University of Liège
Aerospace & Mechanical Engineering

MS3: Abstract 131573 - CFRAC2017

Cohesive Band Model: a triaxiality-dependent cohesive model inside an implicit non-local damage to crack transition framework

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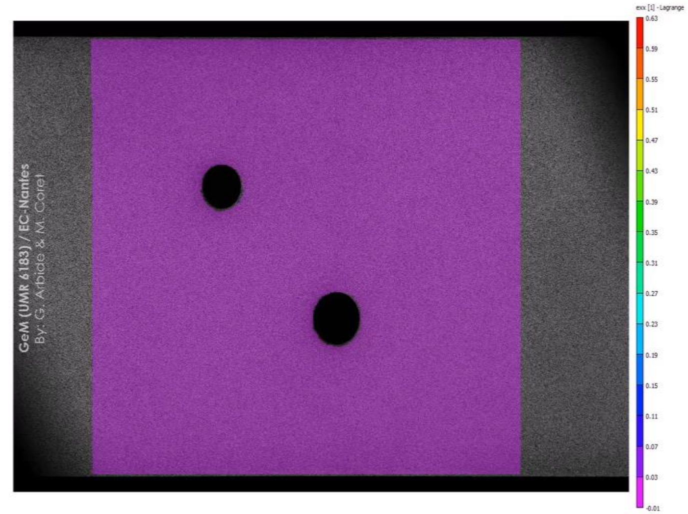
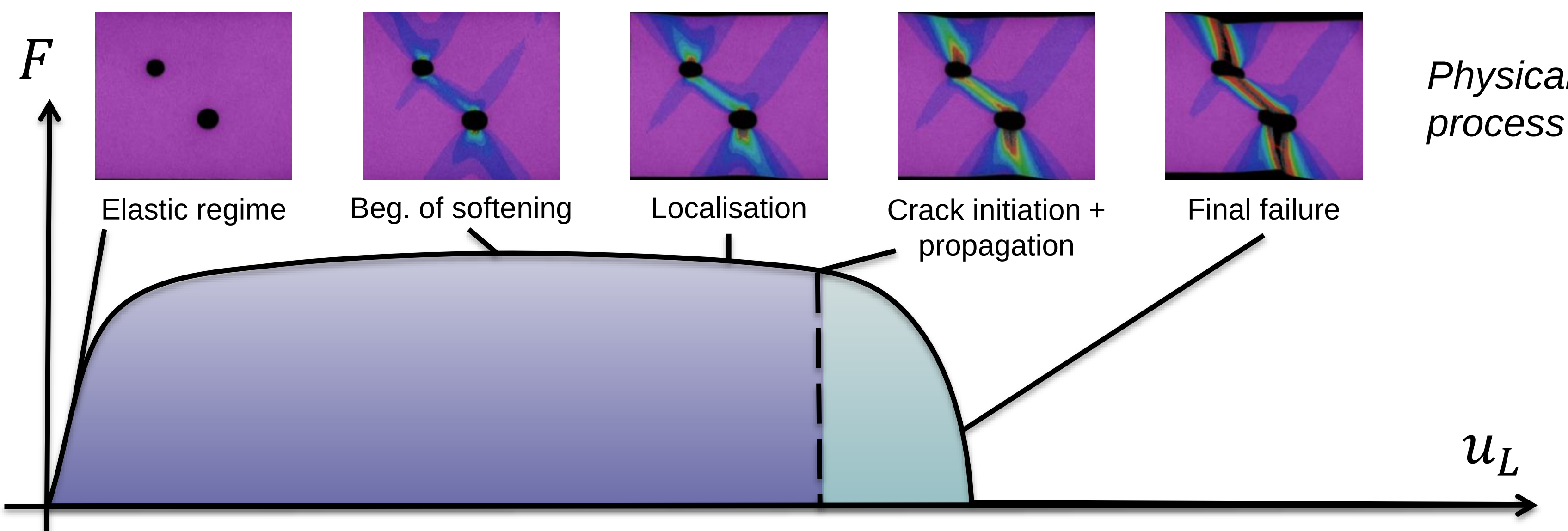
- Goal:
  - To capture the whole ductile failure process:
    - Diffuse damage stage

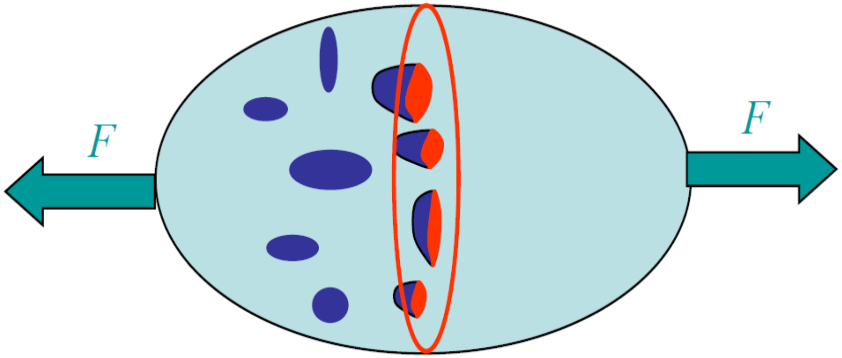
    followed by
    - Crack initiation and propagation



[http://radome.ec-nantes.fr/]



- Material properties degradation modelled by internal variables (= damage):
  - Lemaître-Chaboche model,
  - Gurson model,
    - Porosity evolution
  - …



- Continuous Damage Model (CDM) implementation:
  - Local form
    - Strongly mesh-dependent
  - Non-local form needed [Peerlings et al. 1998]

State of art: two main approaches – 1. Continuous approaches (2)

- Non-local model
  - Principles
    - variable ξ ➔ non-local / “averaged” counterpart $\tilde{\xi}$
  - Formulation
    - Integral form [Bažant 1988]

$$\tilde{\xi}\left(\boldsymbol{x}\right) = \frac{1}{V}\int_V W\left(\boldsymbol{x}-\boldsymbol{y}\right)\xi\left(\boldsymbol{y}\right)dV$$

      » not practical for complex geometries

    - Differential form [Peerlings et al. 2001]
      - Explicit formulation / gradient-enhanced formulation: $\tilde{\xi}\left(\boldsymbol{x}\right) = f\left(\xi, \nabla\xi, \nabla^2\xi, ...\right)$
        » does not remove mesh-dependency
      - Implicit formulation: $\tilde{\xi}\left(\boldsymbol{x}\right) = f\left(\xi, \nabla\tilde{\xi}, \nabla^2\tilde{\xi}, ...\right)$

