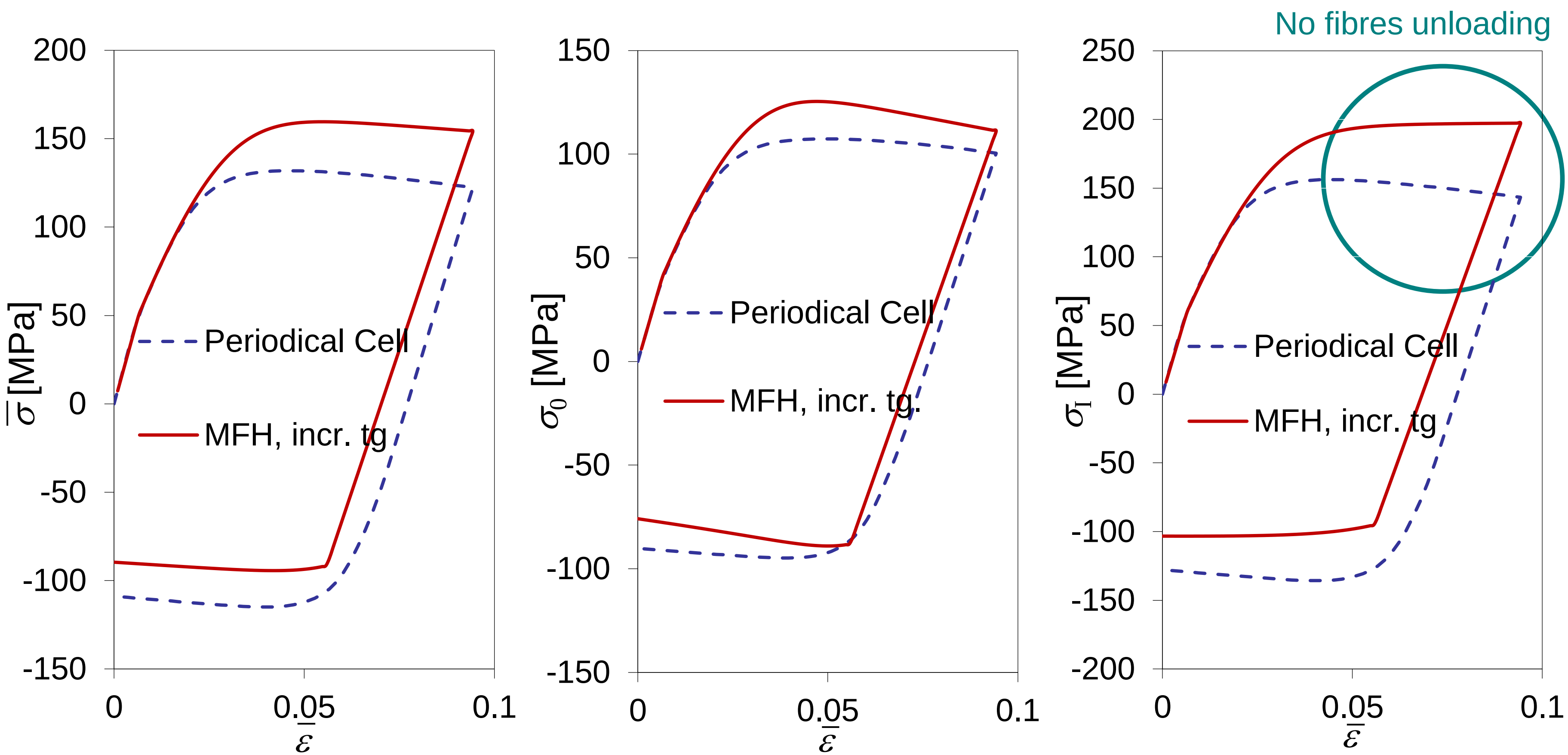
  - Local damage model
    - Apparent-effective stress tensors $\boldsymbol{\sigma} = (1 - D)\hat{\boldsymbol{\sigma}}$
    - Plastic flow in the effective stress space
    - Damage evolution $\Delta D = F_D(\boldsymbol{\varepsilon}, \Delta p)$
  - Non-Local damage model
    - Damage evolution $\Delta D = F_D(\boldsymbol{\varepsilon}, \Delta\tilde{p})$
    - Anisotropic governing equation $\tilde{p} - \nabla \cdot (\boldsymbol{c}_{\text{g}} \cdot \nabla\tilde{p}) = p$
    - Linearization

$$\delta\boldsymbol{\sigma} = \left[(1 - D)\boldsymbol{C}^{\text{alg}} - \hat{\boldsymbol{\sigma}} \otimes \frac{\partial F_D}{\partial \boldsymbol{\varepsilon}}\right] : \delta\boldsymbol{\varepsilon} - \hat{\boldsymbol{\sigma}} \frac{\partial F_D}{\partial \tilde{p}} \delta\tilde{p}$$



Non-local damage-enhanced mean-field-homogenization

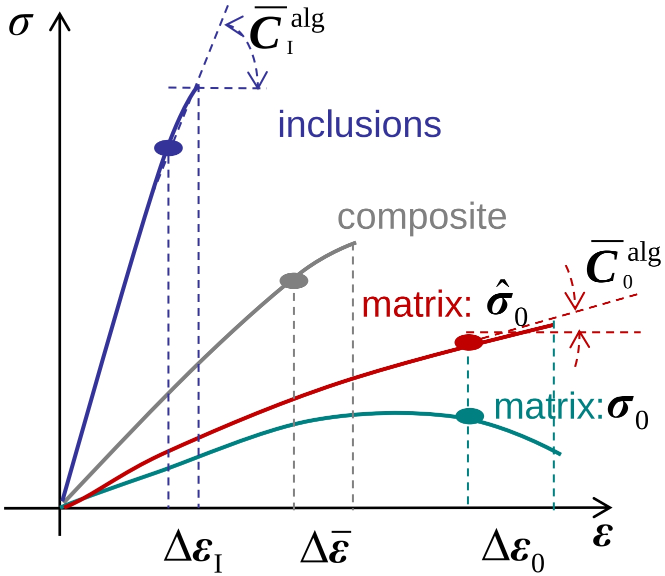
- Limitation of the incremental tangent method
  - Fictitious composite
    - 50%-UD fibres
    - Elasto-plastic matrix with damage
  - Due to the incremental formalism, stress in fibres cannot decrease during loading



- Problem
  - We want the fibres to get unloaded during the matrix damaging process
    - For the incremental-tangent approach

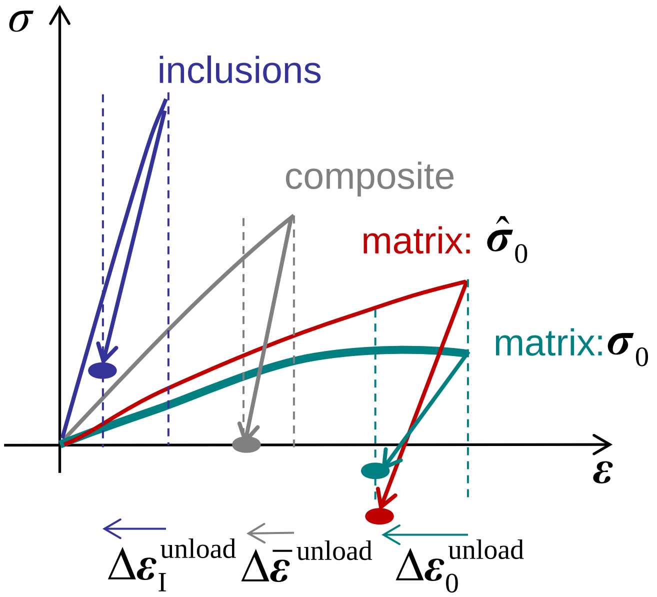
$$\Delta \boldsymbol{\varepsilon}_{\mathrm{I}} = \boldsymbol{B}^{\varepsilon}\left(\mathrm{I}, (1-D)\overline{\boldsymbol{C}}_{0}^{\mathrm{alg}}, \overline{\boldsymbol{C}}_{\mathrm{I}}^{\mathrm{alg}}\right) : \Delta \boldsymbol{\varepsilon}_{0}$$

    - To unload the fibres ($\boldsymbol{\varepsilon}_{\mathrm{I}} < 0$) with such approach would require $\overline{\boldsymbol{C}}_{\mathrm{I}}^{\mathrm{alg}} < 0$
    - We cannot use the incremental tangent MFH
  - We need to define the LCC from another stress state



Non-local damage-enhanced mean-field-homogenization

- Idea
  - New incremental-secant approach
    - Perform a virtual elastic unloading from previous solution
      - Composite material unloaded to reach the stress-free state
      - Residual stress in components



Non-local damage-enhanced mean-field-homogenization

- Idea
  - New incremental-secant approach
    - Perform a virtual elastic unloading from previous solution
      - Composite material unloaded to reach the stress-free state
      - Residual stress in components
    - Apply MFH from unloaded state
      - New strain increments (>0)

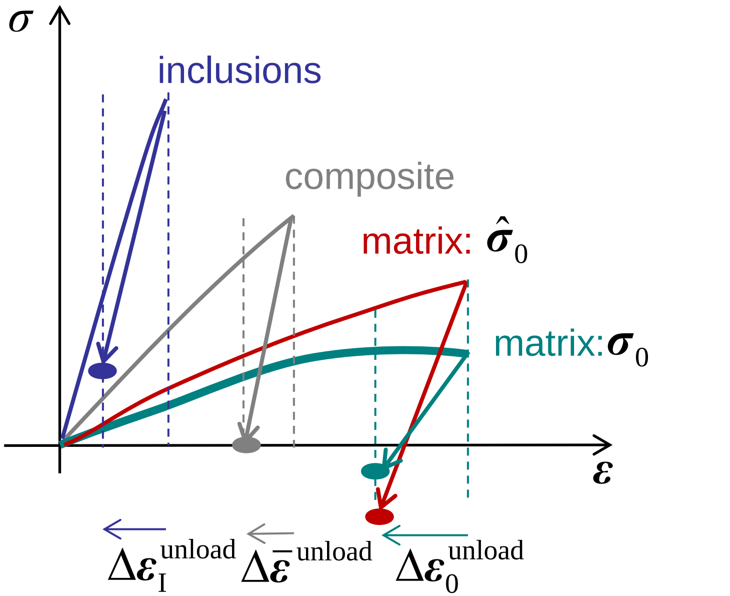
$$\Delta\boldsymbol{\varepsilon}^{\mathrm{r}}_{\mathrm{I/0}} = \Delta\boldsymbol{\varepsilon}_{\mathrm{I/0}} + \Delta\boldsymbol{\varepsilon}^{\mathrm{unload}}_{\mathrm{I/0}}$$

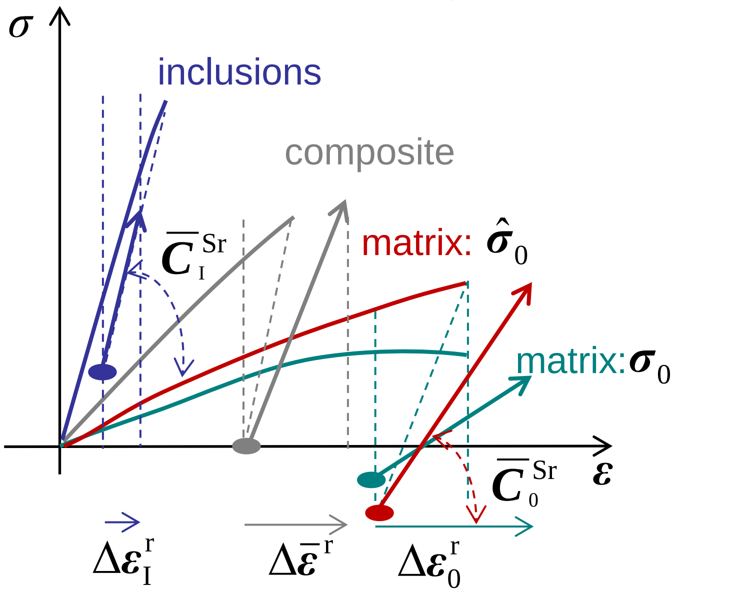
      - Use of secant operators

$$\Delta\boldsymbol{\varepsilon}^{\mathrm{r}}_{\mathrm{I}} = \boldsymbol{B}^{\varepsilon}\left(\mathrm{I}, (1-D)\bar{\boldsymbol{C}}^{\mathrm{Sr}}_{0}, \bar{\boldsymbol{C}}^{\mathrm{Sr}}_{\mathrm{I}}\right) : \Delta\boldsymbol{\varepsilon}^{\mathrm{r}}_{0}$$

