Experimental Aspects of Virtual Tests

Qingda Yang & Daosheng Ling
University of Miami
Brian Cox
Teledyne Scientific Co. LLC, Thousand Oaks, California, USA

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What Would We Do with a Virtual Test?

Interpolate and extrapolate real test data

reduce certification tests X10 ($10^4 \rightarrow 10^3$)

fiber architecture effects
test one or two ply lay-up choices
predict effect of changing ply thickness or orientation

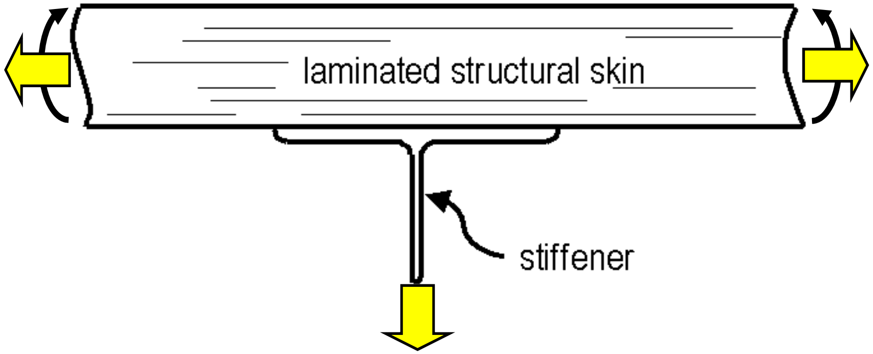
combined thermal & mechanical loading
test in-phase for short duration
predict out-of-phase and long duration

optimal design
match fiber architecture to complex load configurations

generate statistics of performance
trace path from material variance to probability of failure

make best possible prediction of remaining life given limited data

The Top-Down Strategy

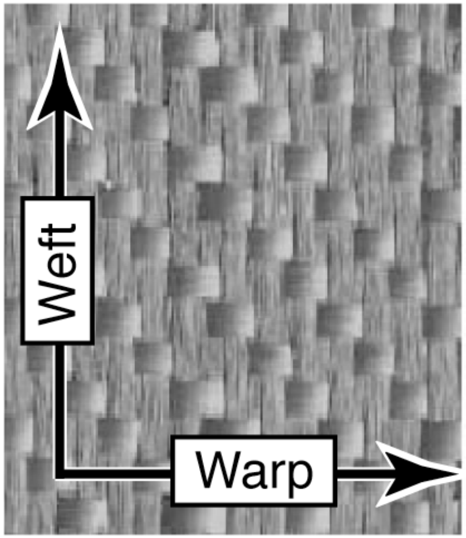


Engineering Functionality — What do you need in the model?

- displacement field for given load
  - including nonlinearity ← continuum damage material description
- ultimate strength
  - proportional loading (easy) ← linear elasticity plus failure criterion
  - one load followed by a different load ← internal damage - major cracks
  - load following fatigue cycles ← physical degradation model
  - load following impact ← dynamic response
  - load coupled to T & environment ← chemical degradation model
- permeability ← microcracking
- appearance ← smoothness/colour

The dirty reality of a thin ceramic composite skin

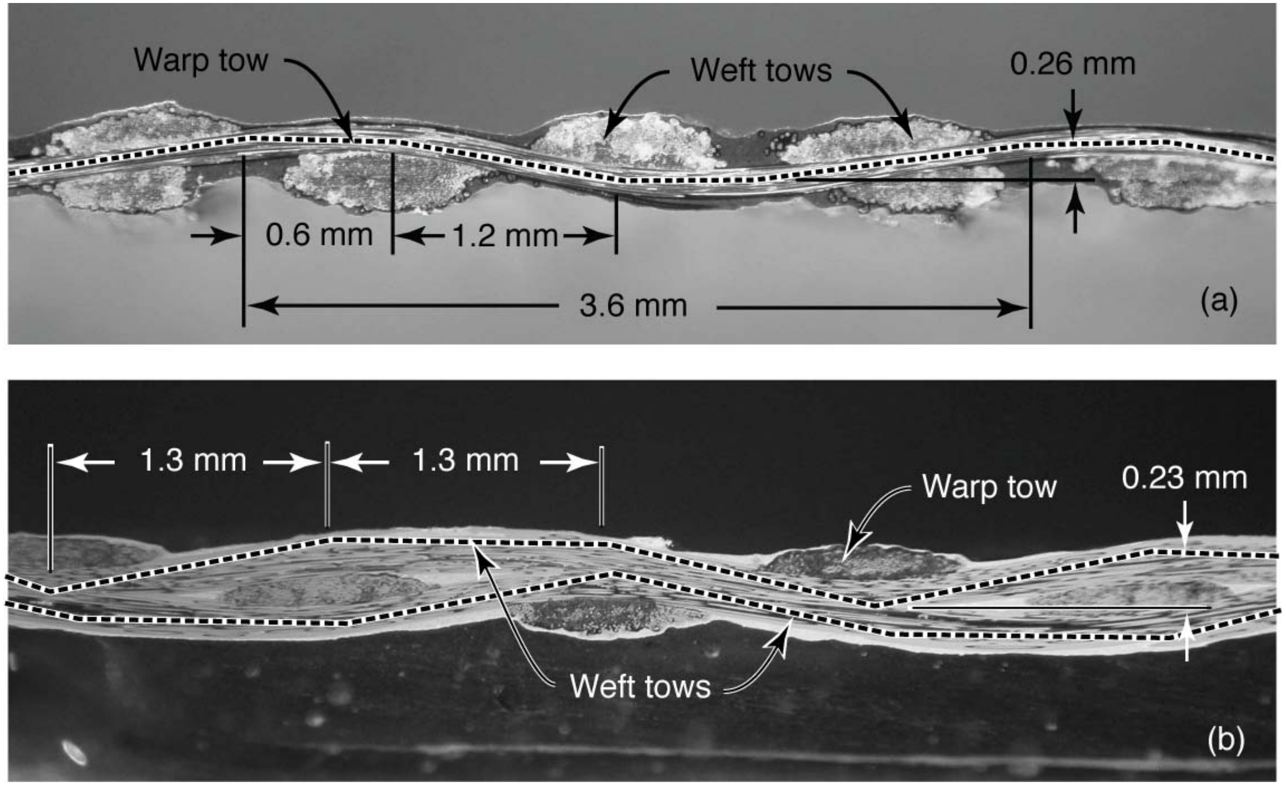
nice in top view



SiC-SiC composite with angle interlock weave for heat exchangers

Flores *et al.*, 2008

not-so-nice in section

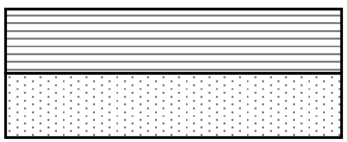


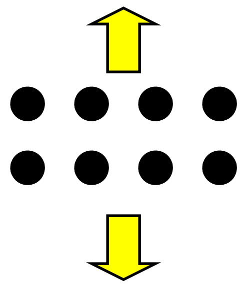
Fiber-Scale Idealizations

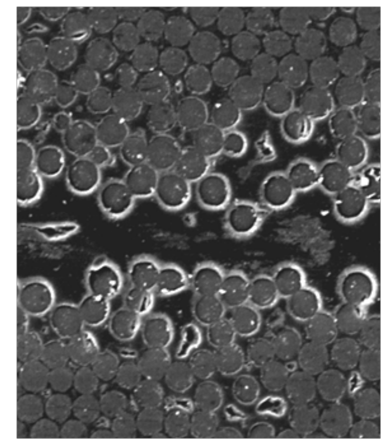
ideal

real

tape laminate

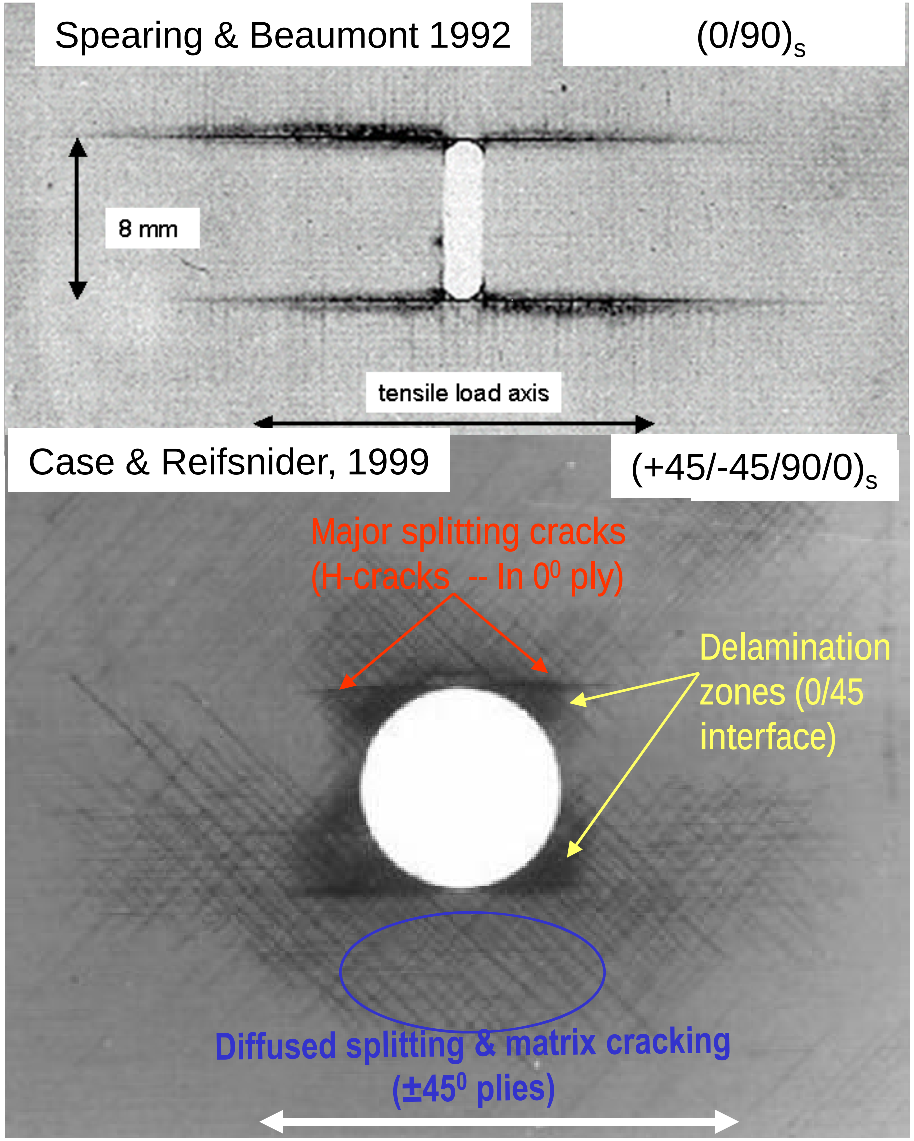






Challenge problem: measure 3D geometrical variance and find mathematical descriptor

