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Aerospace & Mechanical Engineering

Cohesive band model: a triaxiality-dependent cohesive model for damage to crack transition in a non-local implicit discontinuous Galerkin framework

Abstract E6999 – ECCOMAS 2016

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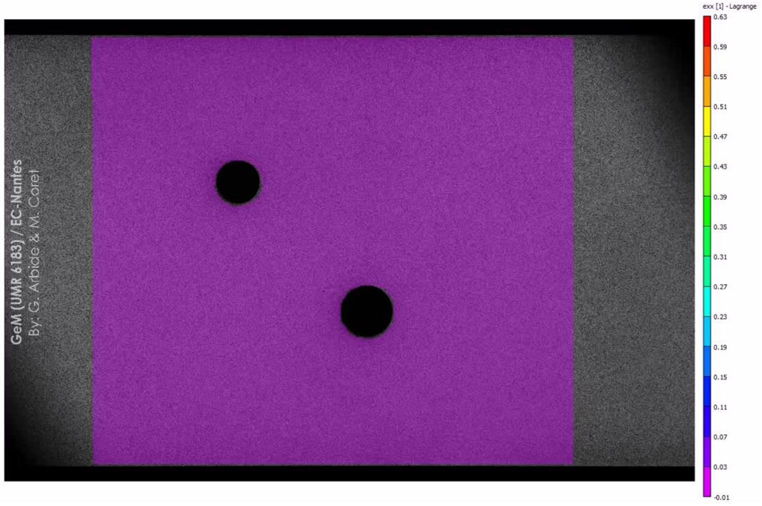
Introduction

- Modelling failure of ductile materials (metals,…) = a challenging topic
- Objective:
  - To model / capture the whole ductile failure process:
    - Diffuse damage stage

    followed by
    - Crack initiation and propagation



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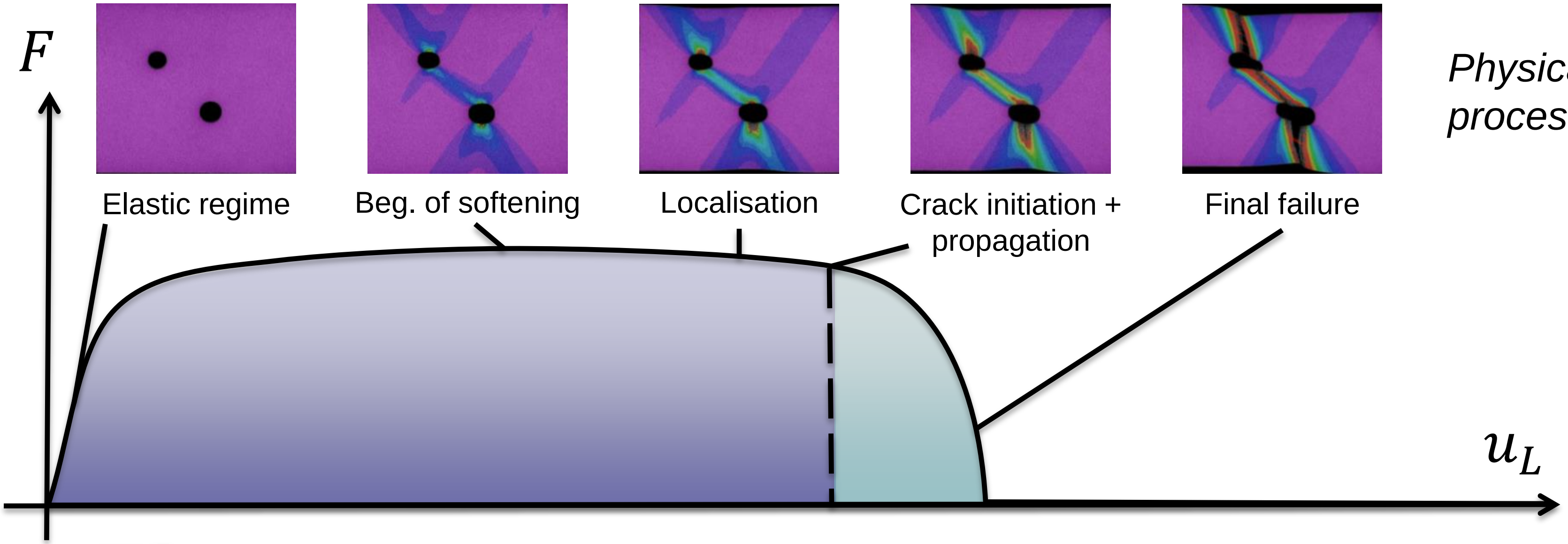
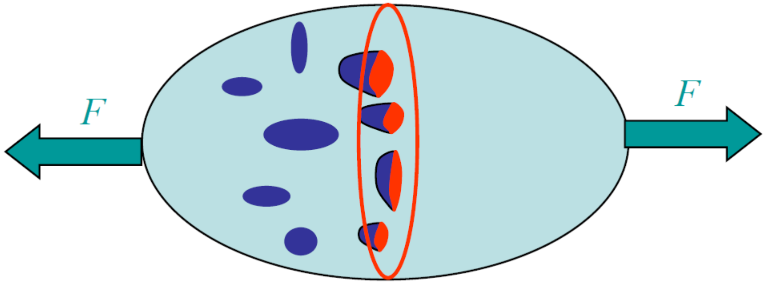


Physical process

State of art: two main approaches - Continuous approaches

- Material properties degradation modelled by internal variables (= damage):
  - Gurson model and its extensions:
    - Description of porosity evolution
    - Void nucleation, growth and coalescence
  - Mean-field homogenisation model:
    - Description of elliptic pores evolution (size, shape and orientation) [Song et al. 2015]
  - …