      - Possibility of have unloading

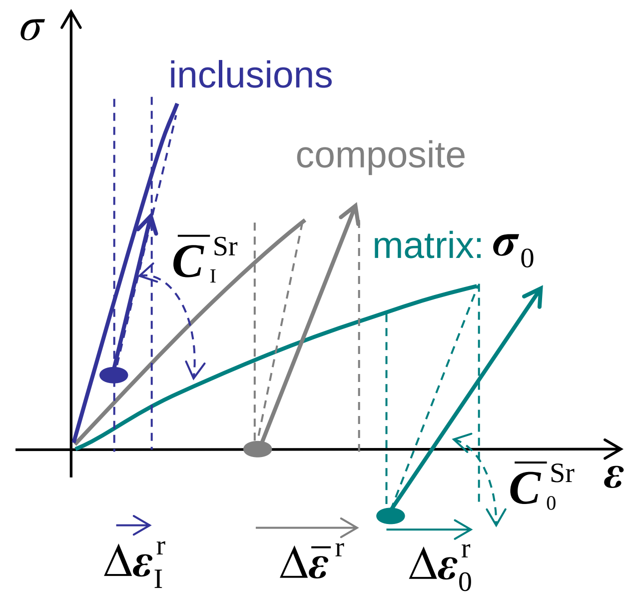
$$\begin{cases} \Delta\boldsymbol{\varepsilon}^{\mathrm{r}}_{\mathrm{I}} > 0 \\ \Delta\boldsymbol{\varepsilon}_{\mathrm{I}} < 0 \end{cases}$$



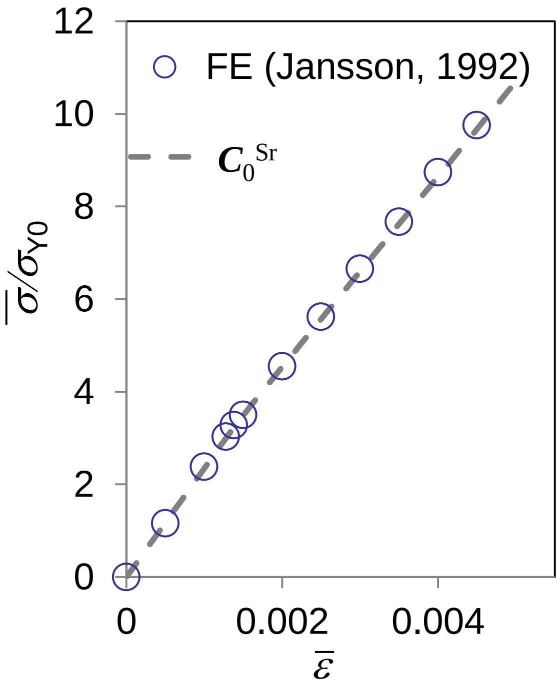


Non-local damage-enhanced mean-field-homogenization

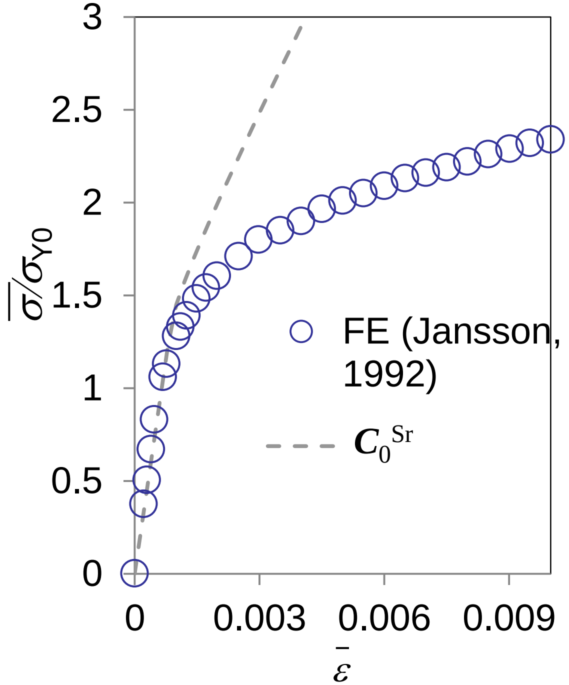
- Zero-incremental-secant method
  - Continuous fibres
    - 55 % volume fraction
    - Elastic
  - **Elasto-plastic matrix (no damage)**
  - For inclusions with high hardening (elastic)
    - Model is too stiff



Longitudinal tension



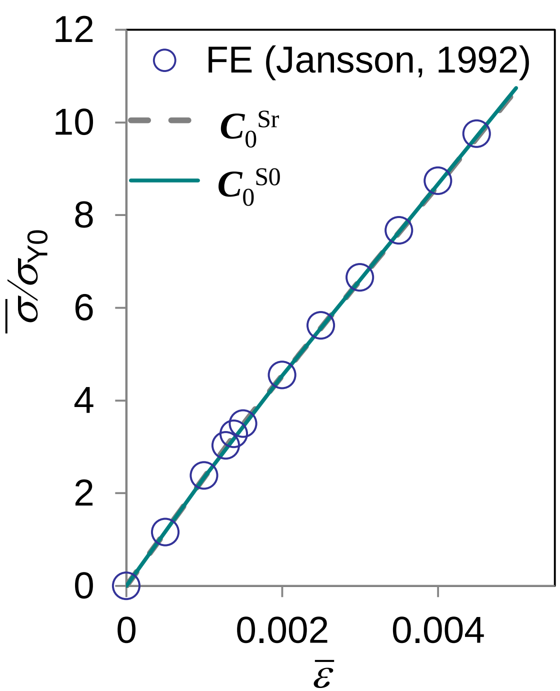
Transverse loading



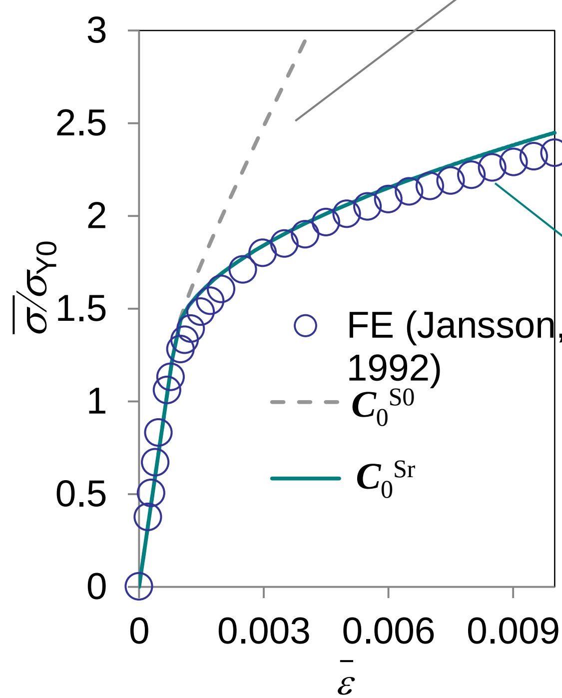
Non-local damage-enhanced mean-field-homogenization

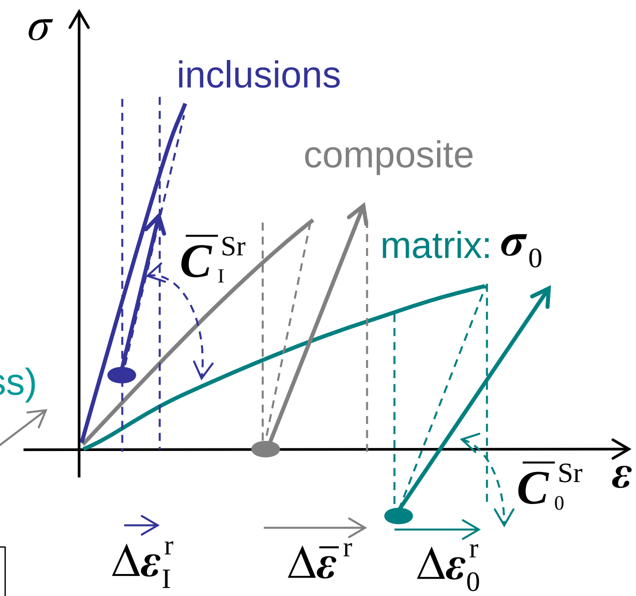
- Zero-incremental-secant method (2)
  - Continuous fibres
    - 55 % volume fraction
    - Elastic
  - **Elasto-plastic matrix (no damage)**
  - Secant model in the matrix
    - Modified if stiffer inclusions (negative residual stress)

