AF-Shell:

AN ENRICHED FINITE ELEMENT FOR EFFICIENT DAMAGE SIMULATION IN COMPOSITE LAMINATES

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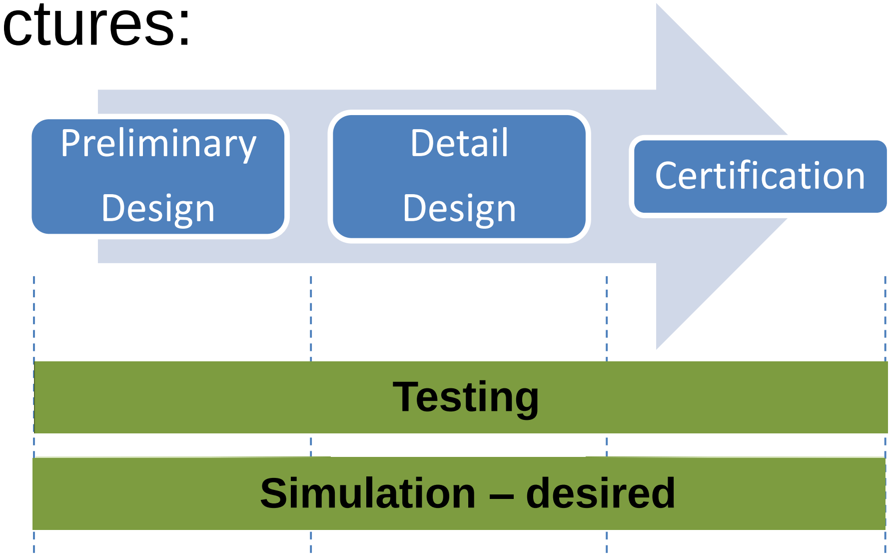
Contents

Motivation and Approach

Design and certification process for composite aerospace structures:

- ➢ Heavily reliant on tests
- ➢ Expensive
- ➢ Simulation tools may reduce the need for some testing



Preliminary Design

Detail Design

Certification

Testing

Simulation – desired

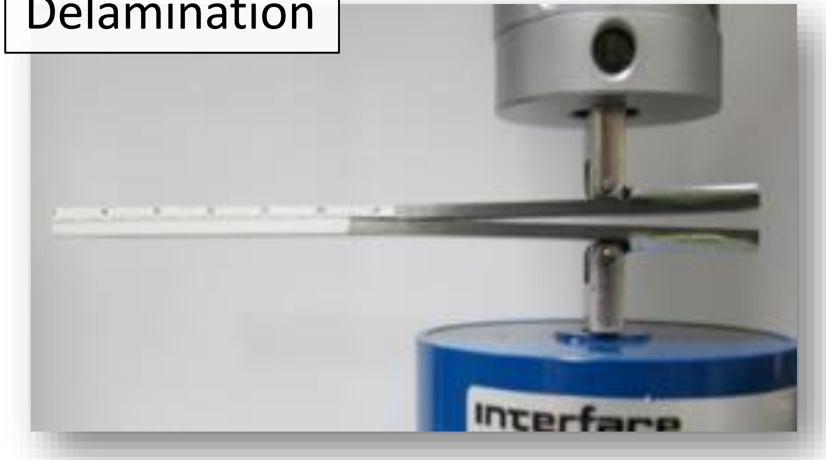
Approach: Enriched shell element model for progressive damage simulation

- ➢ Adaptive Fidelity Shell (AFS)
- ➢ Computationally efficient
- ➢ Rapid design tool

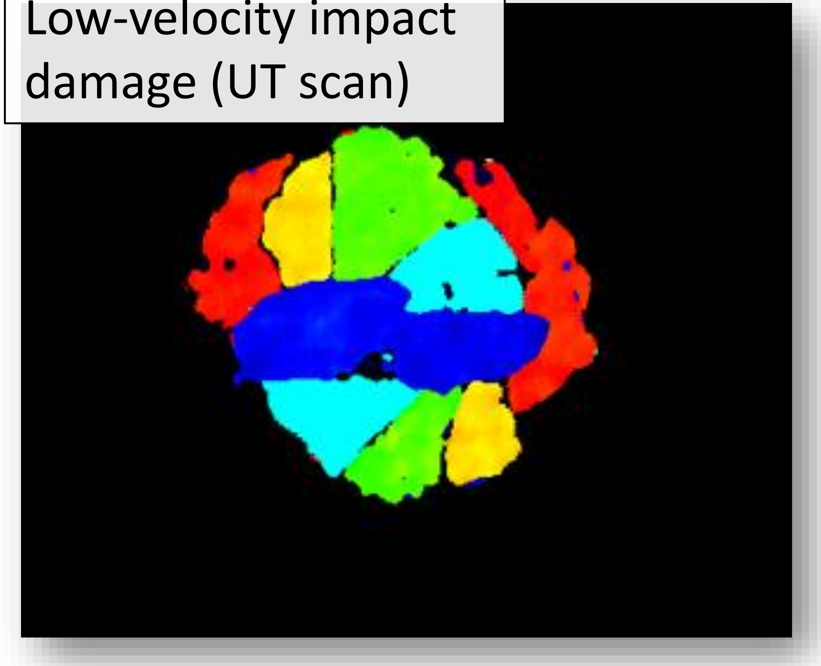
Motivation and Approach

Progressive damage in composite laminates:

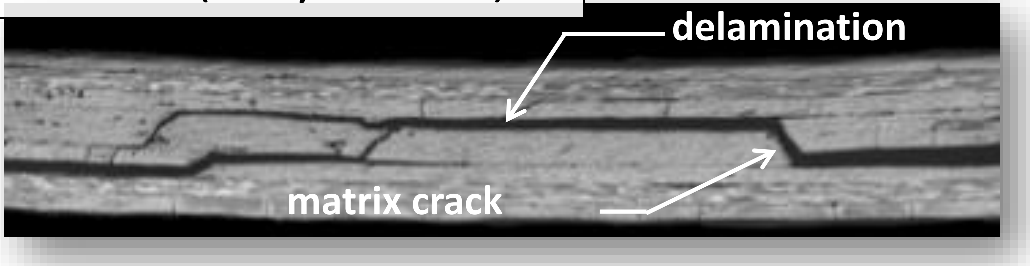
Delamination



Low-velocity impact damage (UT scan)



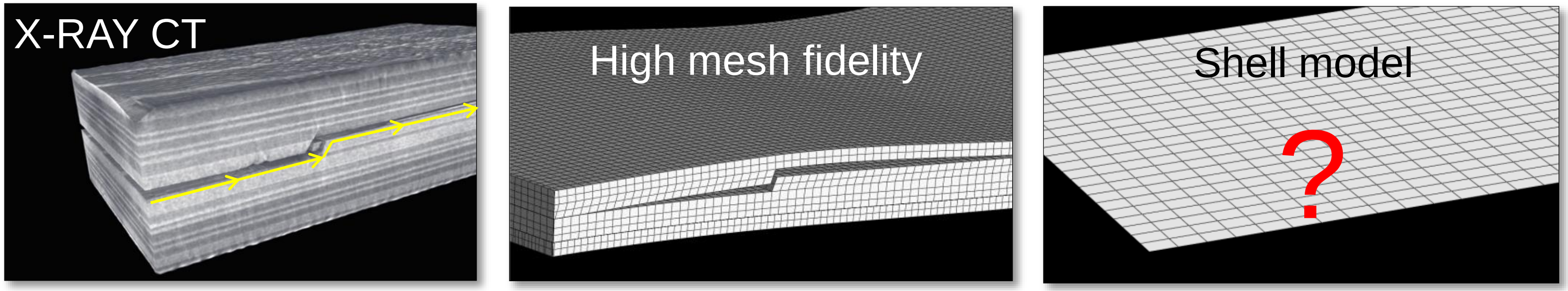
Delamination-matrix crack interaction (X ray CT scan)



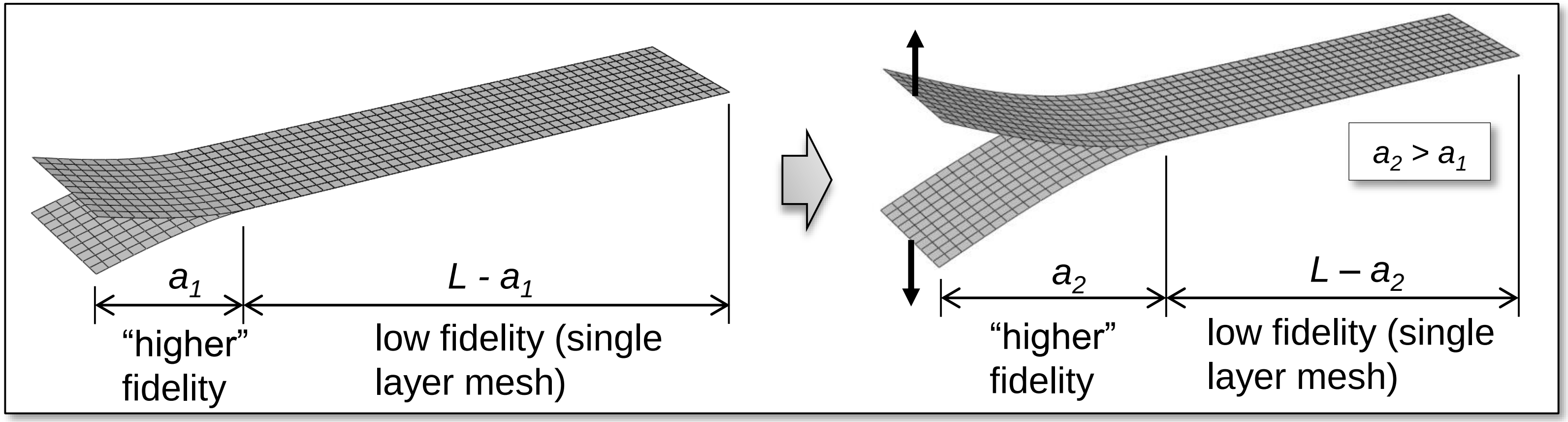
Model Overview

- Computationally efficient & user friendly → shell method requires fundamentally new approach

- Progressive damage simulation: delamination-matrix crack interaction



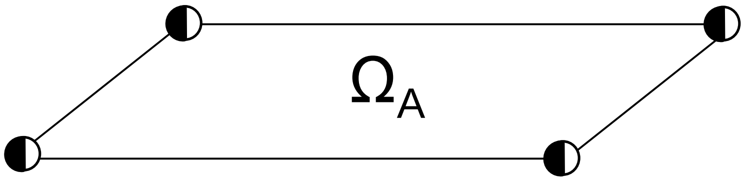
- Adaptive fidelity



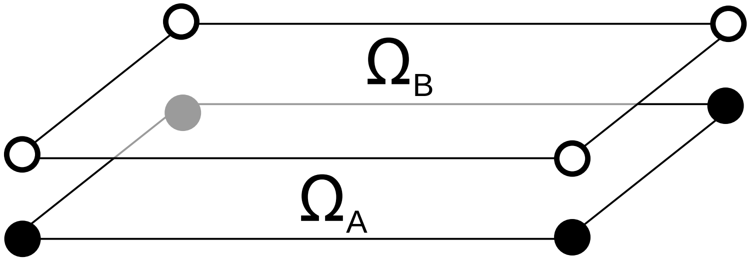
Model Overview: Floating Node Method*

Shell element enrichment to allow adaptive mesh fidelity

Undamaged Element



Split Element



$$K^{(e)} = \begin{bmatrix} \left[K_{\Omega_A}^{(e)}\right]_{24x24} & [0] \\ [0] & [0]_{24x24} \end{bmatrix}_{48x48}$$

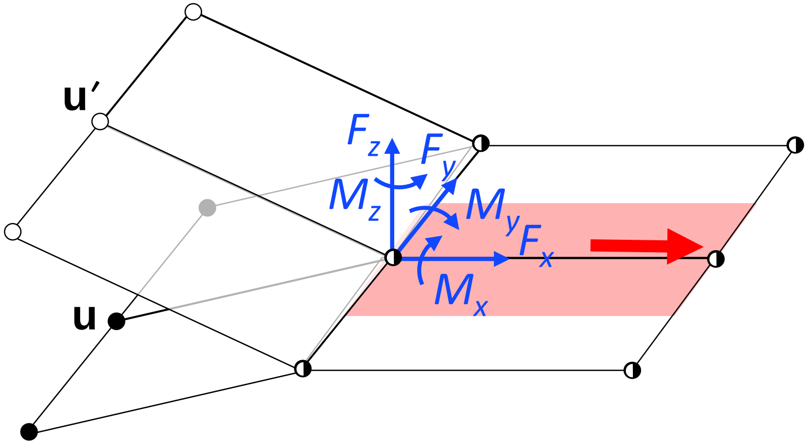
$$K^{(e)} = \begin{bmatrix} \left[K_{\Omega_A}^{(e)}\right]_{24x24} & [0] \\ [0] & \left[K_{\Omega_B}^{(e)}\right]_{24x24} \end{bmatrix}_{48x48}$$

○ = floating node (FN) ● = real node (RN) ◐ = RN and unused FN

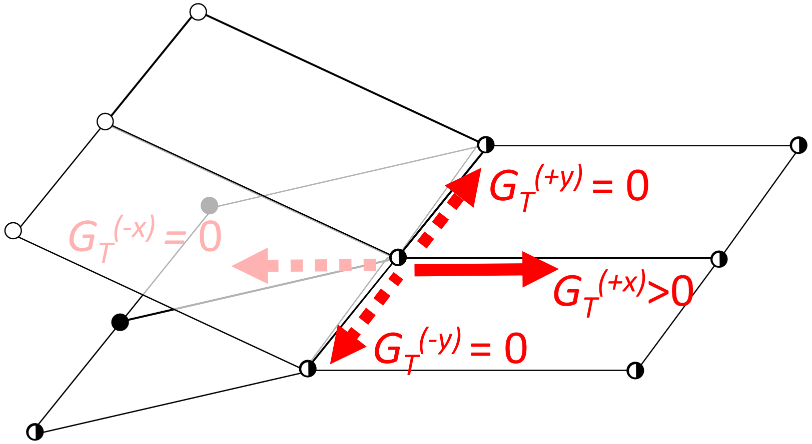
*Chen, B.Y., Pinho, S.T., De Carvalho N.V., Baiz, P.M., Tay, T.E. 2014. "A Floating Node Method for the Modelling of Discontinuities in Composites," *Engineering Fracture Mechanics* 127:104-134.