Interacting Matrix and Delamination Cracks



- Coupled Multiple Damage modes:

  In-plane modes:
  - matrix cracking in off-axis plies
  - matrix/fiber splitting in aligned plies
  - fiber rupture (in tension)
  - kink band (in compression)

  Out-of-plane mode:
  - inter-ply delamination

- Numerical challenges:
  - coupled in-plane & out-of-plane modes
  - arbitrary nucleation & propagation
  - stochastic laminar/interface properties
  - numerical stability

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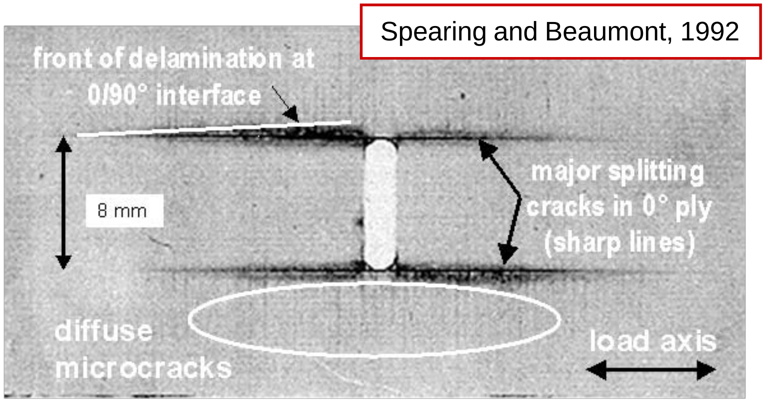
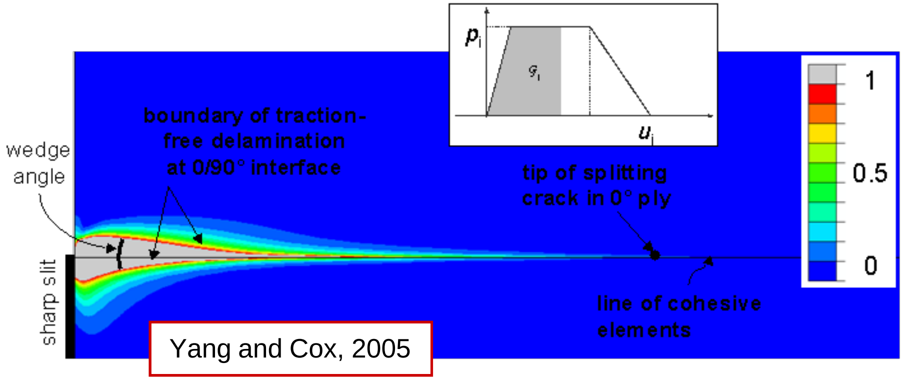
Encouragement for Cohesive Models





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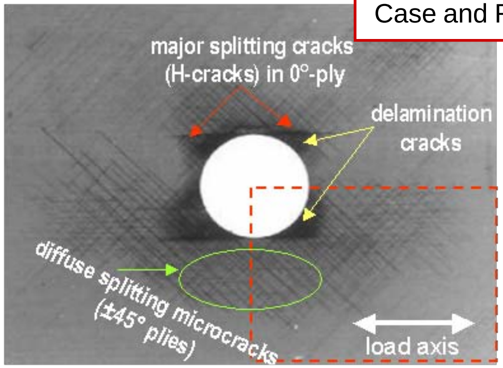
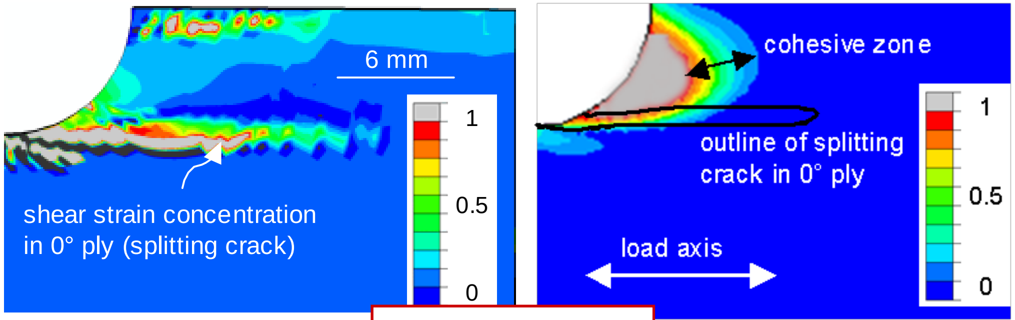
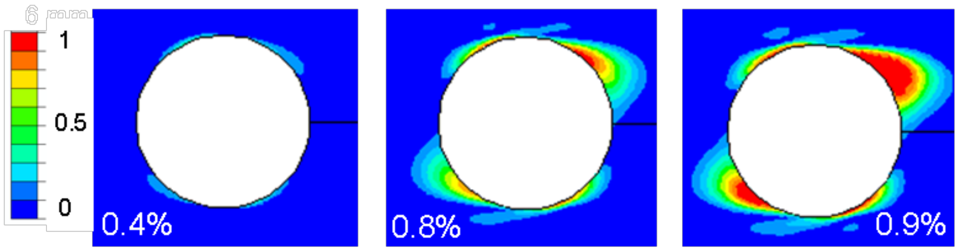
Encouragement for Hybrid Models

Case and Reifsnider, 1999





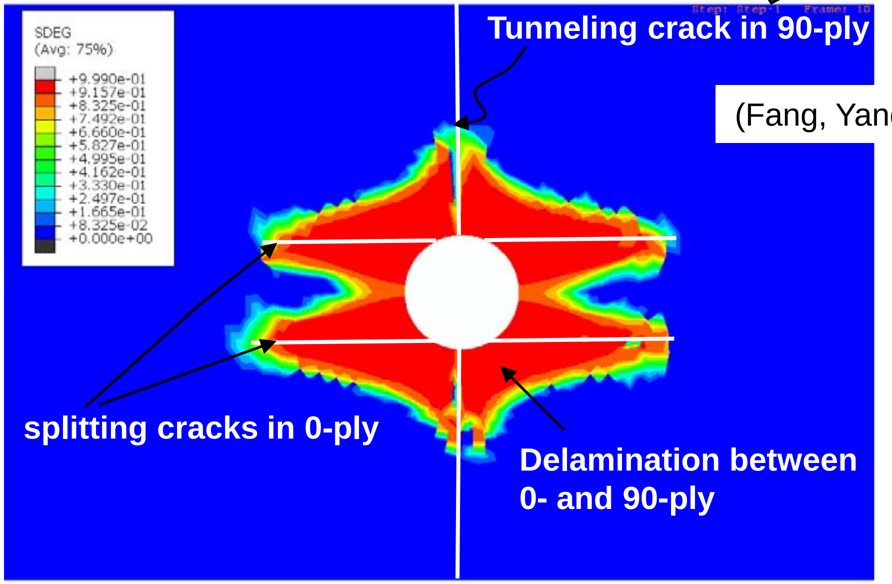
Yang and Cox, 2005



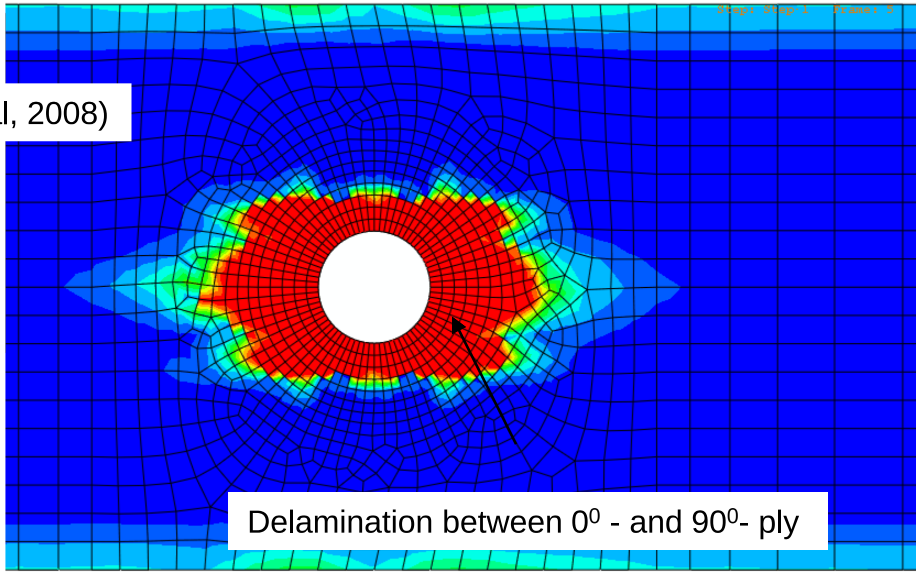
combine
stress/strain $\sigma(\varepsilon)$
+
traction/displacement $\boldsymbol{p}(\boldsymbol{u})$