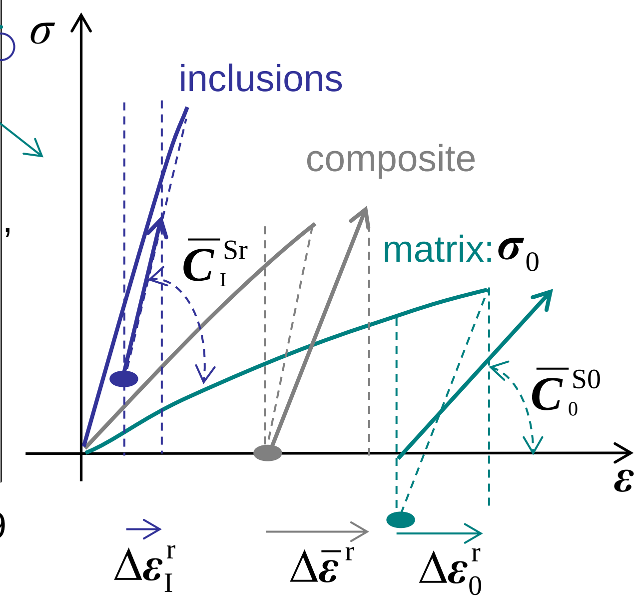
Longitudinal tension



Transverse loading

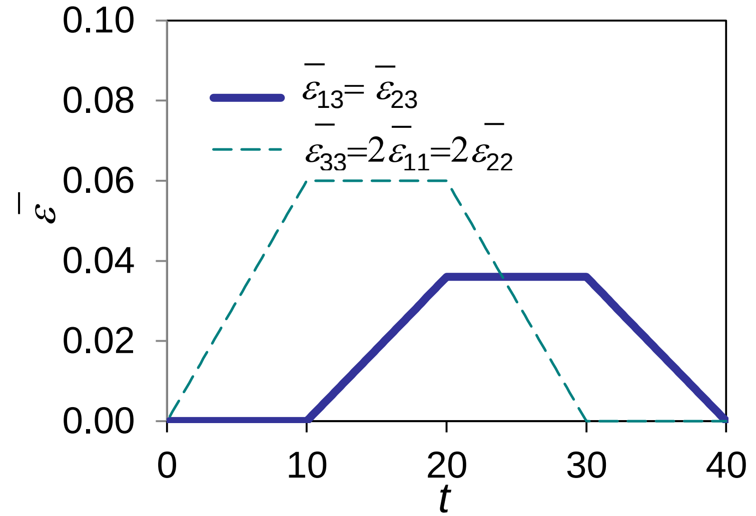


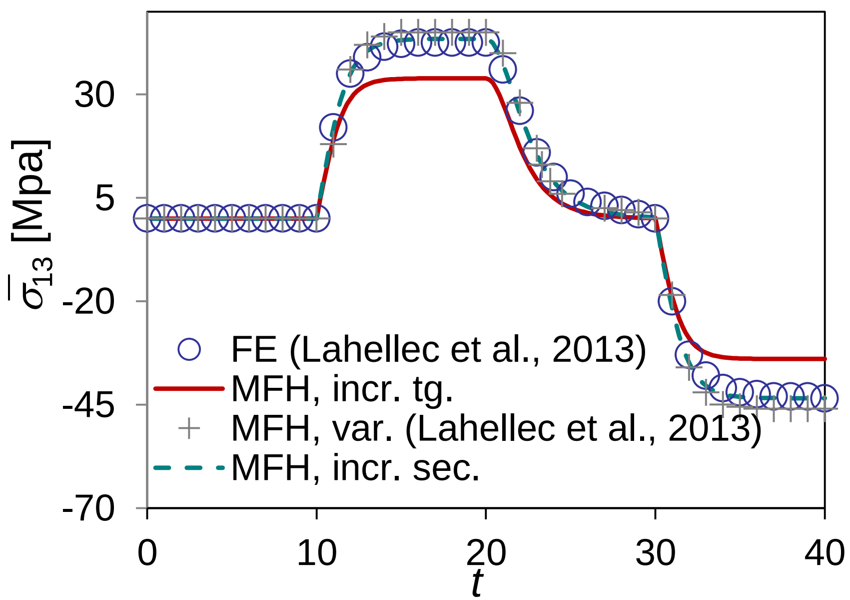


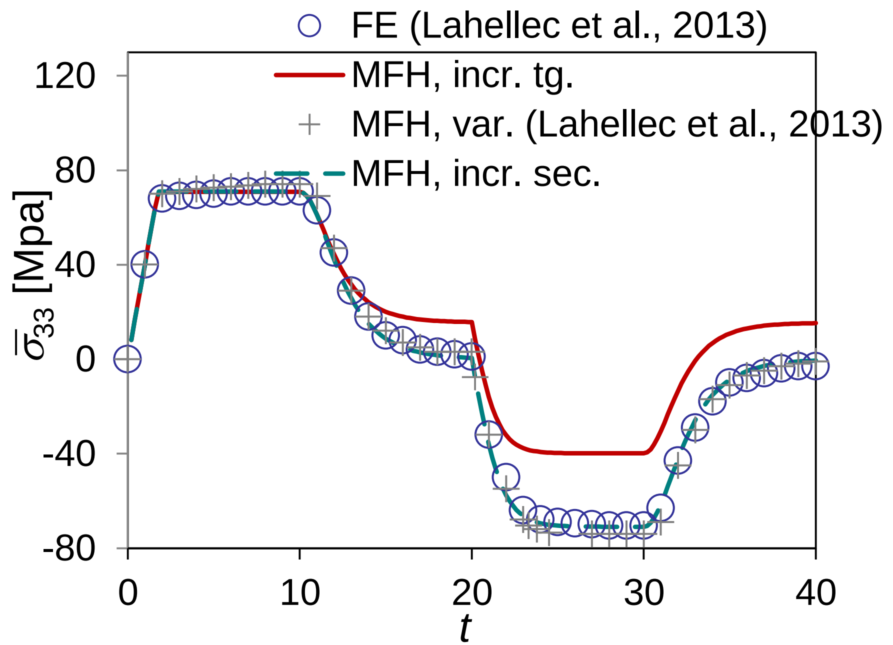


Non-local damage-enhanced mean-field-homogenization

- Verification of the method
  - Spherical inclusions
    - 17 % volume fraction
    - Elastic
  - **Elastic-perfectly-plastic matrix (no damage)**
  - **Non-radial loading**

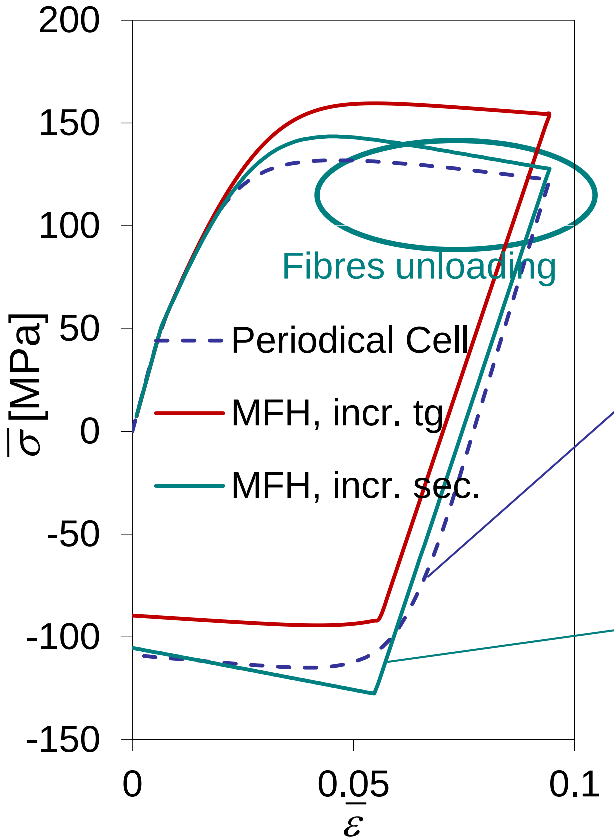


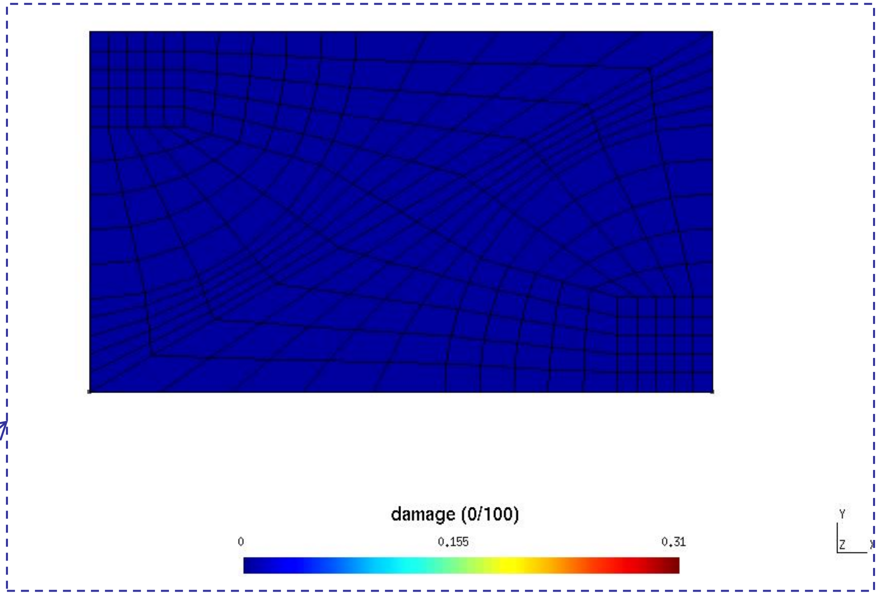


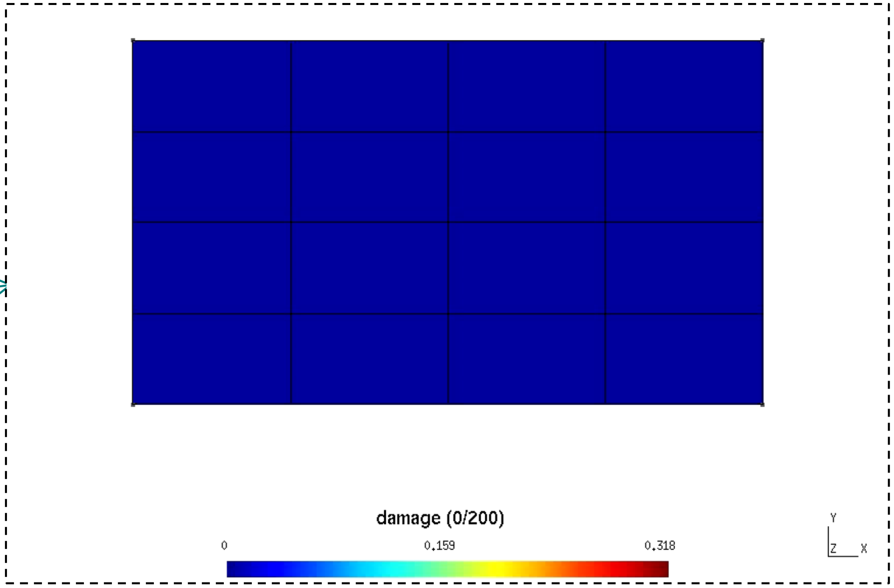


Non-local damage-enhanced mean-field-homogenization

- New results for damage
  - Fictitious composite
    - 50%-UD fibres
  - **Elasto-plastic matrix with damage**







- Weak formulation
  - Strong form

$$\begin{cases} \nabla \cdot \bar{\boldsymbol{\sigma}}^{T} + \boldsymbol{f} = \boldsymbol{0} & \text{for the homogenized composite material} \\ \tilde{p} - \nabla \cdot \left(\boldsymbol{c}_{\mathrm{g}} \cdot \nabla \tilde{p} \right) = p & \text{for the matrix phase} \end{cases}$$

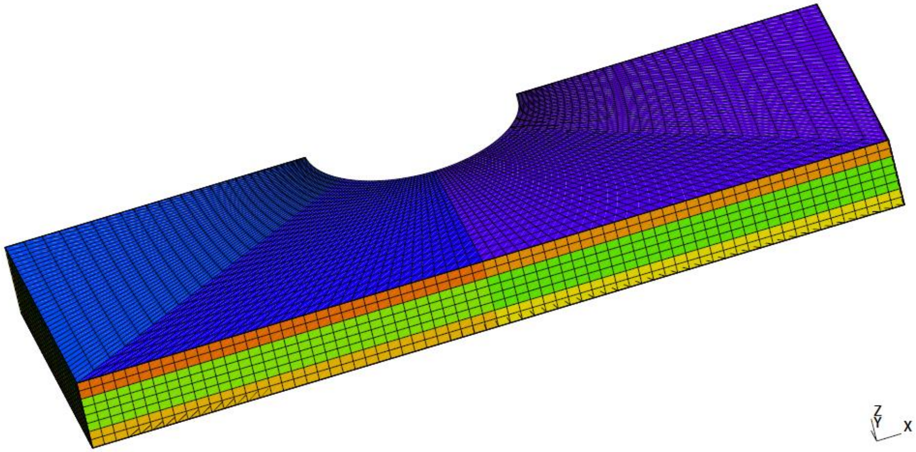
  - Boundary conditions

$$\begin{cases} \boldsymbol{\sigma} \cdot \boldsymbol{n} = \boldsymbol{T} \\ \boldsymbol{n} \cdot \left(\boldsymbol{c}_{\mathrm{g}} \cdot \nabla \tilde{p} \right) = 0 \end{cases}$$

  - Finite-element discretization

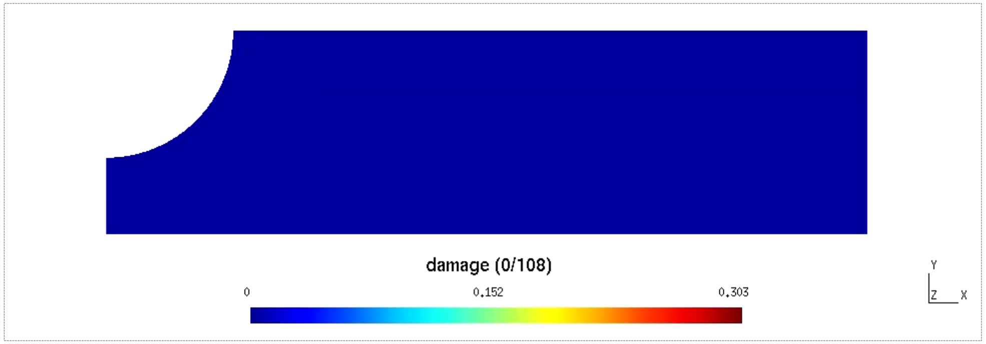
$$\begin{cases} \tilde{p} = N_{\tilde{p}}^{a} \tilde{\boldsymbol{p}}^{a} \\ \boldsymbol{u} = N_{u}^{a} \boldsymbol{u}^{a} \end{cases}$$