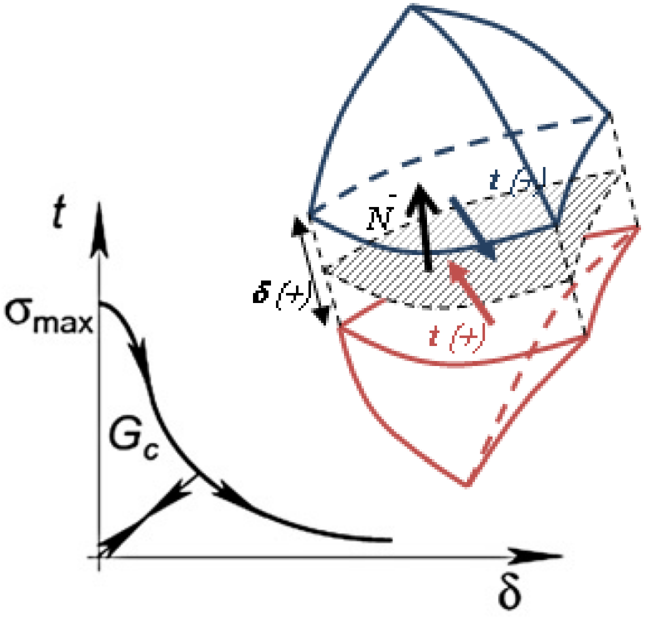
$$\tilde{\xi}\left(\boldsymbol{x}\right) - l_c^2\Delta\tilde{\xi}\left(\boldsymbol{x}\right) = \xi\left(\boldsymbol{x}\right)$$

        » removes mesh-dependency but one added unknown field
        » NB: equivalent to integral form with Green’s functions as $W\left(\boldsymbol{x}-\boldsymbol{y}\right)$

State of art: two main approaches - Comparison (1)

Continuous: Continuous Damage Model (CDM) in a non-local form	**Discontinuous:**
+ Capture the **diffuse damage stage** + Capture stress **triaxiality** and **Lode** variable effects - **Numerical problems** with highly damaged elements - **Cannot represent cracks** without remeshing / element deletion (loss of accuracy, mesh modification ...) - Crack initiation observed for lower damage values	

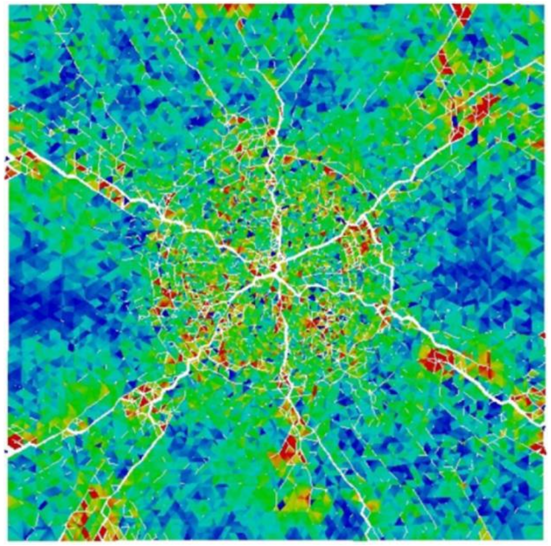
- Similar to fracture mechanics
- One of the most used methods:
  – Cohesive Zone Model (CZM) modelling the crack tip behaviour inserted via:
    - Interface elements between two volume elements
    - Element enrichment (EFEM) [Armero et al. 2009]
    - Mesh enrichment (XFEM) [Moes et al. 2002]
    -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



- Consistent and efficient hybrid framework for brittle fragmentation: [Radovitzky et al. 2011]
  – Extrinsic cohesive interface elements

  +

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



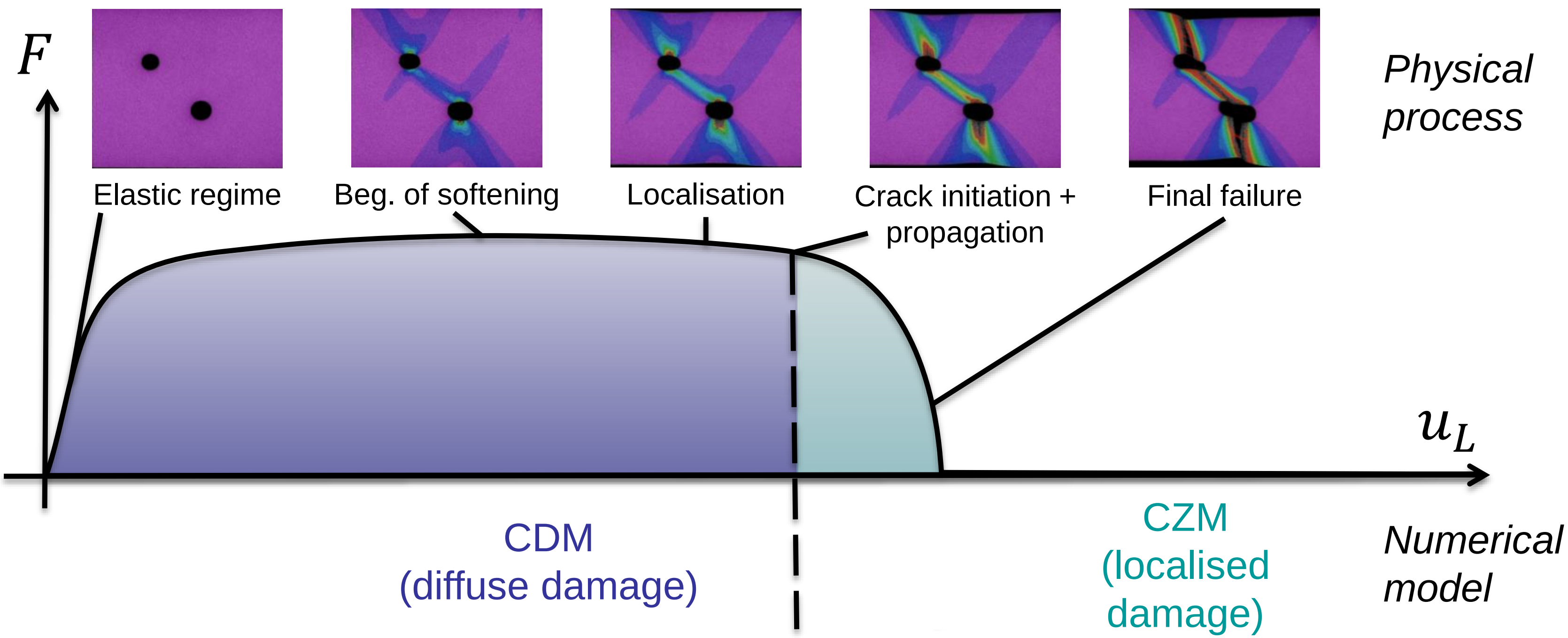
State of art: two main approaches - Comparison (2)