Need of Matrix Cracking & Delamination Coupling

Delamination in $[0/90]_s$ with and without intra-ply cracks



(Fang, Yang et al, 2008)



- **Intra-ply crack locations unknown *a priori***
- **New computational tools required for:**

-- arbitrary crack nucleation and propagation for matrix cracking

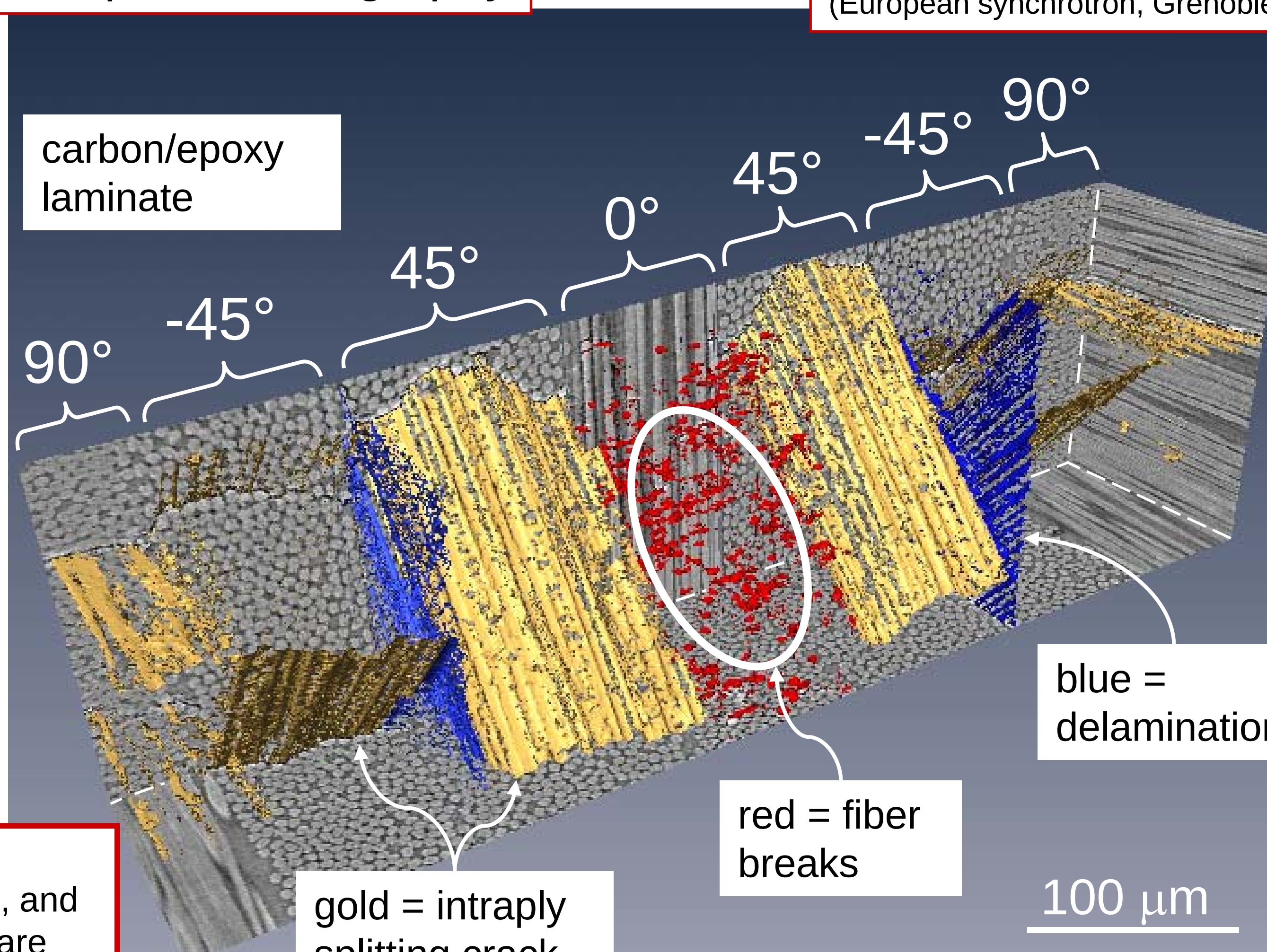
-- direct coupling between delamination and matrix cracking

-- compatible with existing FEM packages (X-FEM not friendly with standard FEM)

Microcracks and Fiber Breaks

X-ray computed tomography

Ian Sinclair, Mark Spearing (2007)
University of Southampton
(European synchrotron, Grenoble)

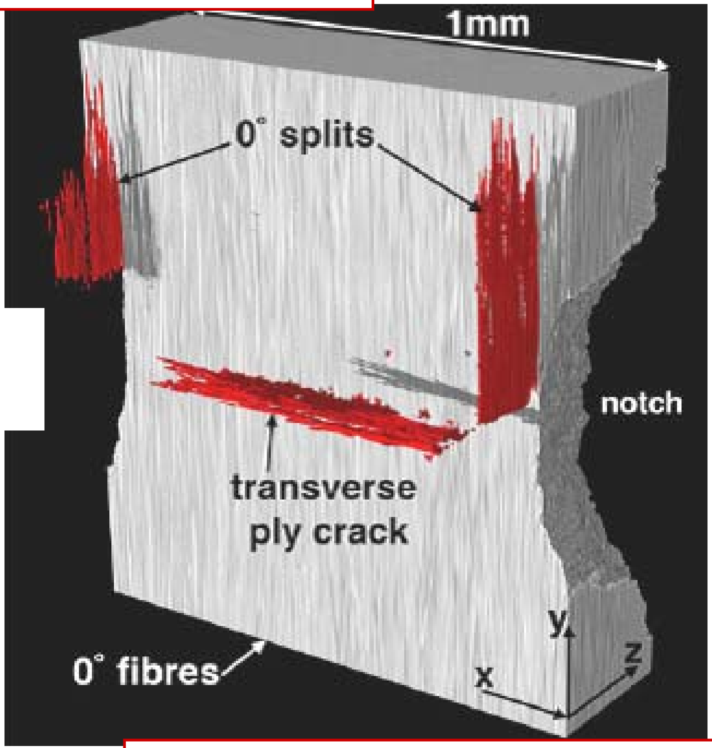


Fiber breaks, splitting cracks, and delaminations are correlated

Transverse and splitting microcracks

X-ray computed tomography

carbon/epoxy laminate



Moffat, Wright, Buffière, Sinclair, and Spearing, 2008

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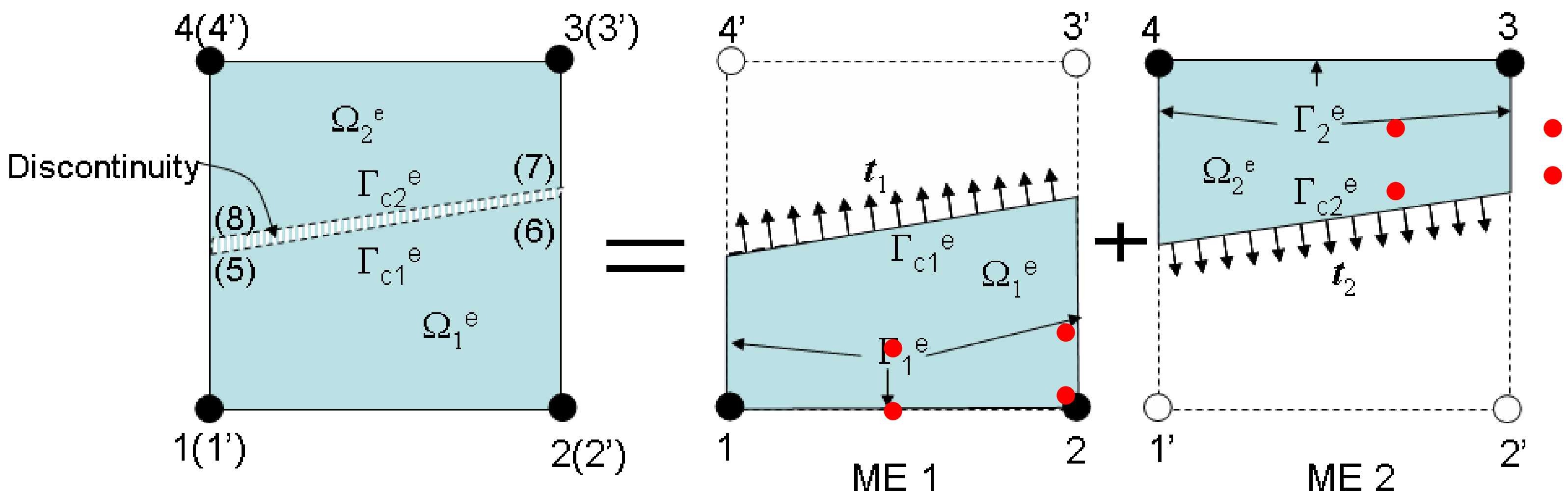
Augmented Finite Element Method (A-FEM)

(Ling, Yang & Cox, 2008)

Related to method first proposed by Hansbo and Hansbo (2005)



Physically discontinuous element (PDE)

Mathematical element 1 (ME1)

Mathematical element 2 (ME2)

Treat discontinuity in:
- material property (heterogeneity)
- displacement (damage band or crack)

