Multi-scale Cohesive Failure Modeling of Heterogeneous Adhesives

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IMECE 2009 – Orlando, Florida

Support: National Science Foundation (CMMI 05-27965)

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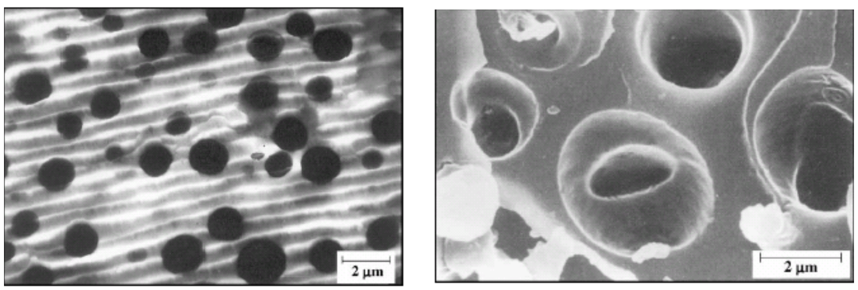
Motivation: High-Toughness Adhesives

Adhesives are often the *weak* links in bonded structures

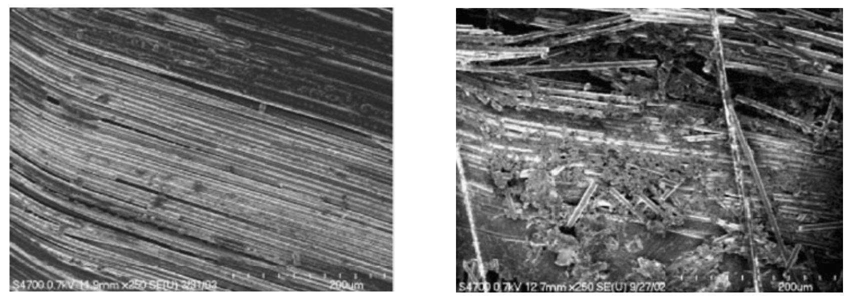
↓

Heterogeneities enhance mechanical and fracture properties



Rubber-toughened epoxy adhesive

Kinloch (2003)



Carbon nanotube-reinforced epoxy adhesives

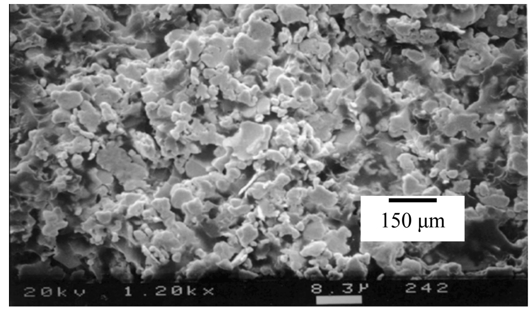
Hsiao *et al.* (2003)

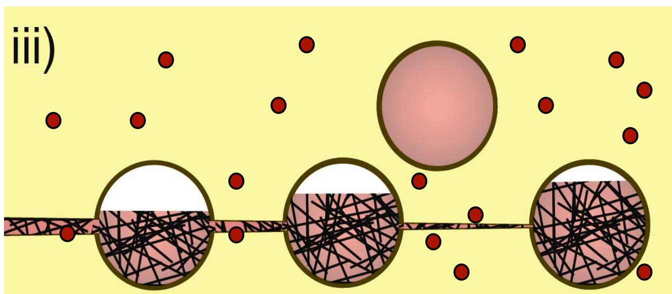
Important to capture microscopic failure processes to develop an accurate model

Motivation: Multi-functional Adhesives

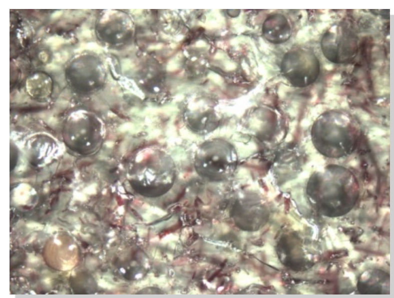
- Silver-enriched epoxy adhesive

Xu *et al.* (2003)





- Self-healing adhesive
  - EPON 828/DETA Epoxy
  - 15 wt% microcapsules (125-180 μm)
  - 2.5 wt% Grubbs' catalyst



Jin *et al.* (2009)