Continuous: Continuous Damage Model (CDM) in a non-local form	**Discontinuous: Extrinsic Cohesive Zone Model + Discontinuous Galerkin elements (CZM/DG)**
+ Capture the **diffuse damage stage** + Capture stress **triaxiality** and **Lode** variable effects	+ **Multiple crack initiation** and propagation naturally managed
- **Numerical problems** with highly damaged elements - **Cannot represent cracks** without remeshing / element deletion (loss of accuracy, mesh modification ...) - Crack initiation observed for lower damage values	- **Cannot capture diffusing damage** - **No triaxiality** effect - Currently valid for brittle / small scale yielding elasto-plastic materials

Goals of research

- Goal:
  - To 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)



Goals of research

- Goal:
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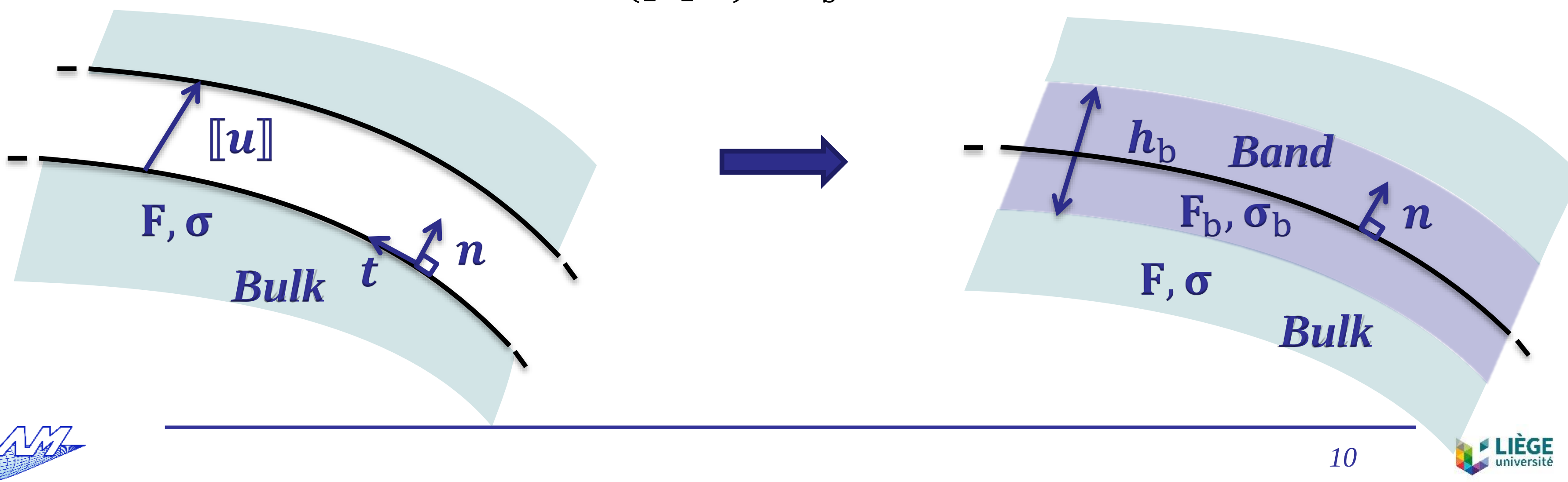
- Main idea:
  - Combination of 2 complementary methods in a single finite element framework:
    - continuous (damage model)

      + transition to
    - discontinuous (cohesive zone model with triaxiality effects)
- Problems:
  - How to combine both methods?
    - Energetic consistency?
    - Cohesive traction-separation law under complex 3D loadings?
    - Triaxiality-dependency of ductile behaviour?

- Solution: Cohesive SURFACE model ➔ Cohesive BAND model to incorporate triaxiality effects:
  - Principles
    - Replacing the traction-separation law of a cohesive zone (CZM) by the behaviour of a uniform band of given thickness h_{b} [Remmers 2013]
  - Methodology
    1. Compute a "band" deformation gradient $\mathbf{F}_{\mathrm{b}}$ computation

$$\mathbf{F}_{\mathrm{b}} = \mathbf{F} + \frac{[\![\boldsymbol{u}]\!] \times \boldsymbol{N}}{h_{\mathrm{b}}} + \frac{1}{2}\boldsymbol{\nabla}_T [\![\boldsymbol{u}]\!]$$

    2. Compute with underlying material behaviour a band stress tensor $\boldsymbol{\sigma}_{\mathrm{b}}$
    3. Recover traction forces $\boldsymbol{t}([\![\boldsymbol{u}]\!], \mathbf{F}) = \boldsymbol{\sigma}_{\mathrm{b}}.\boldsymbol{n}$



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    2. Compute with underlying material behaviour a band stress tensor $\boldsymbol{\sigma}_b$
    3. Recover traction forces $\boldsymbol{t}([\![\boldsymbol{u}]\!], \mathbf{F}) = \boldsymbol{\sigma}_b . \boldsymbol{n}$
  - At crack insertion, framework only dependent on h_b (band thickness)
    - $h_b \neq$ new material parameter
    - A priori determined with underlying non-local CDM to ensure energy consistency

- Isotropic linear elasticity with implicit non-local damage:
  - In small strains and displacements
  - Damage variable D from 0 (undamaged) to 1 (broken):

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

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

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

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

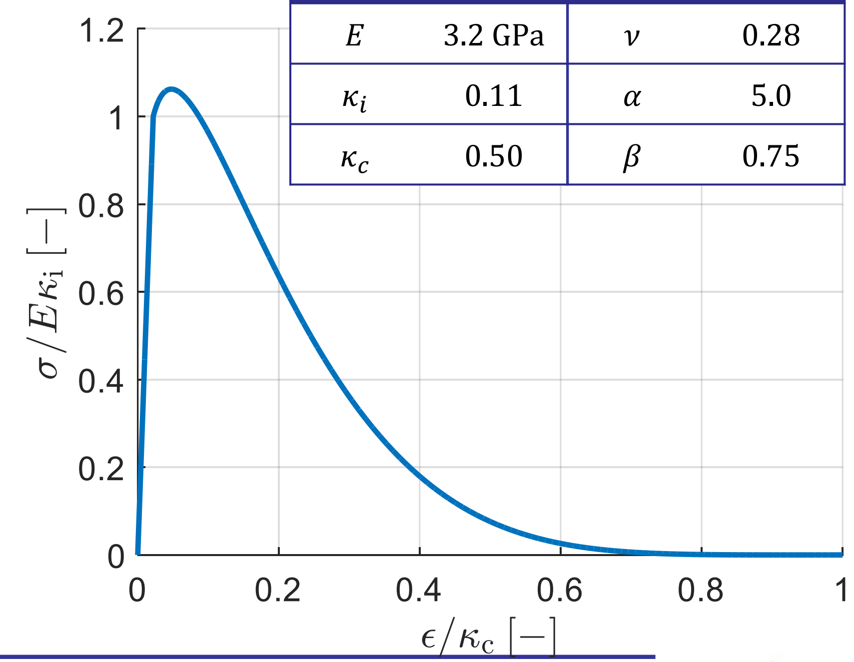
$$\kappa(t) = \max_{\tau}(e(\tau < t))$$