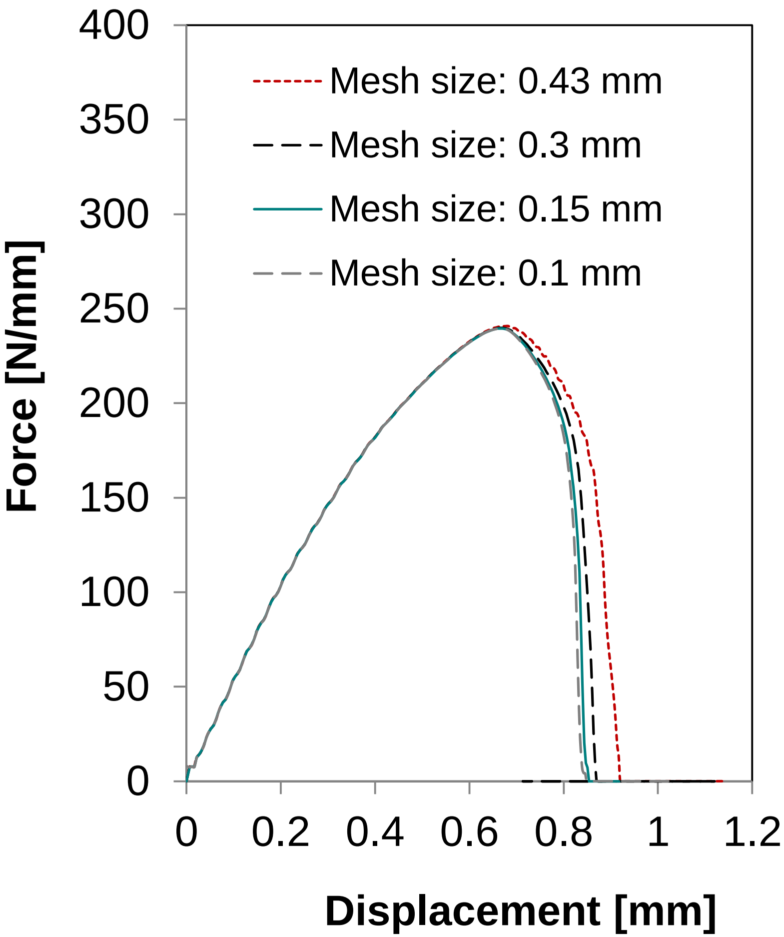
$$\Rightarrow \begin{bmatrix} \boldsymbol{K}_{uu} & \boldsymbol{K}_{u\tilde{p}} \\ \boldsymbol{K}_{\tilde{p}u} & \boldsymbol{K}_{\tilde{p}\tilde{p}} \end{bmatrix} \begin{bmatrix} d\boldsymbol{u} \\ d\tilde{\boldsymbol{p}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{F}_{\mathrm{ext}} - \boldsymbol{F}_{\mathrm{int}} \\ \boldsymbol{F}_{p} - \boldsymbol{F}_{\tilde{p}} \end{bmatrix}$$



Non-local damage-enhanced mean-field-homogenization

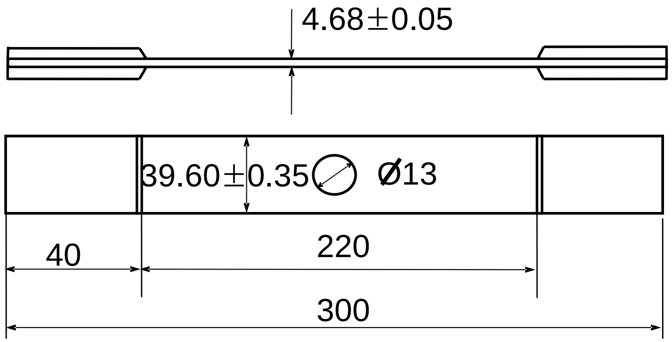
- Mesh-size effect
  - Fictitious composite
    - 30%-UD fibres
    - Elasto-plastic matrix with damage
  - Notched ply

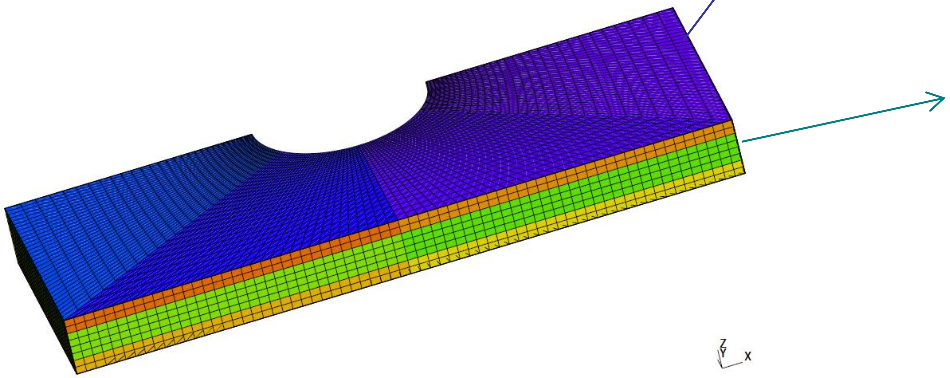


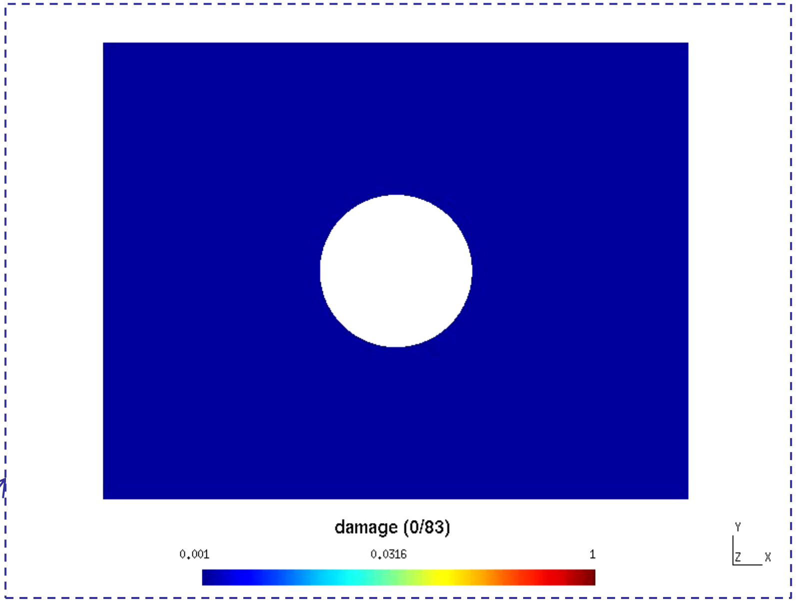


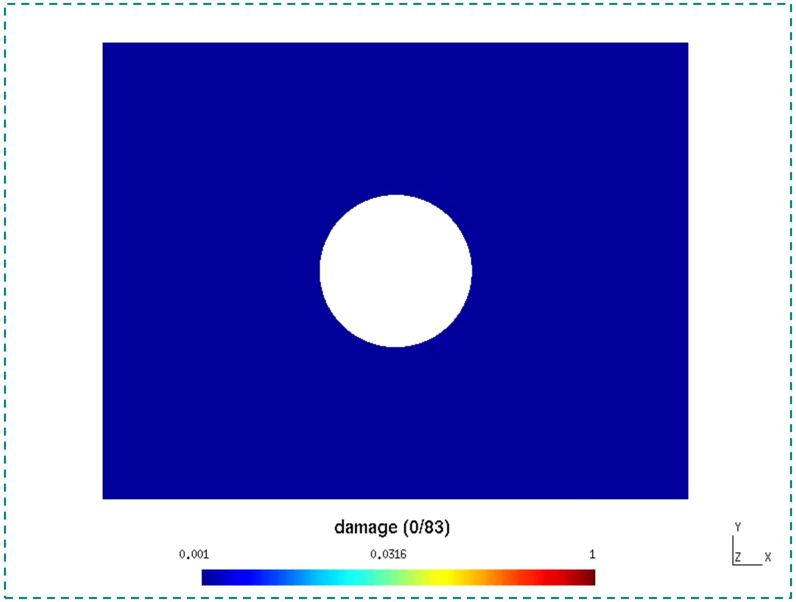
Non-local damage-enhanced mean-field-homogenization

- Laminate plate with hole
  - Carbon-fibres reinforced epoxy
    - 60%-UD fibres
    - Elasto-plastic matrix with damage
  - $[-45_2/45_2]_S$ staking sequence



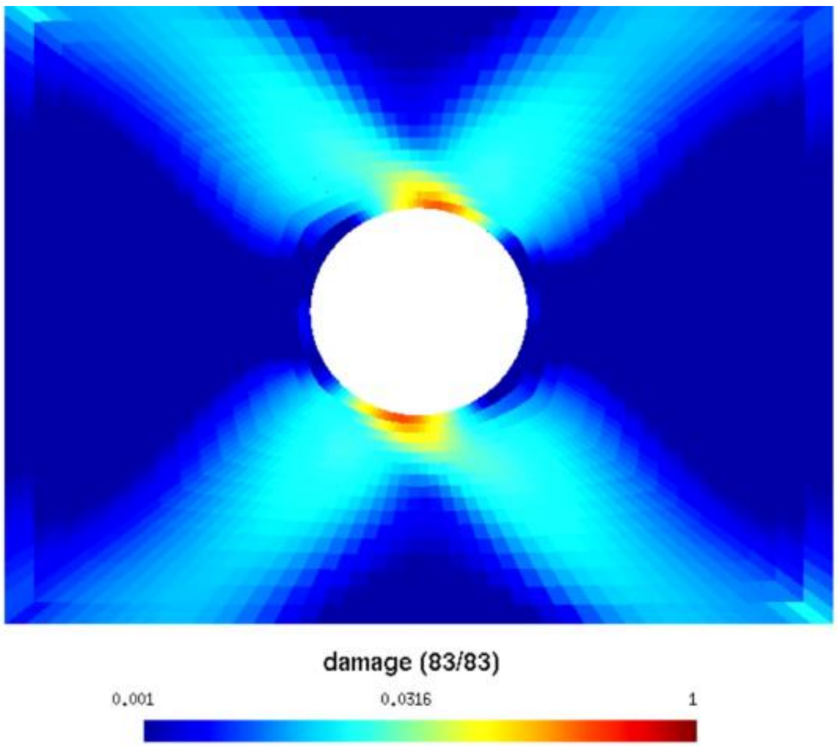


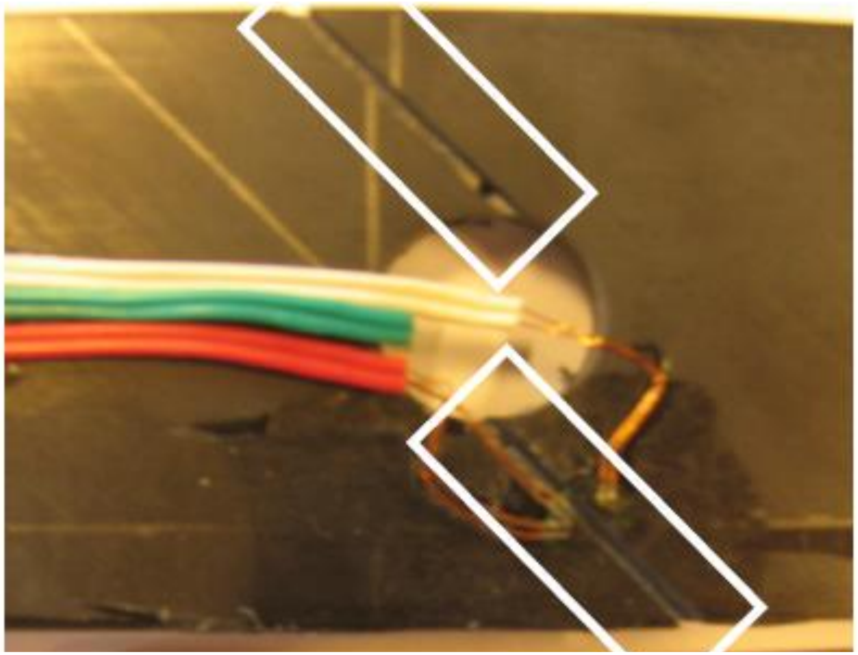


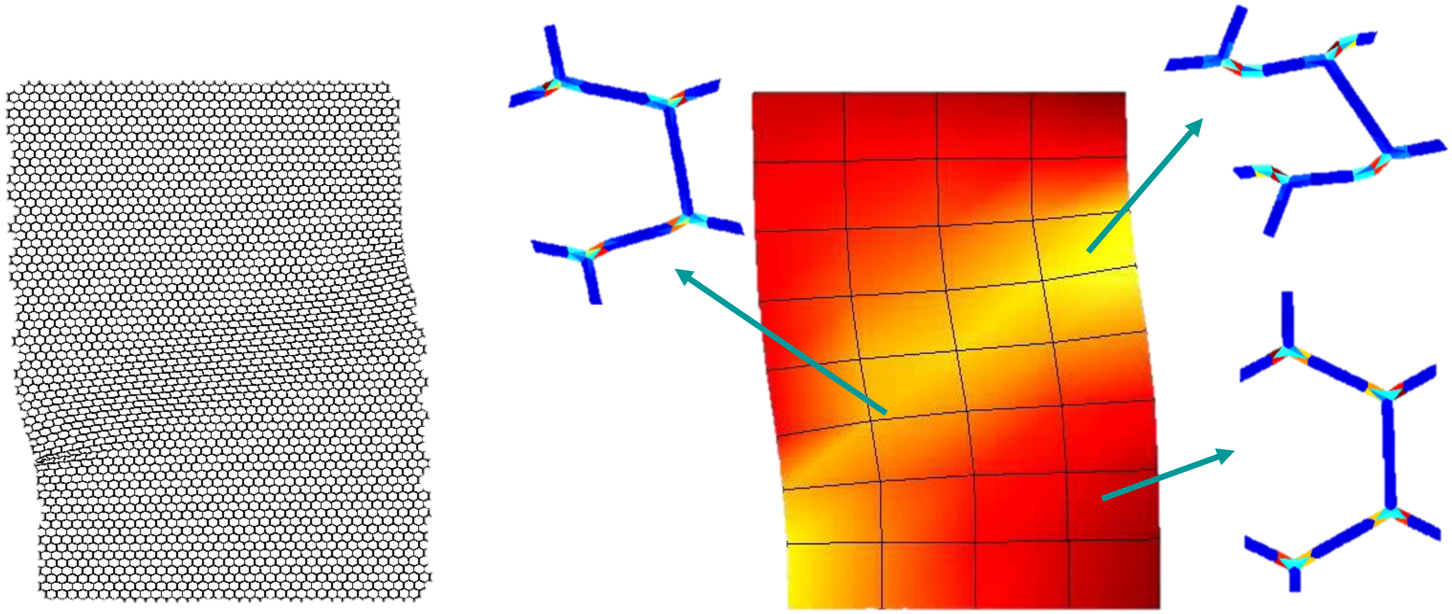


Non-local damage-enhanced mean-field-homogenization

- Laminate plate with hole (2)
  - Carbon-fibres reinforced epoxy
    - 60%-UD fibres
    - Elasto-plastic matrix with damage
  - $[-45_2/45_2]_S$ staking sequence