Model Overview: Delamination Propagation

Virtual Crack Closure Technique (VCCT)



VCCT in AFS model: G_T calculated for delamination growth in 4 directions

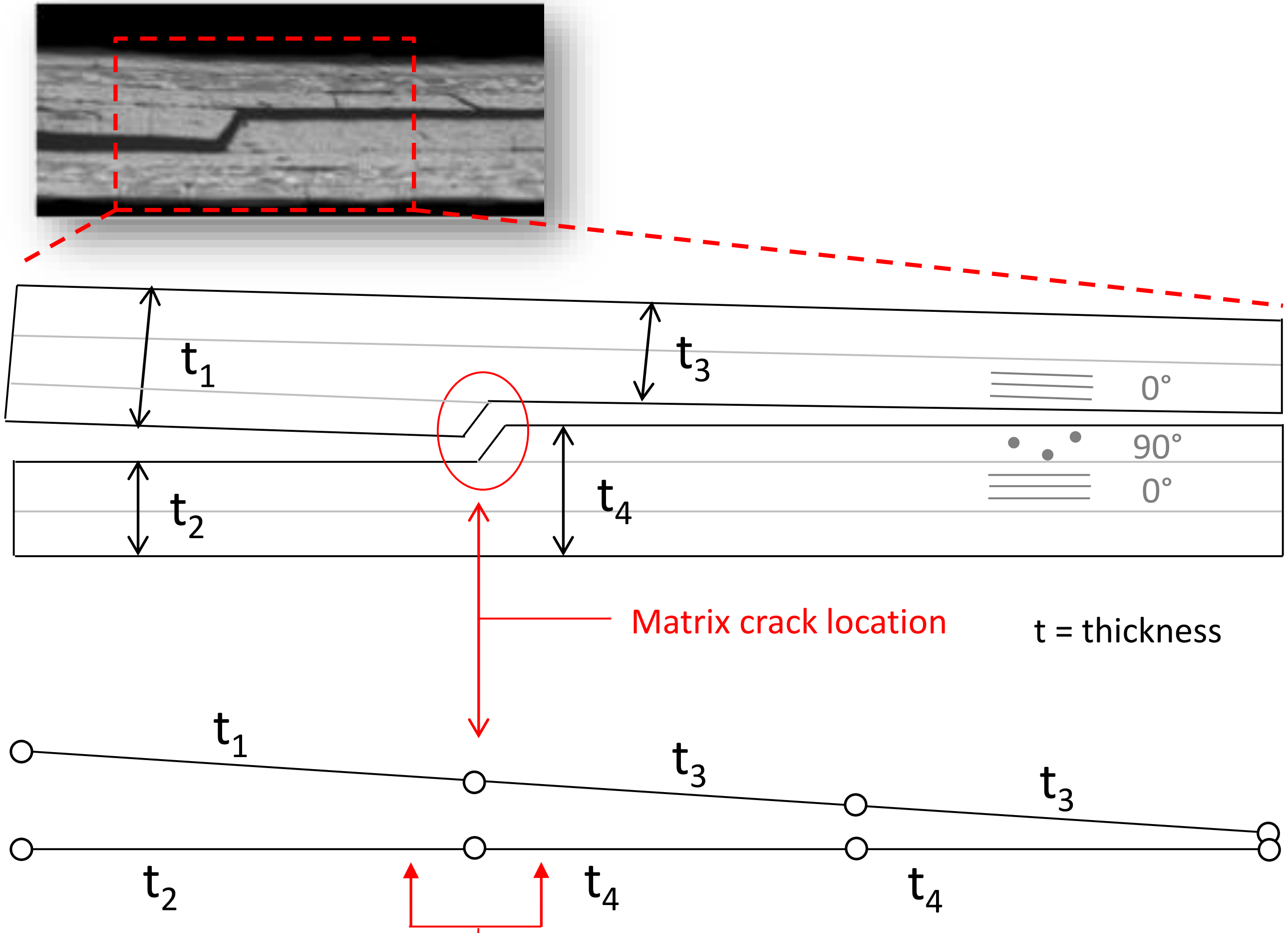


○ = floating node (FN)
● = real node (RN)
◑ = coincident RN and FN
🟥 = change in delamination area if tie is released (ΔA)
→ = growth direction

If $G_T > G_c$ in any direction, tie is released

Model Overview: Transverse Cracks

Representing transverse cracks: delamination-migration



Physical schematic

Matrix crack location

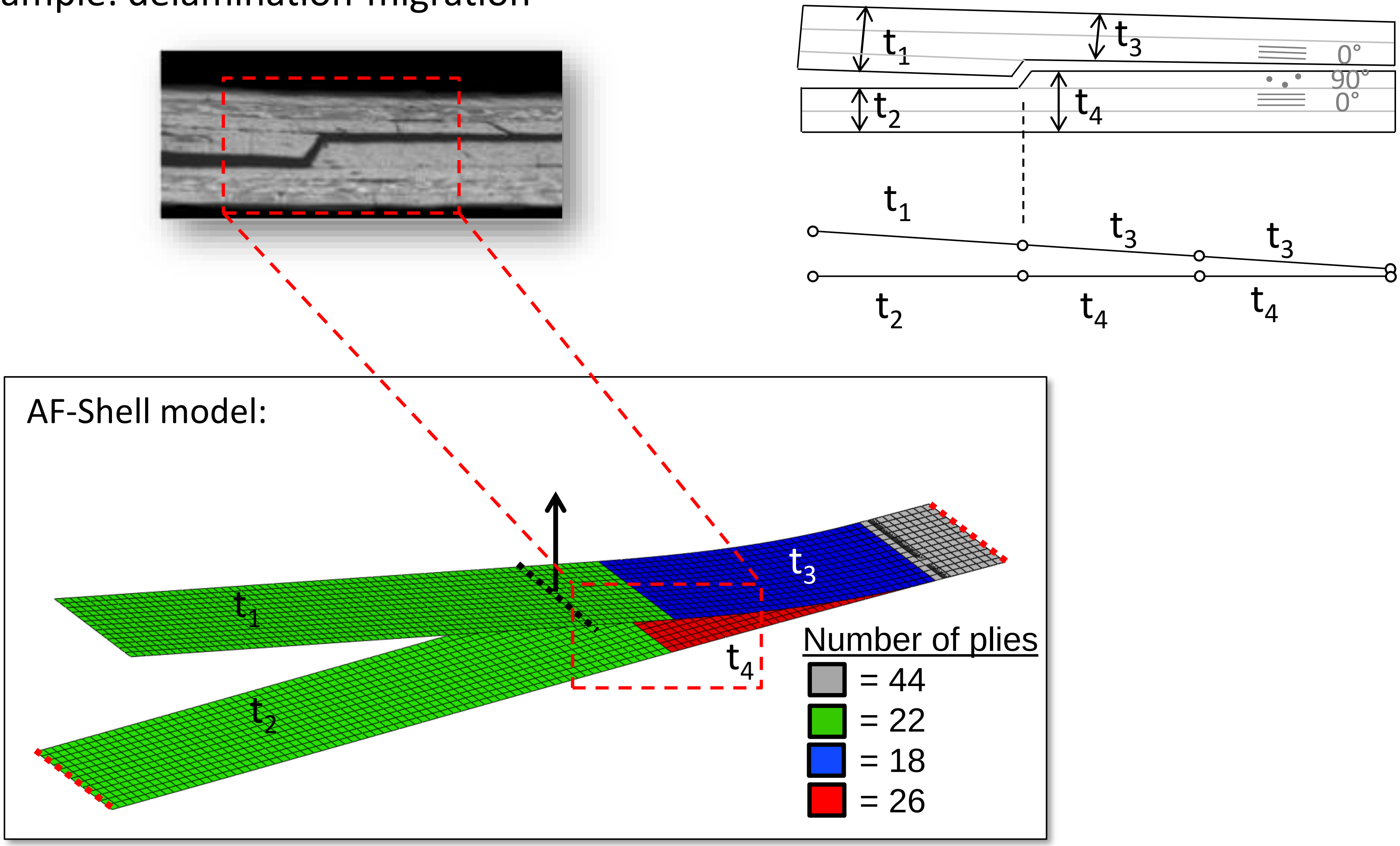
t = thickness

Enriched shell element (side view)

Matrix crack represented as a *stiffness discontinuity* in the model

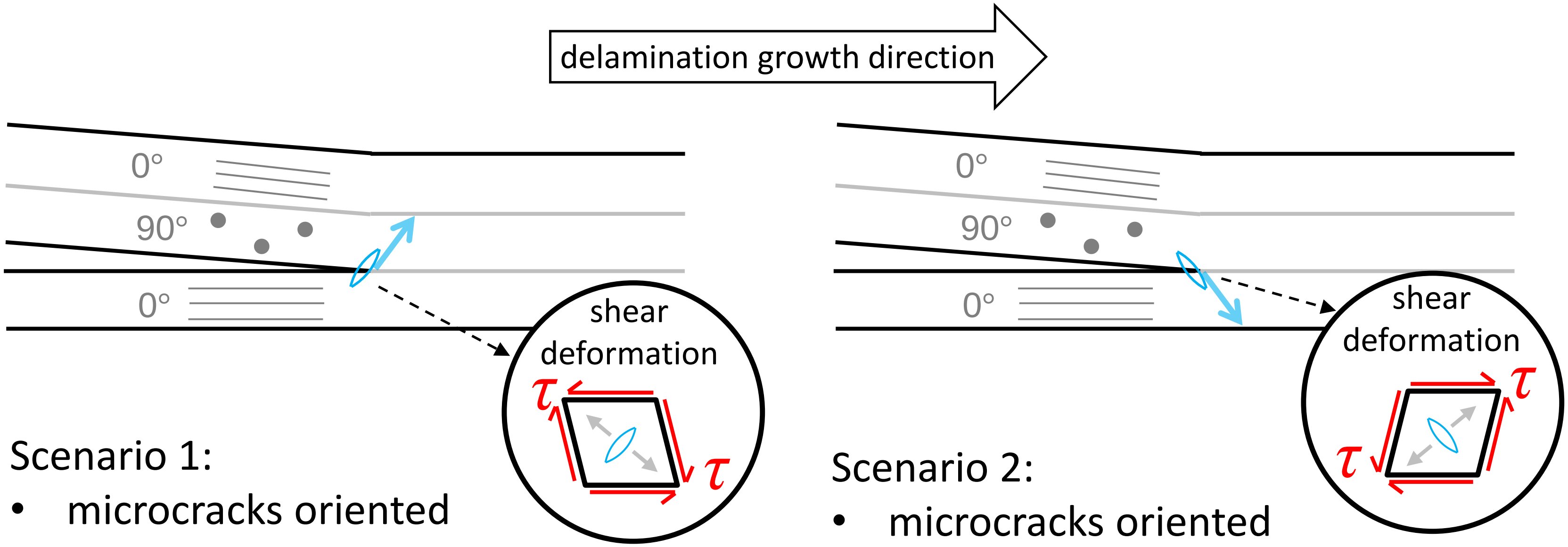
Model Overview: Transverse Cracks

Example: delamination-migration



Predicting Transverse Cracks

Step I: Use shear sign to determine transverse delamination growth tendency



Scenario 1:

- microcracks oriented to guide delamination towards fibers *above*

Scenario 2:

- microcracks oriented to guide delamination towards fibers *below*

↗ = transverse delamination growth tendency

⬭ = microcracks preceding delamination

Predicting Transverse Cracks

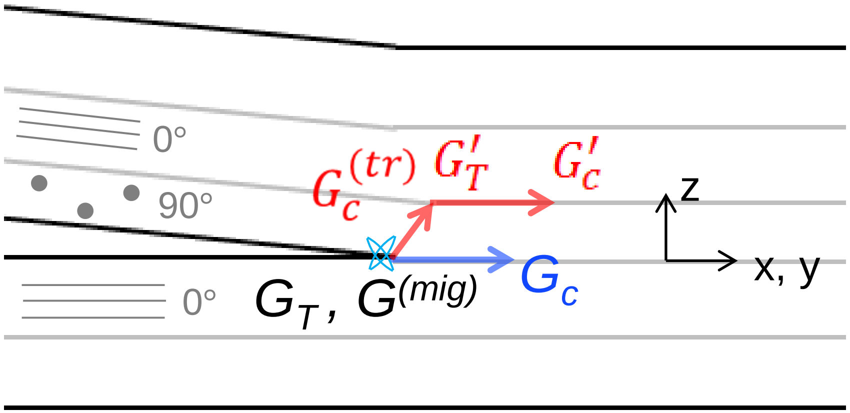
Step II: Energy criterion

Three possibilities:

$$G_T < G_c \rightarrow \text{No growth}$$

$$\left.\begin{array}{c} G_T > G_c \\ \& \\ G^{(mig)} < G_c^{(tr)} \end{array}\right\} \rightarrow \text{Delamination, no migration}$$

$$\left.\begin{array}{c} G_T > G_c \\ \& \\ G^{(mig)} > G_c^{(tr)} \end{array}\right\} \rightarrow \text{Delamination \& migration}$$



$$G_c^{(90^\circ)} = G_{Ic}^{(matrix)}$$

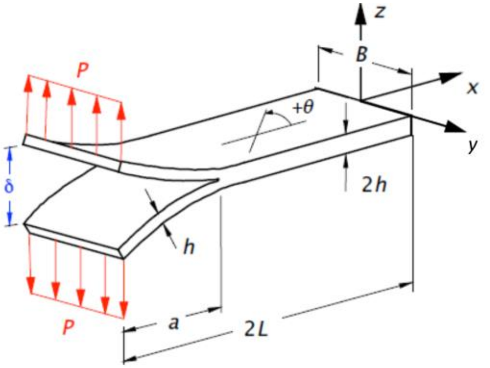
$$G_c^{(0^\circ)} = \infty$$

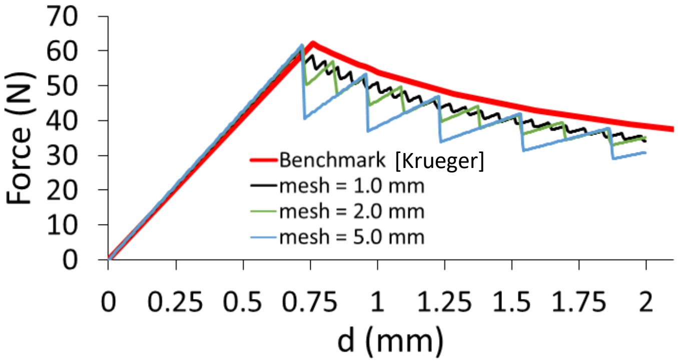
$$\boxed{G^{(mig)} = ?}$$

$$\text{Assumptions}\left\{\begin{array}{l} G'_T \cong G_T \\ \\ \Delta U_{mig} \ll \Delta U_{delam} \end{array}\right.$$

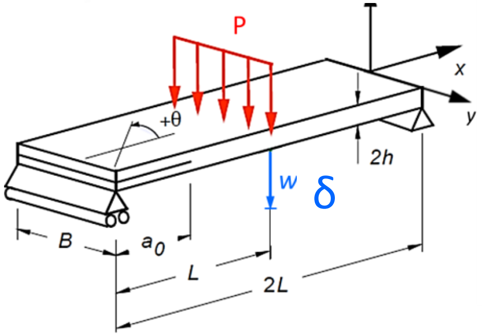
Verification and Validation

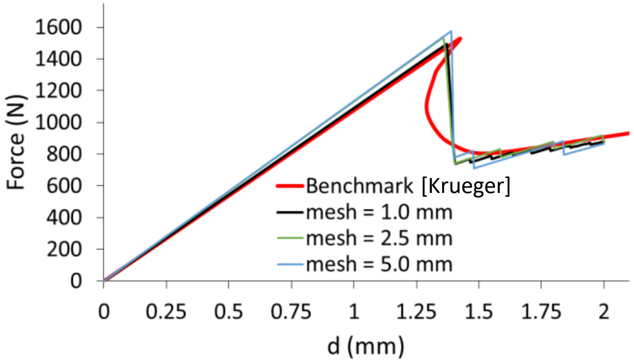
Double Cantilever Beam (Mode I)



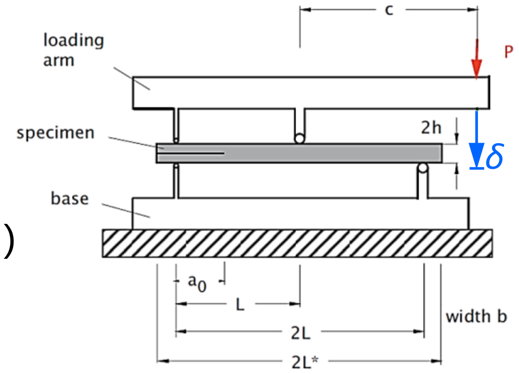


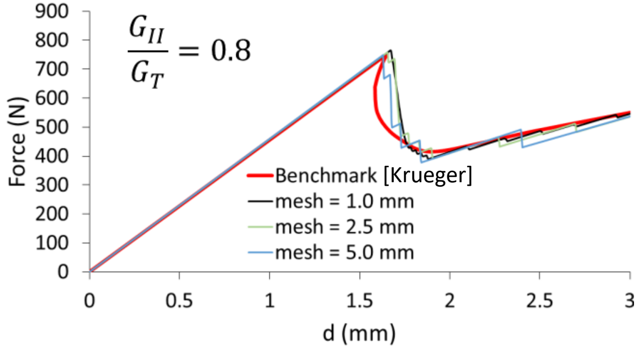
End Notch Flexure (Mode II)





Mixed-mode Bending (Mixed-mode I/II)

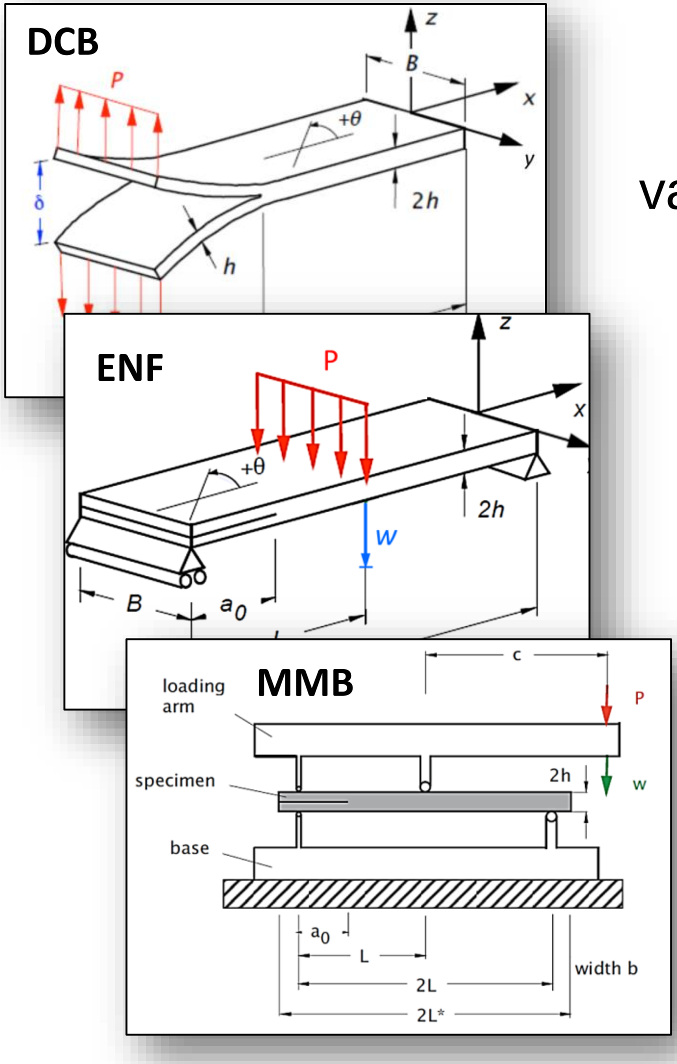




Krueger, R. A summary of benchmark examples and their application to assess the performance of quasi-static delamination propagation prediction capabilities in finite element codes. *Journal of Composite Materials,* vol. 49, pp. 3297-3316, 2015.