- Non-local strain resulting from:

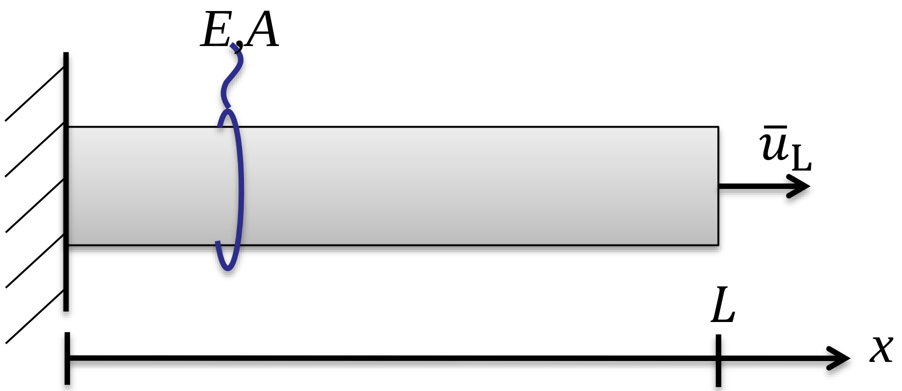
$$\tilde{e} - l_c^2 \Delta \tilde{e} = e = \sqrt{\sum_{i=1,2,3} \left(\epsilon_i^+\right)^2}$$

with ϵ_i^+ = positif **local** principal strains
l_c = non-local length [m]

Material properties (short GFRP)			
E	3.2 GPa	ν	0.28
κ_i	0.11	α	5.0
κ_c	0.50	β	0.75



- Semi-analytic solving:
  – Bar with constrained displacement at the extremities



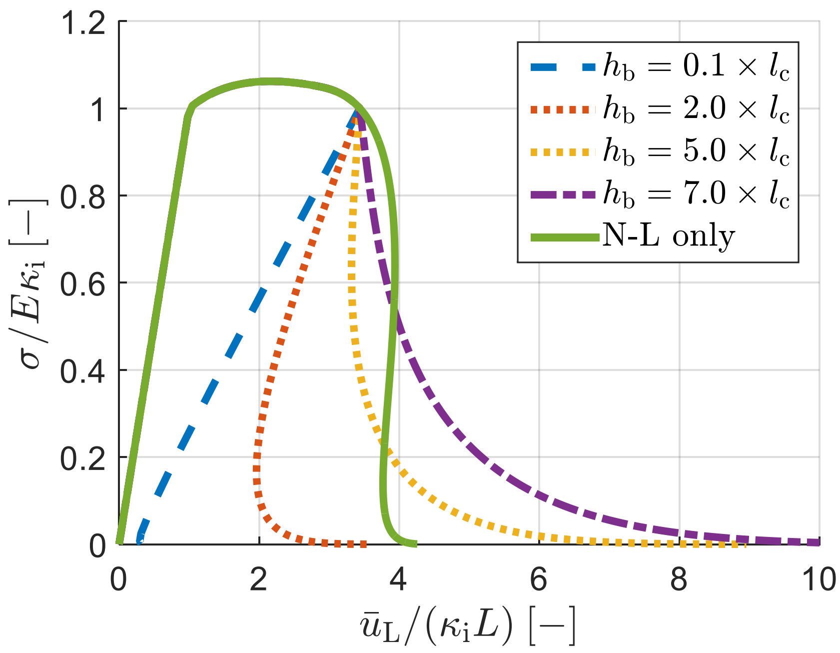
- Discretisation of the strain field $\epsilon_x(x) \rightarrow \epsilon_i$
  – Computation of non-local strains by **convolution** with appropriate Green's functions $W(x,y)$:

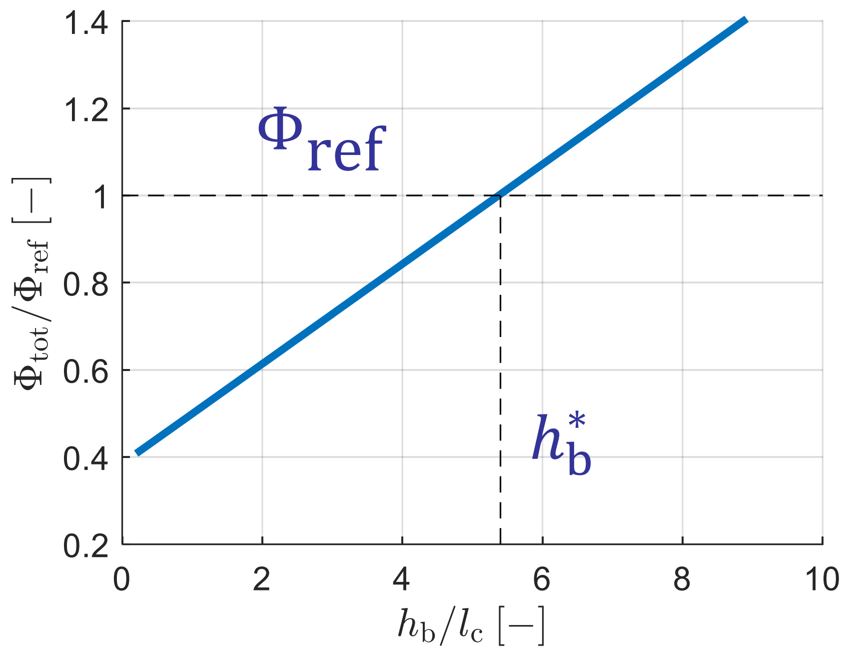
$$\tilde{e}(x) = \int_0^L W(x,y)e(y)dy$$

- Defect at the middle to trigger localisation
- Arc-length method in case of snap-back

Energetic equivalence (computation of h_b)

- Influence of h_b (for a given l_c) on response:
  - Total dissipated energy Φ = linear with h_b:
    - Has to be chosen to conserve energy dissipation (physically based)