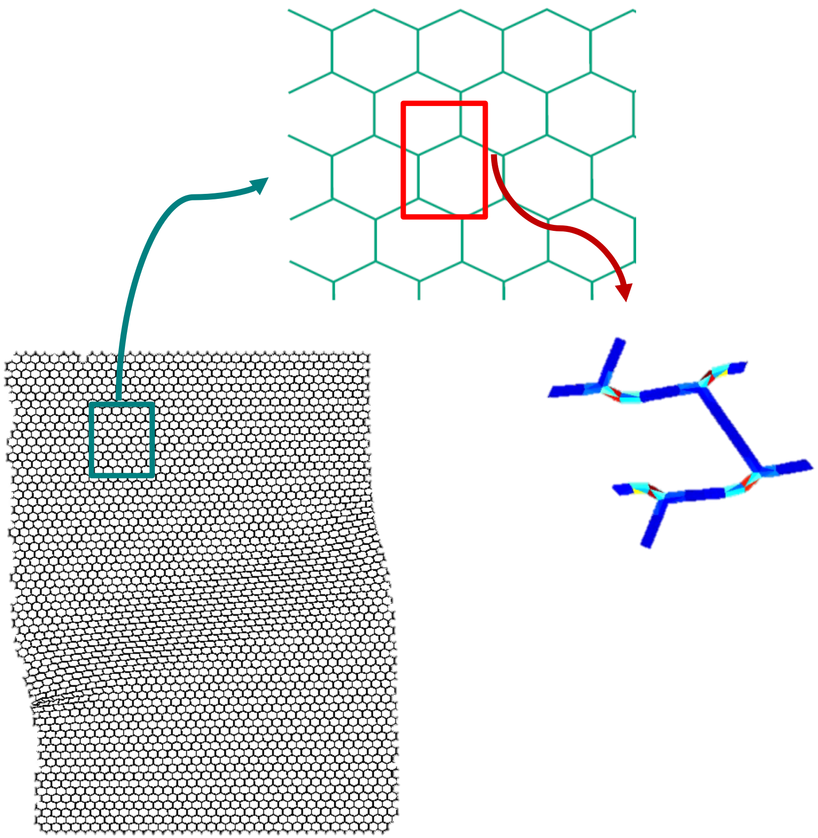


Computational homogenization for cellular materials

Computational homogenization for foamed materials

- Challenges
  - Micro-structure
    - Not perfect with non periodic mesh

⇨ How to constrain the periodic boundary conditions?



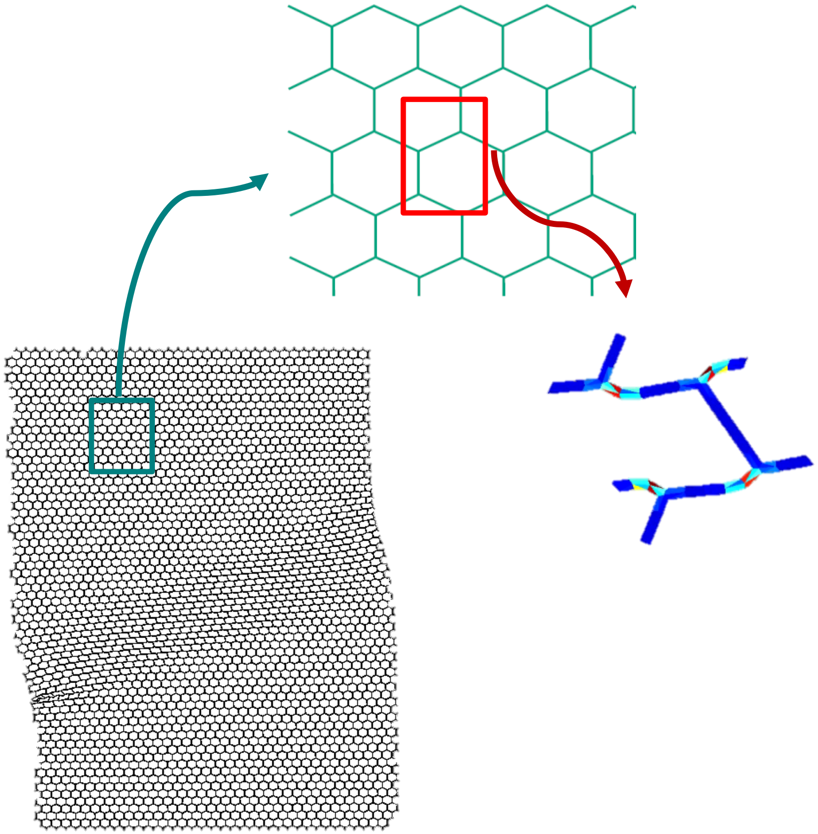
Computational homogenization for foamed materials

- Challenges
  - Micro-structure
    - Not perfect with non periodic mesh

      ⇨ How to constrain the periodic boundary conditions?

    - Thin components
    - Experiences micro-buckling

      ⇨ How to capture the instability?



Computational homogenization for foamed materials

- Challenges
  - Micro-structure
    - Not perfect with non periodic mesh

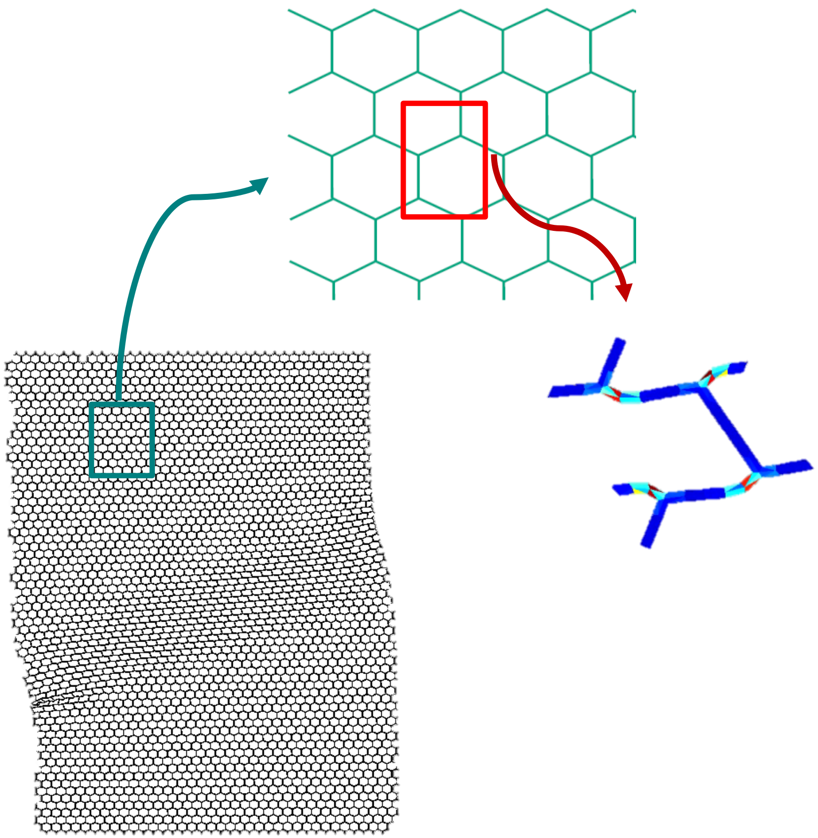
    ⇨ How to constrain the periodic boundary conditions?

    - Thin components
    - Experiences micro-buckling

    ⇨ How to capture the instability?

  - Transition
    - Homogenized tangent not always elliptic
    - Localization bands

    ⇨ How can we recover the solution unicity at the macro-scale?



Computational homogenization for foamed materials

- Challenges
  - Micro-structure
    - Not perfect with non periodic mesh

      ⇨ How to constrain the periodic boundary conditions?

    - Thin components
    - Experiences micro-buckling

      ⇨ How to capture the instability?

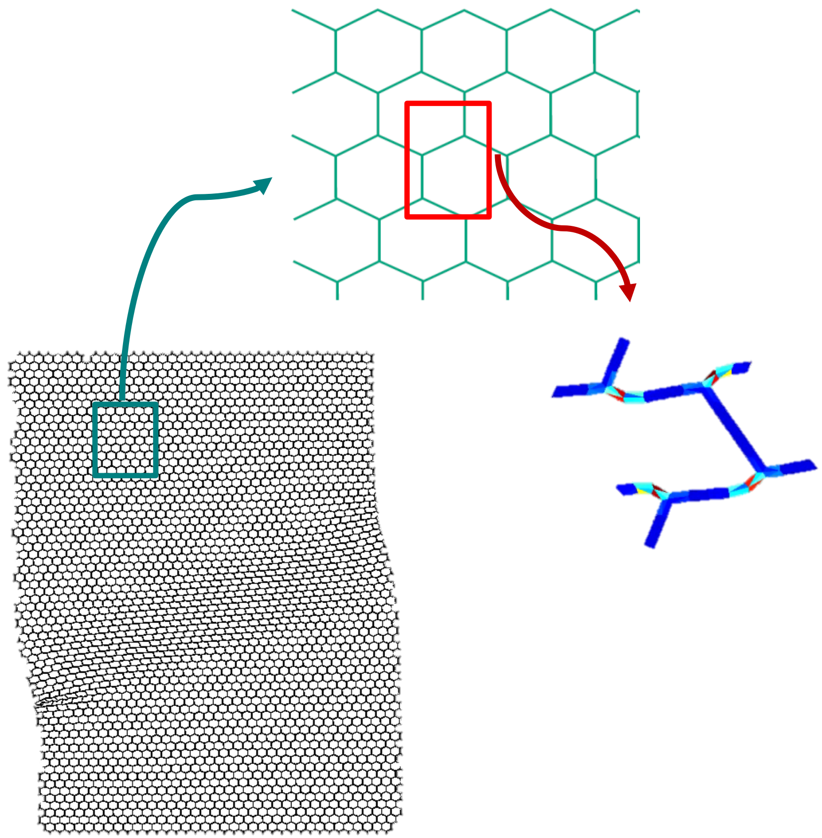
  - Transition
    - Homogenized tangent not always elliptic
    - Localization bands

      ⇨ How can we recover the solution unicity at the macro-scale?

  - Macro-scale
    - Localization bands

      ⇨ How to remain computationally efficient

      ⇨ How to capture the instability?