Verification and Validation

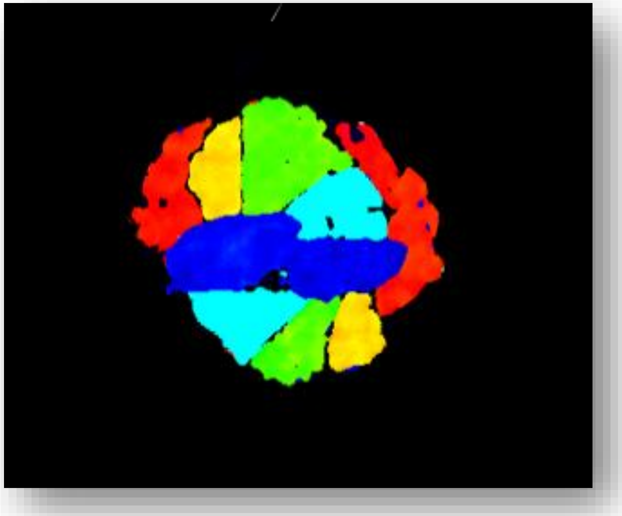
Basic validation data



“medium” complexity validation data

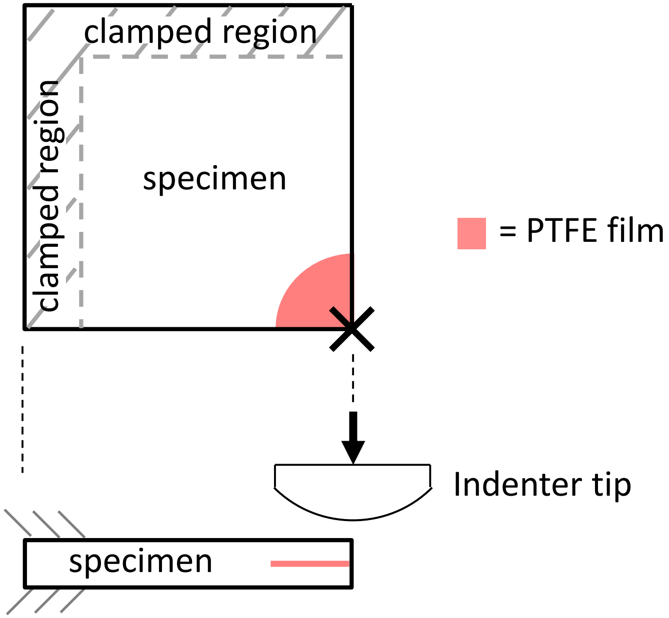
?

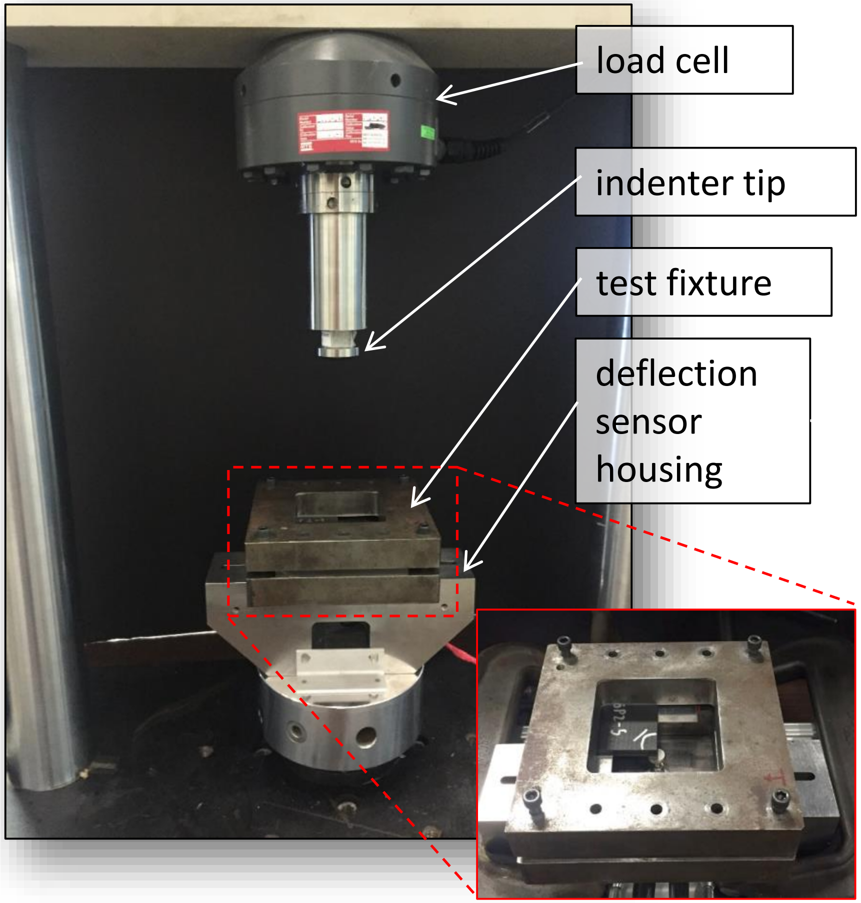
Impact validation data



- Primary damage mechanism: growth and interaction of multiple delaminations and matrix cracks
- “medium” complexity → limit damage to 2-3 interfaces

Verification and Validation: Biaxial-Bending Test (BBT)



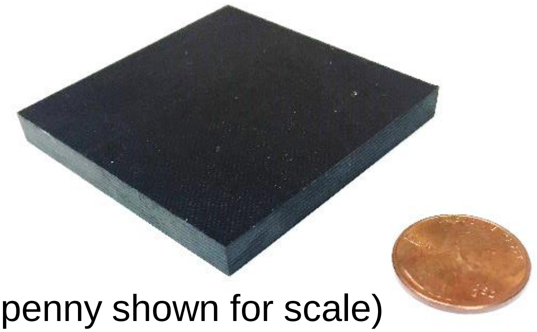


“Quarter plate” design

- 2 free edges on initial delamination
- **Damage limited to delaminations at 2-3 ply interfaces**
- **Stable damage growth**

Note: Similar to Canturri, C, Greenhalgh, ES, Pinho, ST. The relationship between mixed-mode II/III delamination and delamination migration in composite laminates. Composites Science and Technology, 105:102-109, 2014.

Verification and Validation: BBT Specimen

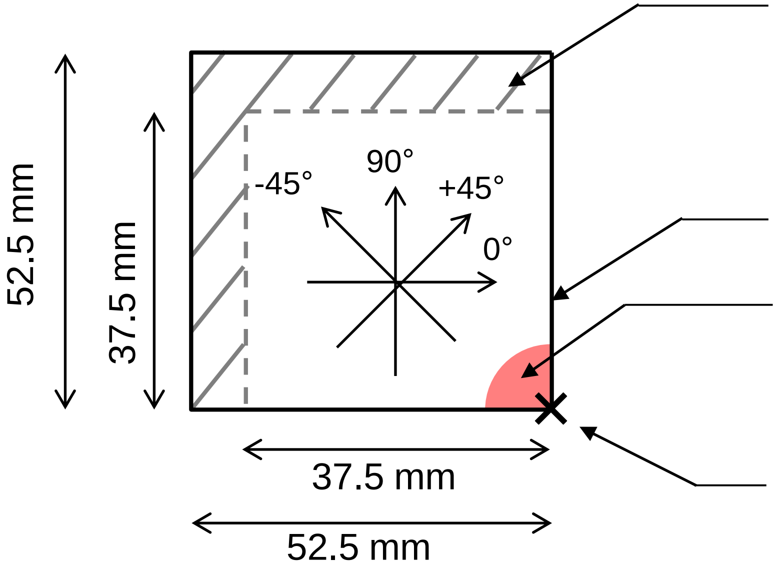

(penny shown for scale)

Layup 1: $[(0_2/90_2)_4/0_2/T/90_2/0_2/(90_2/0_2)_3]$

Layup 2: $[(0_2/90_2)_3/0_2/45_2/0_2/T/-45_2/0_2/(90_2/0_2)_3]$

Layup 3: $[(0_2/90_2)_3/0_2/-45_2/0_2/T/45_2/0_2/(90_2/0_2)_3]$

T = PTFE (Teflon™)



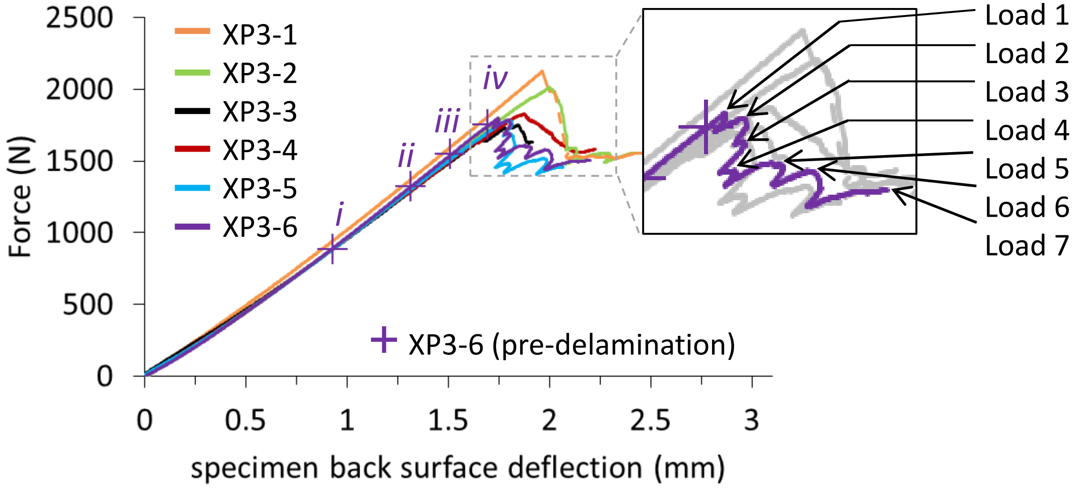
border region clamped

free edges (2)

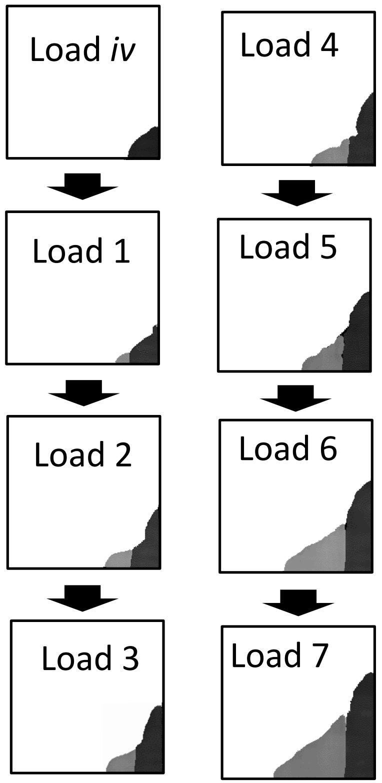
initial delamination, radius = 10 mm
(PTFE thickness = 13.0 μm)