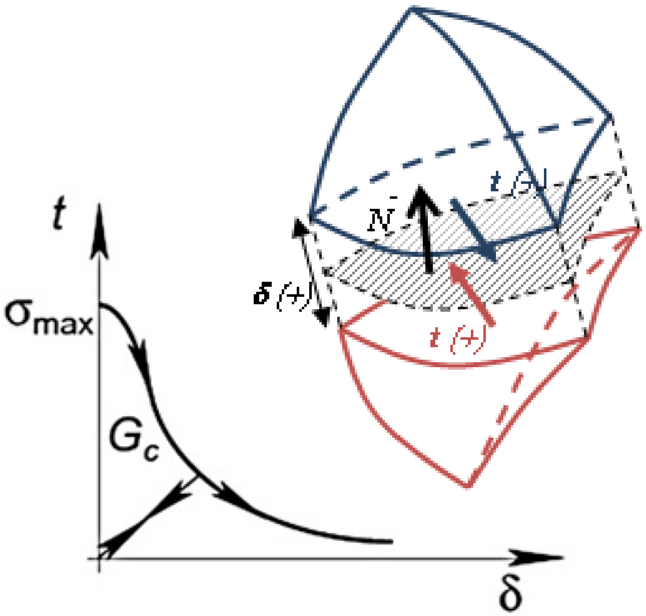
- Continuous Damage Model (CDM) implementation:
  - Local form:
    - Strongly mesh-dependent / loss of solution uniqueness
  - Non-local form needed: [Peerlings et al. 1998]
    - Implicit formulation: one more degree of freedom per node

State of art: two main approaches - Approach comparison (1)

	Continuous: **Continuous Damage Model (CDM) in a non-local form**	**Discontinuous:** **Cohesive Zone Model + Discontinuous Galerkin elements (CZM/DG)**
Advantages (+)	• Capture the **diffuse damage** stage • Capture stress **triaxiality** and Lode variable effects	• **Multiple crack initiation and propagation** naturally managed • Highly scalable + simple implementation • Consistent structural response
Drawbacks (-)	• **Cannot represent discontinuities (cracks,...)** without remeshing • **Numerical problems** with highly damaged elements requiring element deletion (loss of accuracy, mesh modification, ...) • Crack initiation observed for lower damage values	• Cannot capture **diffusing damage** nor shear localisation • No stress **triaxiality** effect • Currently valid for brittle / small scale yielding elasto-plastic materials

State of art: two main approaches - Discontinuous approaches

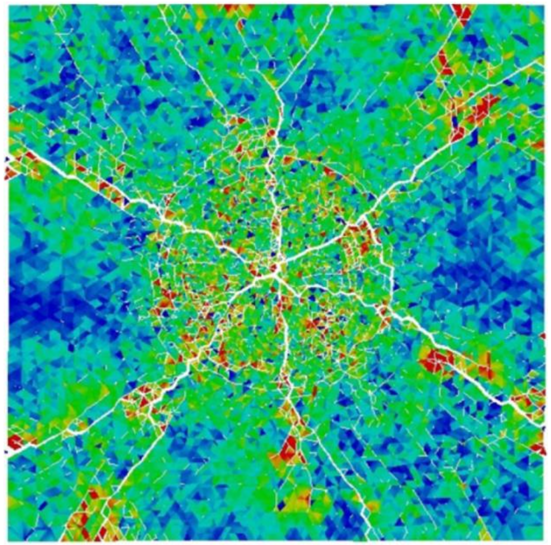
- Similar to fracture mechanics
- One of the most used methods:
  - Cohesive Zone Model (CZM) modelling the crack tip behaviour inserted via:
    - Interface elements between two volume elements
    - Element enrichment (EFEM) [Armero et al. 2009]
    - Mesh enrichment (XFEM) [Moes et al. 2002]
    - …



- Hybrid framework for brittle fragmentation [Radovitzky et al. 2011]:
  - Extrinsic cohesive interface elements

    \+

  - Discontinuous Galerkin (DG) framework (enable inter-elements discontinuities)



State of art: two main approaches - Approach comparison (2)

	Continuous: Continuous Damage Model (CDM) in a non-local form	**Discontinuous: Extrinsic Cohesive Zone Model + Discontinuous Galerkin elements (CZM/DG)**
Advantages (+)	• Capture the **diffuse damage** stage • Capture stress **triaxiality** and Lode variable effects	• **Multiple crack initiation and propagation** naturally managed • Highly scalable + simple implementation • Consistent structural response
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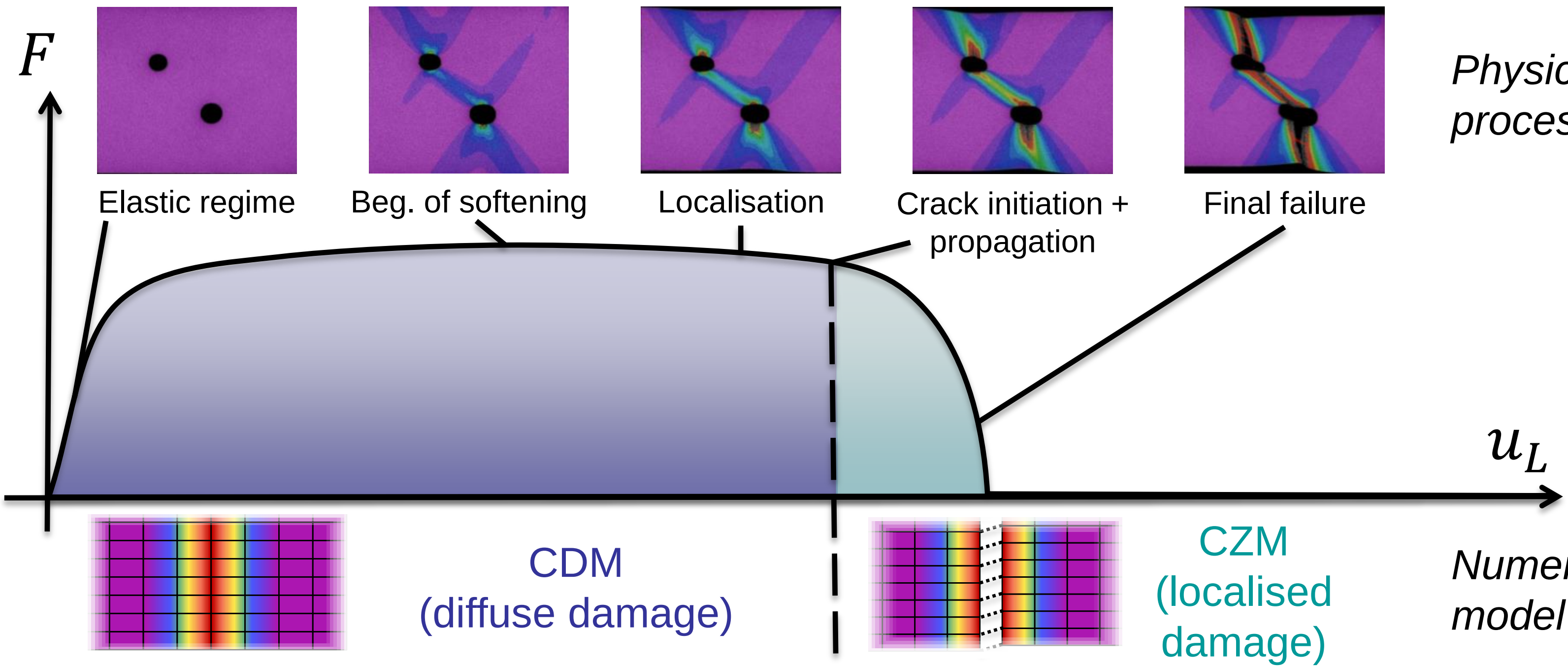
Goals of the research