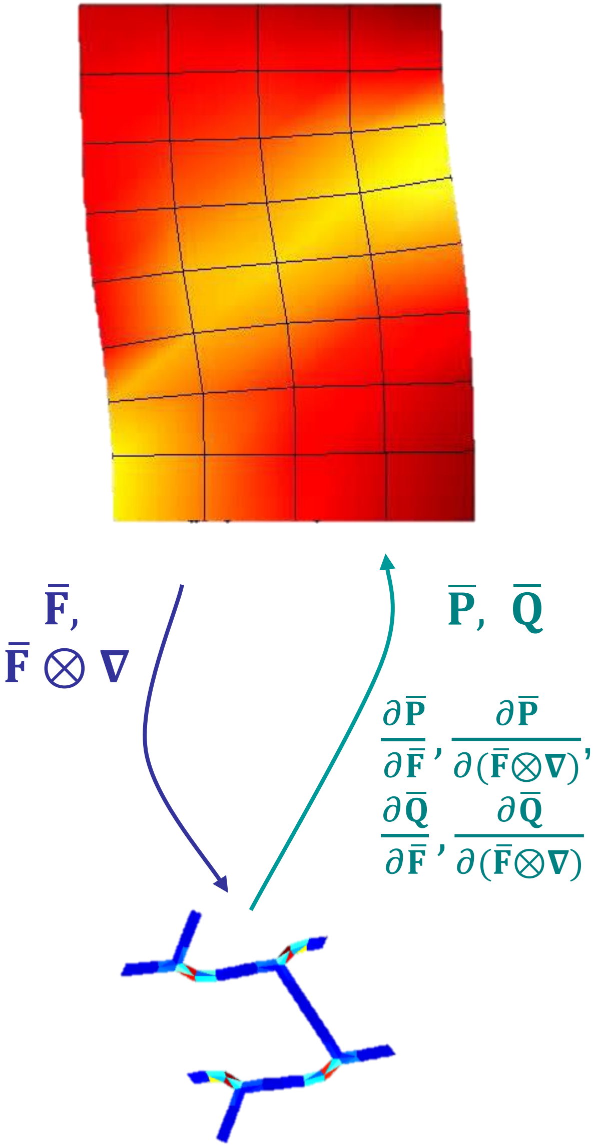


- Recover solution unicity: second-order FE²
  - Macro-scale
    - High-order Strain-Gradient formulation

$$\bar{\mathbf{P}}(\bar{X}) \cdot \nabla_0 - \bar{\mathbf{Q}}(\bar{X}) : (\nabla_0 \otimes \nabla_0) = 0$$

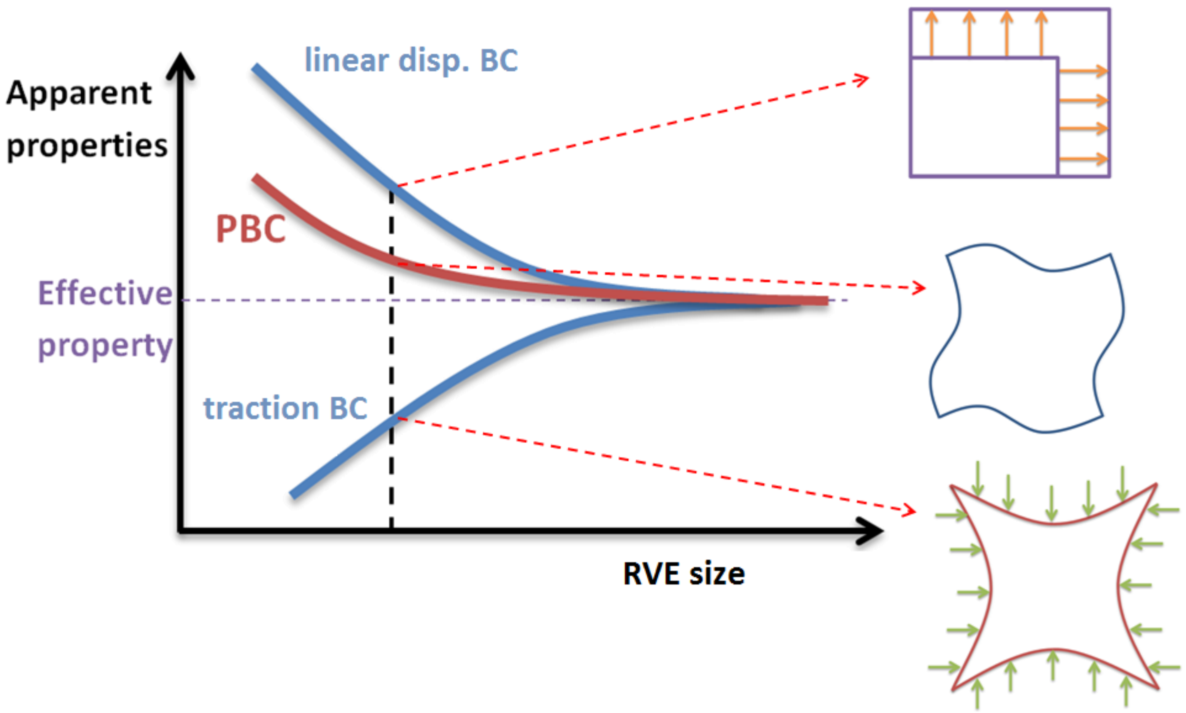
    - Partitioned mesh (//)
  - Transition
    - Gauss points on different processors
    - Each Gauss point is associated to one mesh and one solver
  - Micro-scale
    - Usual continuum

$$\mathbf{P}(X) \cdot \nabla_0 = 0$$



Computational homogenization for foamed materials

- Micro-scale periodic boundary conditions
  - Convergence in terms of RVE size



  - Periodic boundary conditions is the optimum choice for periodic structures
  - Periodic boundary conditions remain the optimum choice for non-periodic structures

Computational homogenization for foamed materials

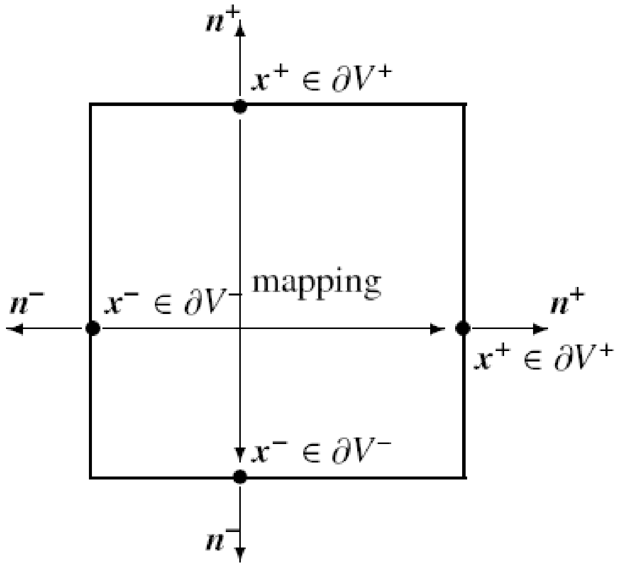
- Micro-scale periodic boundary conditions (2)
  - Defined from the fluctuation field

$$\boldsymbol{w} = \boldsymbol{u} - (\bar{\mathbf{F}} - \mathbf{I}) \cdot \boldsymbol{X} + \frac{1}{2}(\bar{\mathbf{F}} \otimes \nabla_0) : (\boldsymbol{X} \otimes \boldsymbol{X})$$

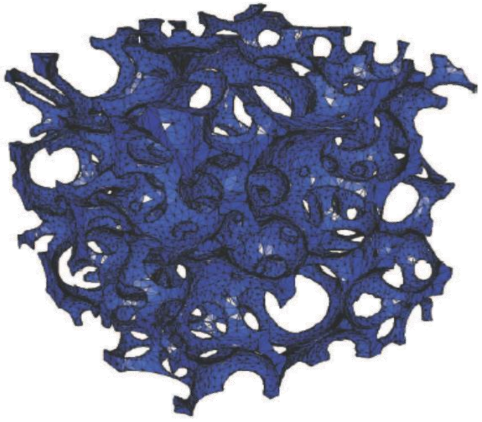
  - Stated on opposite RVE sizes

$$\begin{cases} \boldsymbol{w}(\boldsymbol{X}^+) = \boldsymbol{w}(\boldsymbol{X}^-) \\ \int_{\partial V^-} \boldsymbol{w}(\boldsymbol{X}) d\partial V = 0 \end{cases}$$

  - Can be achieved by constraining opposite nodes

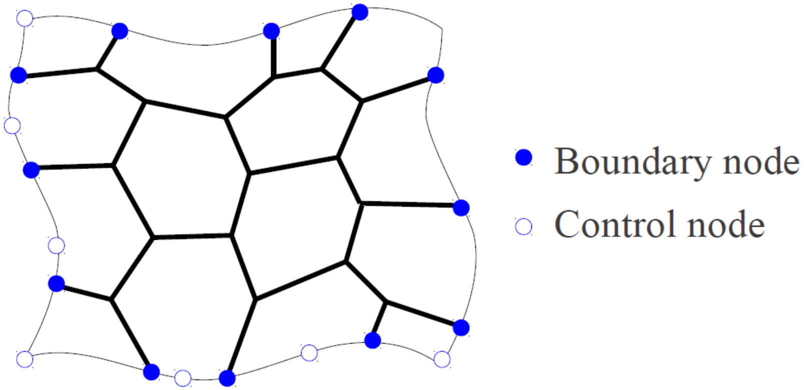


- Foamed materials
  - Usually random meshes
  - Important voids on the boundaries
- Honeycomb structures
  - Not periodic due to the imperfections



- Micro-scale periodic boundary conditions (2)
  - New interpolant method

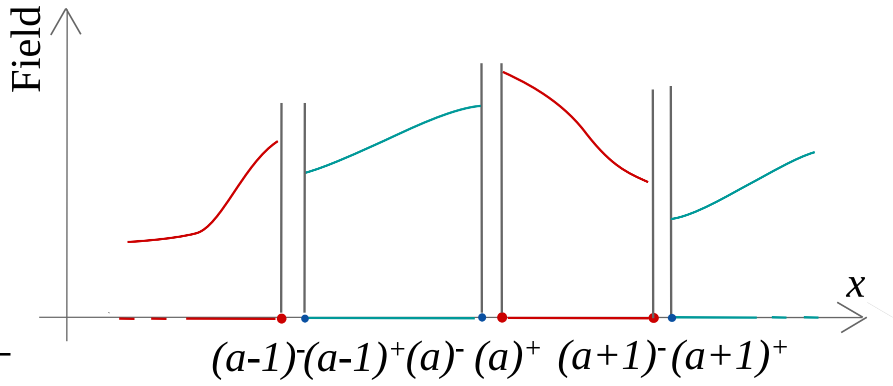
$$\begin{cases} \boldsymbol{w}(\boldsymbol{X}^-) = \sum_k \mathrm{N}(\boldsymbol{X})\boldsymbol{w}^k \\ \boldsymbol{w}(\boldsymbol{X}^+) = \sum_k \mathrm{N}(\boldsymbol{X})\boldsymbol{w}^k \\ \int_{\partial V^-} \left(\sum_k \mathrm{N}(\boldsymbol{X})\boldsymbol{w}^k\right) d\partial V = 0 \end{cases}$$



  - Use of Lagrange, cubic spline .. interpolations
  - Fits for
    - Arbitrary meshes
    - Important voids on the RVE sides
  - Results in new constraints in terms of the boundary and control nodes displacements

$$\tilde{\boldsymbol{C}}\,\tilde{\boldsymbol{u}}_b - \boldsymbol{g}(\bar{\mathbf{F}}, \bar{\mathbf{F}} \otimes \boldsymbol{\nabla}_{\mathbf{0}}) = 0$$

- Discontinuous Galerkin (DG) implementation of the second order continuum
  - Finite-element discretization
  - Same **discontinuous** polynomial approximations for the
    - **Test** functions φ_h and
    - **Trial** functions $\delta\varphi$



  - Definition of operators on the interface trace:
    - **Jump** operator: $[\![\cdot]\!] = \cdot^+ - \cdot^-$
    - **Mean** operator: $\langle\cdot\rangle = \frac{\cdot^+ + \cdot^-}{2}$
  - Continuity is weakly enforced, such that the method
    - Is consistent
    - Is stable
    - Has the optimal convergence rate
  - Can be used to weakly enforce higher discontinuities

- Second-order FE2 method
  - Macro-scale second order continuum

$$\bar{\mathbf{P}}(\bar{\boldsymbol{X}}) \cdot \boldsymbol{\nabla}_0 - \bar{\mathbf{Q}}(\bar{\boldsymbol{X}}) : (\boldsymbol{\nabla}_0 \otimes \boldsymbol{\nabla}_0) = 0$$

  - Requires $\mathbb{C}^1$ shape functions on the mesh
  - The $\mathbb{C}^1$ can be weakly enforced using the DG method

$$a(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) = a^{\text{bulk}}(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) + a^{\text{PI}}(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) + a^{\text{QI}}(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) = b(\delta\bar{\boldsymbol{u}})$$

- Second-order FE2 method
  - Macro-scale second order continuum

$$\bar{\mathbf{P}}(\bar{\boldsymbol{X}}) \cdot \boldsymbol{\nabla}_0 - \bar{\mathbf{Q}}(\bar{\boldsymbol{X}}) : (\boldsymbol{\nabla}_0 \otimes \boldsymbol{\nabla}_0) = 0$$