load application location

Verification and Validation: BBT-1 Simulation



Intermittent damage scans

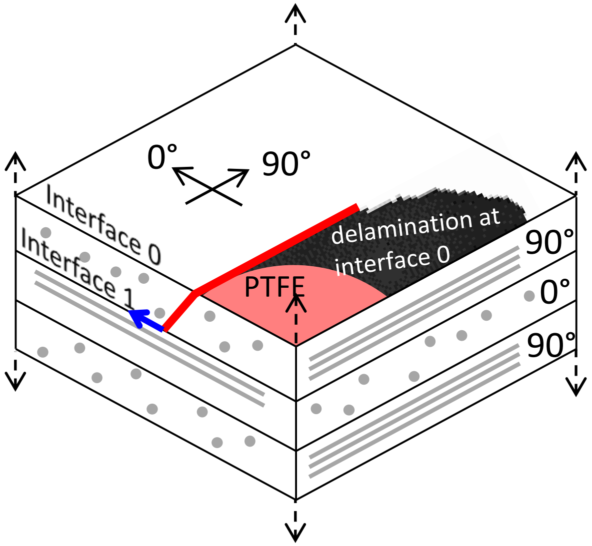


■ = delamination at interface 0

▨ = delamination at interface 1

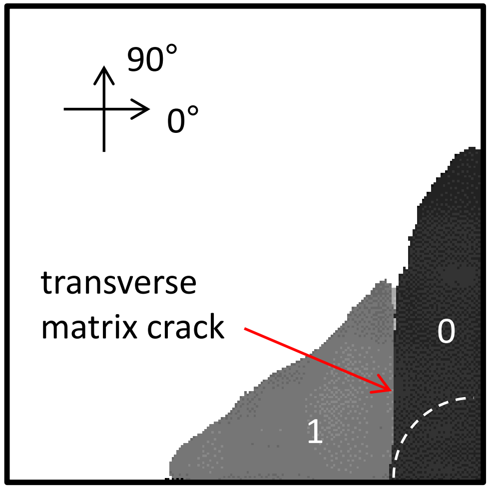
0 1

$[(0_2/90_2)_4/0_2/T/90_2/0_2/(90_2/0_2)_3]$

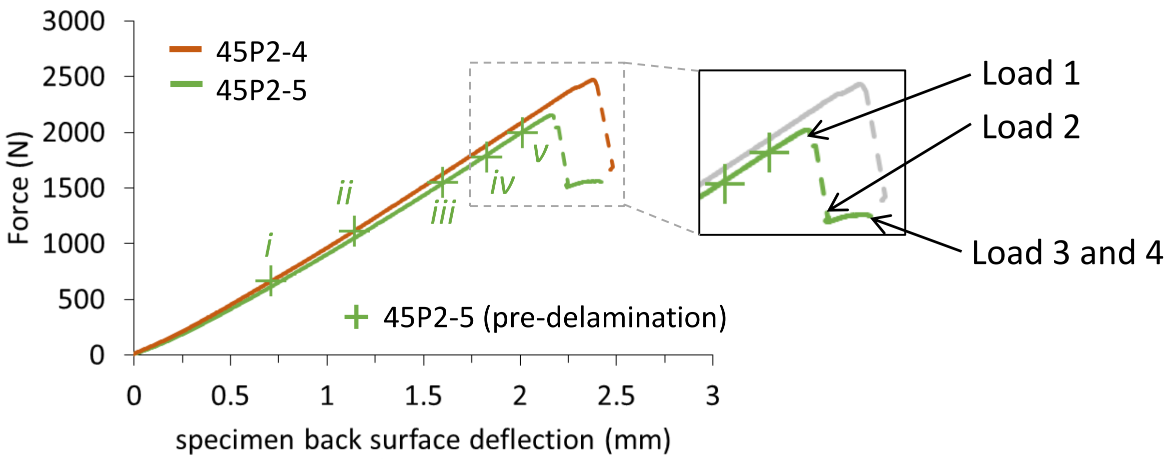


▬ = matrix crack

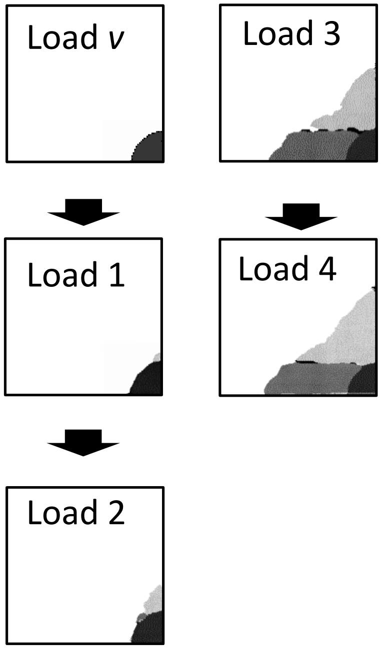
→ = delamination growth

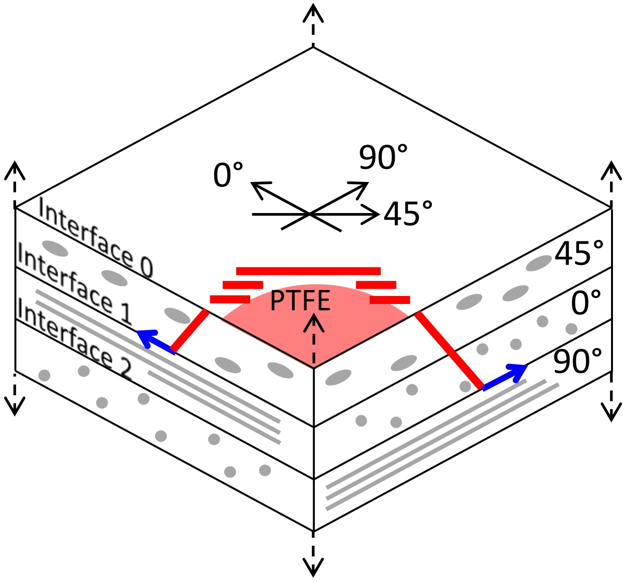


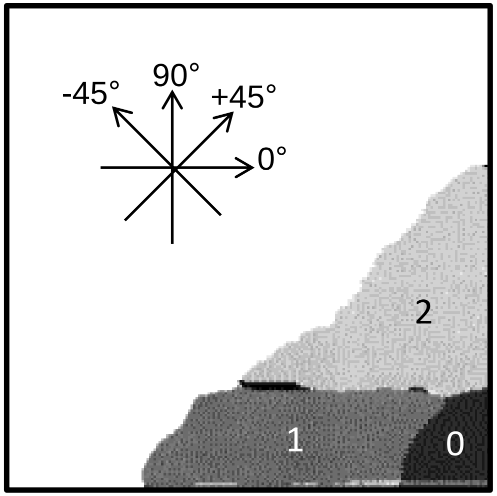
Verification and Validation: BBT-3



Intermittent damage scans







■ = delamination at interface 0

▨ = delamination at interface 1

□ = delamination at interface 2

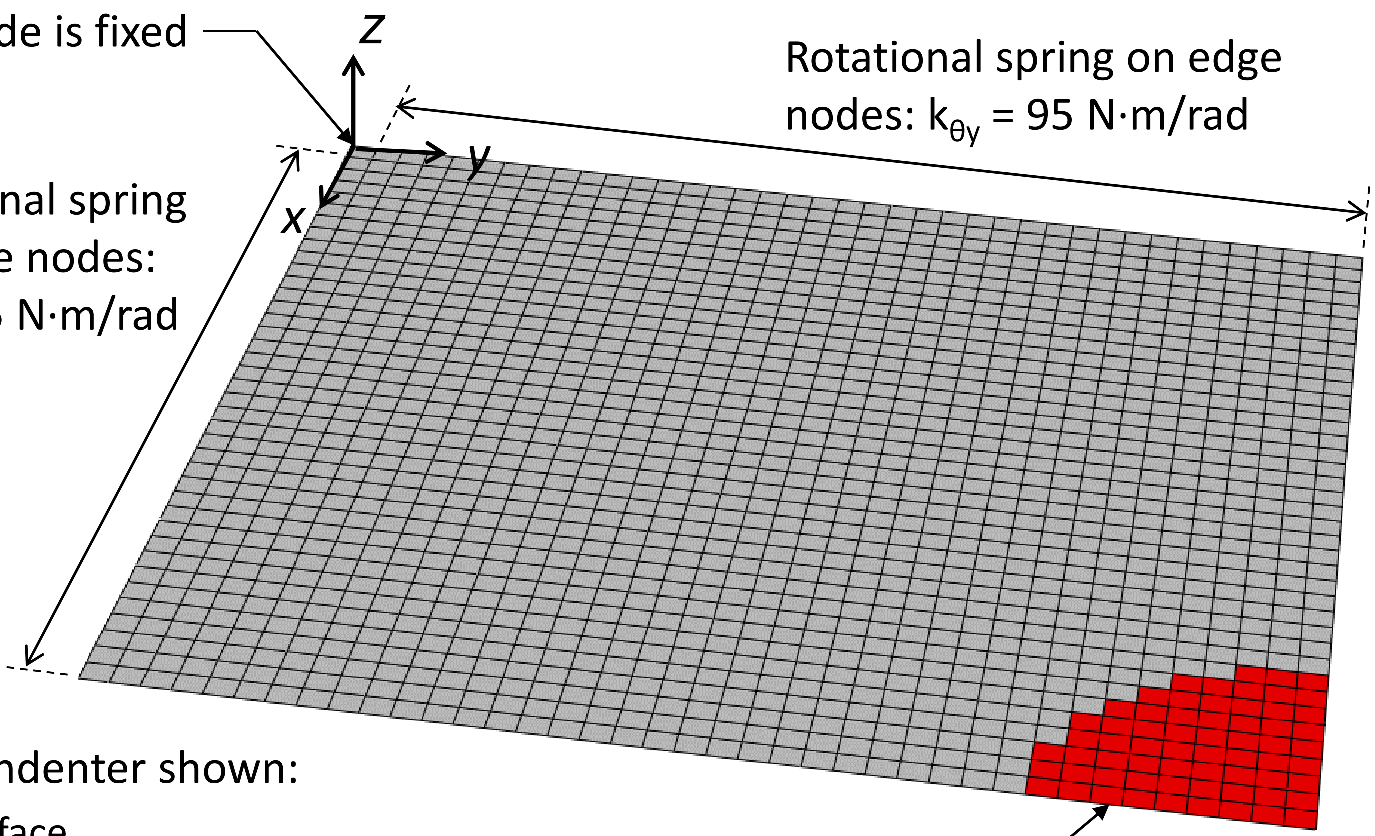
— = matrix crack

→ = delamination growth

↓0 ↓1 ↓2

$[(0_2/90_2)_3/0_2/-45_2/0_2/T/45_2/0_2/(90_2/0_2)_3]$

Verification and Validation: BBT Simulation



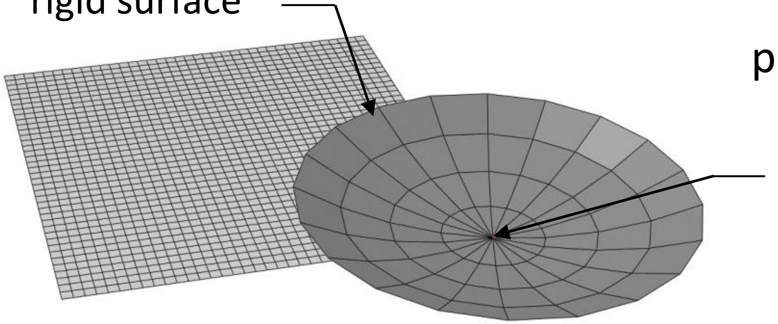
“origin” node is fixed

Rotational spring on edge nodes: $k_{\theta y}$ = 95 N·m/rad

Rotational spring on edge nodes: $k_{\theta x}$ = 95 N·m/rad

pre-existing crack

Detail with indenter shown:



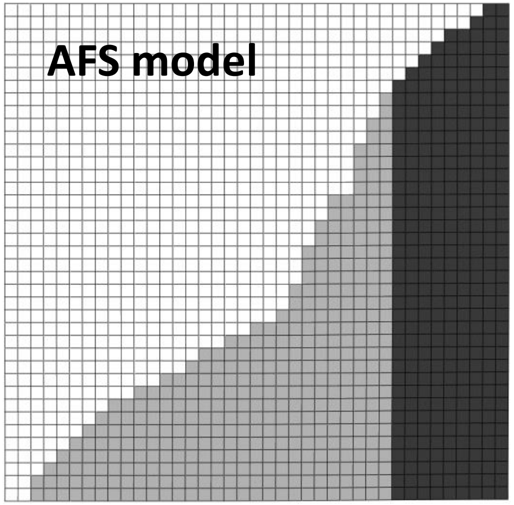
rigid surface

Quasi-static: prescribed displacement

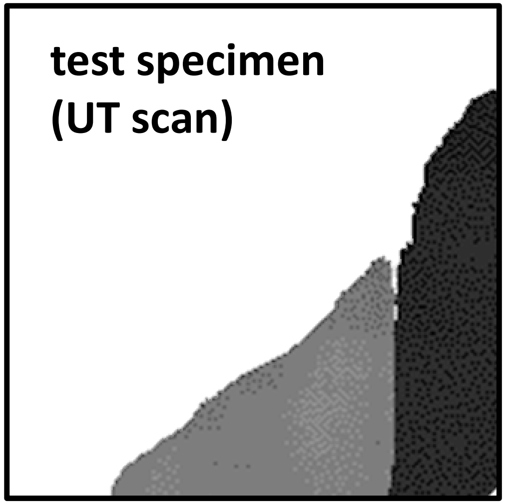
Impact: mass element and initial velocity

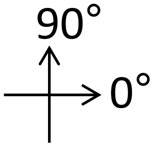
Verification and Validation: BBT-1 Simulation

$\alpha_c = 55°$



(δ = 2.18 mm)

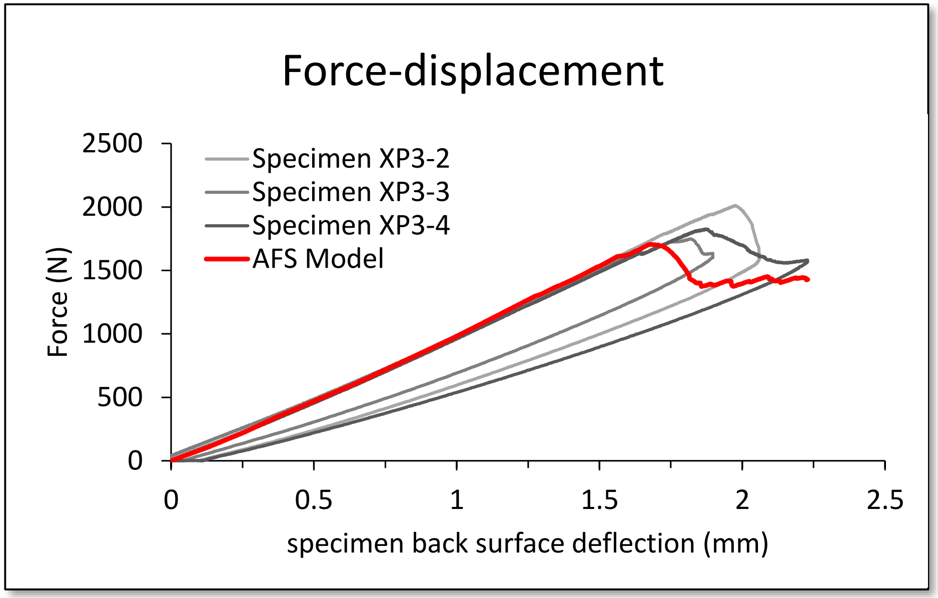




■ = delamination at interface 0

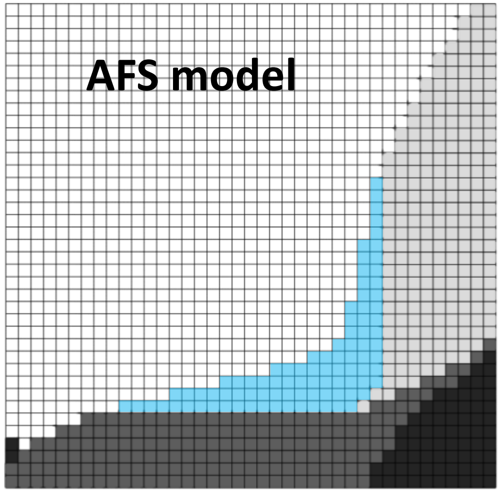
▨ = delamination at interface 1

$$[(0_2/90_2)_4/0_2/\color{red}{T}\overset{\overset{0}{\downarrow}}{/}90_2\overset{\overset{1}{\downarrow}}{/}0_2/(90_2/0_2)_3]$$

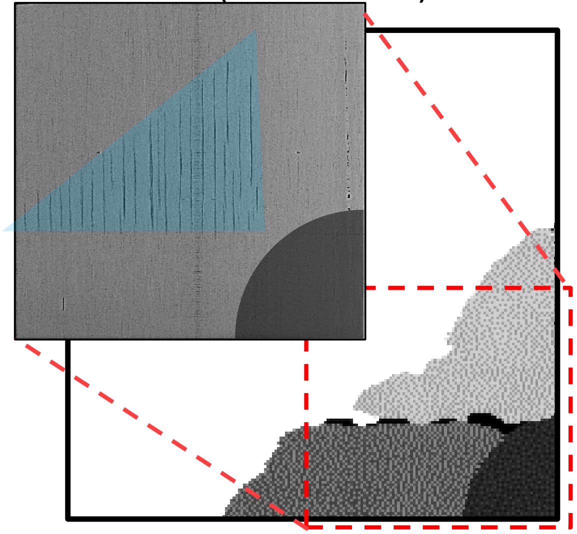


Verification and Validation: BBT-3 Simulation

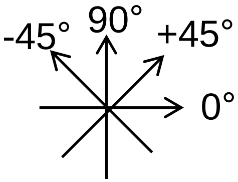
$\alpha_c = 50°$



(δ = 2.18 mm)



test specimen (UT scan)