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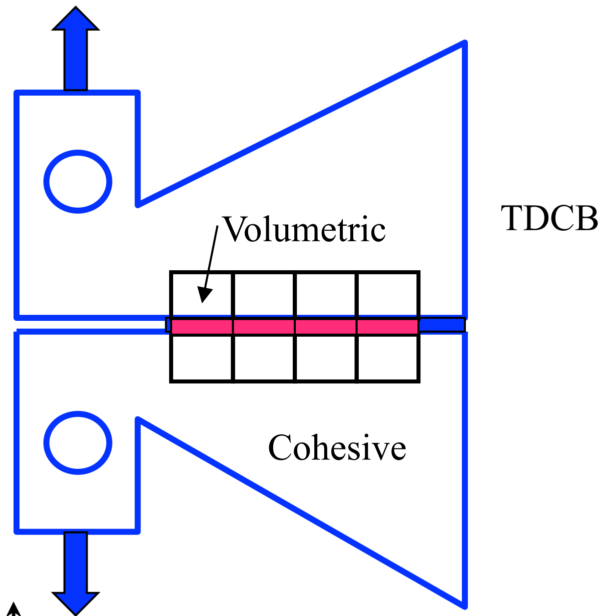
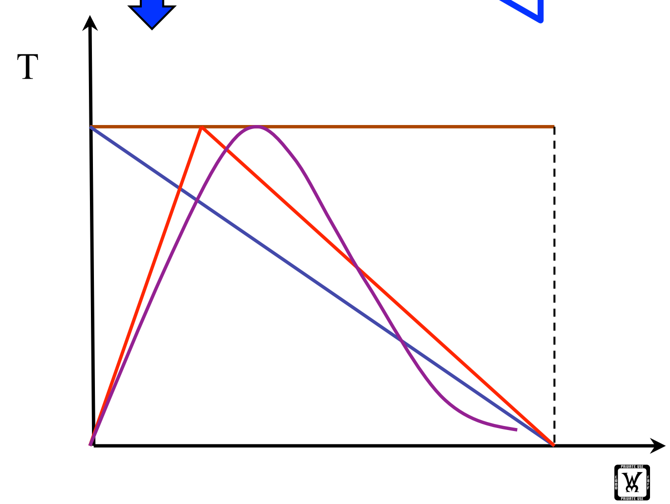
Macroscopic Failure Modeling

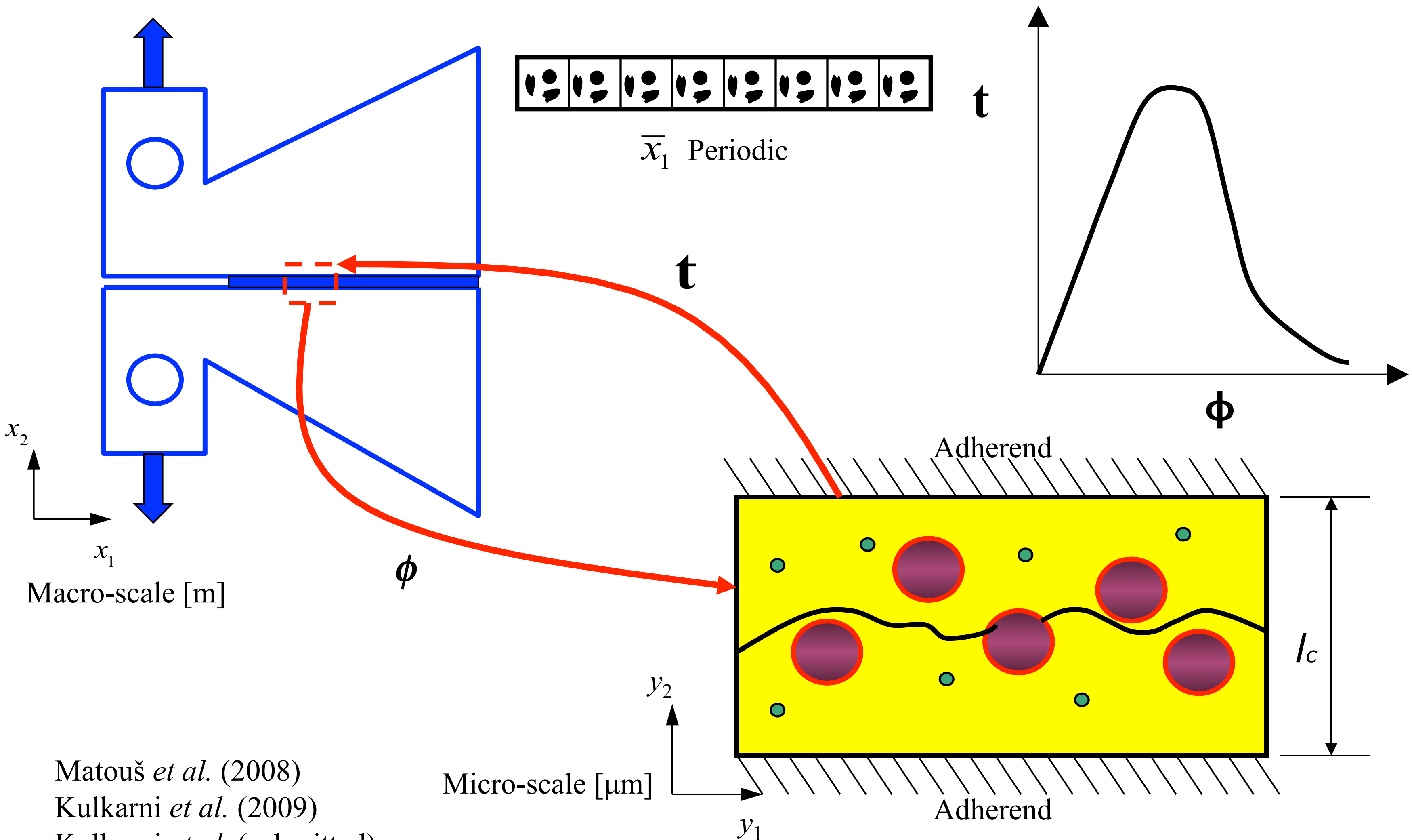
- Cohesive finite element method
  - Collapses adhesive layer to 2D (or 1D) cohesive zone
  - Efficient and well-established scheme
  - Cohesive failure model chosen for mathematical convenience
  - Little connection to *microscopic* failure processes
- Objective: Develop a multi-scale cohesive model to obtain cohesive laws that embed physics from the micro-scale