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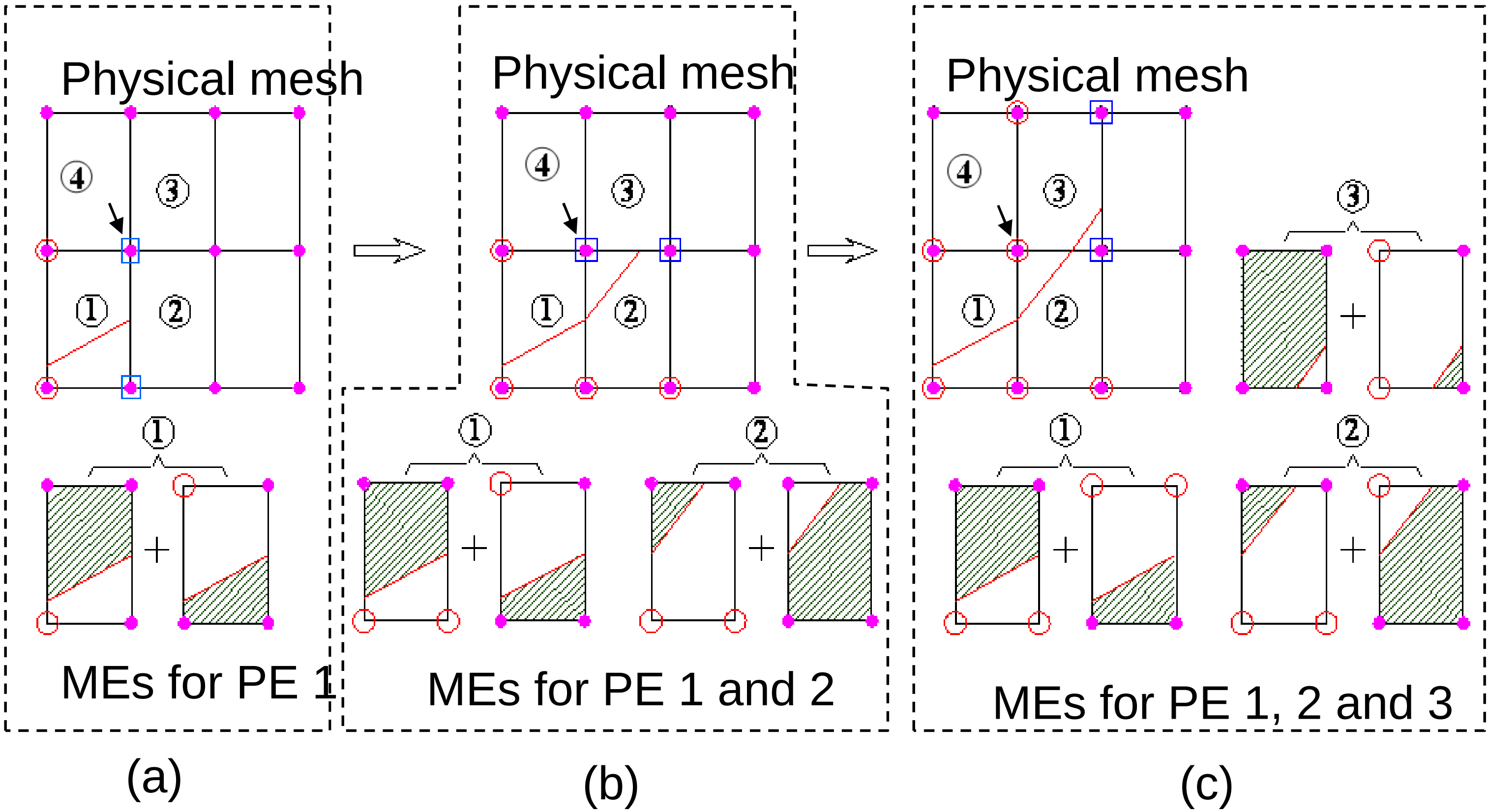
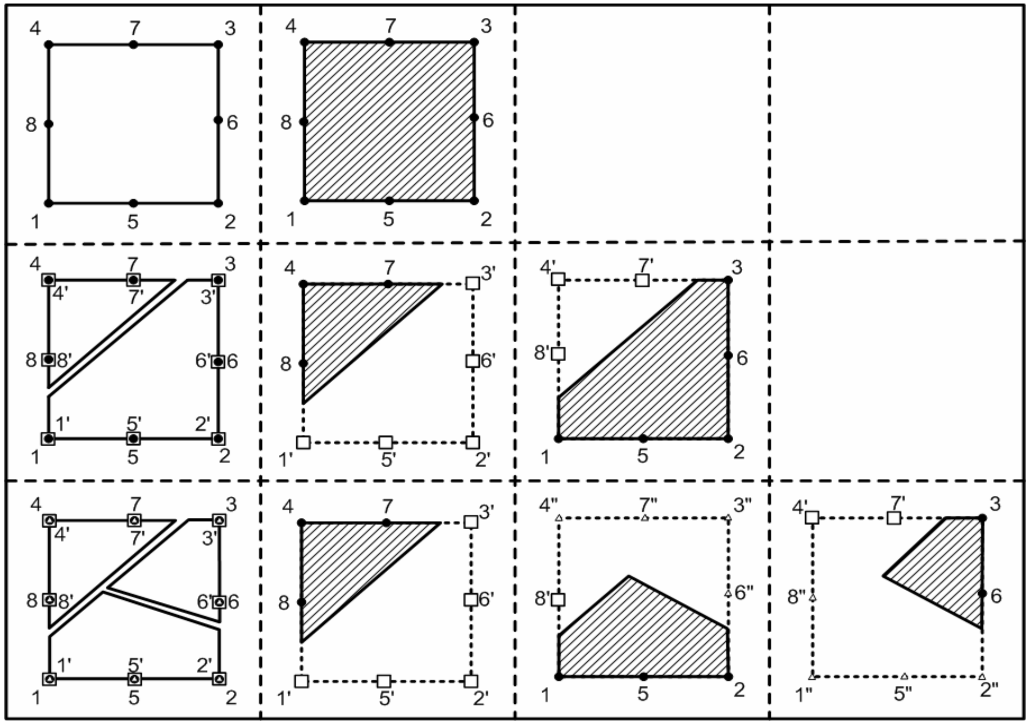
Enforcing Global Continuity of a Crack



Augmentation of element is <u>local</u>: contiguous elements need no modification
$\Rightarrow$ method can be implemented in, e.g., ABAQUS as a User Element

Multiple cracking in a single element



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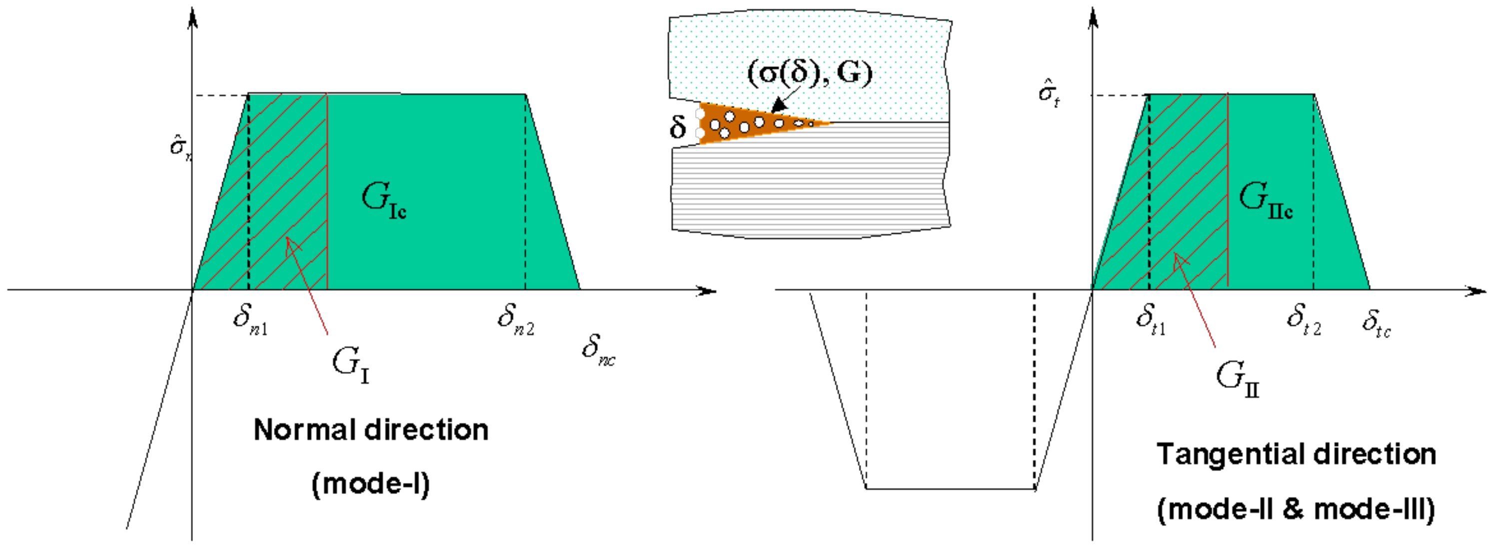
Integration of cohesive zone model into A-FEM

e.g., mode-dependent cohesive law (Yang and Thouless 2001)



Initiation criterion $$\left(\frac{\sigma_{22}}{\hat{\sigma}_n}\right)^2+\left(\frac{\tau_{12}}{\hat{\sigma}_t}\right)^2+\left(\frac{\tau_{13}}{\hat{\sigma}_t}\right)^2=1$$

Propagation criterion $$\frac{G_I}{G_{Ic}}+\frac{G_{II}}{G_{IIc}}+\frac{G_{III}}{G_{IIIc}}=1$$