- Objective:
  - To model / capture the whole ductile failure process
- Main idea:
  - Combination of 2 complementary methods in a single finite element framework:
    - Continuous (damage model)

      + transition to
    - Discontinuous (cohesive zone model with triaxiality effects)



Elastic regime

Beg. of softening

Localisation

Crack initiation + propagation

Final failure

Physical process

CDM (diffuse damage)

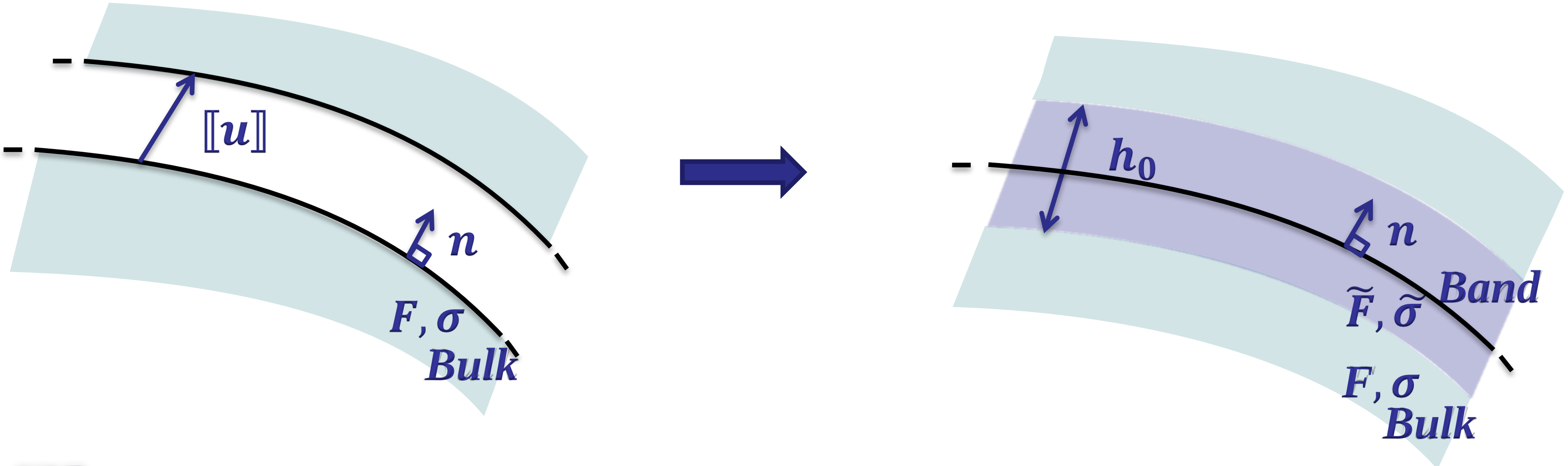
CZM (localised damage)

Numerical model

Cohesive zone with triaxiality (1)

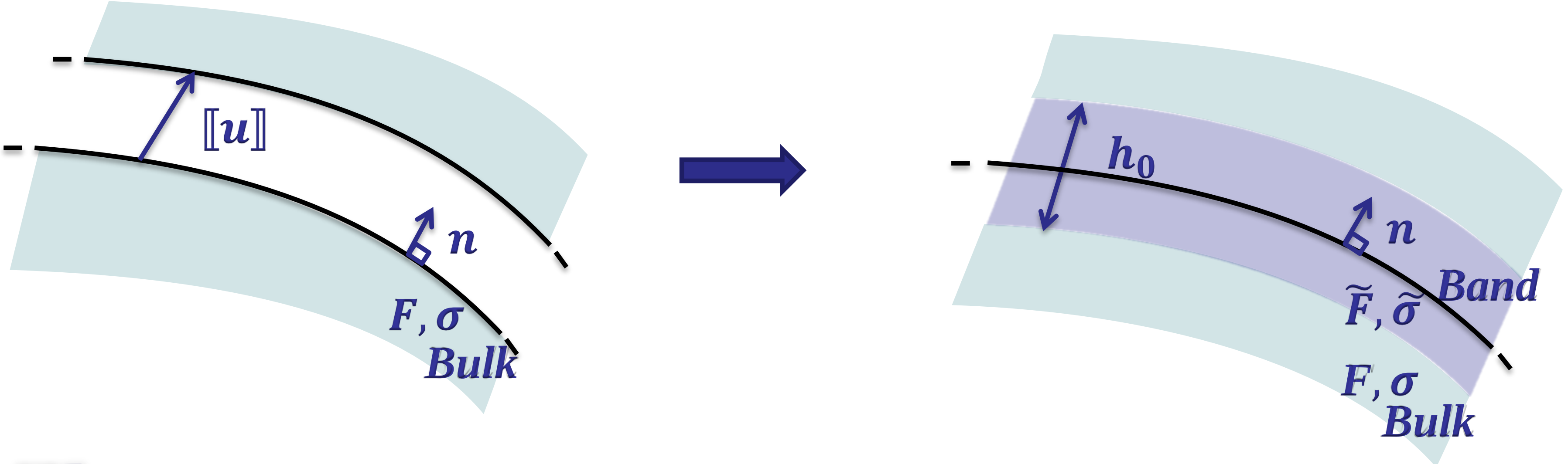
- How to combine both methods?
  - Problems:
    - Energetic consistency? Cohesive traction-separation law (TSL) under complex 3D loadings? Triaxiality-dependency of ductile behaviour?