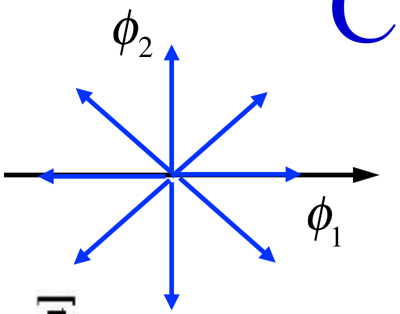
Xu and Needleman (1994), Camacho and Ortiz (1996)
Geubelle and Baylor (1998)

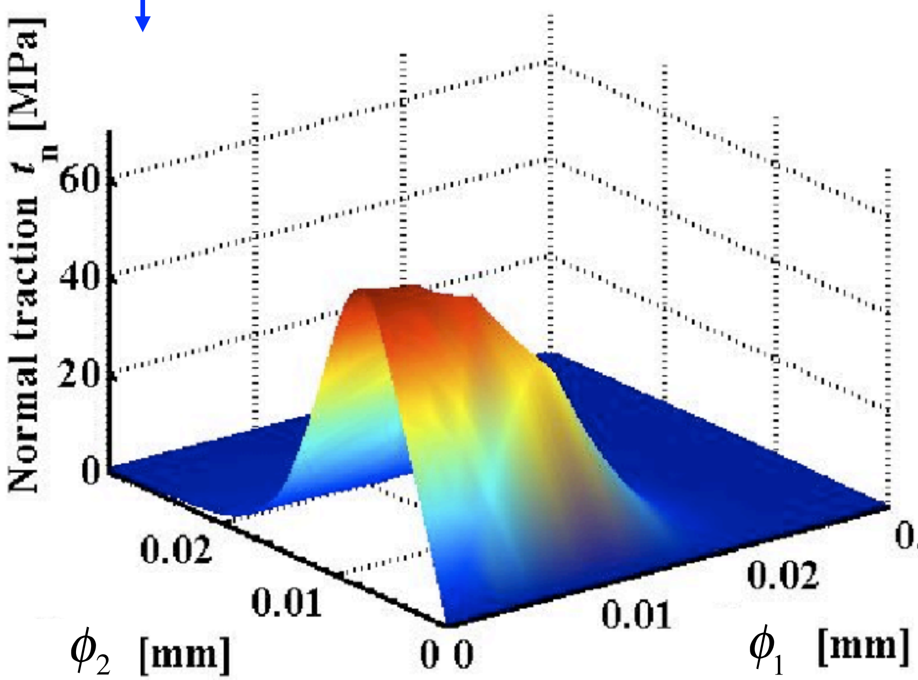
Multi-scale Cohesive Approach



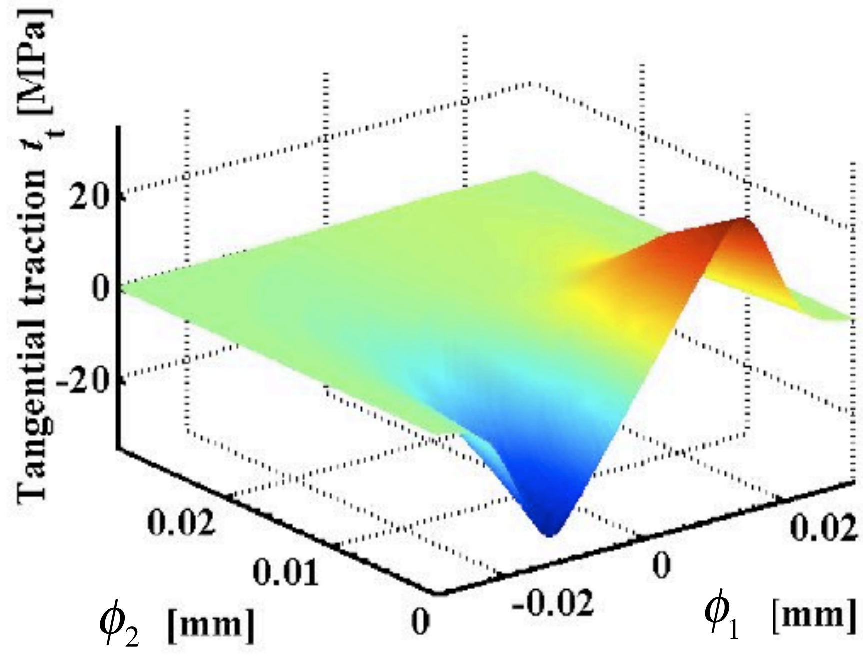
Matouš *et al.* (2008)