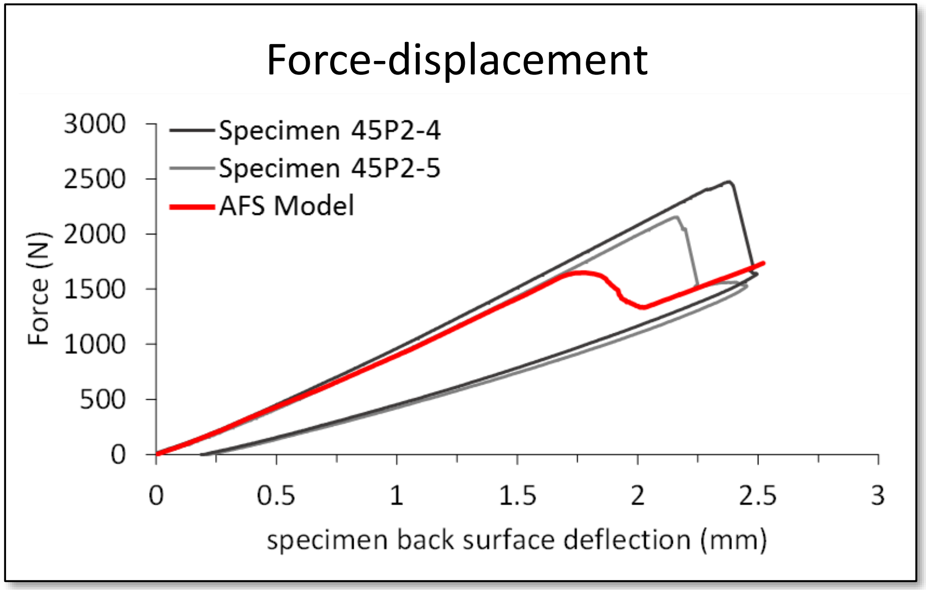
■ = delamination at interface 0

▩ = delamination at interface 1

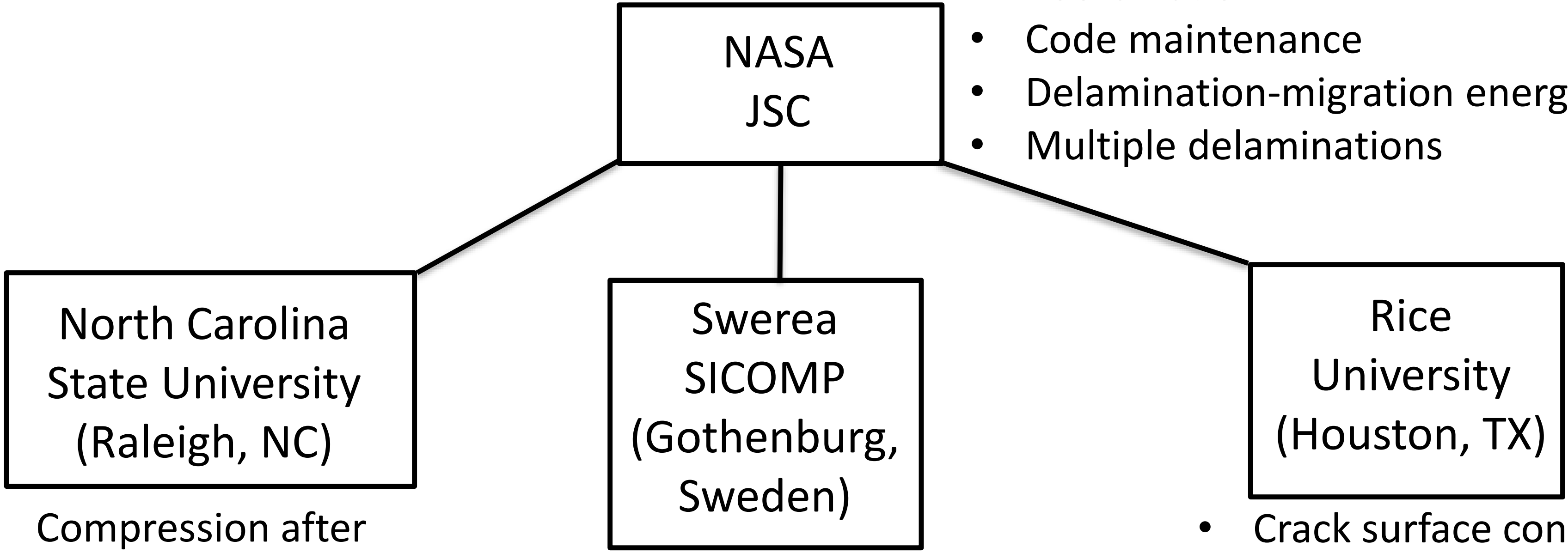
░ = delamination at interface 2

🟦 = delamination at interface 3

$$[(0_2/90_2)_3/0_2/-45_2/0_2/T\overset{0}{\downarrow}/45_2\overset{1}{\downarrow}/0_2\overset{2}{\downarrow}/(\overset{3}{\downarrow}90_2/0_2)_3]$$



Ongoing Work: Collaboration Structure



NASA
JSC

- Coordination
- Code maintenance
- Delamination-migration energy
- Multiple delaminations

North Carolina
State University
(Raleigh, NC)

- Compression after impact
- Damage initiation

Swerea
SICOMP
(Gothenburg, Sweden)

- Application & testing

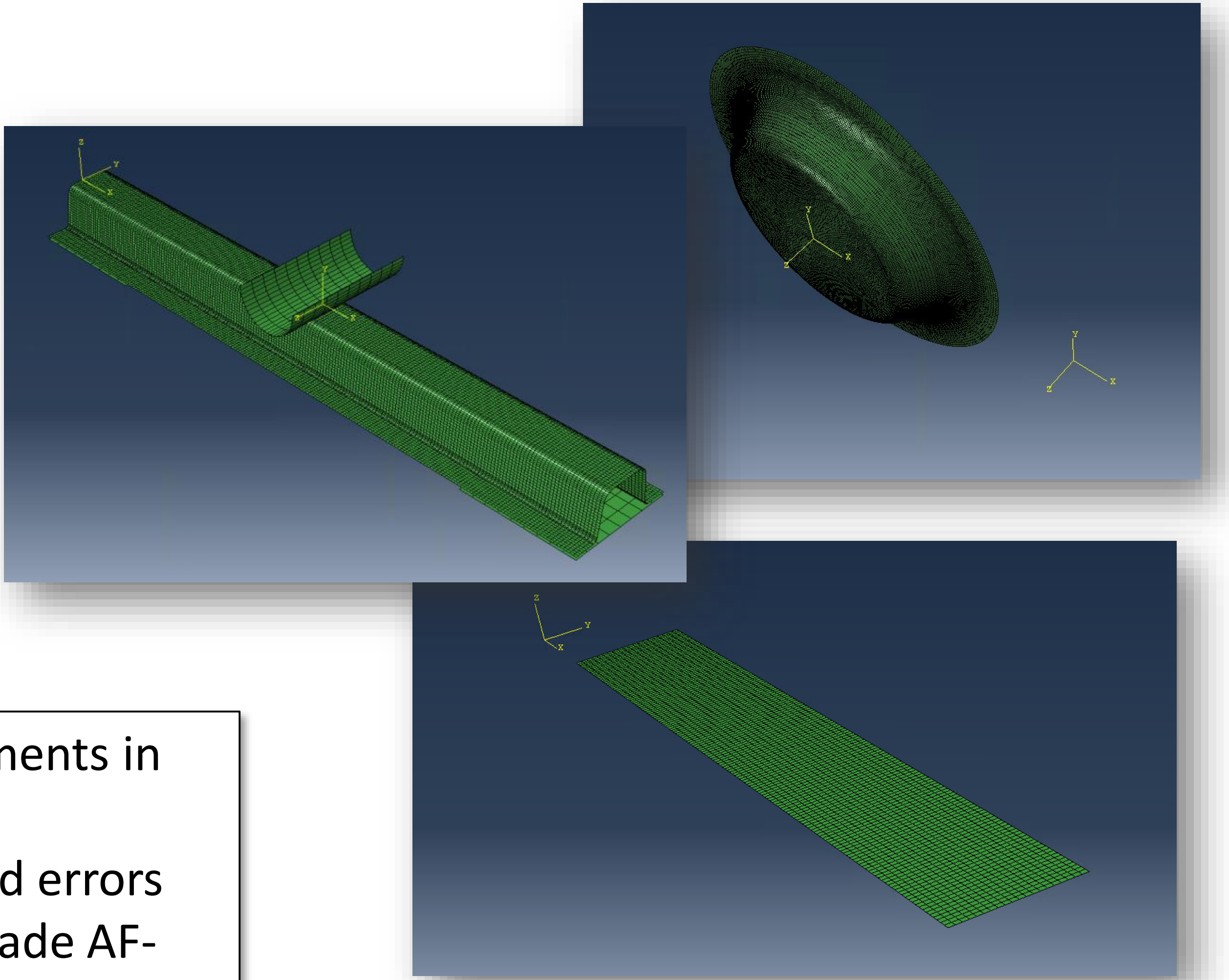
Rice
University
(Houston, TX)

- Crack surface contact
- Friction characterization
- Impact dynamics

Ongoing Work: Software Application and Testing

Goal: mature AF-Shell from a bespoke research code to a general analysis tool

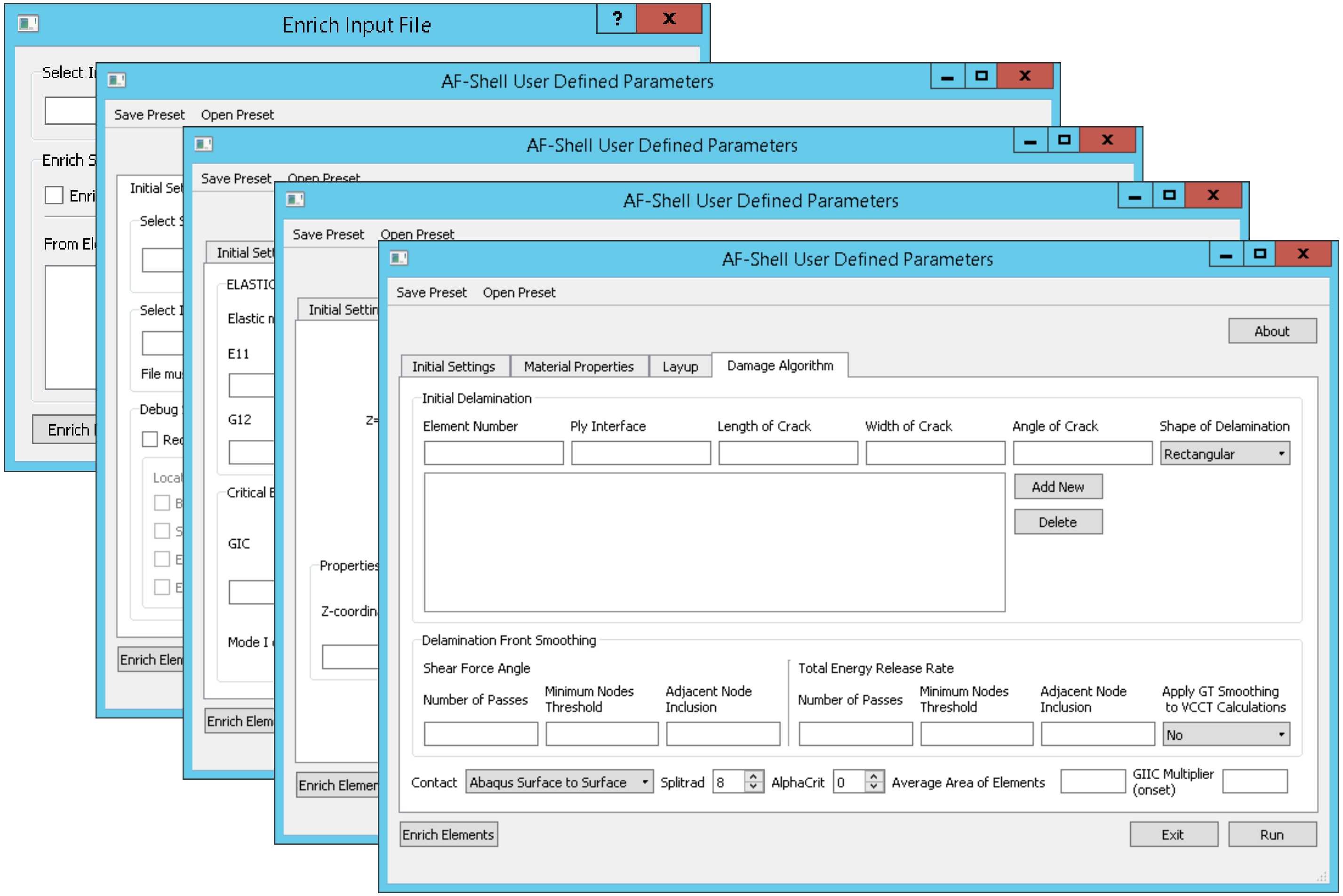
Approach: apply AF-Shell to existing models



1. Enrich shell elements in existing models
2. Identify bugs and errors
3. Debug and upgrade AF-Shell as needed

Ongoing Work: Graphical User Interface

- Enrich pre-existing model file
- Set up user defined parameters in AF-Shell
- Run analyses



Shape of Delamination: Rectangular

Apply GT Smoothing to VCCT Calculations: No

Contact: Abaqus Surface to Surface

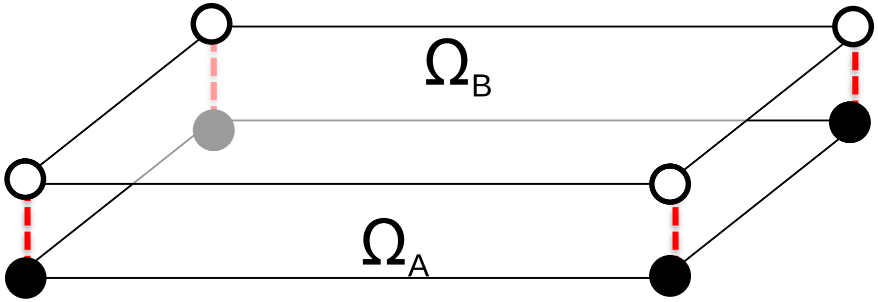
Splitrad: 8

AlphaCrit: 0

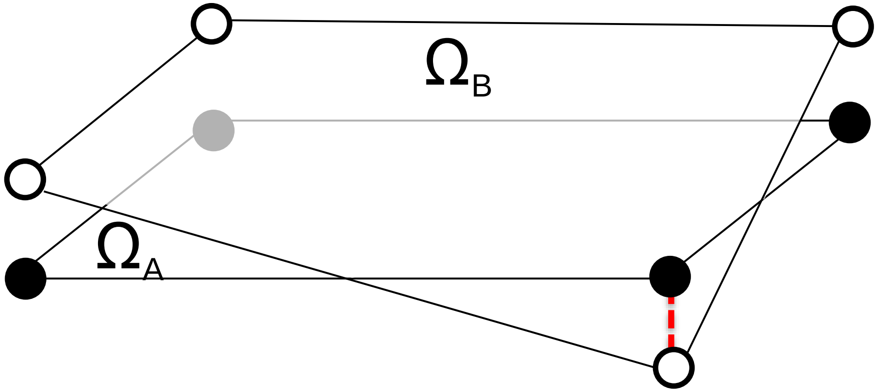
Ongoing Work: Contact

Current "work-around" contact options in AF-Shell

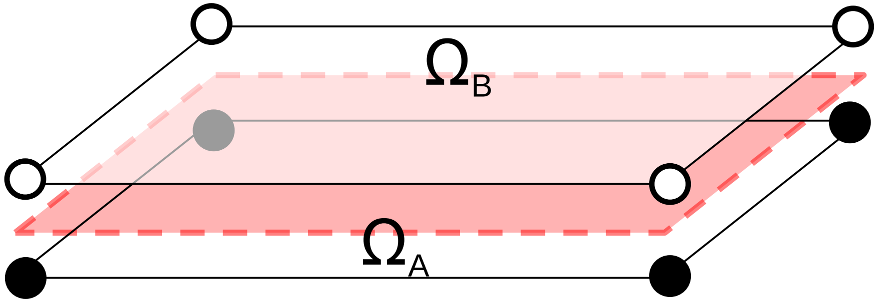
1. Transverse DOF nodal ties



2. Conditional transverse DOF nodal ties



3. Abaqus surface-to-surface contact

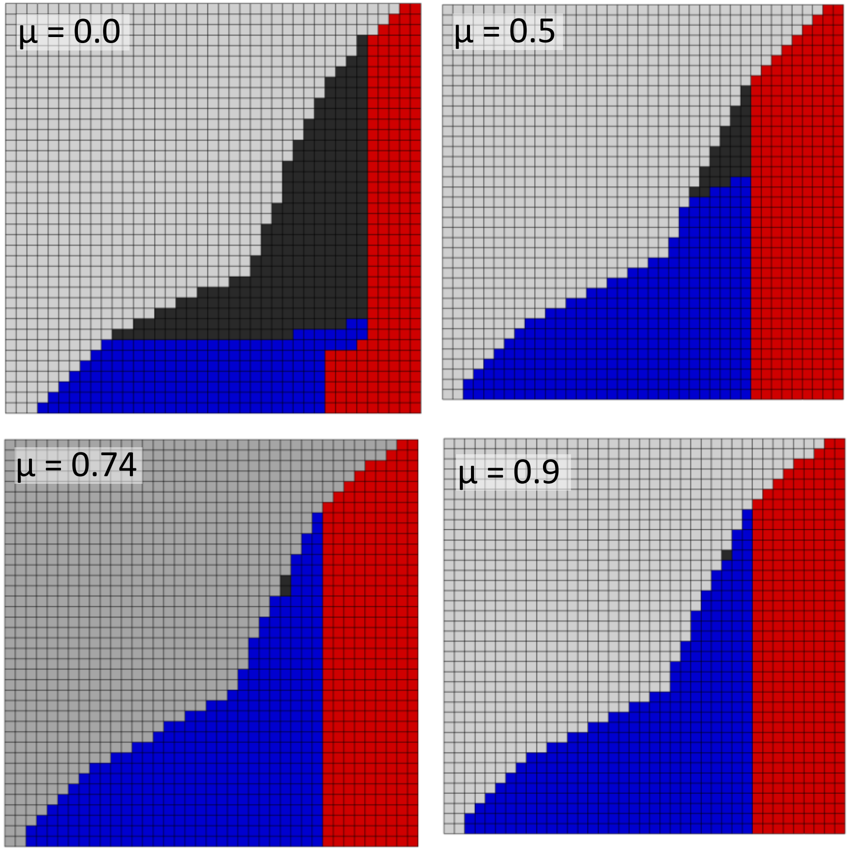


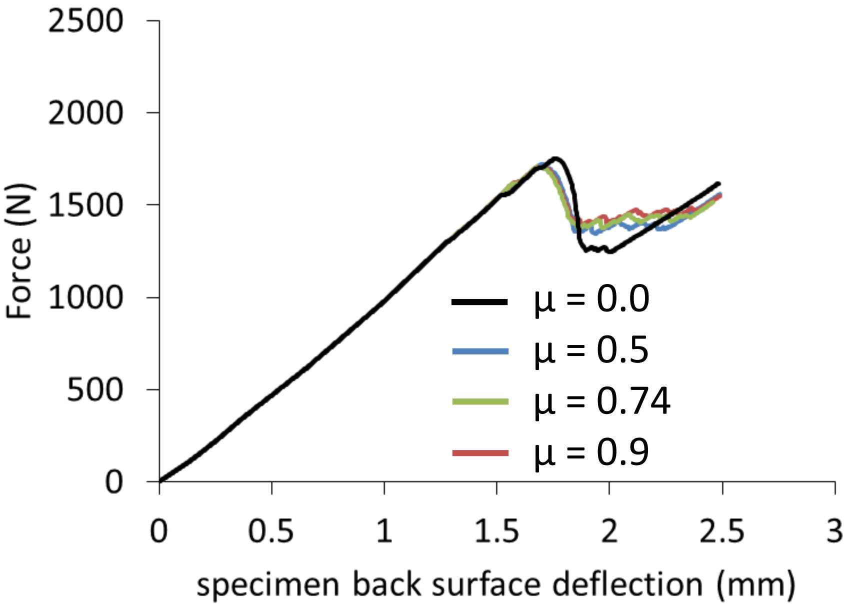
○ = floating node (FN)