  - Solution: Cohesive SURFACE model ➔ Cohesive BAND model
    - CZM with a numerical thickness h_0 to recreate a 3D state [Remmers et al, 2013]
    - Replace cohesive law by the behaviour of a uniform thin band of thickness h_0
    - Band strains = composed of bulk strains and contributions from crack opening
    - $\boldsymbol{t}(\llbracket \boldsymbol{u} \rrbracket) \Rightarrow \boldsymbol{t}(\llbracket \boldsymbol{u} \rrbracket, <\boldsymbol{\epsilon}>)$



Cohesive zone with triaxiality (2)

- Cohesive Band Model (CBM) to incorporate triaxiality effects
  - Methodology:
    1. Computation of band deformation gradient at the interface: $\tilde{\mathbf{F}} = <\mathbf{F}> + {[\![\mathbf{u}]\!] \times \mathbf{N}}/{h_0}$
    2. Band stress computation: $\tilde{\boldsymbol{\sigma}} = \tilde{\boldsymbol{\sigma}}\left(\tilde{\mathbf{F}}, D\left(\tilde{\mathbf{F}}, \text{Internal variables}\right)\right)$
    3. Traction force computation: $\boldsymbol{t} = \tilde{\boldsymbol{\sigma}}.\boldsymbol{n}$
  - Values of thickness h_0?
    - Not a new parameter!
    - A priori determined with underlying non-local CDM to ensure energy consistency



Cohesive zone with triaxiality (3)

- Proof of concept
  - Basic material law:
    - Small strains and displacements,
    - Elastic material (no plasticity) coupled with non-local damage
  - Energetic equivalence (computation of h_0)
    - 1D semi-analytical simulations
  - Finite element simulation
    - 3D tests in *GMSH*
  - Comparison with non-local models as reference

Material law

- Implicit non-local damage model:
  - Damaged material with the damage variable D from 0 (undamaged) to 1 (totally damaged):

$$\boldsymbol{\sigma} = (1 - D)\boldsymbol{\mathcal{H}}:\boldsymbol{\epsilon}$$

- Damage power-law in terms of a memory variable κ :

$$D = \begin{cases} 0 & \text{if } \kappa < \kappa_i \\ 1 - \left(\dfrac{\kappa_i}{\kappa_c}\right)^{\beta}\left(\dfrac{\kappa_c - \kappa}{\kappa_c - \kappa_i}\right)^{\alpha} & \text{if } \kappa_i < \kappa < \kappa_c \\ 1 & \text{if } \kappa_c < \kappa \end{cases}$$

- Memory variable determined in terms of a **non-local equivalent strain**:

$$\kappa(t) = \max_{\tau}(e(\tau < t))$$

- Non-local strain resulting from a diffusion equation:

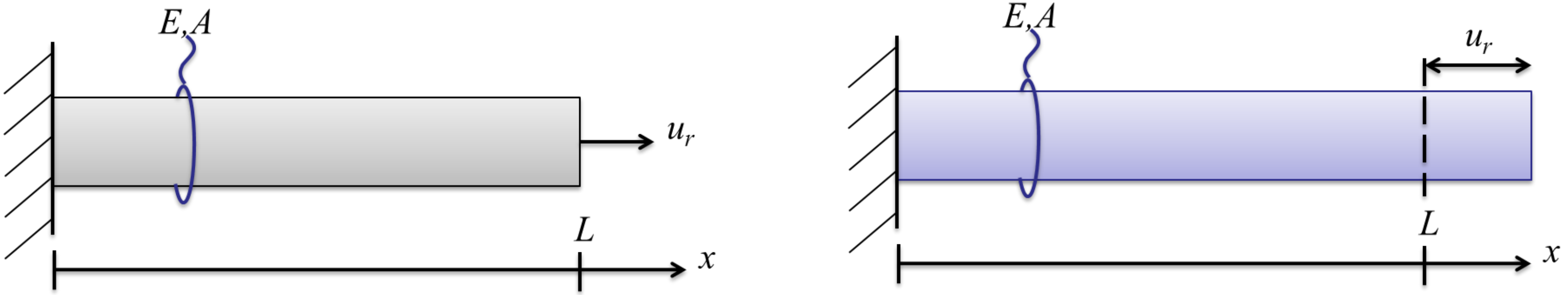
$$e - c_L^2 \Delta e = \sqrt{\sum_{i=1,2,3} \left(\epsilon_i^+\right)^2}$$

With $\epsilon_i^+ = \text{positif } \textbf{local} \text{ principal strains}$

$c_L = \text{non} - \text{local length [m]}$

Energetic equivalence (1)

- Energetic equivalence (computation of h_0):
  - Semi-analytic solving:
    - Bar of uniform area with constrained displacement at the extremities



- Discretisation of the strain field $\epsilon_x(x) \rightarrow \epsilon_i$
  - Computation of non-local strains by convolution with Green's functions linked to the non-local problem:

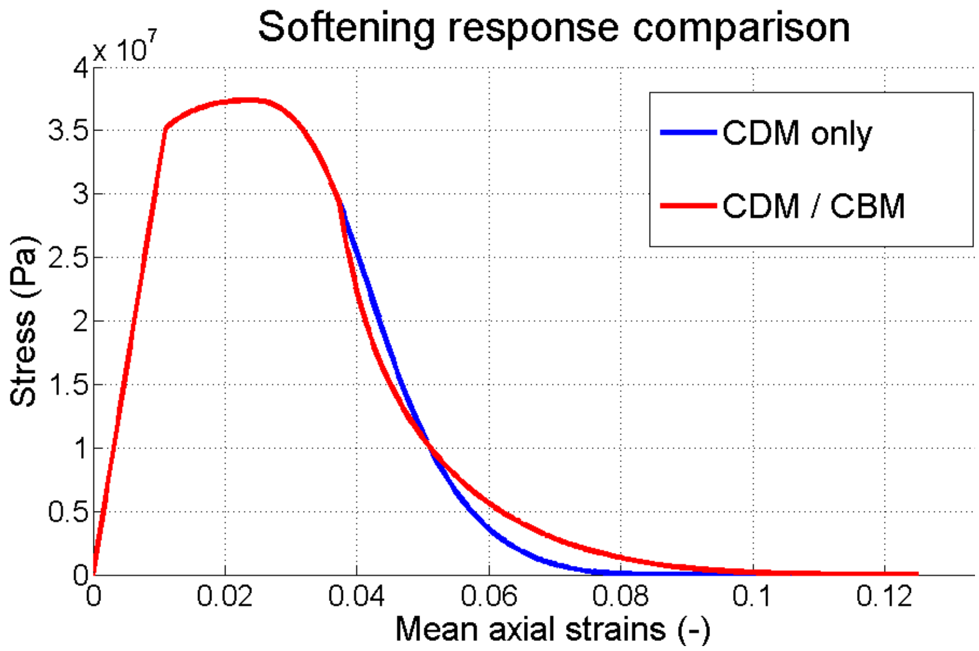
$$e(x) = \int_0^L W(x-y)\epsilon(y)dy$$

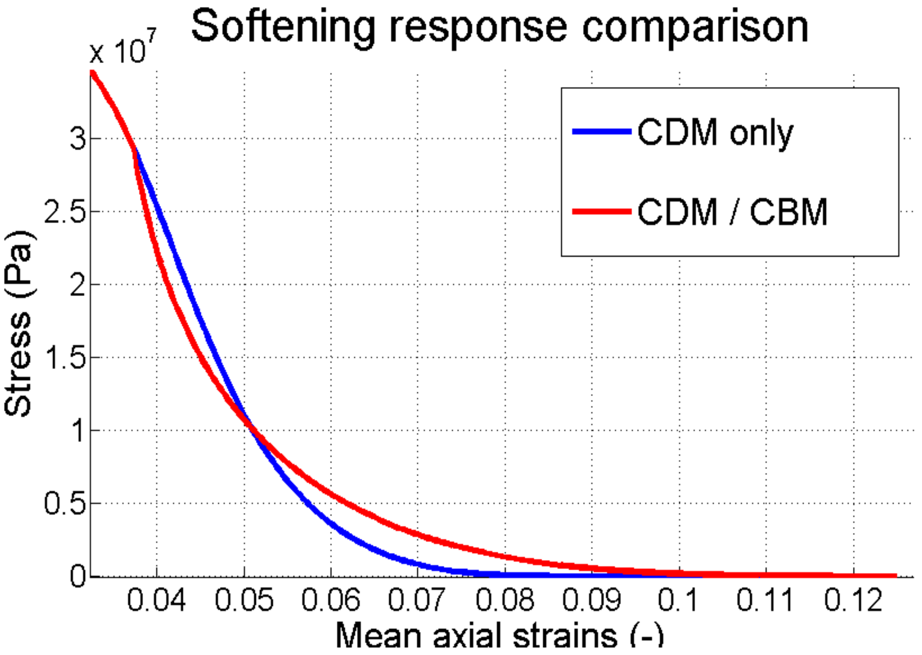
- Defect at the middle to trigger localisation

Energetic equivalence (2)

- Influence of h_0:
  - Acts as effective thickness of damage zone / process zone
  - Has to be chosen to conserve energy dissipation (physically based)

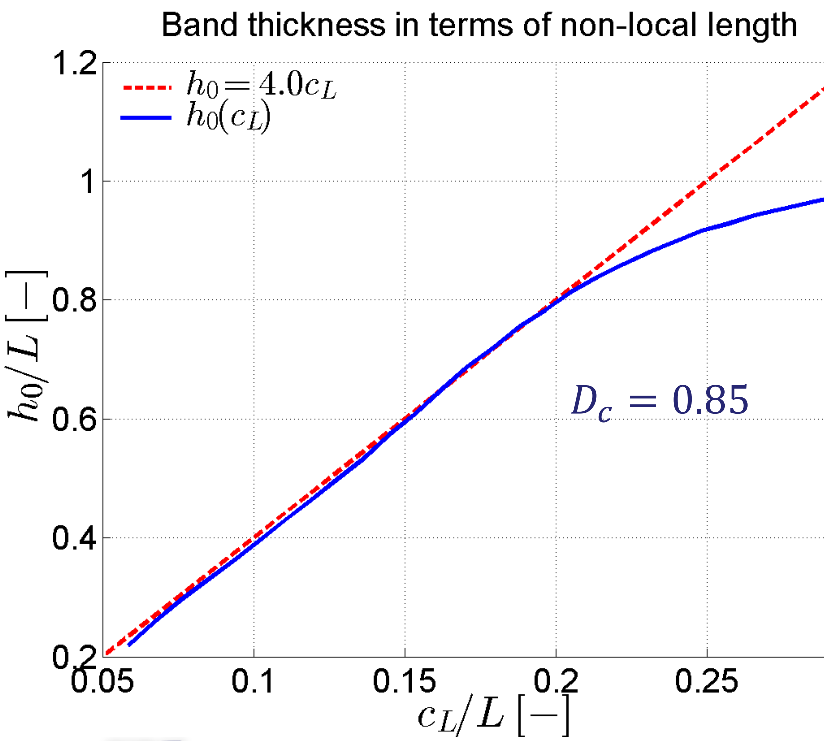
Material properties (short GFRP)			
E	3.2 GPa	L	0.04 m
κ_i	0.11	α	5.0
κ_c	0.50	β	0.75
c_L/L	0,2	D_c	0.9
h_0	2.8 c_L		