A-FEM fails an entire element at once
This is OK as long as cohesive zone length is not less than element width

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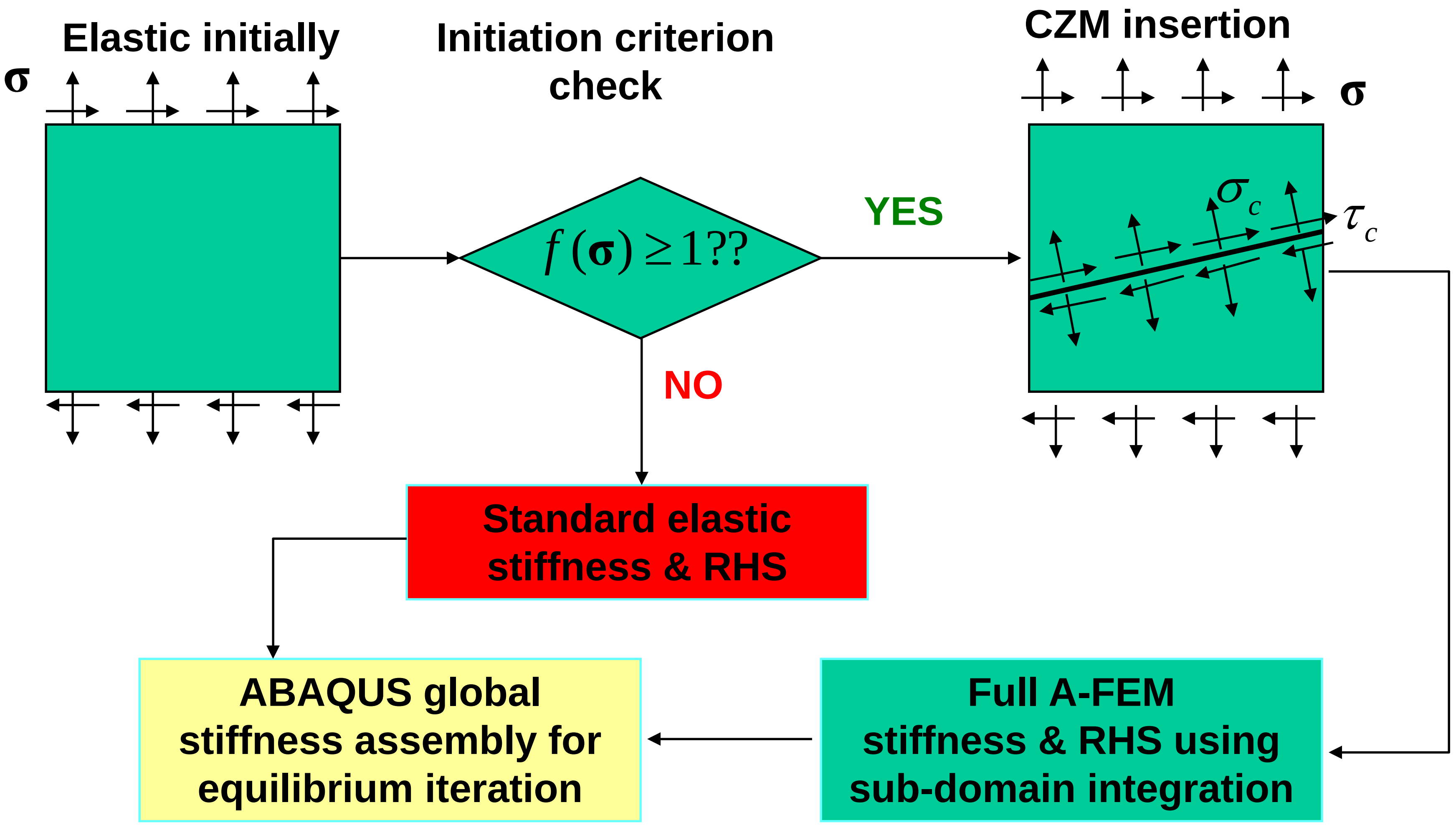
Implementing A-FEM into ABAQUS as a User Element



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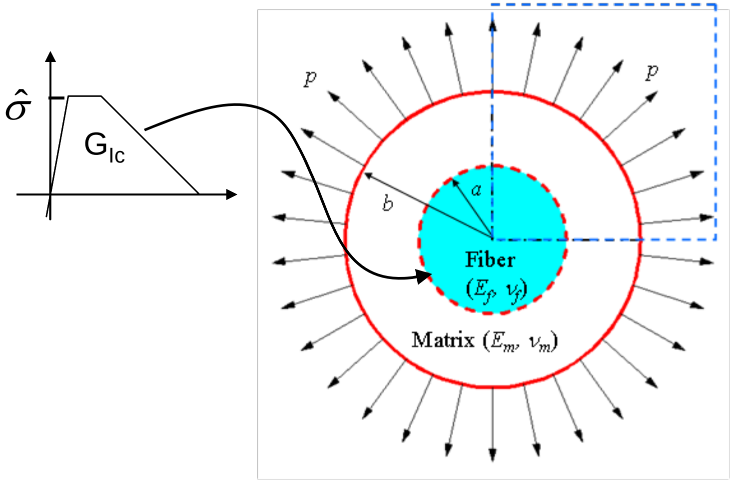
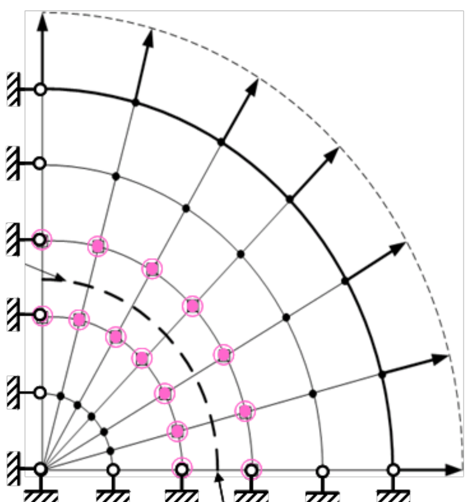
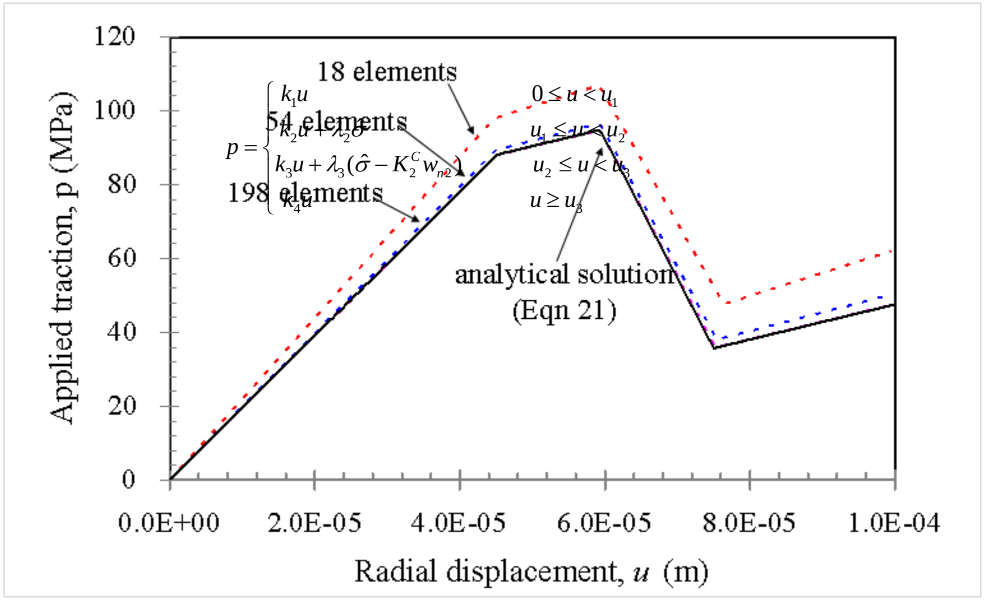
Convergence