● = real node (RN)

Ongoing Work: Contact

Behavioral dependency in model on coefficient of friction:





Layup 1

0 1 2

$[(0_2/90_2)_4/0_2/T/90_2/0_2/(90_2/0_2)_3]$

delamination

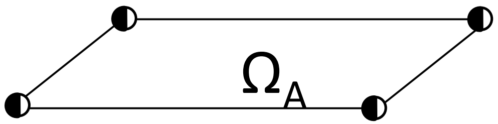
🟥 interface 0

🟦 interface 1

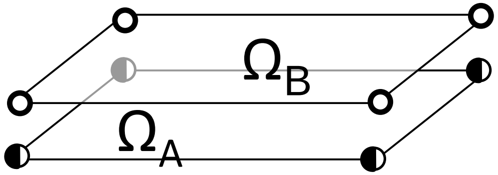
⬛ interface 2

Ongoing Work: Multiple Delaminations

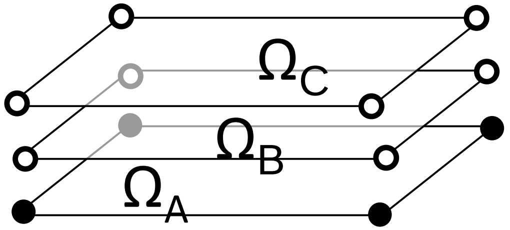
Multiple delaminations using the Floating Node Method



$$K^{(e)} = \begin{bmatrix} \left[K^{(e)}_{\Omega_A}\right]_{24\times24} & [0] & [0] \\ [0] & [0]_{24\times24} & [0] \\ [0] & [0] & [0]_{24\times24} \end{bmatrix}_{72\times72}$$



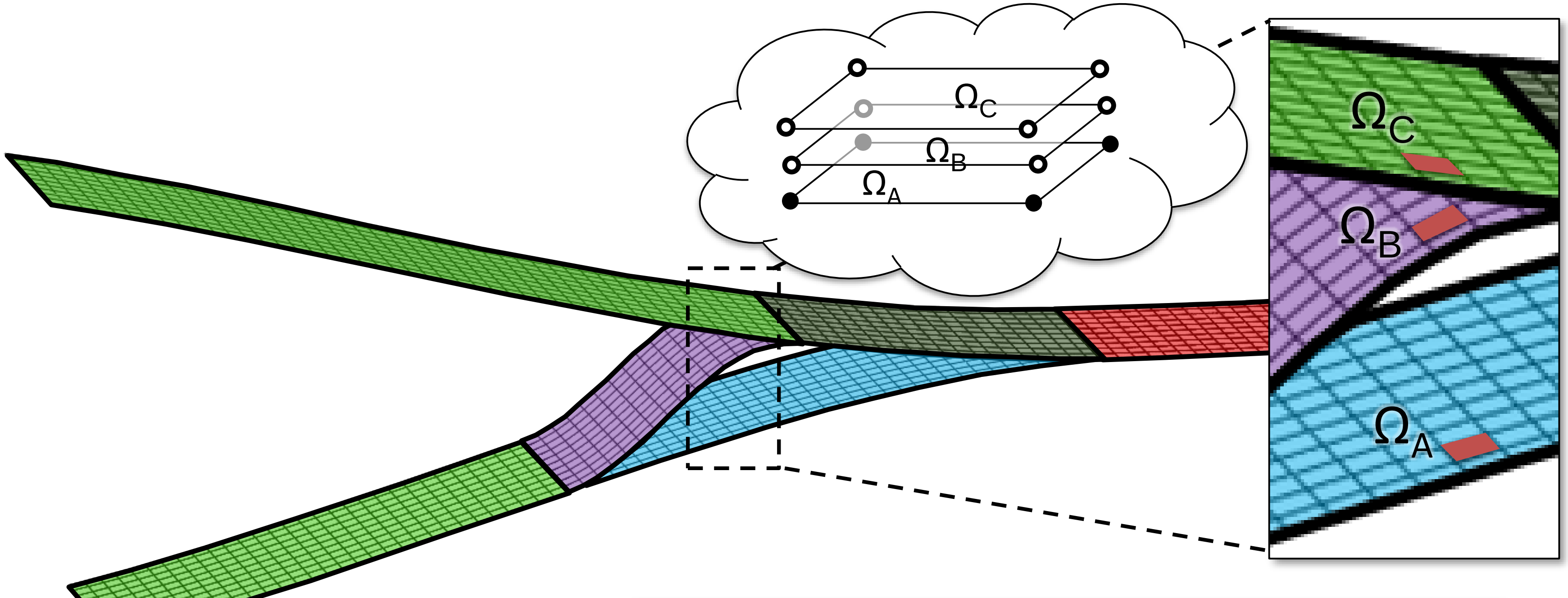
$$K^{(e)} = \begin{bmatrix} \left[K^{(e)}_{\Omega_A}\right]_{24\times24} & [0] & [0] \\ [0] & \left[K^{(e)}_{\Omega_B}\right]_{24\times24} & [0] \\ [0] & [0] & [0]_{24\times24} \end{bmatrix}_{72\times72}$$

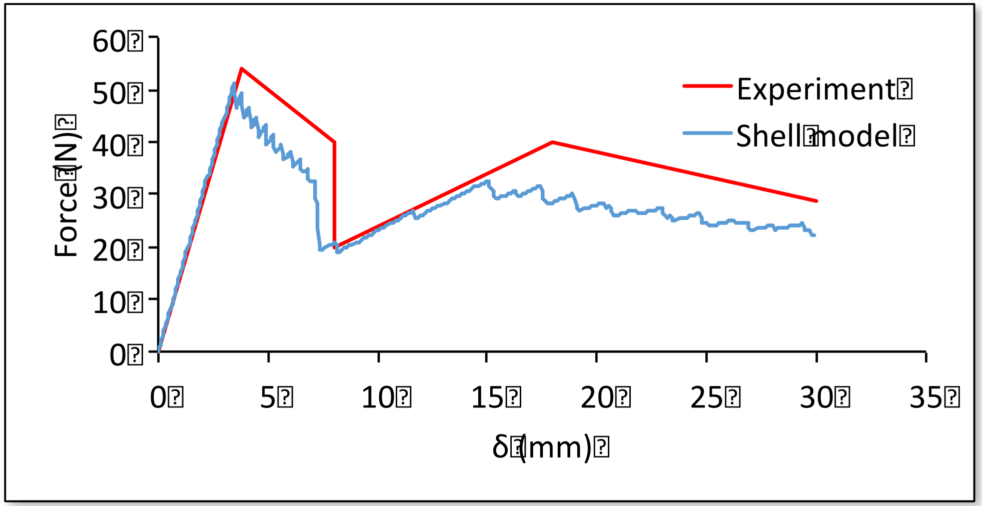


$$K^{(e)} = \begin{bmatrix} \left[K^{(e)}_{\Omega_A}\right]_{24\times24} & [0] & [0] \\ [0] & \left[K^{(e)}_{\Omega_B}\right]_{24\times24} & [0] \\ [0] & [0] & \left[K^{(e)}_{\Omega_C}\right]_{24\times24} \end{bmatrix}_{72\times72}$$

○ = floating node (FN) ● = real node (RN) ◐ = RN and unused FN

Ongoing Work: Multiple Delaminations





Number of plies

- 🟪 = 2
- 🟦 = 10
- 🟩 = 12
- ▩ = 14
- 🟥 = 24

Ongoing Work: Other

1. Damage initiation
   - Advanced laminate theories (Zig Zag)
   - Stress recovery
2. Code efficiency and robustness
3. Impact simulation
   - Dynamic behavior
   - Explicit solver
4. Alternate Interface
   - Independent solver (decouple from Abaqus)
   - Create Abaqus plug-in
5. Additional failure modes
   - Fiber breakage
   - Fiber kinking
6. Trade study
   - Testing
   - Quantify enhanced efficiency
   - Develop best practices

Concluding Remarks

- AF-Shell: shell element enrichment that allows for efficient damage simulation in composite laminates
- Initial verification and validation complete
- Software development is ongoing via NASA-organized collaboration
- Main areas of needed and ongoing development
    - Application and Testing
    - Contact
    - Multiple delaminations
    - Other: damage initiation, code improvements, impact dynamics, alternate interface, additional failure modes, trade study

QUESTIONS

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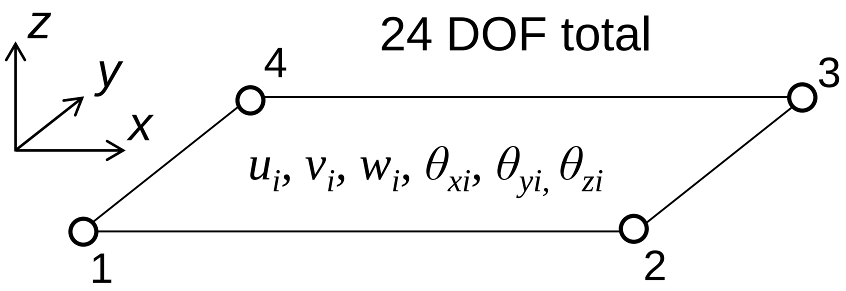
BACK UP

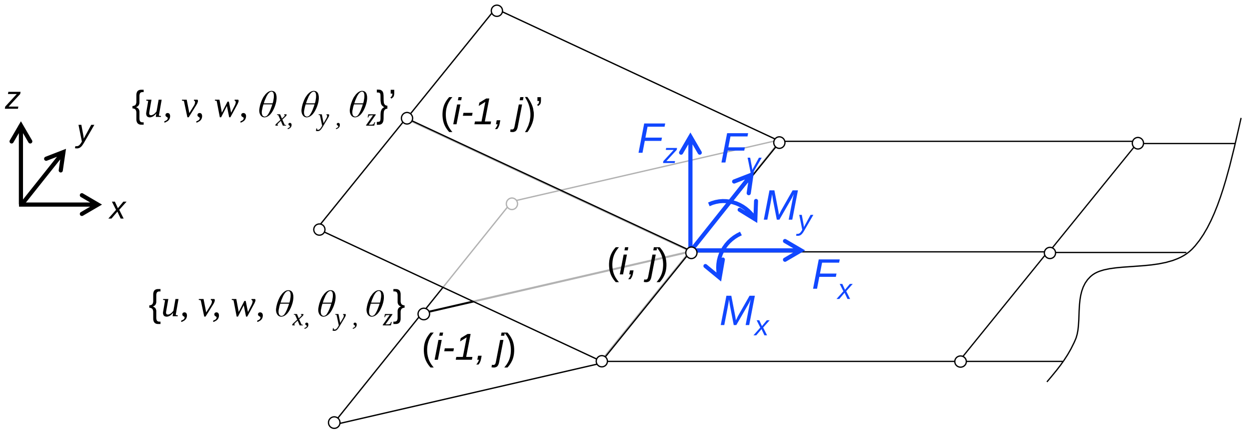
Baseline Element Formulation

Mindlin Composite Shell Element



- Four nodes, 6 DOF per node
- Linear shape functions
- Orthotropic material
- Transverse shear deformable
- Composite section: Classical laminate theory
- Shear locking: full integration w/assumed linear transverse shear strain distribution
- Behaves well for thick and thin shells
- Coded into an Abaqus® 6.14/Standard User Element Subroutine (UEL)

Virtual Crack Closure Technique (VCCT)



Energy release rate equations for shells [Wang]
(example: propagation in +*x* direction)

$$G_I^{(+x)} = \frac{-1}{2\Delta A^{(e)}}\left[F_z^{(i,j)}\left(w^{(i-1,j)'} - w^{(i-1,j)}\right) + M_x^{(i,j)}\left(\theta_x^{(i-1,j)'} - \theta_x^{(i-1,j)}\right) + M_y^{(i,j)}\left(\theta_y^{(i-1,j)'} - \theta_y^{(i-1,j)}\right)\right]$$

$$G_{II}^{(+x)} = \frac{-1}{2\Delta A^{(e)}}\left[F_x^{(i,j)}\left(u^{(i-1,j)'} - u^{(i-1,j)}\right)\right]$$

$$G_T^{(+x)} = G_I^{(+x)} + G_{II}^{(+x)}$$

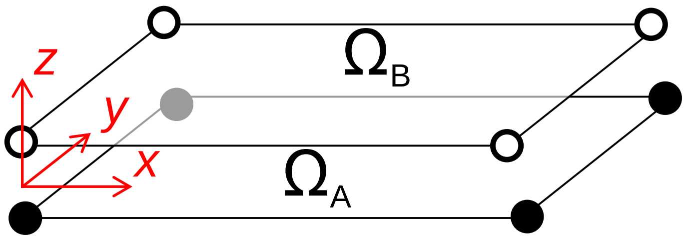
Mixed-mode critical energy release rate [Benzeggagh], G_c

$$G_c^{(+x)} = G_{Ic} + (G_{IIc}\text{-}G_{Ic})\left(G_{II}^{(+x)}/G_T^{(+x)}\right)^{\eta}$$

Wang, J.T., and Raju, I.S. "Strain energy release rate formulae for skin-stiffener debond modeled with plate elements." *Engineering Fracture Mechanics* 54.2 (1996): 211-228.

Benzeggagh, M.L., M. Kenane. 1996. “Measurement of Mixed-Mode Delamination Fracture Toughness of Unidirectional Glass/Epoxy Composites with Mixed-Mode Bending Apparatus,” *Composites Science and Technology*, 56(4):439-449.