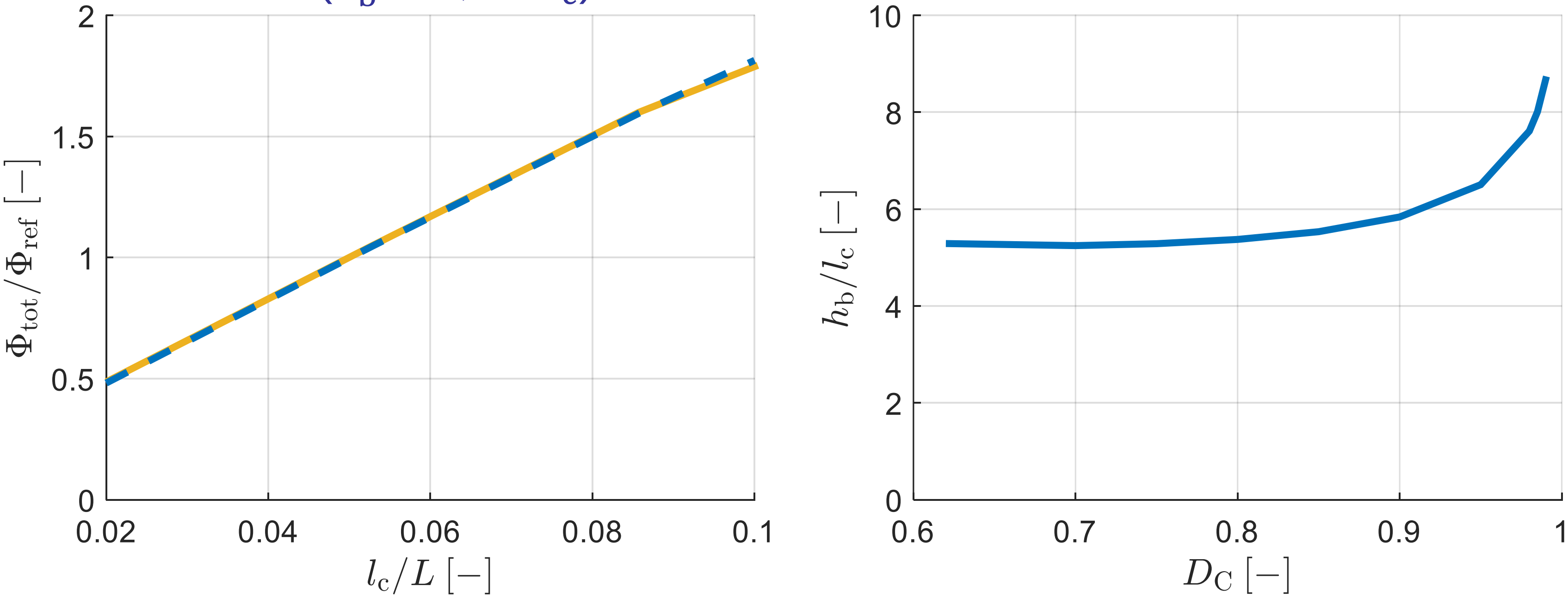
Material properties			
l_c/L	$1/20$	D_c	0,8

Energetic equivalence (computation of h_b)

- Influence of others parameters on h_b^*:
  - Linear with non-local length l_c
    - As long as crack insertion occurs during localisation
  - Constant with insertion damage D_C:
    - Medium value (0.6-0.8): constant
    - High value (>0.8): growing due to (unphysical) damage spread

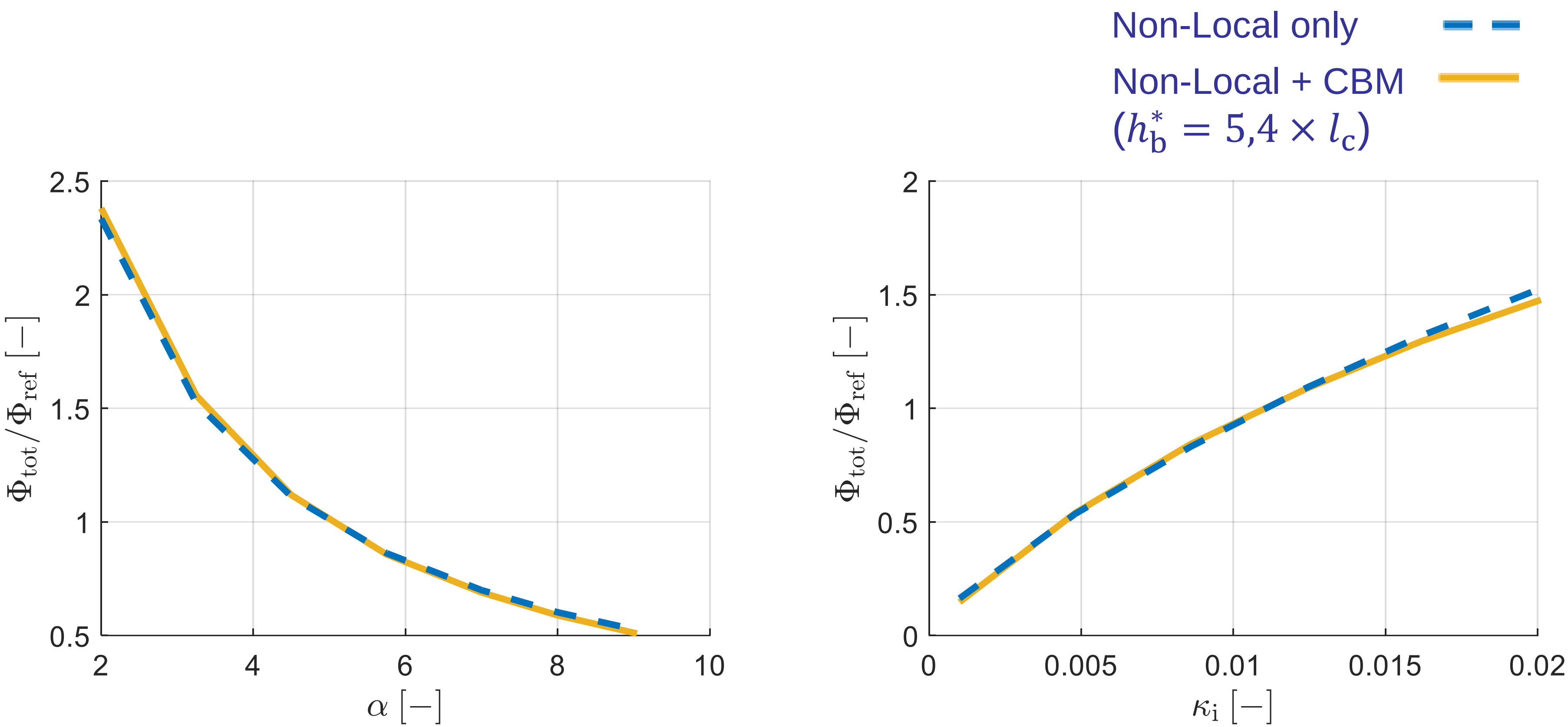
Non-Local only

Non-Local + CBM ($h_\mathrm{b}^* = 5{,}4 \times l_\mathrm{c}$)