Axisymmetric tension of single fiber/matrix



Fiber/matrix interface



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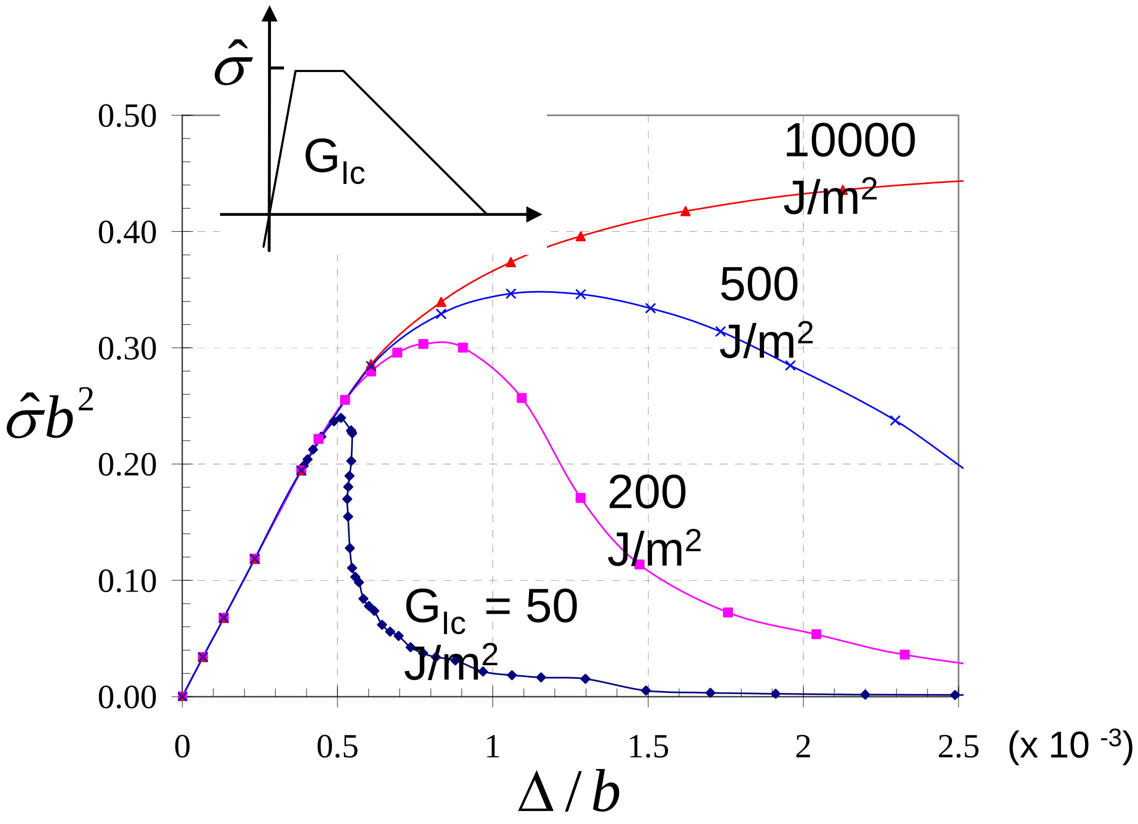
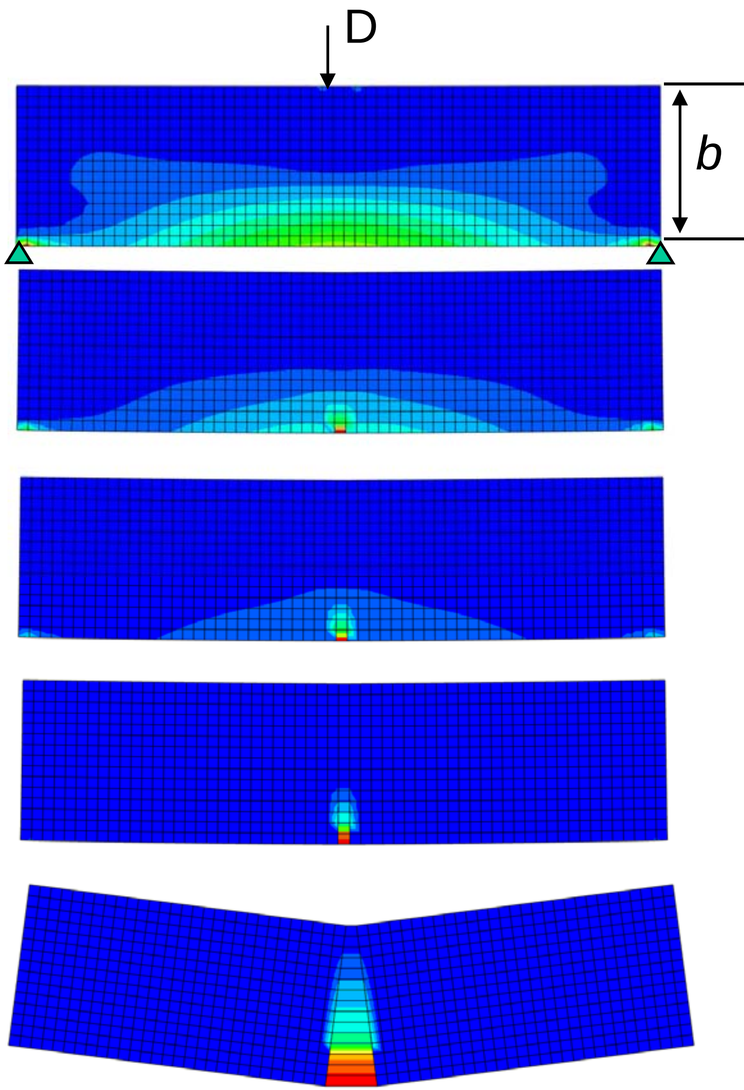
A-FEM Validation 1: Three Point Bending Beam (mode-I)





- **excellent agreement with X-FEM results of Möes and Belytschko 2002**
- **Arc length method in ABAQUS helped capture snap-back behavior**

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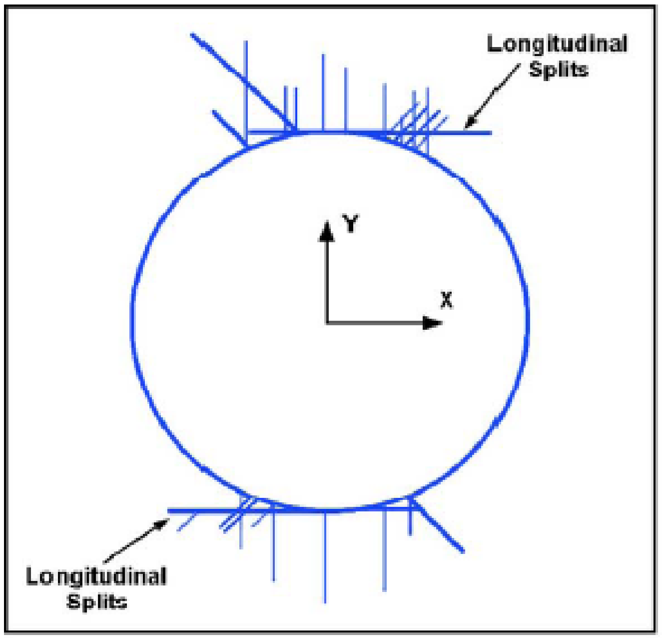
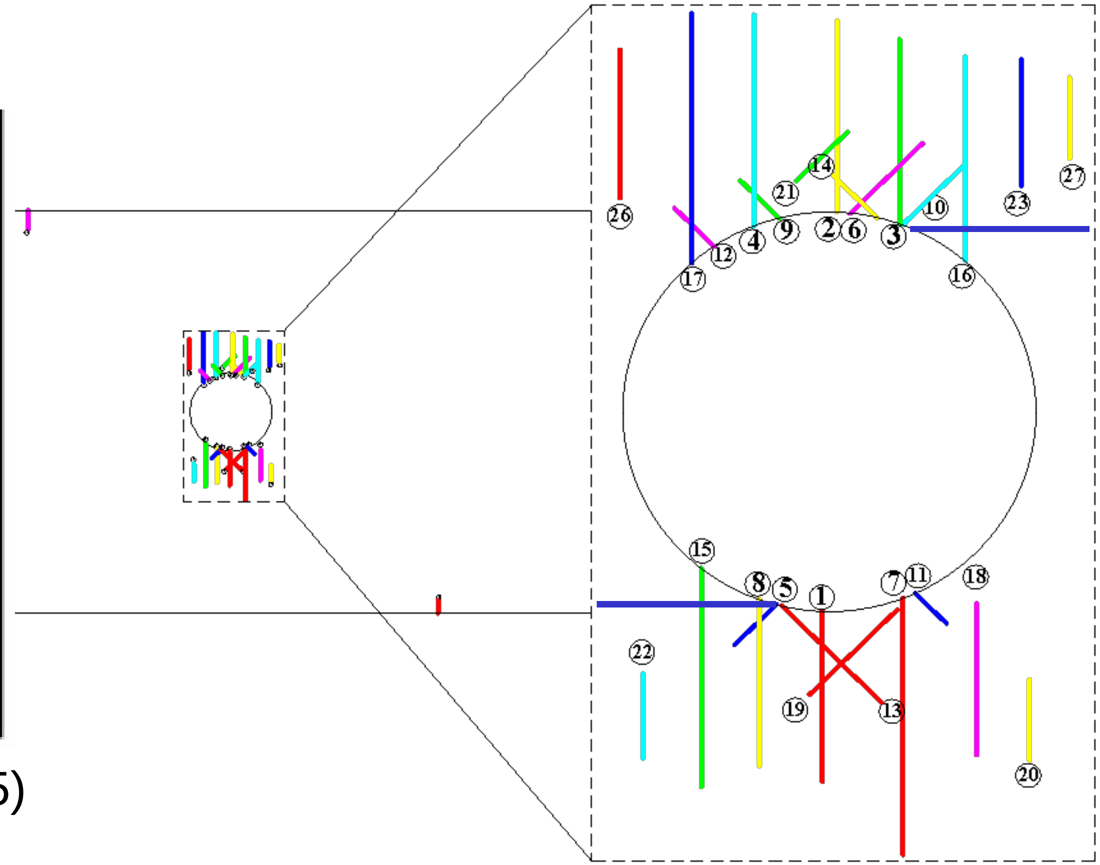
Simulated Arbitrary Cracking in [0/90/+45/-45]$_s$ Laminate

- arbitrary intra-ply matrix crack initiation



C-scan image (Iarve et al., 2005)