Kulkarni *et al.* (2009)
Kulkarni *et al.* (submitted)

Cohesive Damage Envelope





Normal cohesive envelope



Tangential cohesive envelope

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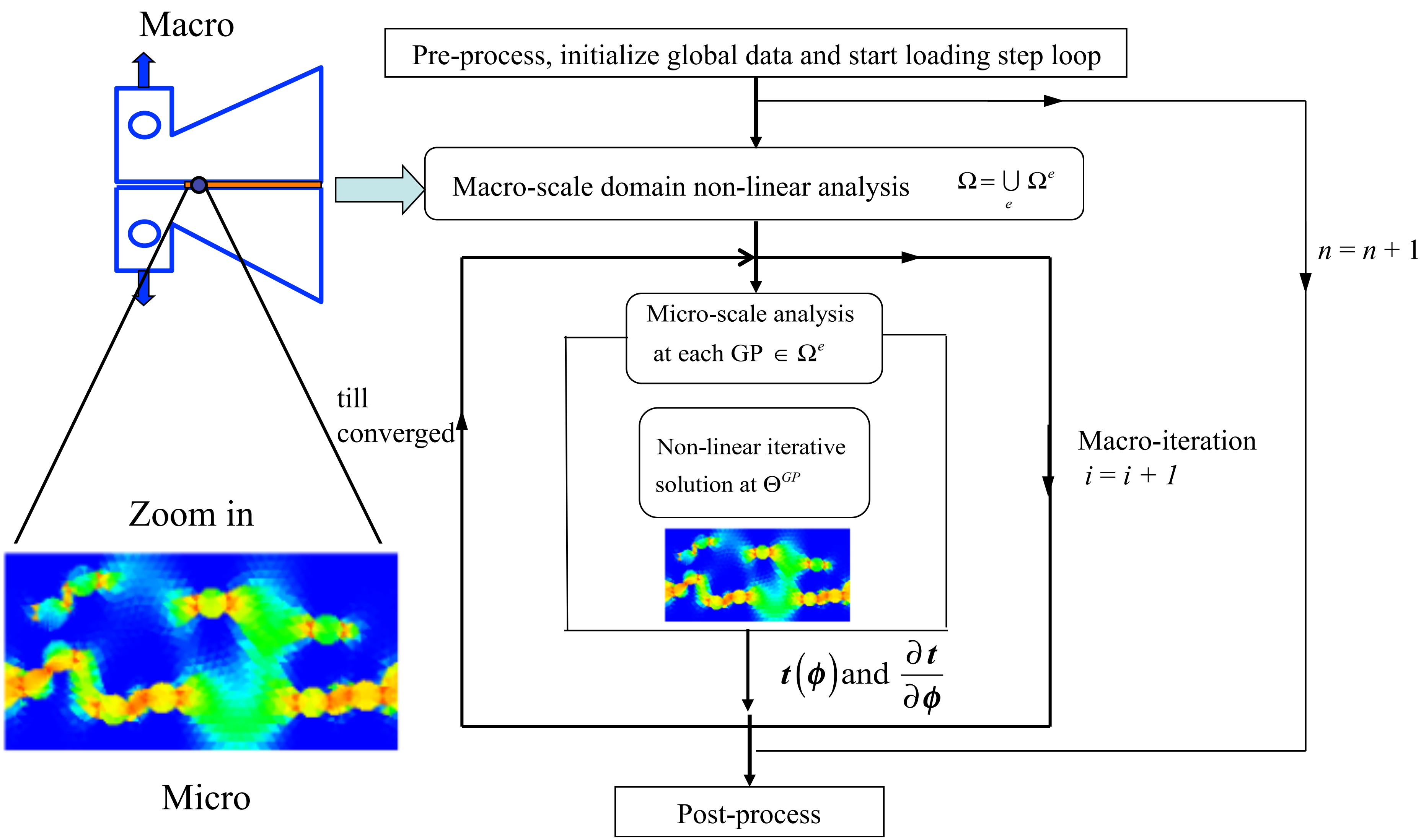
Nested Iterative Algorithm