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$$a(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) = a^{\mathrm{bulk}}(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) + a^{\mathrm{PI}}(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) + a^{\mathrm{QI}}(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) = b(\delta\bar{\boldsymbol{u}})$$

    - Usual volume terms

$$a^{\mathrm{bulk}}(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) = \int_{\bar{V}} [\bar{\mathbf{P}}(\bar{\boldsymbol{u}}) : (\delta\bar{\boldsymbol{u}} \otimes \boldsymbol{\nabla}_{\mathbf{0}}) + \bar{\mathbf{Q}}(\bar{\boldsymbol{X}}) \vdots (\delta\bar{\boldsymbol{u}} \otimes \boldsymbol{\nabla}_0 \otimes \boldsymbol{\nabla}_0)] dV$$

Computational homogenization for foamed materials

- Second-order FE2 method
  - Macro-scale second order continuum

$$\overline{\mathbf{P}}(\overline{\boldsymbol{X}}) \cdot \boldsymbol{\nabla}_0 - \overline{\mathbf{Q}}(\overline{\boldsymbol{X}}) : (\boldsymbol{\nabla}_0 \otimes \boldsymbol{\nabla}_0) = 0$$

  - Requires $\mathbb{C}^1$ shape functions on the mesh
  - The $\mathbb{C}^1$ can be weakly enforced using the DG method

$$a(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) = a^{\text{bulk}}(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) + a^{\text{PI}}(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) + a^{\text{QI}}(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) = b(\delta\overline{\boldsymbol{u}})$$

- Weak enforcement of the $\mathbb{C}^0$
  - Continuity
  - Consistency
  - Stability

between the finite elements

$$a^{\text{PI}}(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) = \int_{\partial_I \overline{V}} \left[\begin{array}{c} [\![\delta\overline{\boldsymbol{u}}]\!] \cdot \langle \overline{\mathbf{P}} - \overline{\mathbf{Q}} \cdot \boldsymbol{\nabla}_0 \rangle \cdot \overline{\boldsymbol{N}} + [\![\overline{\boldsymbol{u}}]\!] \cdot \langle \overline{\mathbf{P}}(\delta\overline{\boldsymbol{u}}) - \overline{\mathbf{Q}}(\delta\overline{\boldsymbol{u}}) \cdot \boldsymbol{\nabla}_0 \rangle \cdot \overline{\boldsymbol{N}} + \\ [\![\overline{\boldsymbol{u}}]\!] \otimes \overline{\boldsymbol{N}} : \langle \frac{\beta_P}{h_s} \mathbf{C}^{\mathbf{0}} \rangle : [\![\delta\overline{\boldsymbol{u}}]\!] \otimes \overline{\boldsymbol{N}} \end{array} \right] dV$$

  - Allows efficient parallelization as elements are disjoint

- Second-order FE2 method
  - Macro-scale second order continuum

$$\overline{\mathbf{P}}(\overline{\boldsymbol{X}}) \cdot \boldsymbol{\nabla}_0 - \overline{\mathbf{Q}}(\overline{\boldsymbol{X}}) : (\boldsymbol{\nabla}_0 \otimes \boldsymbol{\nabla}_0) = 0$$

  - Requires $\mathbb{C}^1$ shape functions on the mesh
  - The $\mathbb{C}^1$ can be weakly enforced using the DG method

$$a(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) = a^{\mathrm{bulk}}(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) + a^{\mathrm{PI}}(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) + a^{\mathrm{QI}}(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) = b(\delta\overline{\boldsymbol{u}})$$

- Weak enforcement of the $\mathbb{C}^1$
  - Continuity
  - Consistency
  - Stability

between the finite elements

$$a^{\mathrm{QI}}(\overline{\boldsymbol{u}}, \delta\overline{\boldsymbol{u}}) = \int_{\partial_I \overline{V}} \left[\begin{array}{c} [\![\delta\overline{\boldsymbol{u}} \otimes \boldsymbol{\nabla}_{\mathbf{0}}]\!] \cdot \langle \overline{\mathbf{Q}} \rangle \cdot \overline{\boldsymbol{N}} + [\![\overline{\boldsymbol{u}} \otimes \boldsymbol{\nabla}_{\mathbf{0}}]\!] \cdot \langle \overline{\mathbf{Q}}(\delta\overline{\boldsymbol{u}}) \rangle \cdot \overline{\boldsymbol{N}} + \\ [\![\overline{\boldsymbol{u}} \otimes \boldsymbol{\nabla}_{\mathbf{0}}]\!] \otimes \overline{\boldsymbol{N}} : \langle \frac{\beta_P}{h_s} \mathbf{J}^{\mathbf{0}} \rangle : [\![\delta\overline{\boldsymbol{u}} \otimes \boldsymbol{\nabla}_{\mathbf{0}}]\!] \otimes \overline{\boldsymbol{N}} \end{array} \right] dV$$

  - Allows efficient parallelization as elements are disjoint

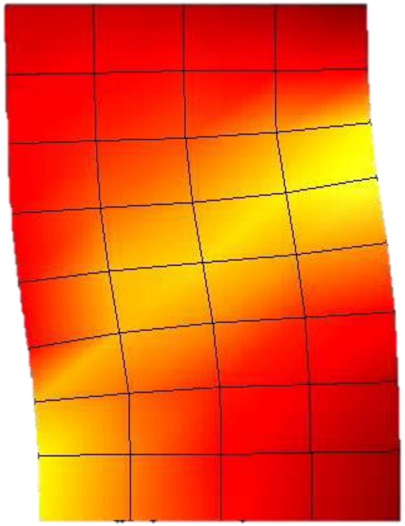
- Capturing instabilities
  - Macro-scale: localization bands

    - Path following method on the applied loading

$$a(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) = \bar{\mu}\, b(\delta\bar{\boldsymbol{u}})$$

    - Arc-length constraint on the load increment

$$\bar{h}(\Delta\bar{\boldsymbol{u}}, \Delta\bar{\mu}) = \frac{\Delta\bar{\boldsymbol{u}} \cdot \Delta\bar{\boldsymbol{u}}}{\bar{X}_0^2} + \Delta\bar{\mu}^2 - \Delta L^2 = 0$$



Computational homogenization for foamed materials

- Capturing instabilities
  - Macro-scale: localization bands
    - Path following method on the applied loading

$$a(\bar{\boldsymbol{u}}, \delta\bar{\boldsymbol{u}}) = \bar{\mu}\, b(\delta\bar{\boldsymbol{u}})$$

    - Arc-length constraint on the load increment

$$\bar{h}(\Delta\bar{\boldsymbol{u}}, \Delta\bar{\mu}) = \frac{\Delta\bar{\boldsymbol{u}} \cdot \Delta\bar{\boldsymbol{u}}}{\bar{X}_0^2} + \Delta\bar{\mu}^2 - \Delta L^2 = 0$$

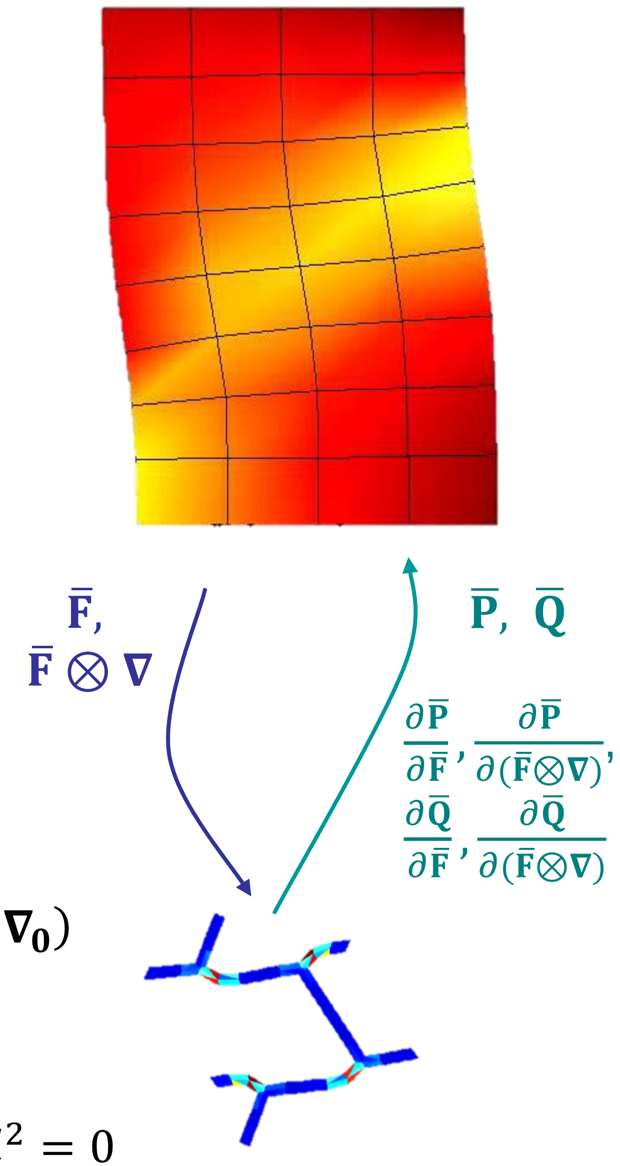
  - Micro-scale
    - Path following method on the applied boundary conditions

$$\widetilde{\boldsymbol{C}}\, \widetilde{\boldsymbol{u}}_b - \boldsymbol{g}(\bar{\mathbf{F}}, \bar{\mathbf{F}} \otimes \boldsymbol{\nabla}_{\mathbf{0}}) = 0$$

$$\begin{cases} \bar{\mathbf{F}} = \bar{\mathbf{F}}_0 + \mu\, \Delta\bar{\mathbf{F}} \\ \bar{\mathbf{F}} \otimes \boldsymbol{\nabla}_{\mathbf{0}} = (\bar{\mathbf{F}} \otimes \boldsymbol{\nabla}_{\mathbf{0}})_0 + \mu\, \Delta(\bar{\mathbf{F}} \otimes \boldsymbol{\nabla}_{\mathbf{0}}) \end{cases}$$

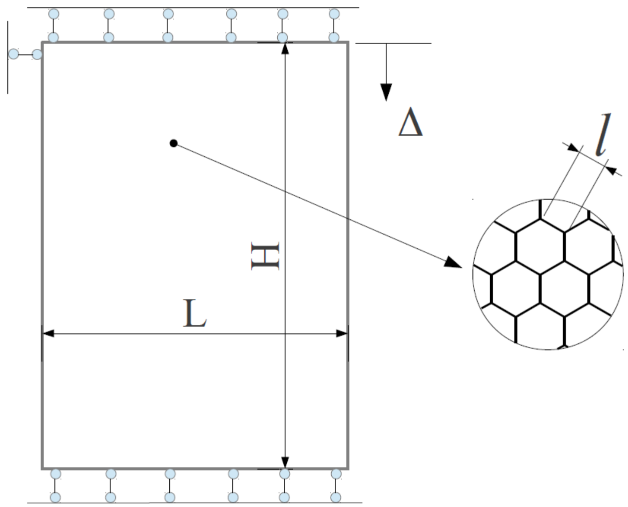
    - Arc-length constraint on the load increment

$$h(\Delta\boldsymbol{u}, \Delta\mu) = \frac{\Delta\boldsymbol{u} \cdot \Delta\boldsymbol{u}}{X_0^2} + \Delta\mu^2 - \Delta l^2 = 0$$



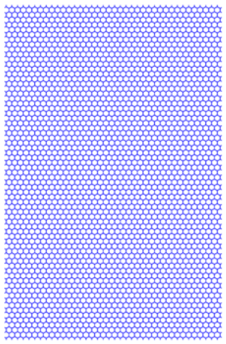
Computational homogenization for foamed materials