Floating Node Method



Laminate shell element stiffness integration

$$K^{(e)} = \int_b \int_b H^T \left[\boxed{\int_{-\frac{h}{2}}^{\frac{h}{2}}} C(A,B,D,G)dz \right] H\, dydx$$

$$A = \int_{-\frac{h}{2}}^{\frac{h}{2}} C_p dz\,, \quad B = \int_{-\frac{h}{2}}^{\frac{h}{2}} zC_p dz\,, \quad D = \int_{-\frac{h}{2}}^{\frac{h}{2}} z^2 C_p dz\,, \quad G = \int_{-\frac{h}{2}}^{\frac{h}{2}} C_s dz$$

split *z*-integration limits about discontinuity location, *z'*

Two integration domains

$$K_{\Omega_A}^{(e)} = \iint_{A^{(e)}} H_{\Omega_A}^T \left[\boxed{\int_{-h/2}^{z'}} C(A,B,D,G)_{\Omega_A} dz \right] H_{\Omega_A}\, dA$$

$$K_{\Omega_B}^{(e)} = \iint_{A^{(e)}} H_{\Omega_B}^T \left[\boxed{\int_{z'}^{h/2}} C(A,B,D,G)_{\Omega_B} dz \right] H_{\Omega_B} dA$$

$$K^{(e)} = K_{\Omega_A}^{(e)} + K_{\Omega_B}^{(e)}$$

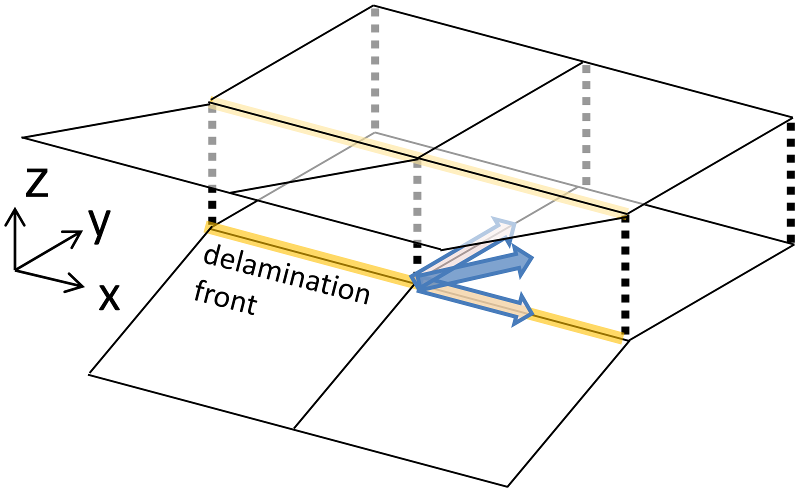
$$K^{(e)} = \begin{bmatrix} \left[K_{\Omega_A}^{(e)}\right]_{24x24} & [0] \\ [0] & \left[K_{\Omega_B}^{(e)}\right]_{24x24} \end{bmatrix}_{48x48}$$

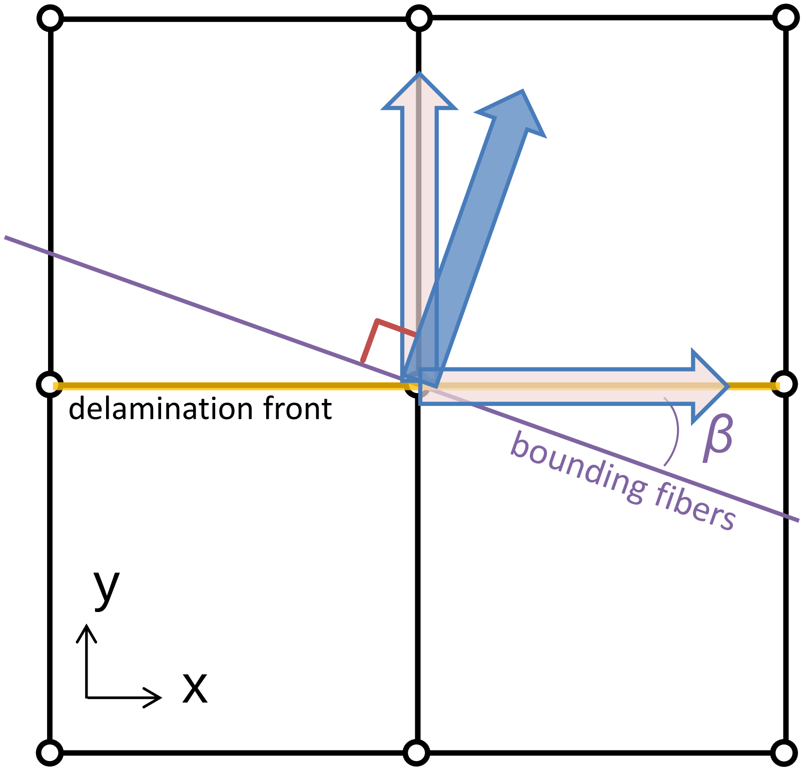
○ = floating node (FN)

● = real node (RN)

Predicting Transverse Cracks

Assumption: $G^{(mig)}$ is associated with delamination growth perpendicular to bounding fibers





⇨ delamination growth directions considered with VCCT } G_{IIx} *and* G_{IIy}

➡ delamination growth perpendicular to bounding fibers } $G^{(mig)}$

Predicting Transverse Cracks

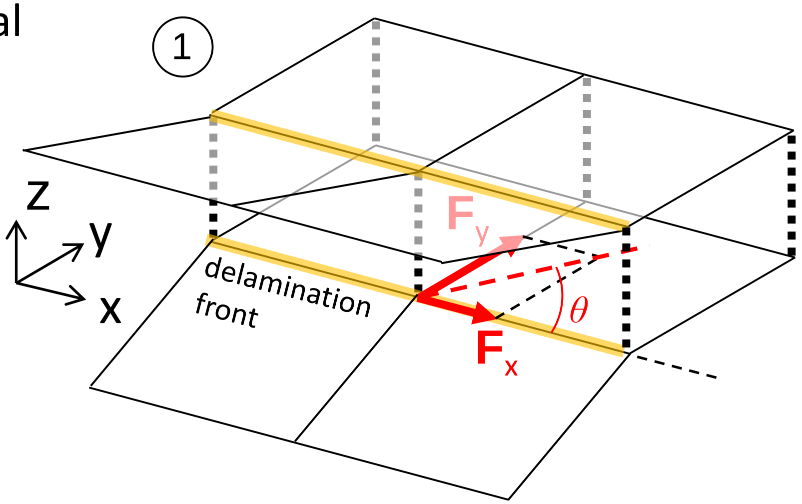
① In-plane shear force vector sum = global growth direction

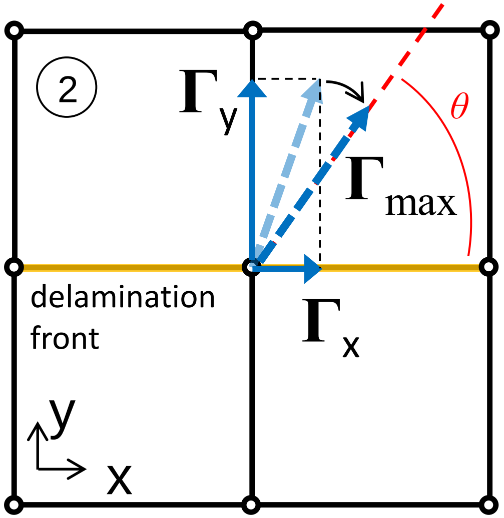
② $|\Gamma_x| = G_{IIx}$ & $|\Gamma_y| = G_{IIy}$

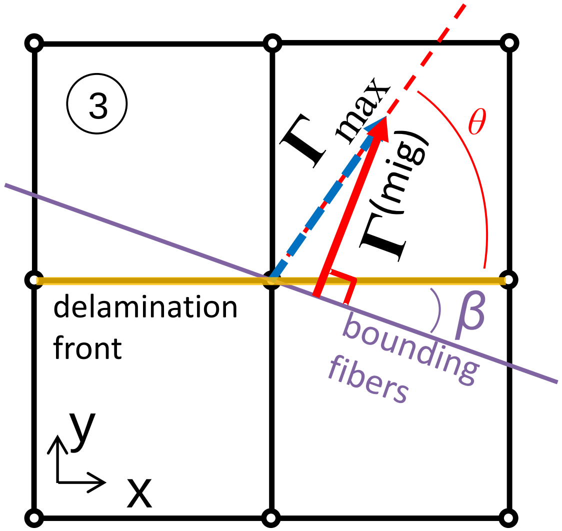
$\Gamma_{max} = \Gamma_x + \Gamma_y$ (analogous to G_{max})

③ $\Gamma^{(mig)}$ is Γ_{max} component perpendicular to bounding fibers

④ $G^{(mig)} = |\Gamma^{(mig)}|$

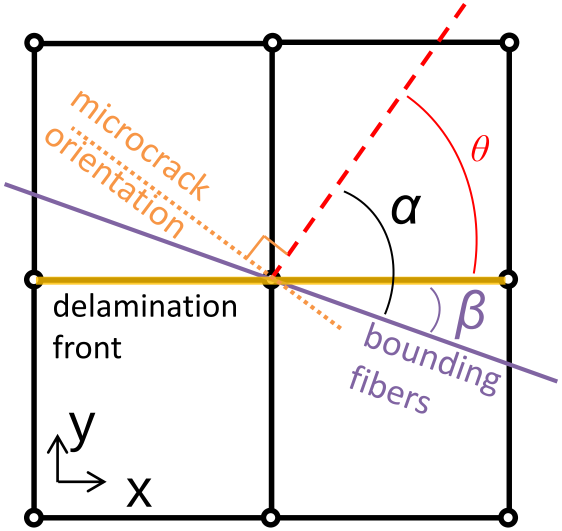


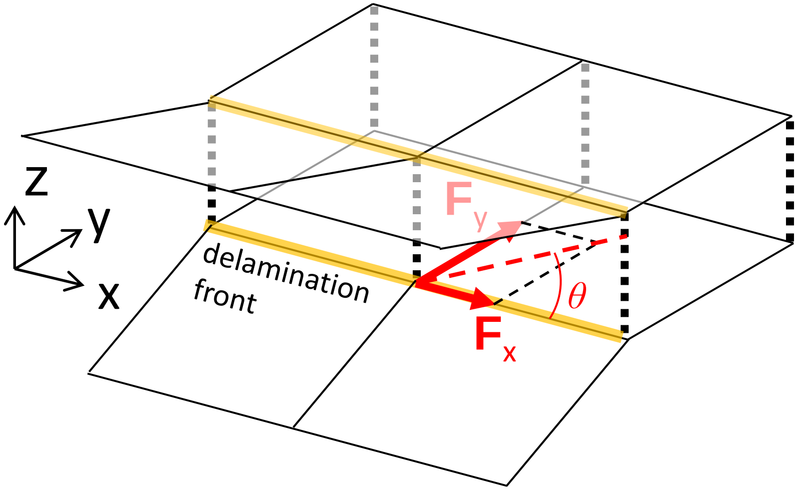




Predicting Transverse Cracks

Step III: Relative angle between shear vector and bounding fibers



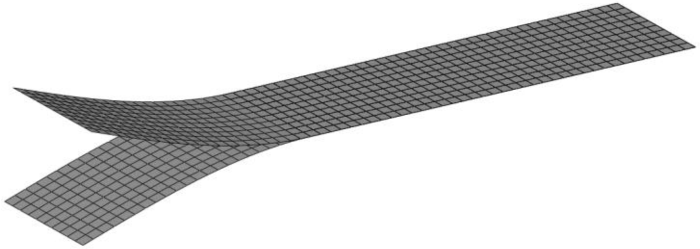


Conditions for a transverse crack:

$$G^{(mig)} \geq G_c^{(tr)} \text{ AND } \alpha \geq \alpha_c$$

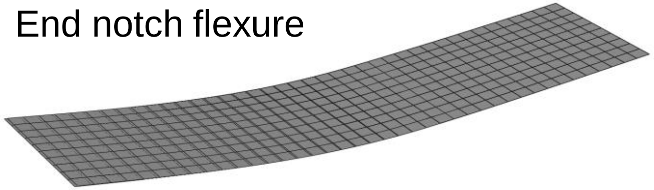
Computational Efficiency

Double cantilever beam

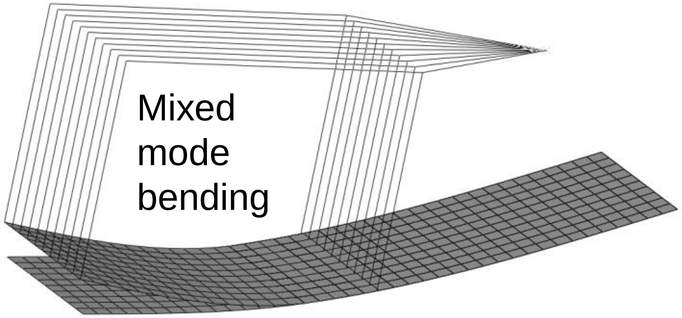


	Mesh size	Runtime
AFS	1.0 mm	37 minutes
	2.5 mm	6 minutes
	5.0 mm	1.5 minutes
High fidelity [Krueger]	**1.0 mm**	**31 hours**

End notch flexure



	Mesh size	Runtime
AFS	1.0 mm	34 minutes
	2.0 mm	8 minutes
	5.0 mm	1.5 minutes



Mixed mode bending

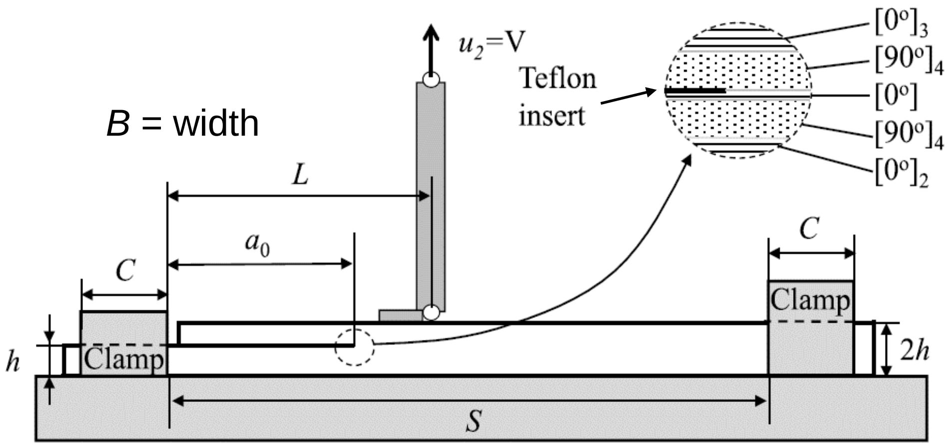
	Mesh size	Runtime
AFS	1.0 mm	50 minutes
	2.5 mm	8.5 minutes
	5.0 mm	1.5 minutes

Note: All analyses use 1 CPU

Krueger, R. A summary of benchmark examples and their application to assess the performance of quasi-static delamination propagation prediction capabilities in finite element codes. *Journal of Composite Materials,* vol. 49, pp. 3297-3316, 2015.

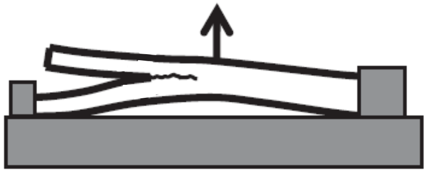
Delamination-Migration Test

Delamination-migration experiment [Ratcliffe, De Carvalho]

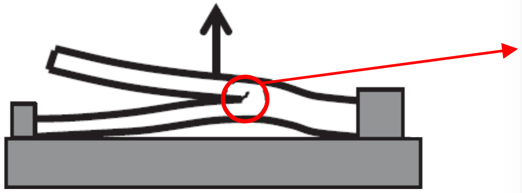


$[90_4/0_3/(90/0)_{2s}/0_2/0/90_4/T/0/90_4/0_2/(90_4/0_2)_{2S}/0_2/90_3/0/90]$

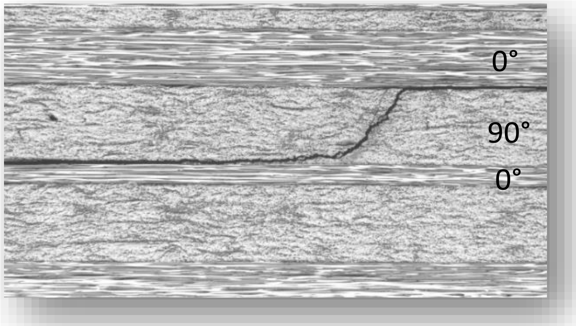
Dimensions (mm)				
B	$2h$	C	S	a_0
12.7	5.25	12.7	115	49



1. Delamination growth



2. Migration

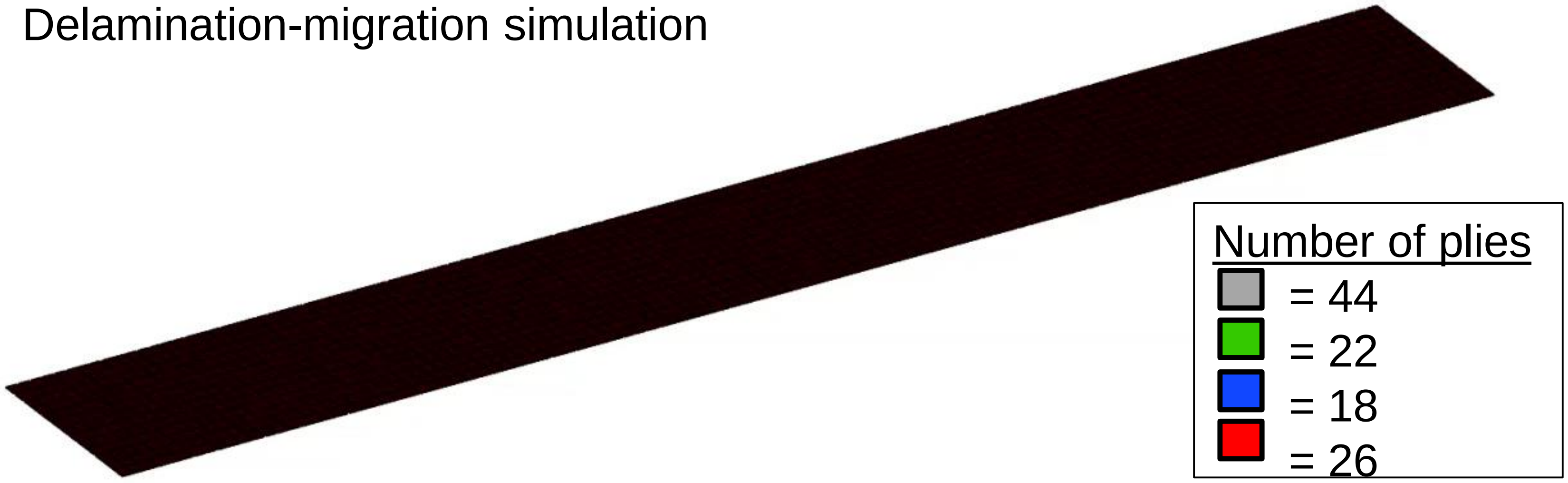


Ratcliffe, J., Czabaj, M., O'Brien, T.K. A test for characterizing delamination migration in carbon/epoxy tape laminates. 2013. NASA/TM-2013-218028.