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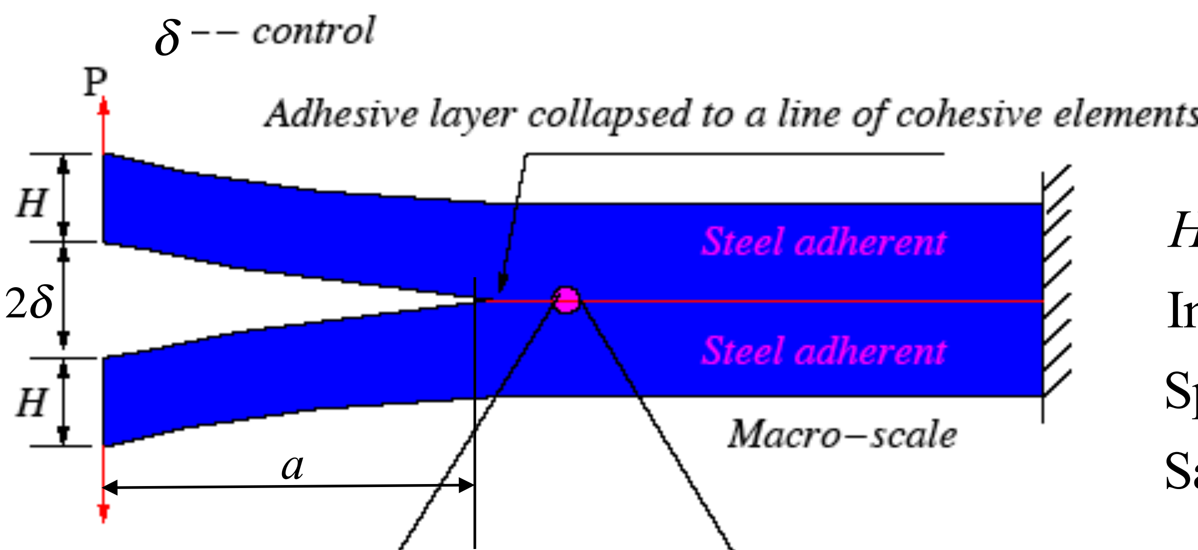
Application #1: Mode I DCB