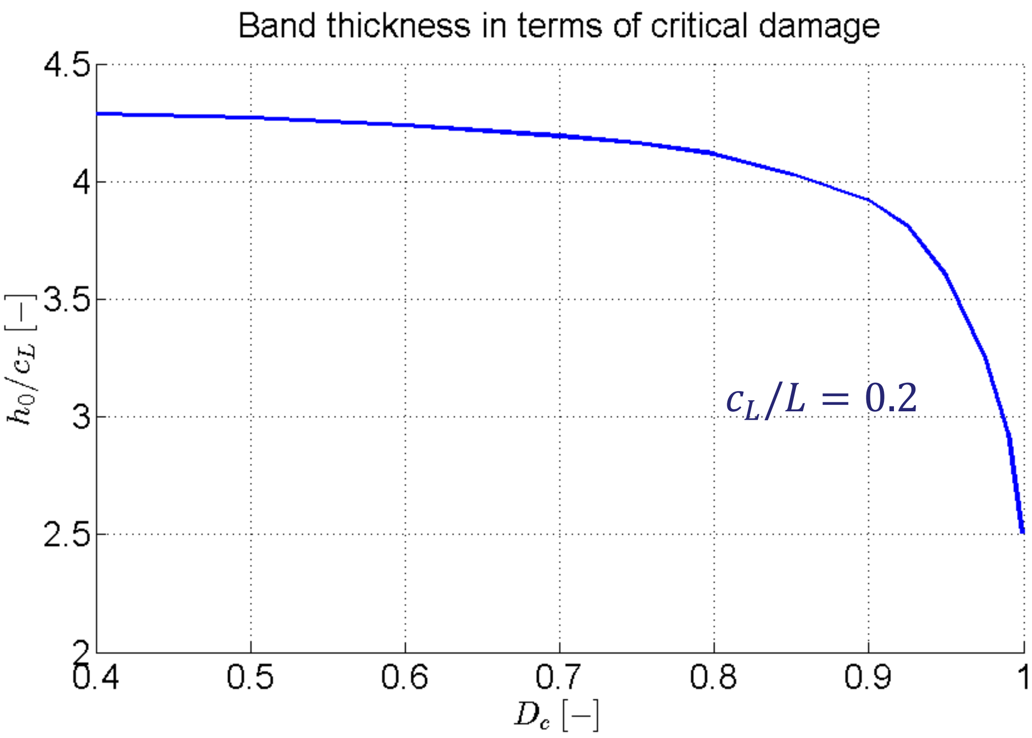

Softening response comparison


Softening response comparison

Energetic equivalence (3)

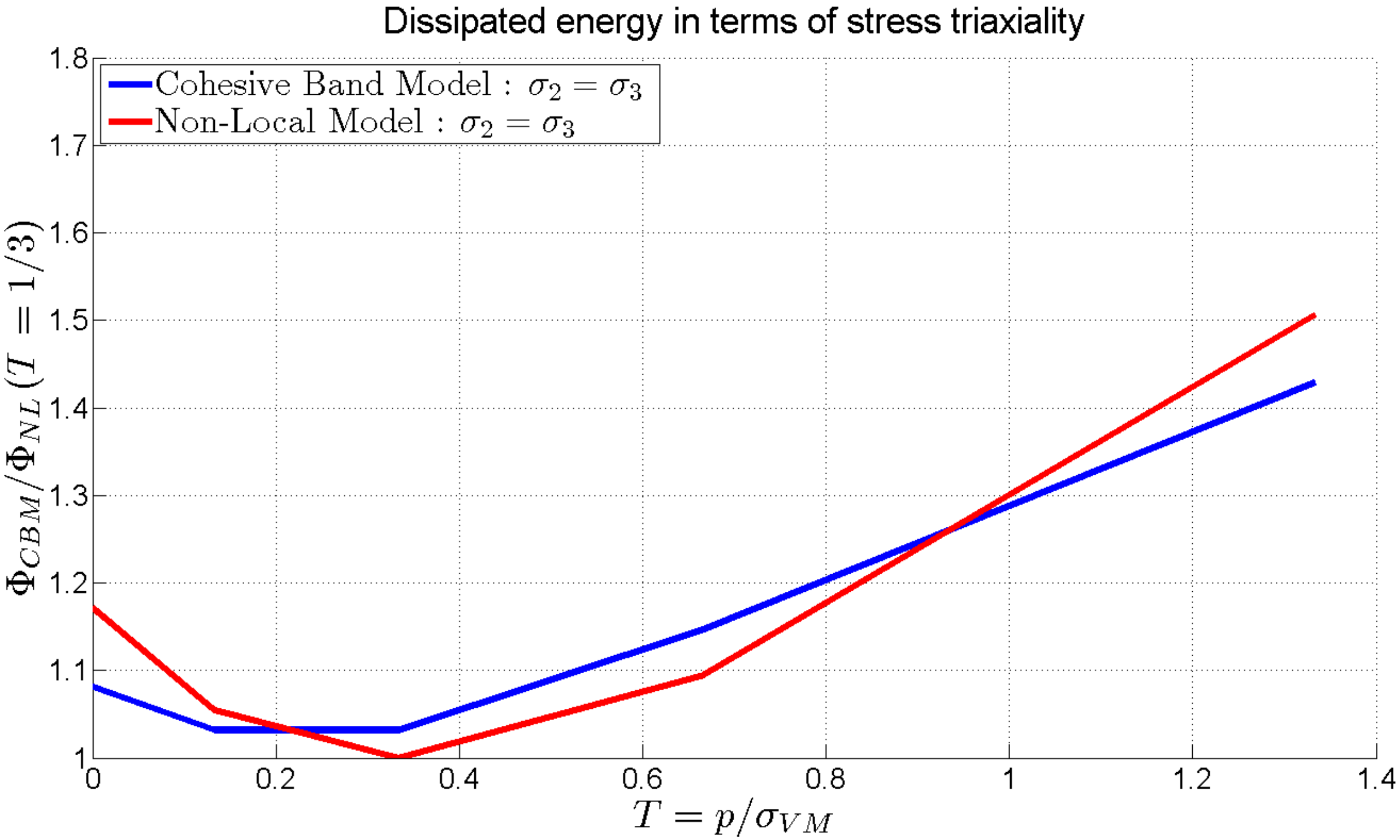
- h_0 value for energy consistency = linked to the process/damage zone size
  - Dependent on only 2 key parameters:
    - Non-local length
      - h_0 is proportional to c_L
    - Critical damage value
      - Damage zone size decreases with damage evolution
  - h_0 independent of other damage model parameters





