Multi-scale Cohesive Failure Modeling of Heterogeneous Adhesives

Philippe Geubelle, Mohan Kulkarni
University of Illinois at Urbana-Champaign

Karel Matous
University of Notre Dame

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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)
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
Nested Iterative Algorithm

Macro-scale domain non-linear analysis

\[ \Omega = \bigcup \Omega^e \]

Micro-scale analysis at each GP \( \in \Omega^e \)

Non-linear iterative solution at \( \Theta^{GP} \)

Post-process

Pre-process, initialize global data and start loading step loop

Macro-iteration
\[ i = i + 1 \]

Zoom in

Macro

Micro

till converged

\[ n = n + 1 \]
Application #1: Mode I DCB

Adhesive layer collapsed to a line of cohesive elements

$H = 2\text{ mm}$,
Initial crack length $= 4\text{ mm}$
Specimen length $= 40\text{ mm}$
Same micro-scale properties

Macro-scale

Mixed-enhanced strain elements at macro-scale

$h_{\text{macro}}$
Damage Evolution

Macroscopic mesh

(a) Step # 14
(b) Step # 16
(c) Step # 20
Location A
(d) Step # 20
(e) Step # 22
(f) Step # 26
Location B
**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)
Comparison with DNS

Beam length = 20 mm

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