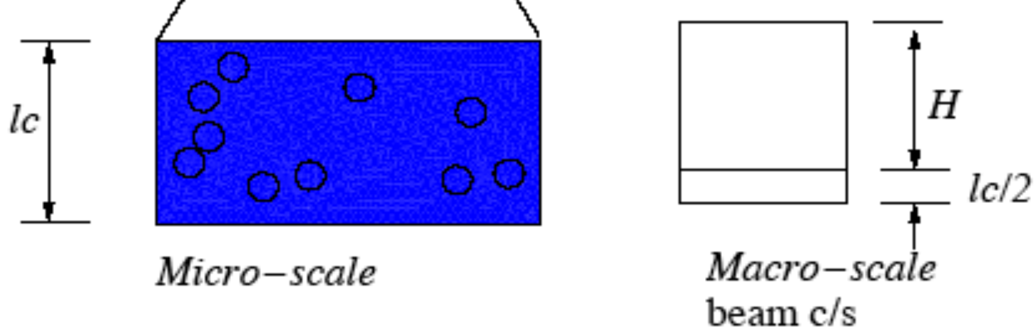


$H = 2$ mm,

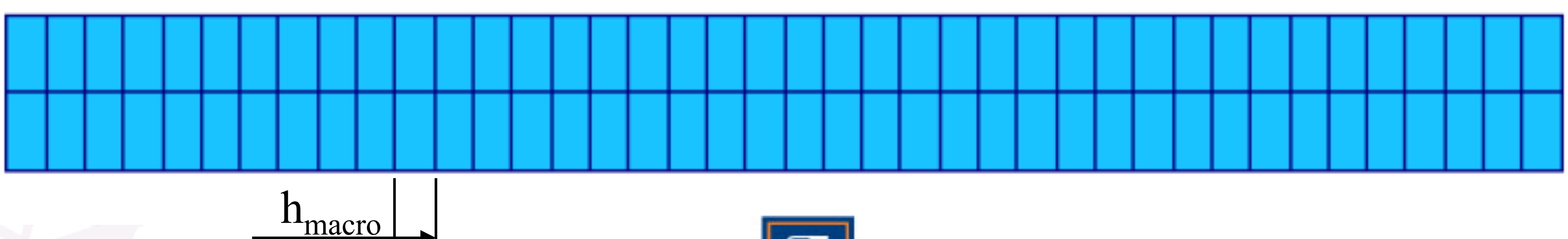
Initial crack length = 4 mm

Specimen length = 40 mm

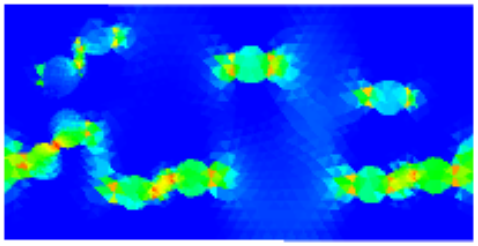
Same micro-scale properties



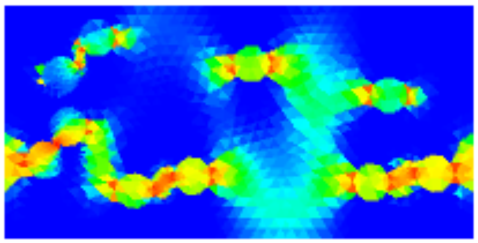
Mixed-enhanced strain elements at macro-scale