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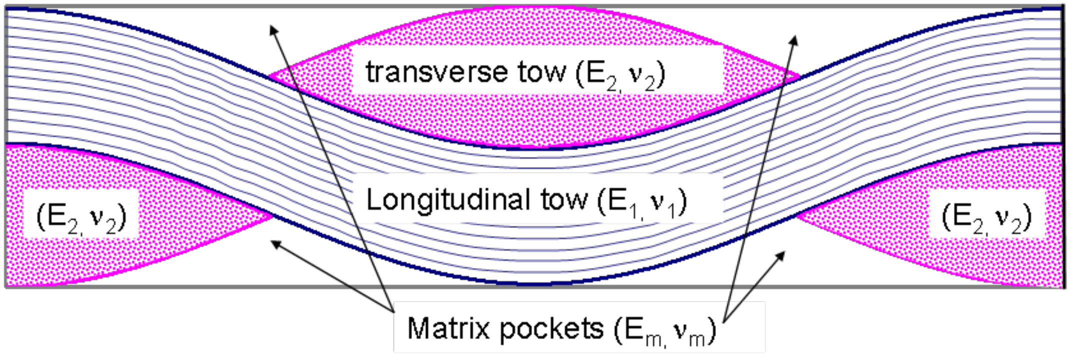
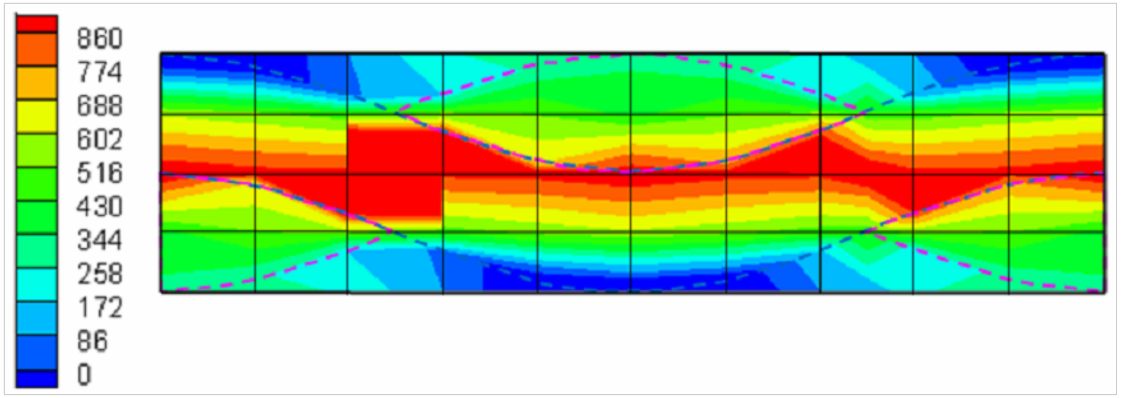
A-FEM for Material Heterogeneity in Textile Composites





A-FEM Features:

- Mesh need not conform to complex material morphology
- Pre-processor traces each material boundary and records element augmentation
- Displacement continuity across material boundary guaranteed by tying ghost DoFs to physical DoFs (no penalty method needed)

Longitudinal modulus check:

A-FEM	(40 elements):	46.1 GPa
ABAQUS	(387 elements):	46.7 GPa
OWAA	(analytic approx.):	45.6 GPa

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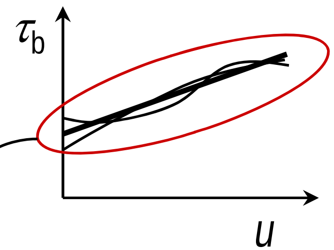
Determining the Traction Law by Fracture Experiments

Mode II example - long cohesive zones due to stitching (Massabò, Mumm, and Cox, 1996)

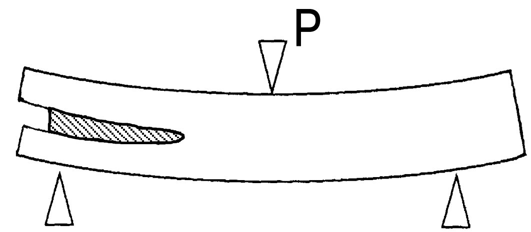
determine information content of experiments from residual uncertainty

traction law:



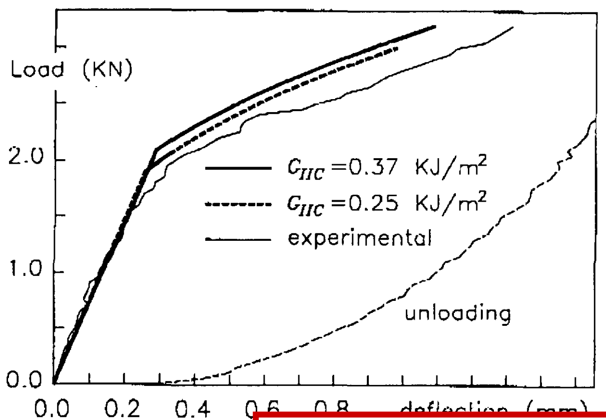
+

load and test configuration:

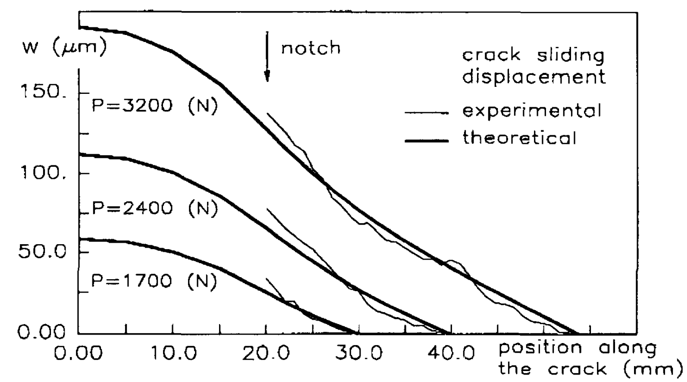


inverse problem maps data onto law via model kernel

load/deflection curves:



crack sliding profiles:



top-down philosophy: if detail in cohesive law cannot be determined from test, it does not matter

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Mixed Mode Cohesive Laws

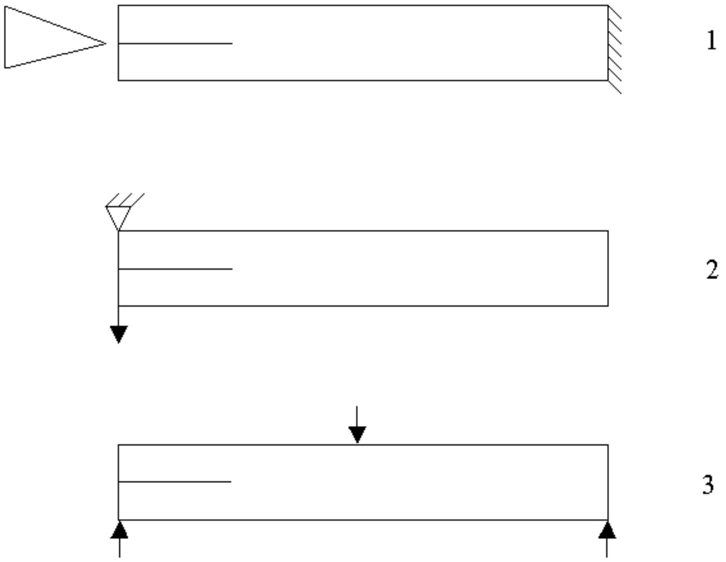
Length scales:

Polymer craze zone: 0.3 - 1.0 mm

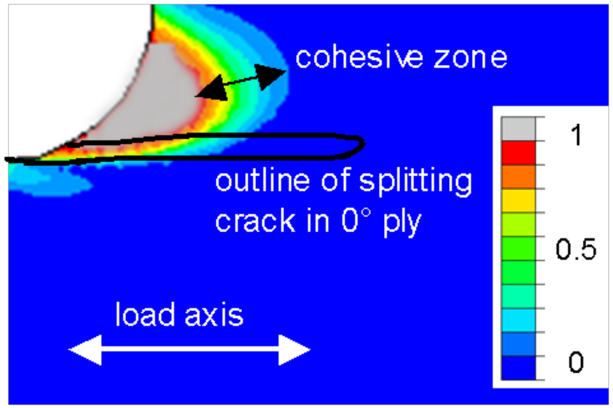
Fiber bridging zone: 0 ~ 2.5 mm

Stitches/pins: 10 - 100 mm

Candidate mixed-mode tests



Most challenging problem:
Can we measure displacements
- across a delamination front?
- at edge initiation?

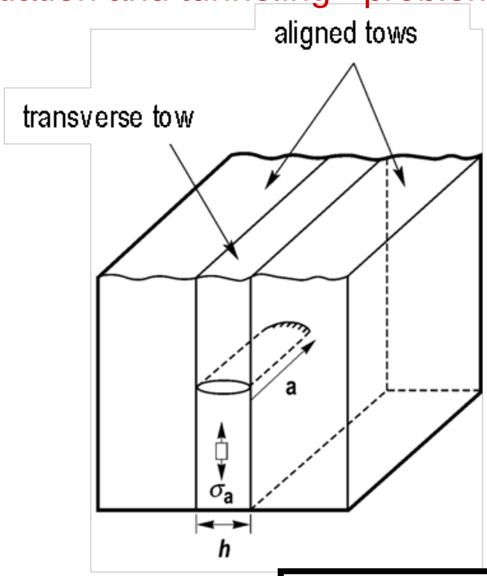


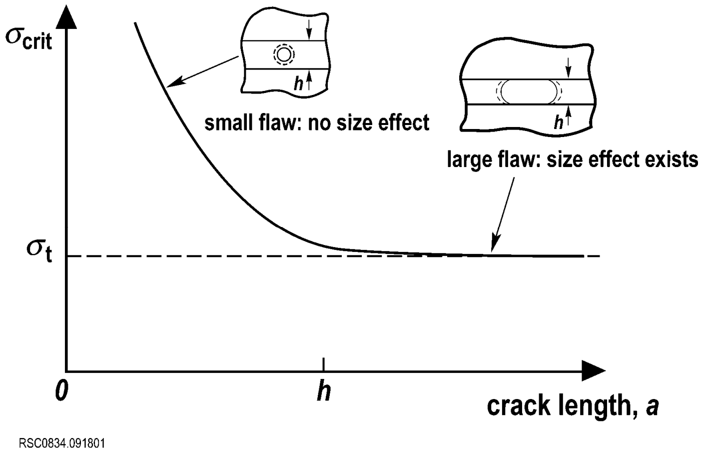
***u*(*x*)**:	X-ray CT with image correlation
zone width:	X-radiography ultrasound

How much information is in variation of width of the cohesive zone around crack front?