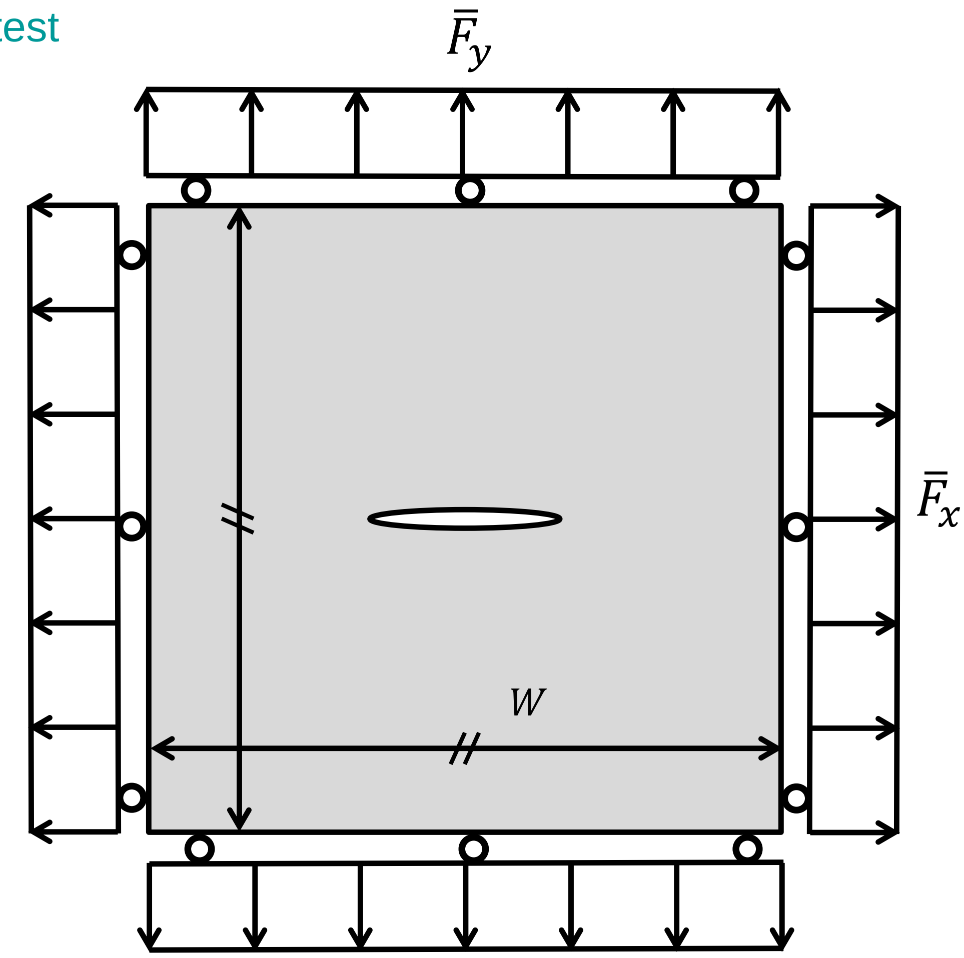


Energetic equivalence (computation of h_{b})

- Influence of others parameters on h_{b}^{*}:
  - Constant with other damage model parameters:
    - As long as crack insertion occurs during localisation

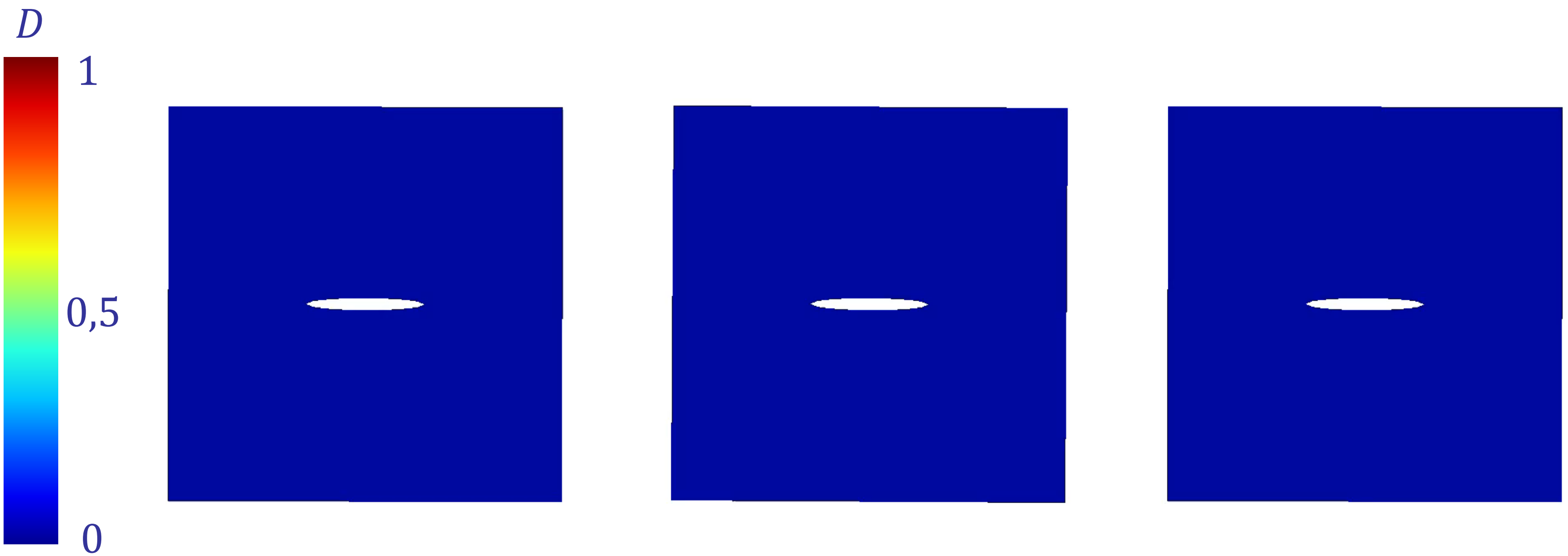


- 2D plate with a defect
  - In plane strain
  - Biaxial loading
    - Ratio $\bar{F}_x/\bar{F}_y$ constant during a test
  - Path following method