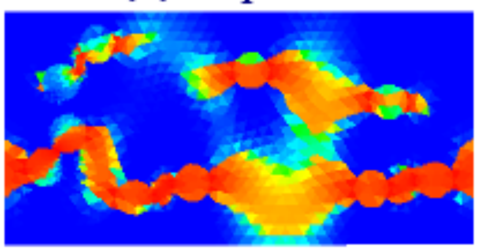
Damage Evolution



(a) Step # 14

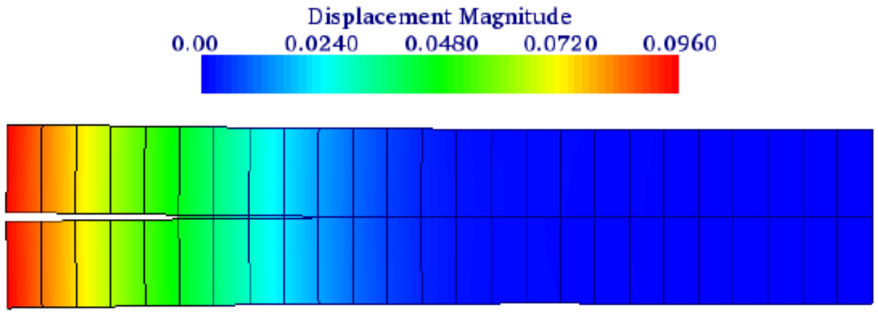


(b) Step # 16

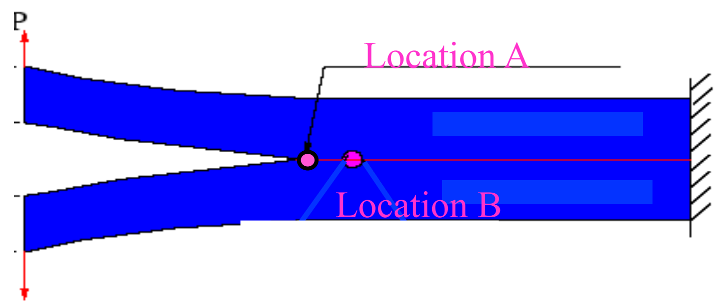


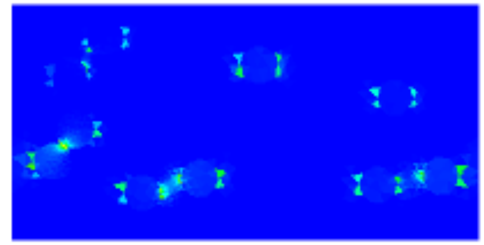
(c) Step # 20

Location A

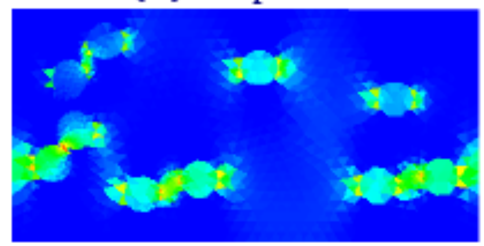


Macroscopic mesh

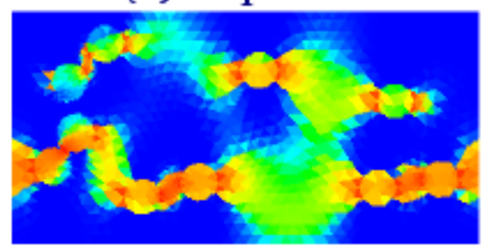




(d) Step # 20



(e) Step # 22



(f) Step # 26

Location B

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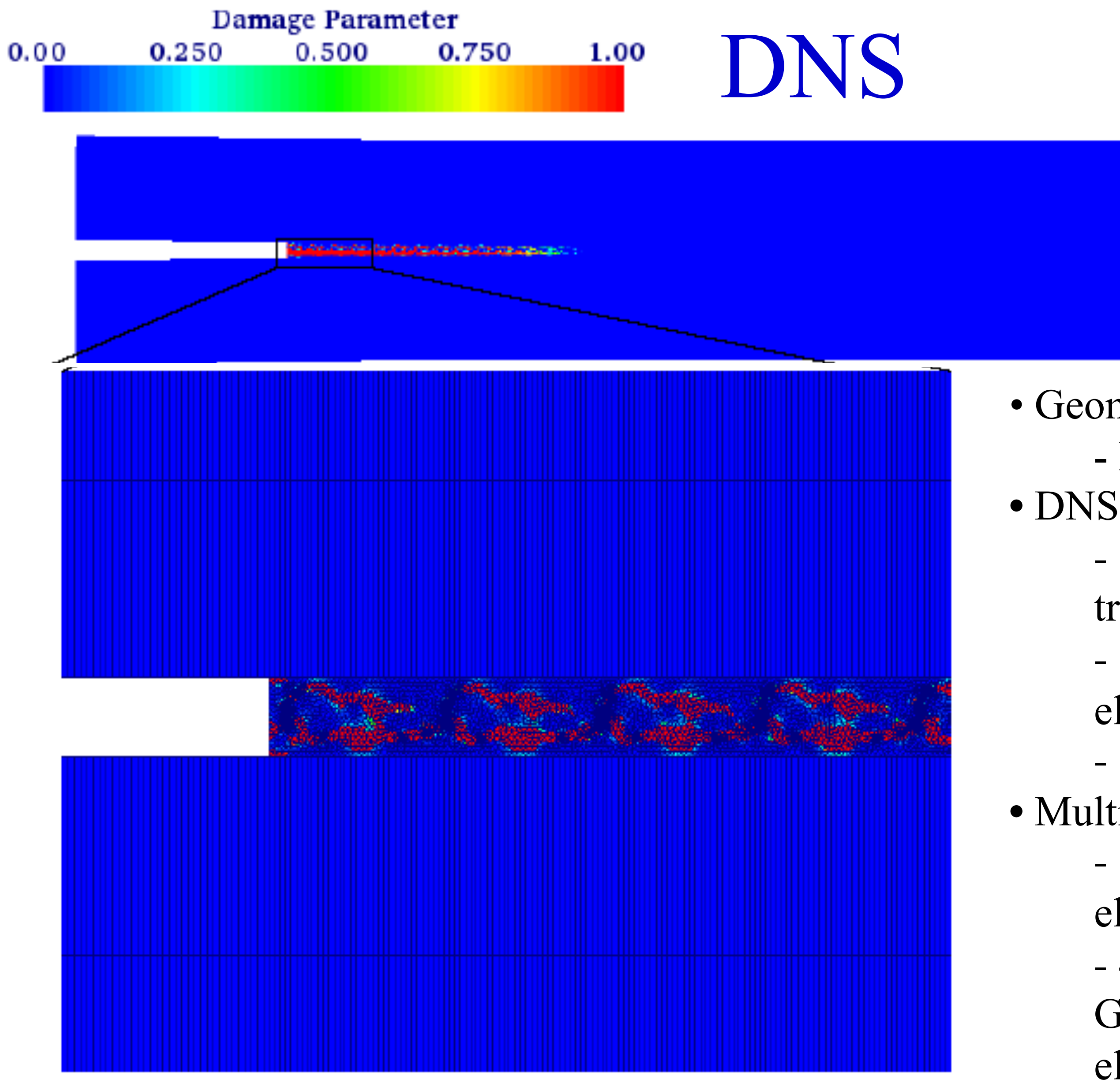
DNS