The Challenge of Microcrack Initiation

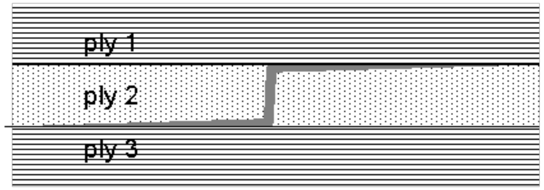
Initiation and tunneling - problems in 3D





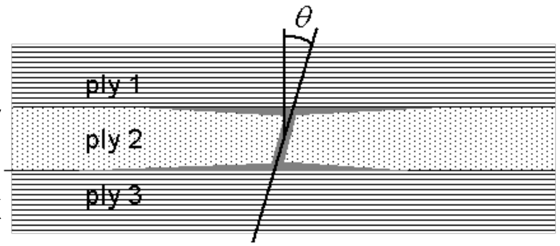
Calibration and validation – can we see such details experimentally!?

Microcrack-delamination interactions - problems in 3D



delamination switches plane via microcrack

delaminations triggered by transverse microcrack



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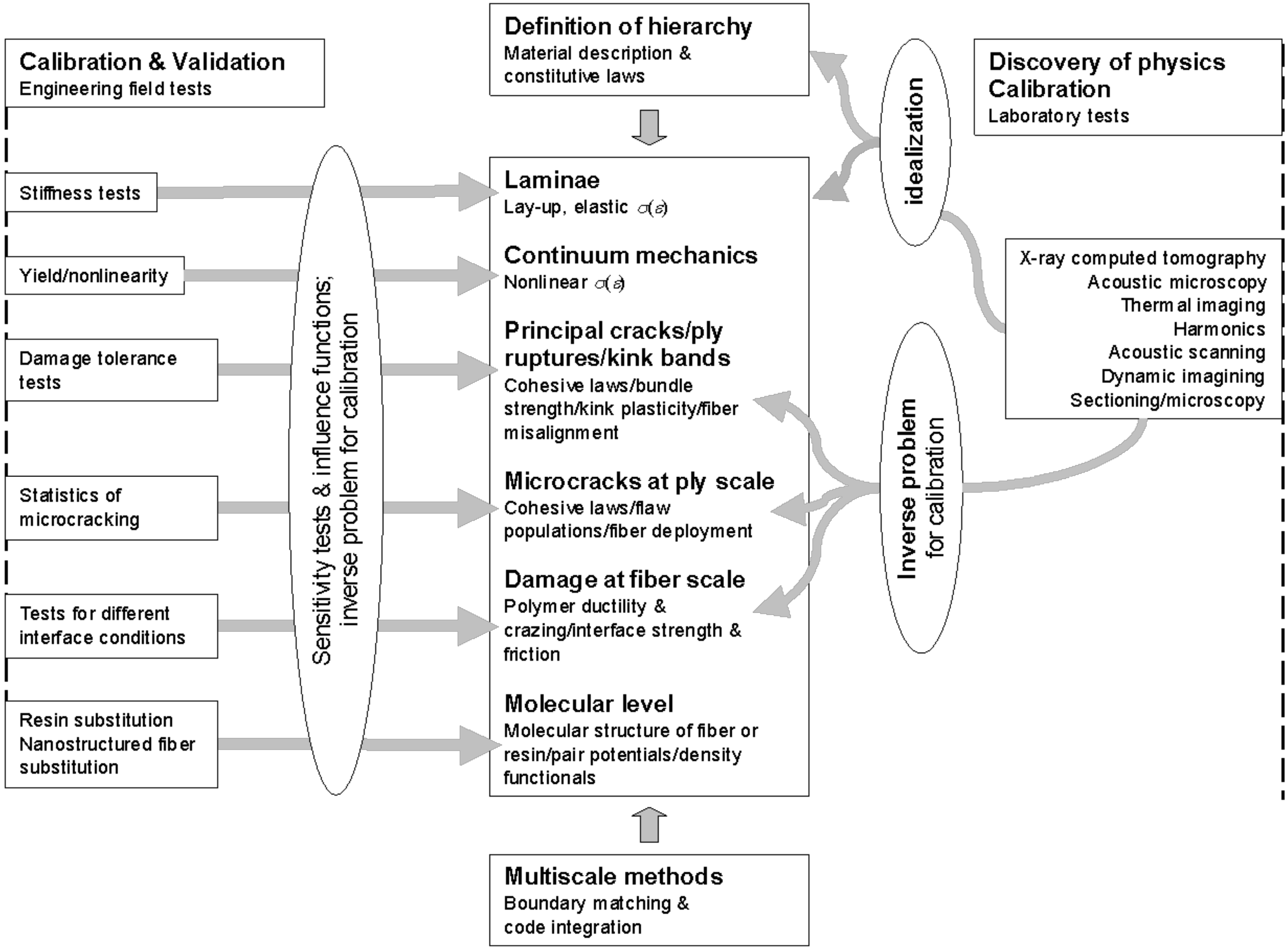
Setting Up and Executing a Virtual Test

It's not just a simulation!

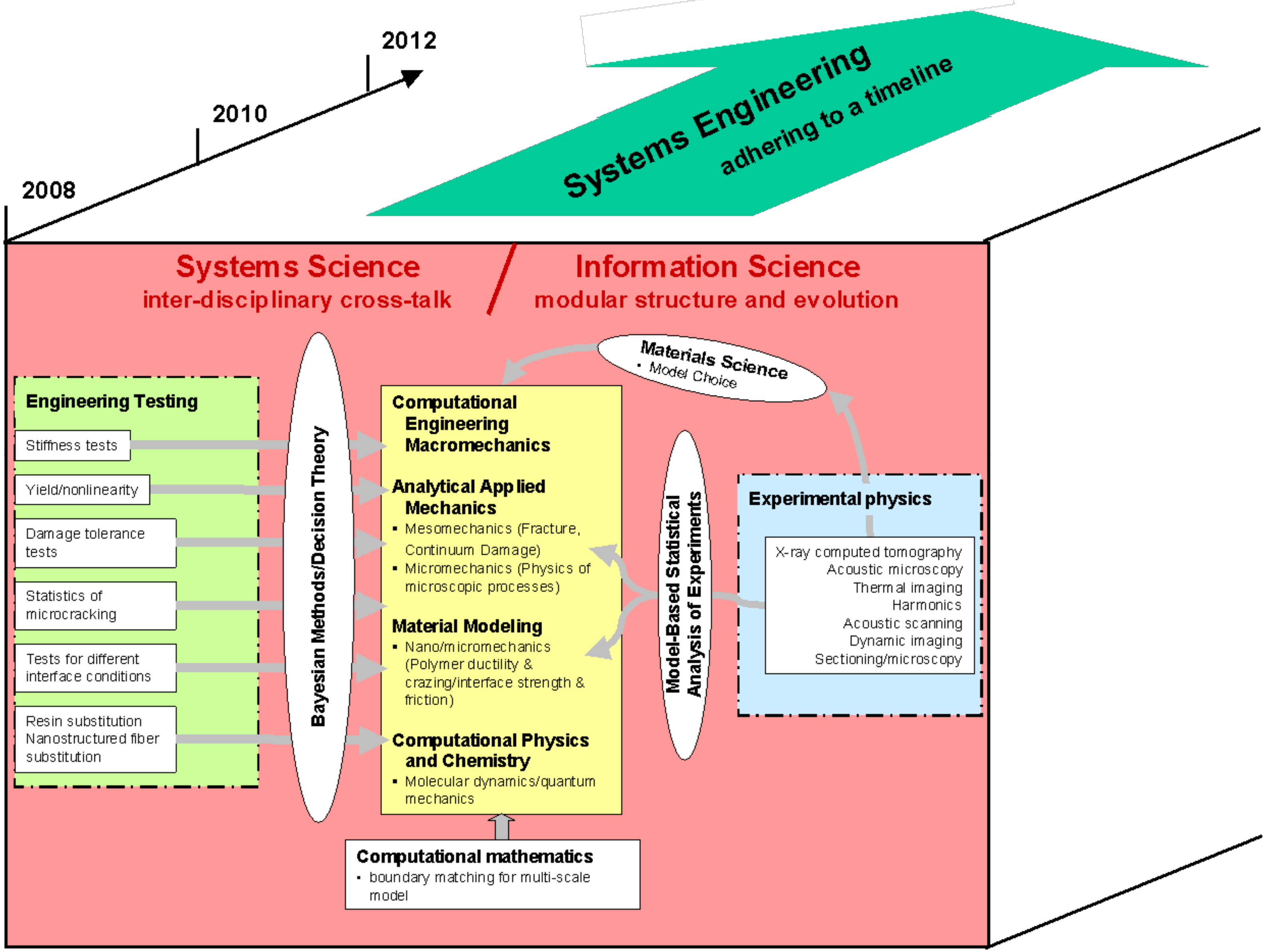
Essential steps:

1. Measure geometry of composite material
2. Generate idealized model of geometry
3. Observe mechanisms that matter
4. Formulate idealized models of mechanisms
5. Calibrate mechanism models by model-based analysis of experiments
6. Validate virtual test against test data
7. Vary geometry or material in model

The Structure of a Virtual Test



The Disciplines of a Virtual Test



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Summary Remarks

- A virtual test is a multi-disciplinary system
- Experimental challenges are at least as great as modeling challenges
- Model-based analysis of experiments (for calibration/validation) requires new development
- Decision theory/mathematical statistics/information science will bind it all together