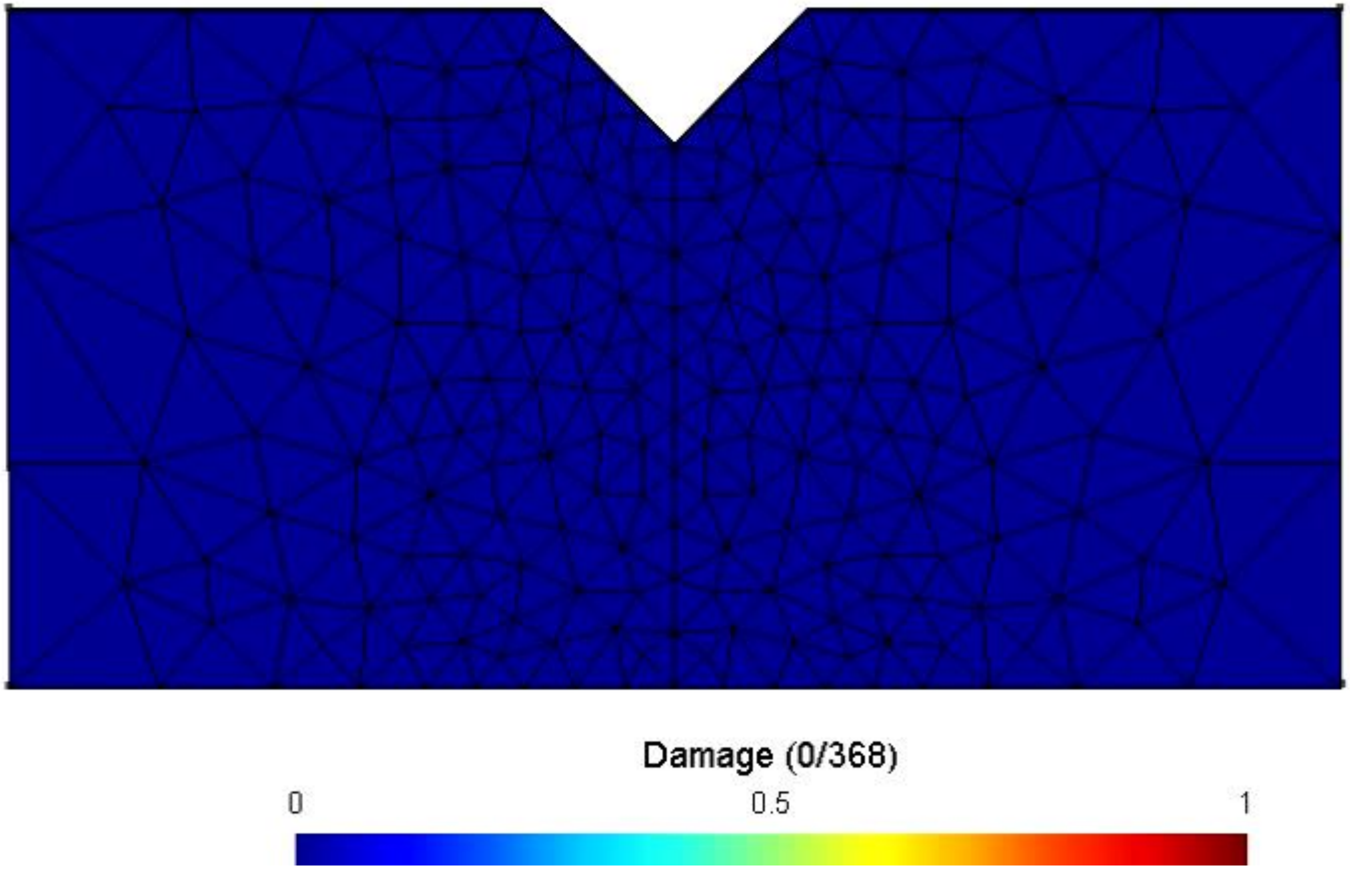
Energetic equivalence (4)

- Influence of triaxiality on dissipated energy
  - Possibility to add perpendicular uniform stress triaxiality along the bar ($\sigma_{22}, \sigma_{33} = \alpha.\sigma_{11}, so\ \epsilon_{22}, \epsilon_{33} \neq 0$, and other components $= 0$)



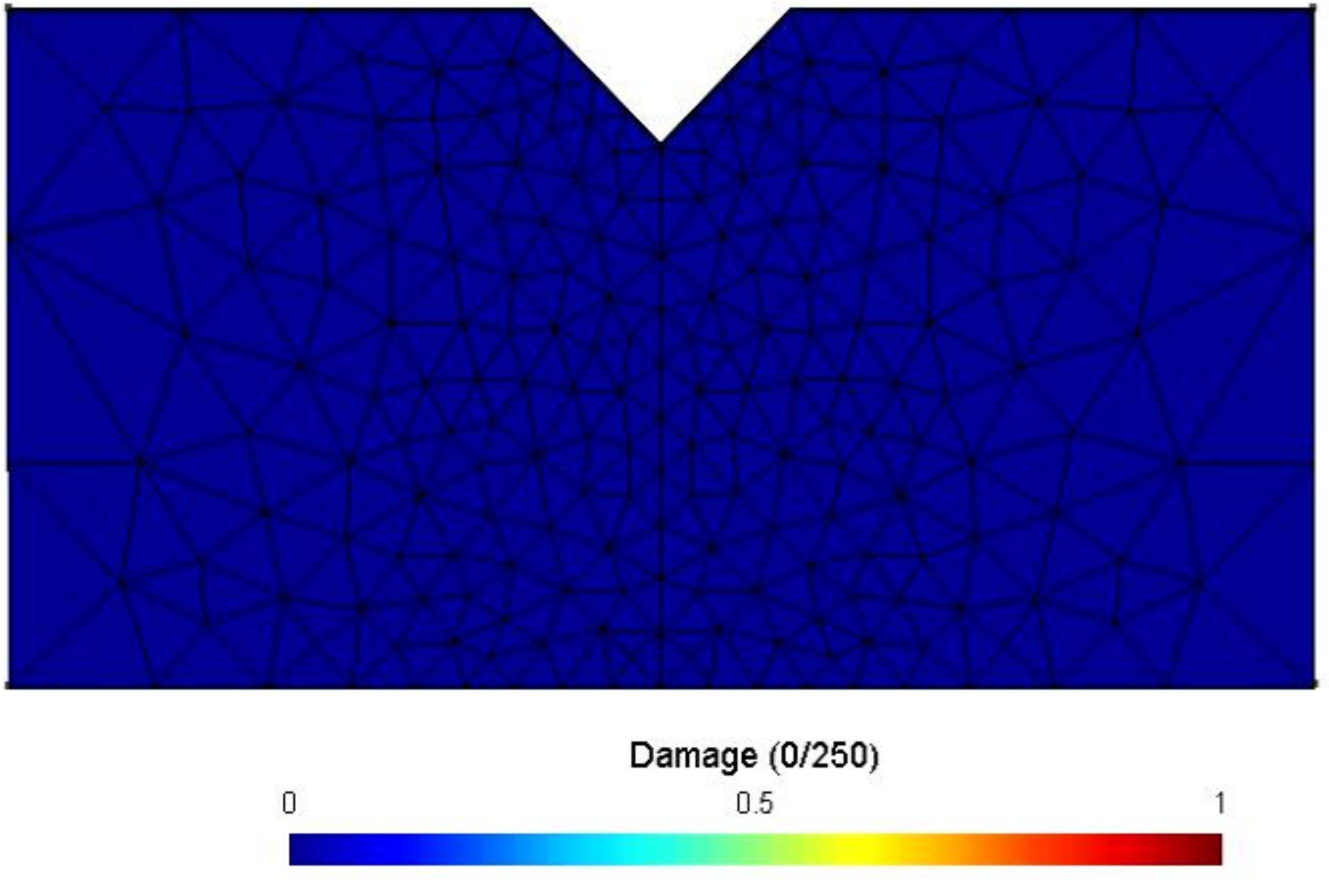
Finite element simulation in GMSH (1)