Proof of triaxiality sensitivity

- 2D plate in plane strain: $\bar{F}_x/\bar{F}_y$ = 0



Non-local only | Non-local + CZM | Non-local + CBM

no crack insertion

cohesive models calibrated on 1D bar in plane stress

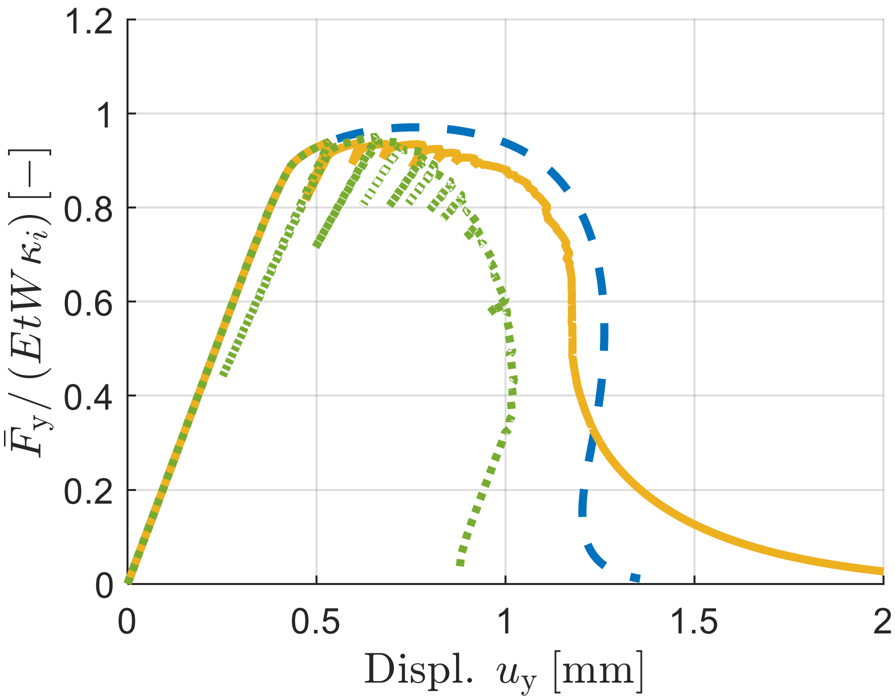
- 2D plate in plane strain:

Non-Local only

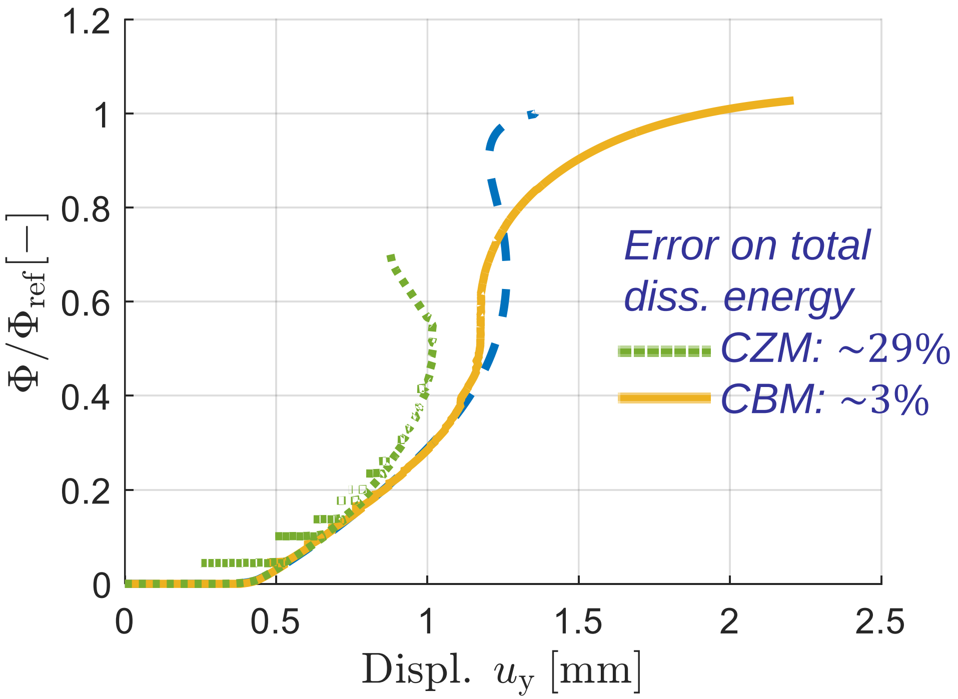
Non-Local + CZM

Non-Local + CBM

- Force evolution



- Dissipated energy evolution



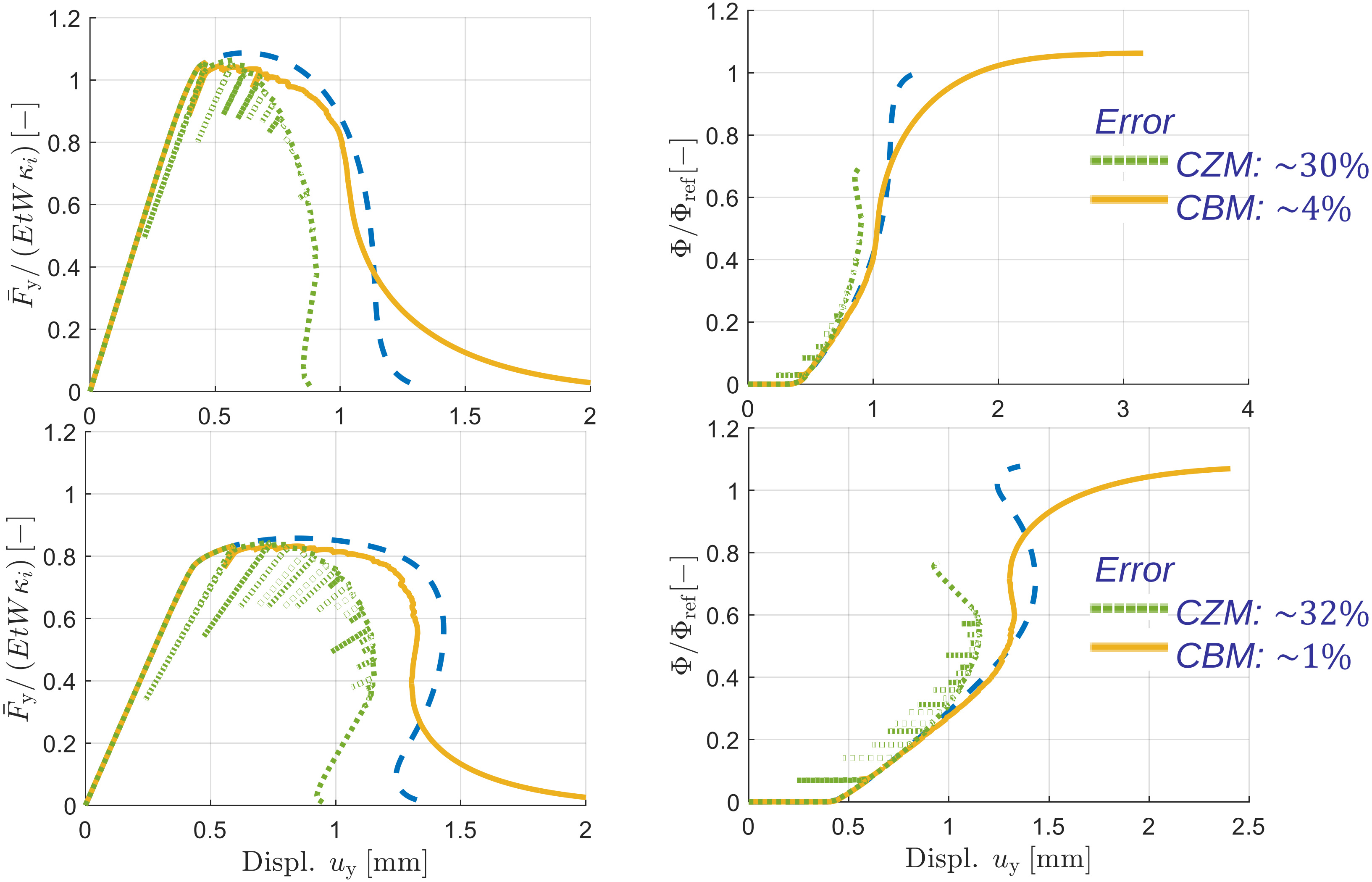
Proof of triaxiality sensitivity

- 2D plate in plane strain:
  - Same trends with ≠ force ratio

Non-Local only
Non-Local + CZM
Non-Local + CBM

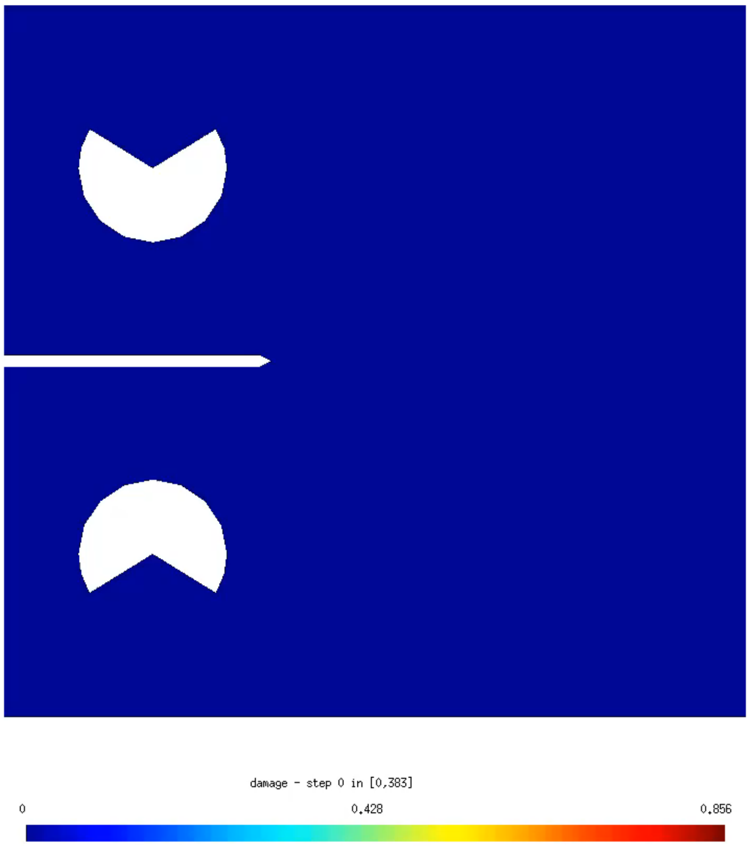
$$\frac{\bar{F}_x}{\bar{F}_y} = +0{,}5$$

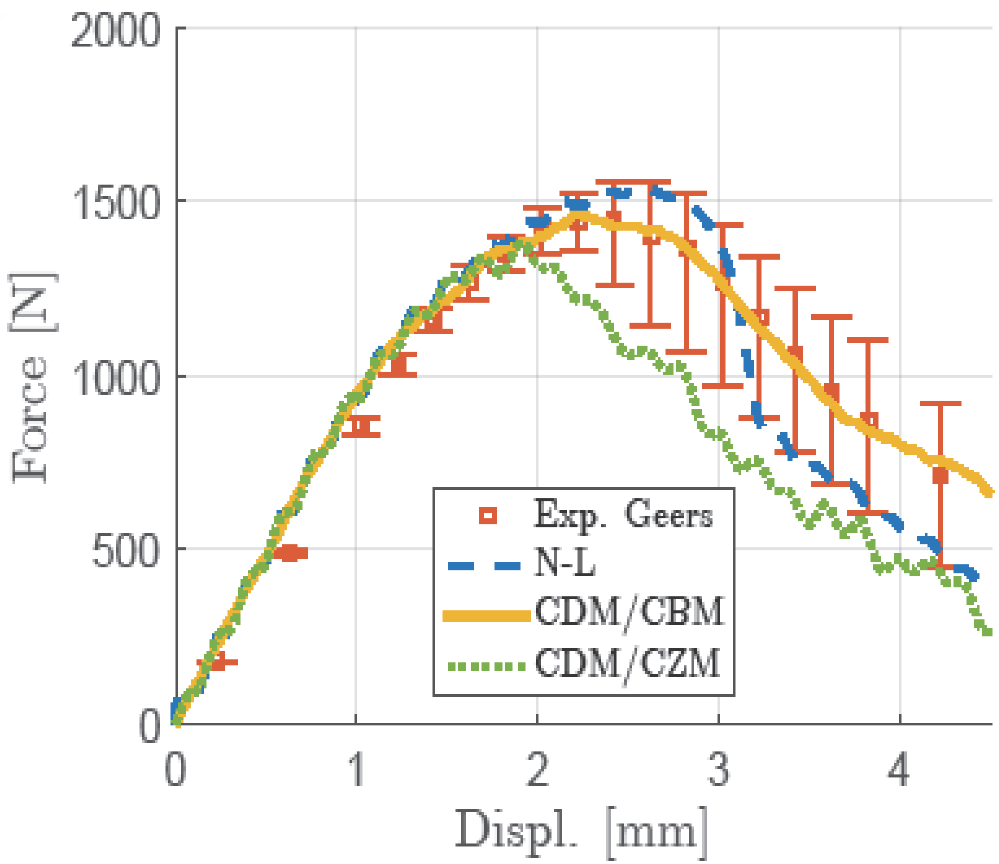
$$\frac{\bar{F}_x}{\bar{F}_y} = -0{,}5$$



Comparison with experiment - validation

- Compact Tension Specimen:
  - Better agreement with the cohesive band model





Conclusion

- Goal:
  - Simulation of material degradation and crack initiation / propagation during the ductile failure process

- Already done:
  - Cohesive Band model developed to include triaxiality effects
    - Application to isotropic elastic law with non-local damage
      - Calibration with 1D bar
      - Proof of triaxiality sensitivity
      - Experimental validation

- Perspectives:
  - Hybrid framework extended for metals
    - Choice of a non-local damage model
    - Determination of transition criterion and cohesive model parameters

Thank you for your attention

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