Damage pattern periodic except at notch tip

- Geometry:
  - Beam length = 20 mm
- DNS:
  - 68766 constant strain triangles
  - 11248 mixed-enhanced quad elements
  - 96000 degrees of freedom
- Multi-scale:
  - 80 mixed-enhanced quad elements
  - 40 cohesive elements (3 Gauss quadrature points per element)
  - 1436 nodes, 2750 elements

Kasper and Taylor (2000)

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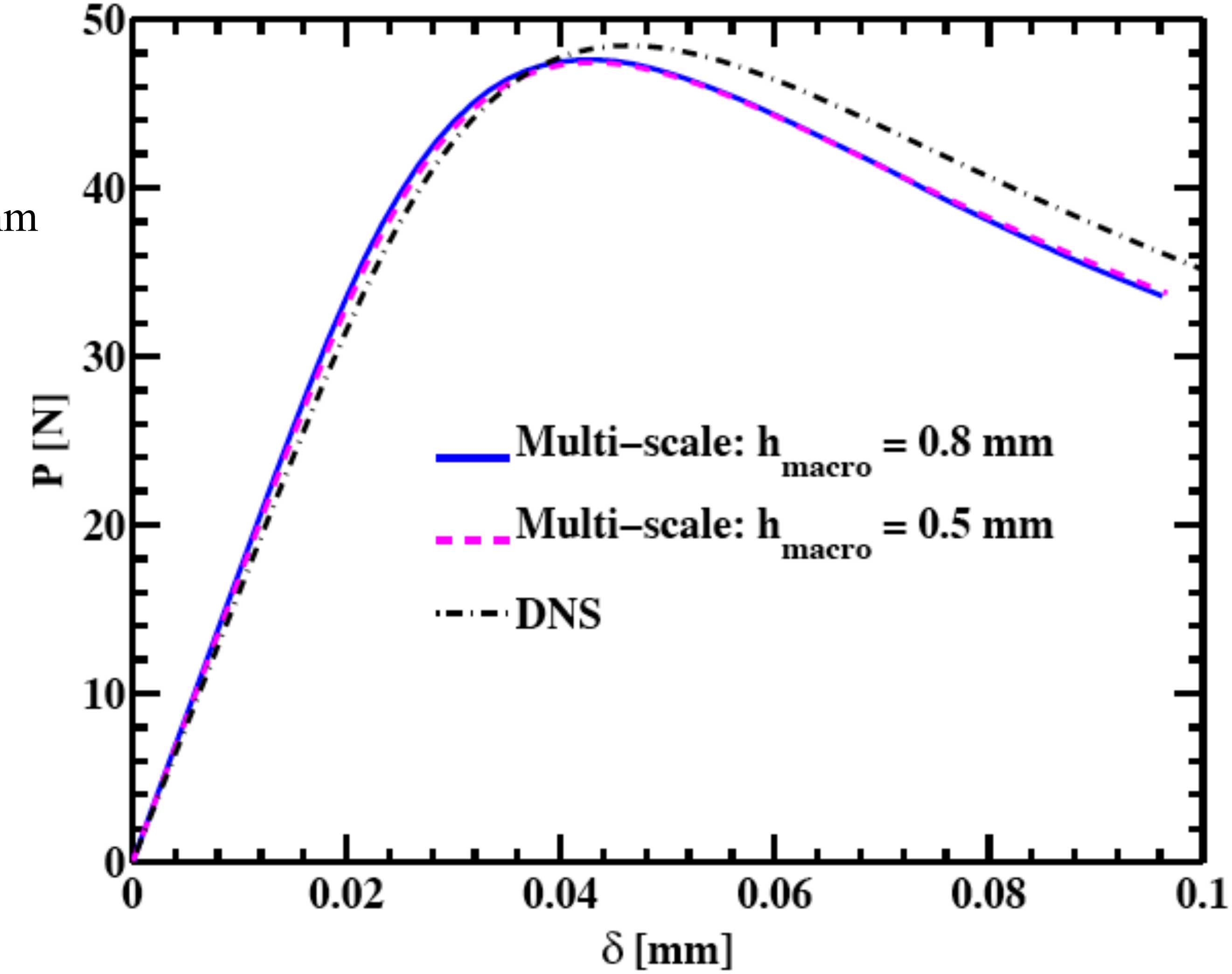
Comparison with DNS

Beam length = 20 mm

Minor differences due to non-periodicity of solution in front of the crack tip



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