De Carvalho, N.V., Chen, B.Y., Pinho, S.T., Ratcliffe, J.G., Baiz, P.M., Tay, T.E. 2015. "Modeling delamination migration in cross-ply tape laminates," *Composites: Part A* 71:192-203.

Delamination-Migration Simulation

Delamination-migration simulation



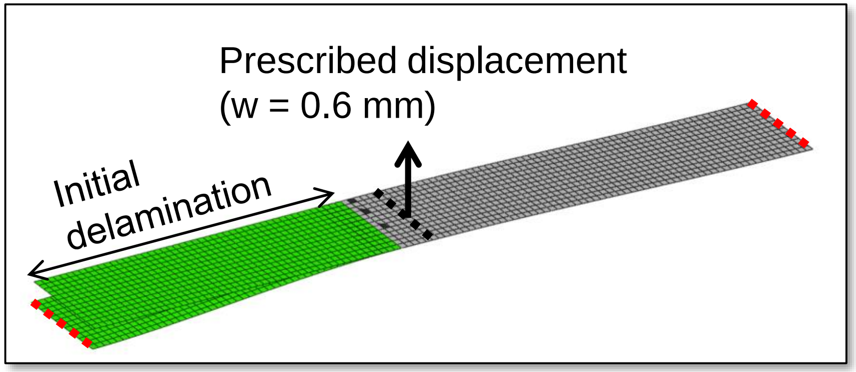
Number of plies

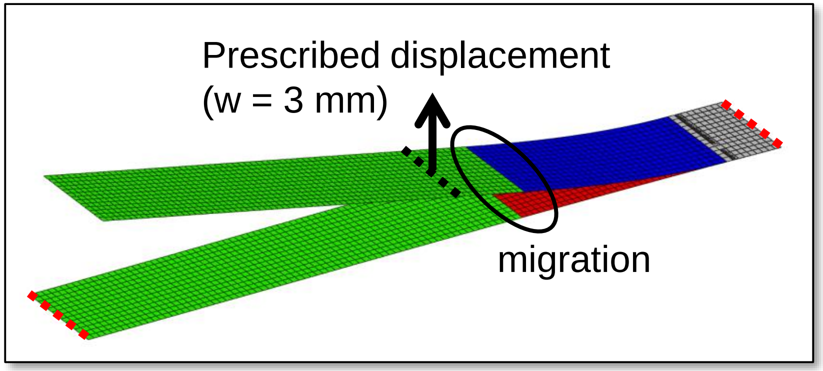
⬜ = 44

🟩 = 22

🟦 = 18

🟥 = 26

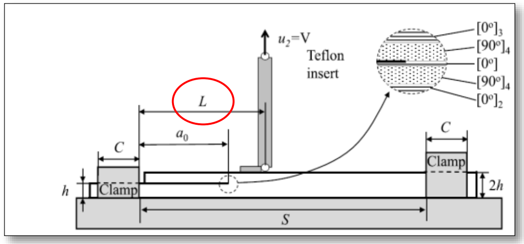


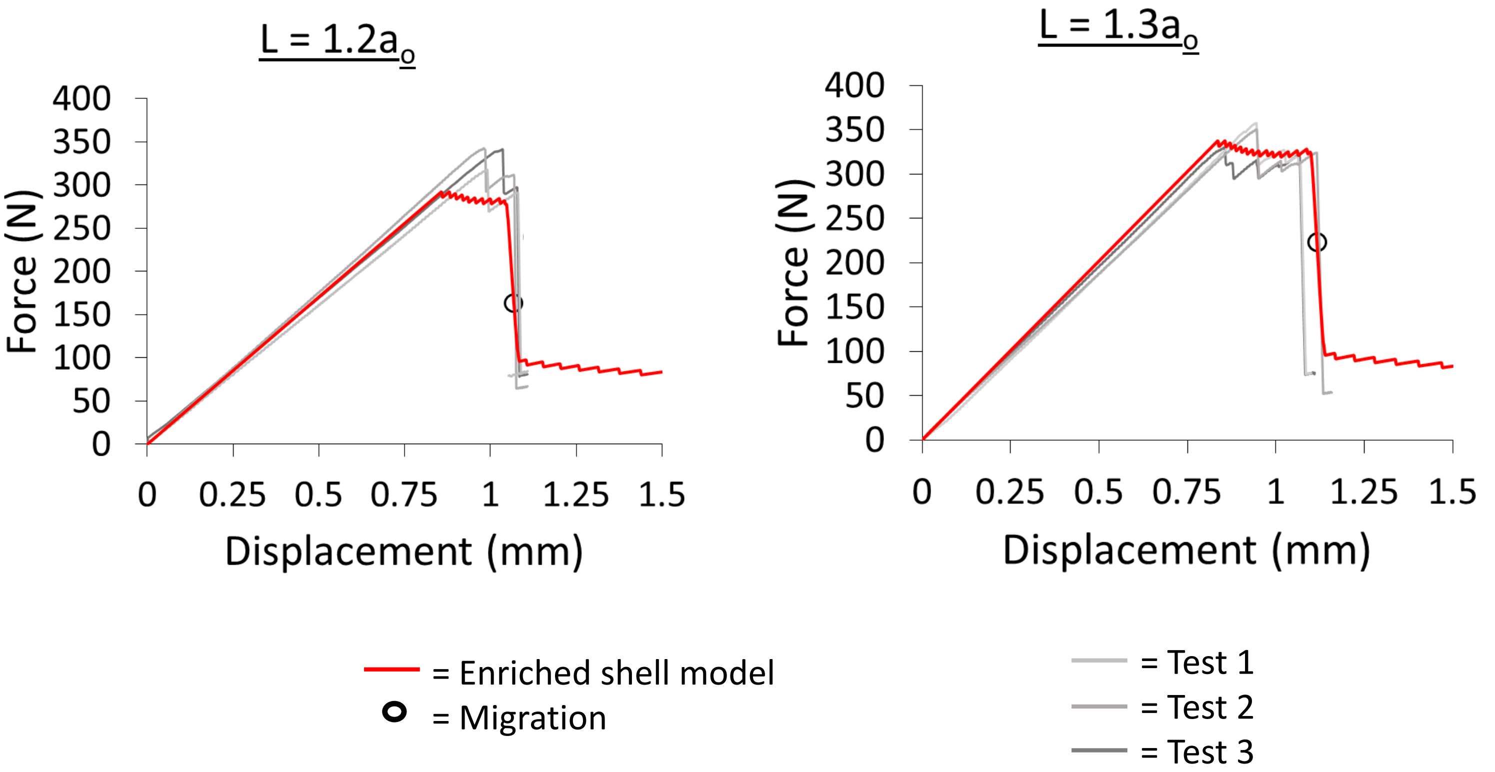


···· = Rotational springs

Delamination-Migration Simulation

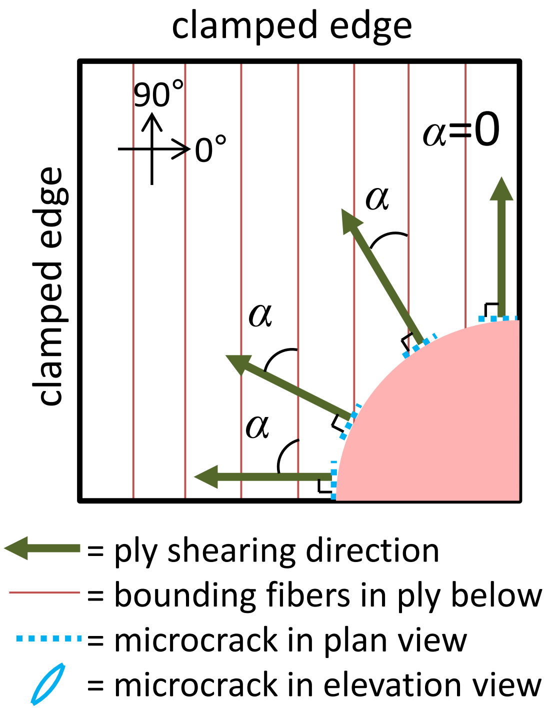
Force-displacement comparison to experiments:





De Carvalho, N.V., Chen, B.Y., Pinho, S.T., Ratcliffe, J.G., Baiz, P.M., Tay, T.E. 2015. “Modeling delamination migration in cross-ply tape laminates,” *Composites: Part A* 71:192-203.

Test Results BBT-1 Detail

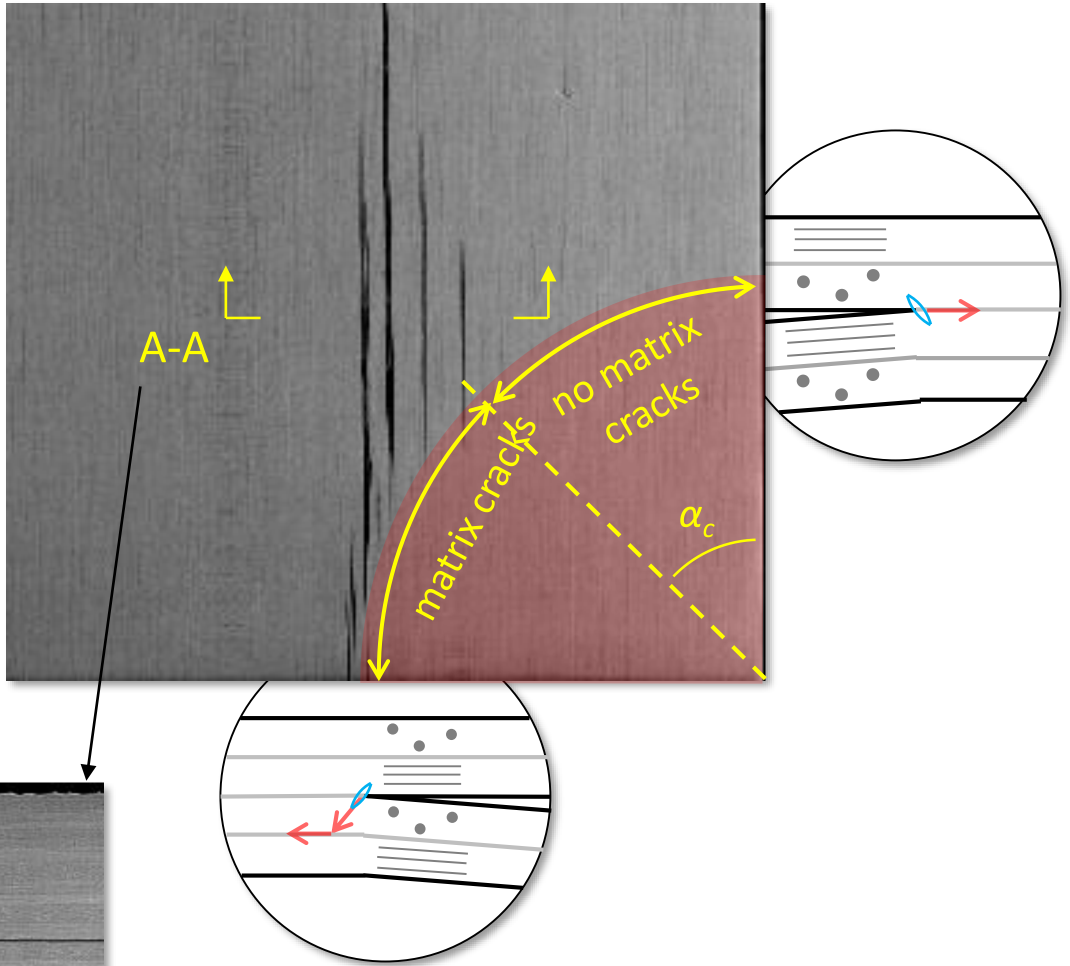


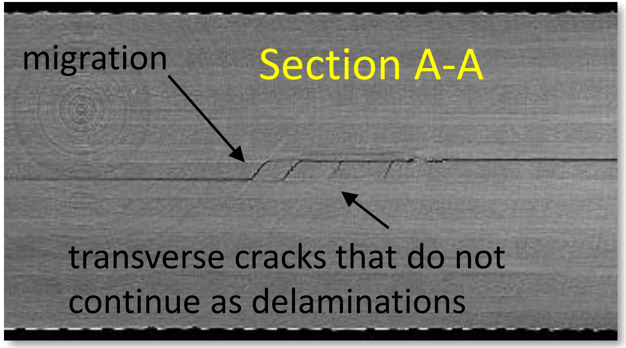
🟩 = ply shearing direction

🟥 = bounding fibers in ply below

┅ = microcrack in plan view

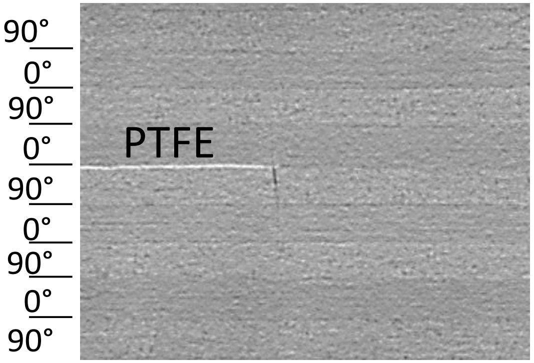
⬯ = microcrack in elevation view



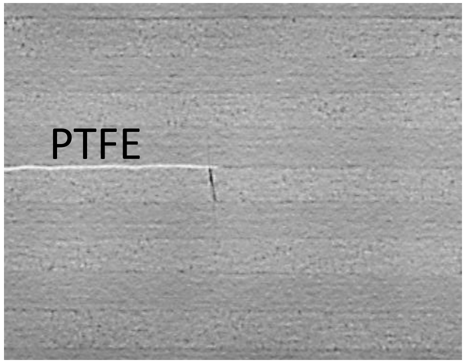


transverse cracks that do not continue as delaminations

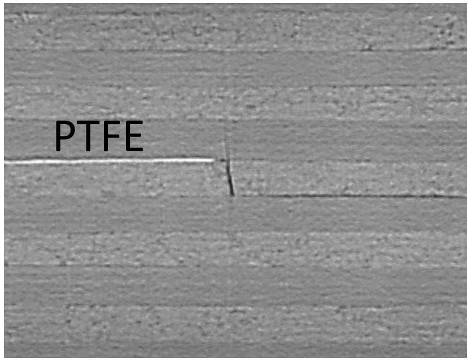
Test Results BBT-1 Detail



pre-delamination *i*: matrix crack partially through ply block



pre-delamination *iii*: matrix crack fully through ply block



load 1: migration complete