- Compression of an hexagonal honeycomb
  - Elasto-plastic material

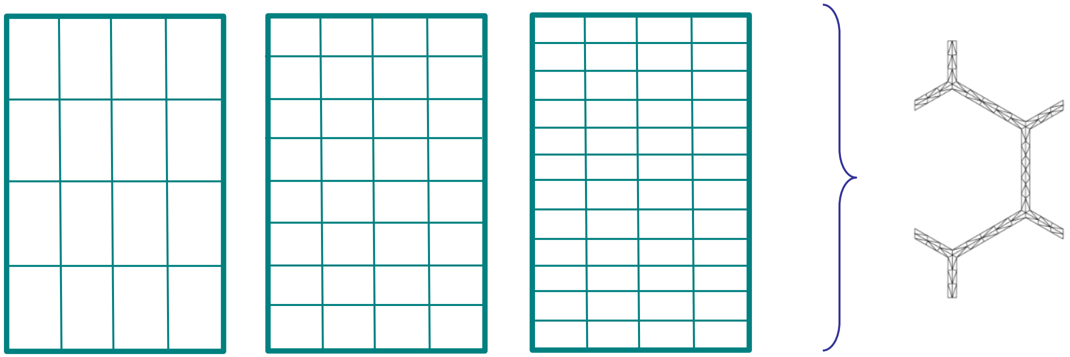


- Comparison of different solutions

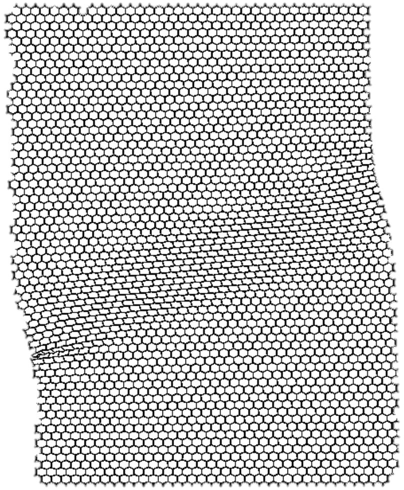
Full direct simulation

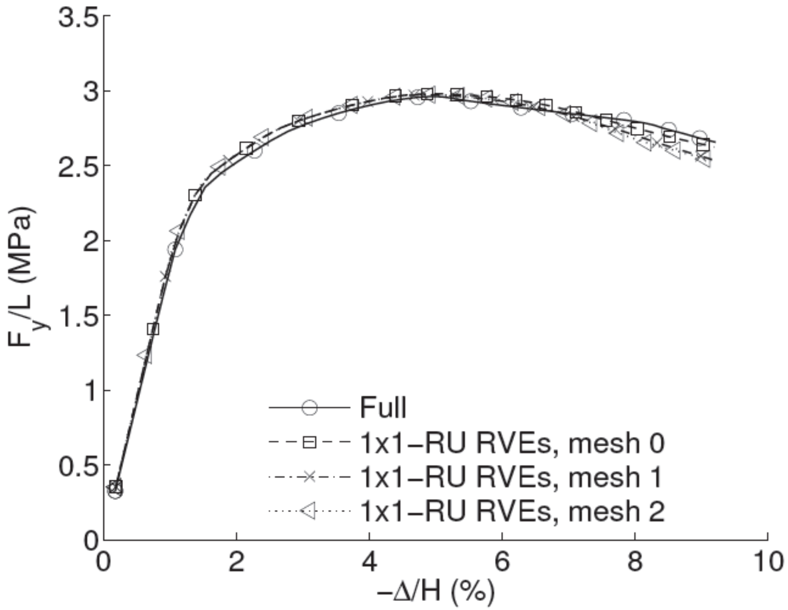


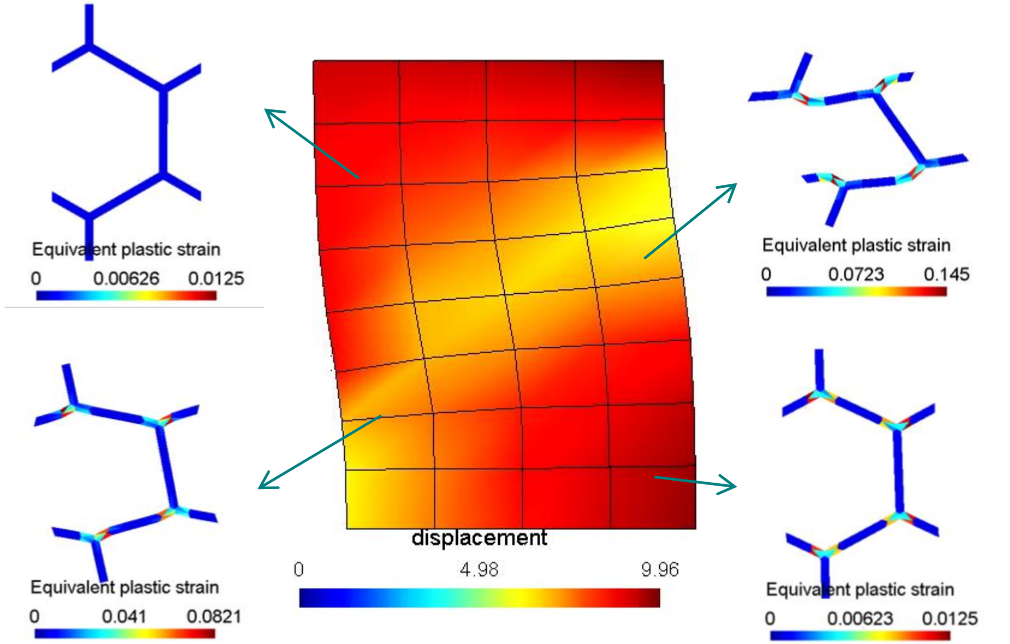
Multiscale with different macro-meshes



- Compression of an hexagonal honeycomb (2)
  - Captures of the softening onset
  - Captures the softening response
  - No macro-mesh size effect

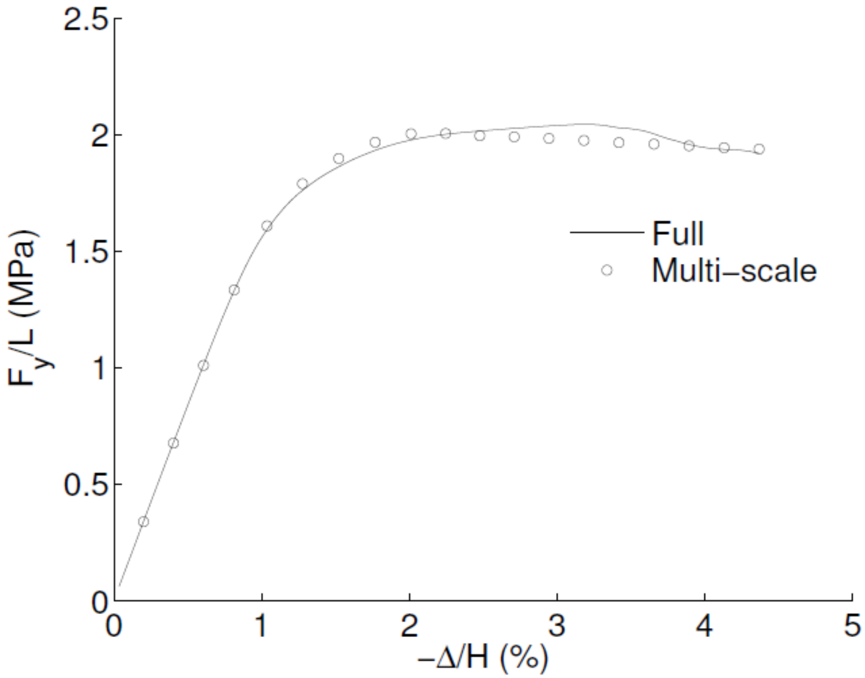


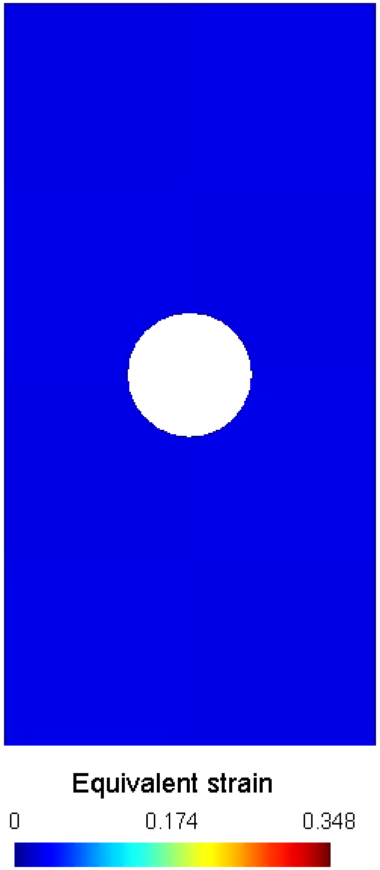


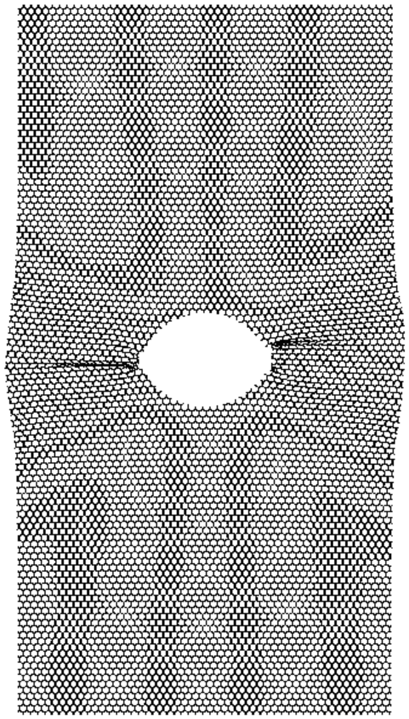


Computational homogenization for foamed materials

- Compression of an hexagonal honeycomb plate with a centered hole
  - Results given by full and multi-scale models are comparable







Conclusions

- Non-local damage-enhanced mean-field-homogenization
  - MFH with damage model for the matrix material
  - Non-local implicit formulation
  - Can capture the strain softening
  - More in
    - 10.1016/j.ijsolstr.2013.07.022
    - 10.1016/j.ijplas.2013.06.006
    - 10.1016/j.cma.2012.04.011
    - 10.1007/978-1-4614-4553-1_13
- Computational homogenization for foamed materials
  - Second-order FE^2 method
  - Micro-buckling propagation
  - General way of enforcing PBC
  - More in
    - 10.1016/j.cma.2013.03.024
    - 10.1016/j.commatsci.2011.10.017
    - 10.1016/j.ijsolstr.2014.02.029
- Open-source software
  - Implemented in GMSH
    - http://geuz.org/gmsh/

Computational & Multiscale
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L. Homsi, V. Lucas, S. Mulay,
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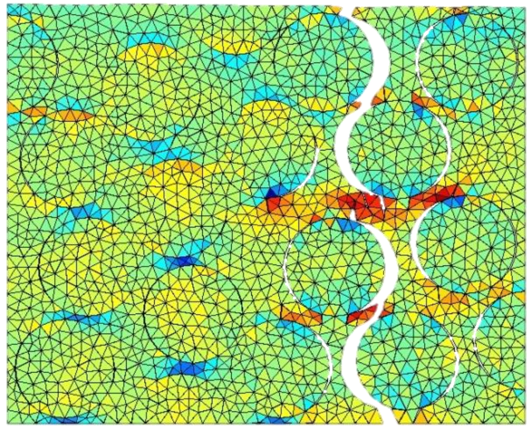
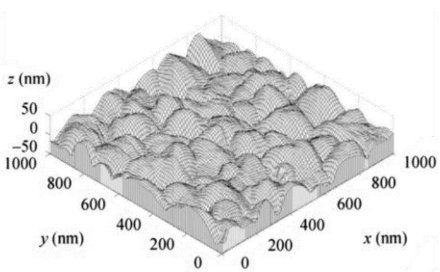
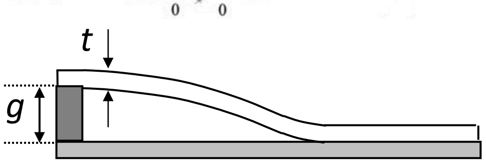
QC method for grain-boundary sliding

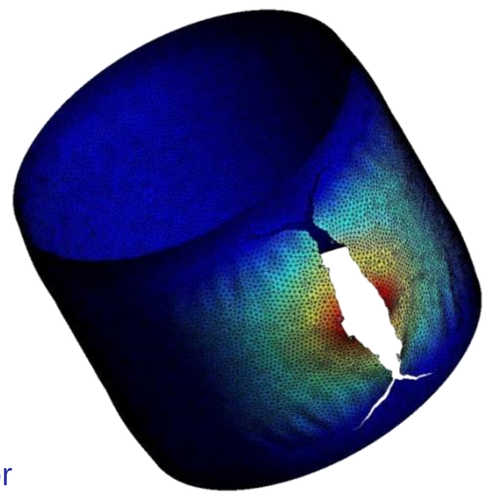


DG-based fracture framework





Stiction failure in a MEMS sensor



DG-based fracture framework

SVE size effect on meso-scale properties