- Non-local model only



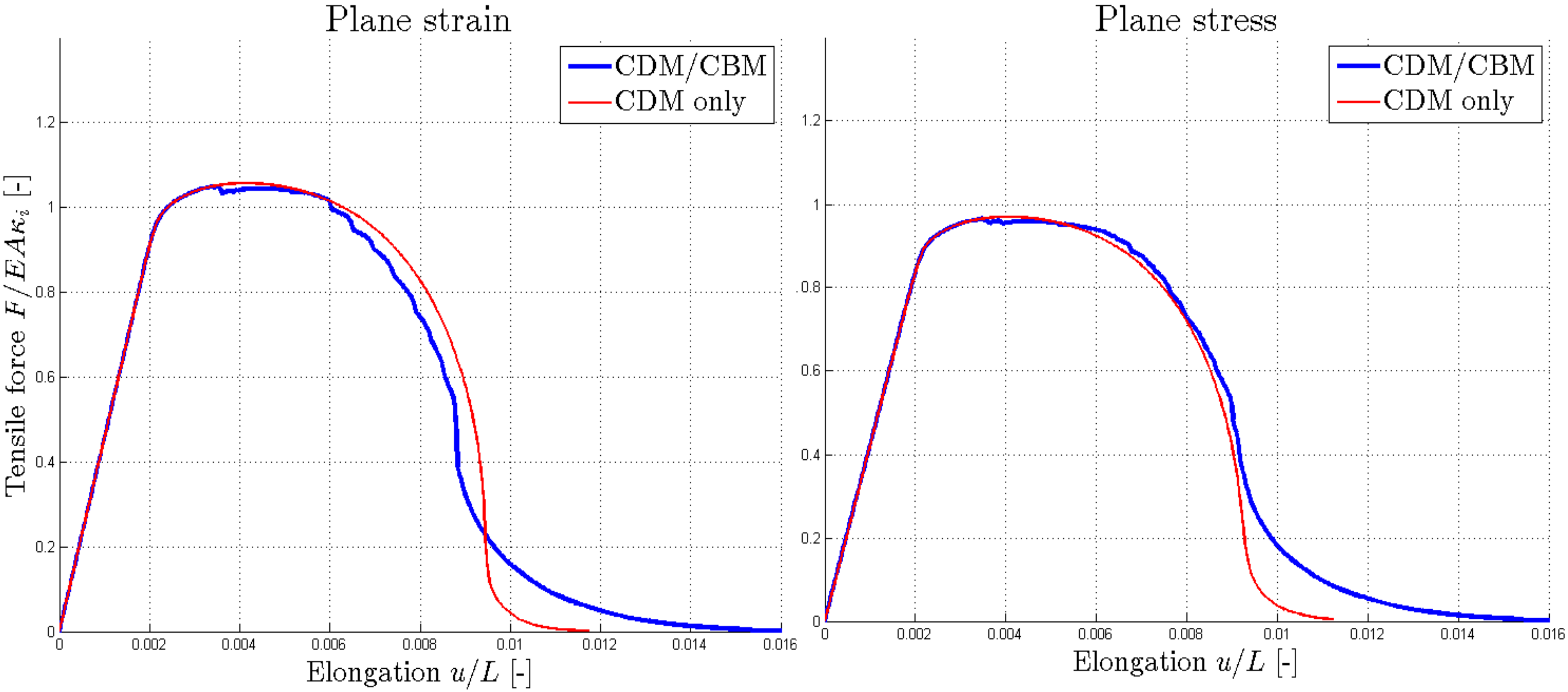
Finite element simulation in GMSH (2)

- Non-local model with cohesive band model

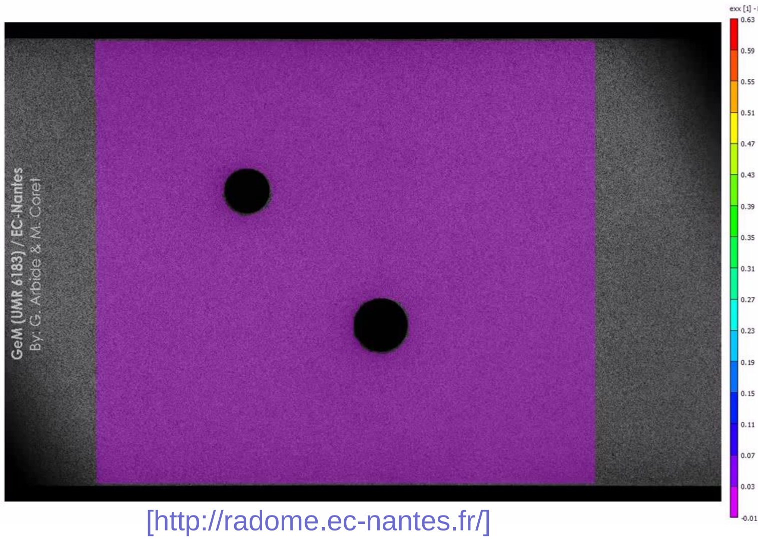


Finite element simulation in GMSH (3)

- Comparison of force vs. displacement curve
  - Relative error on dissipated energy: ~3.0 %



Conclusion



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- Objective:
  - To model material degradation and crack initiation / propagation with high accuracy in ductile materials
- Already done:
  - Cohesive Band Model created to include triaxiality effects:
    - Determination of thickness with a 1D elastic bar
    - Proof of sensibility to triaxiality state
    - Currently tested in 3D
- Perspectives:
  - Cohesive band model
    - Extend to more complex cases (plasticity, Gurson model, large displacements,…)
  - Hybrid framework for metals
    - Choice of a non-local model
    - Determination of transition criterion and cohesive model parameters
    - Model comparison and validation with literature or experimental results

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Thank you for your attention

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