

A Three-Dimensional Mesoscale Model for In-Plane and Out-of-Plane Fiber Kinking

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Dynamics, and Materials Conference

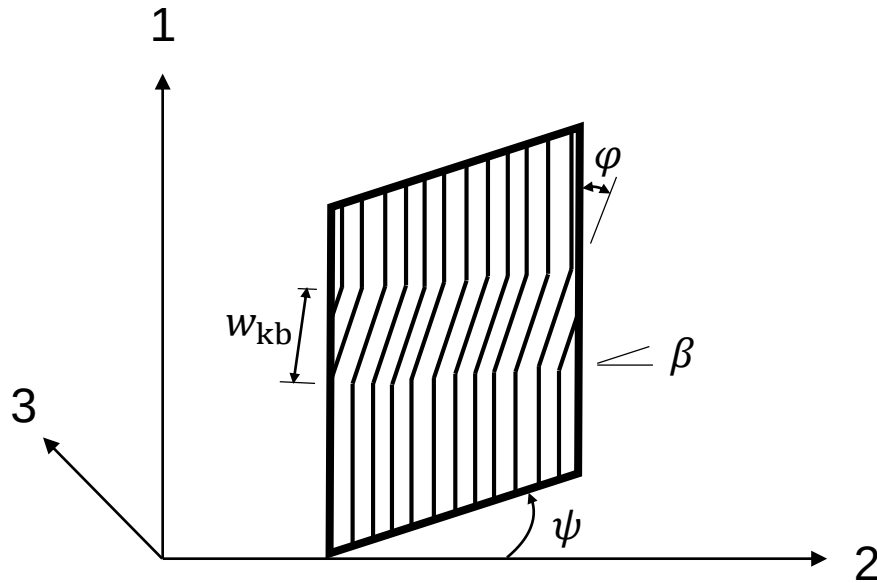
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January 7–11, 2019

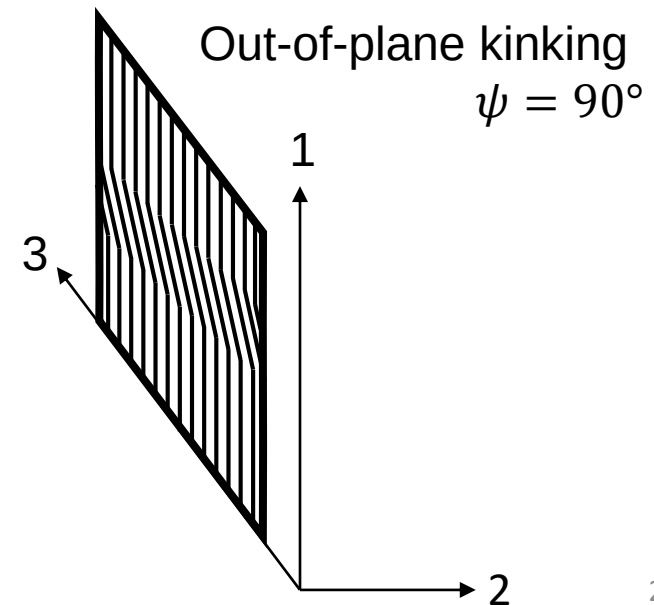
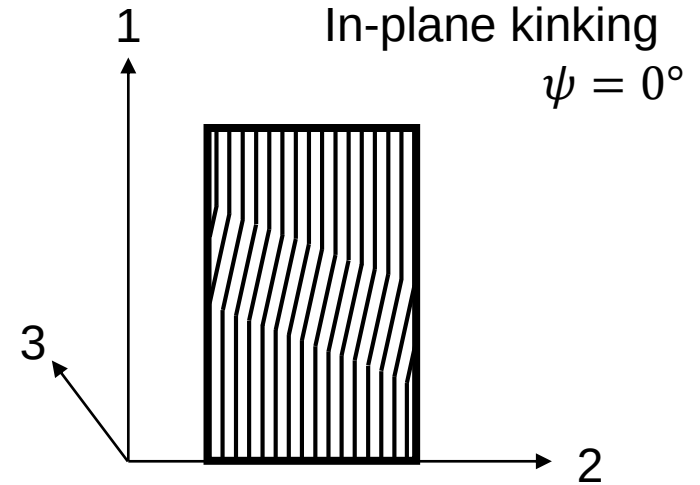
Fiber Kinking Plane

Three-dimensional kink band idealization

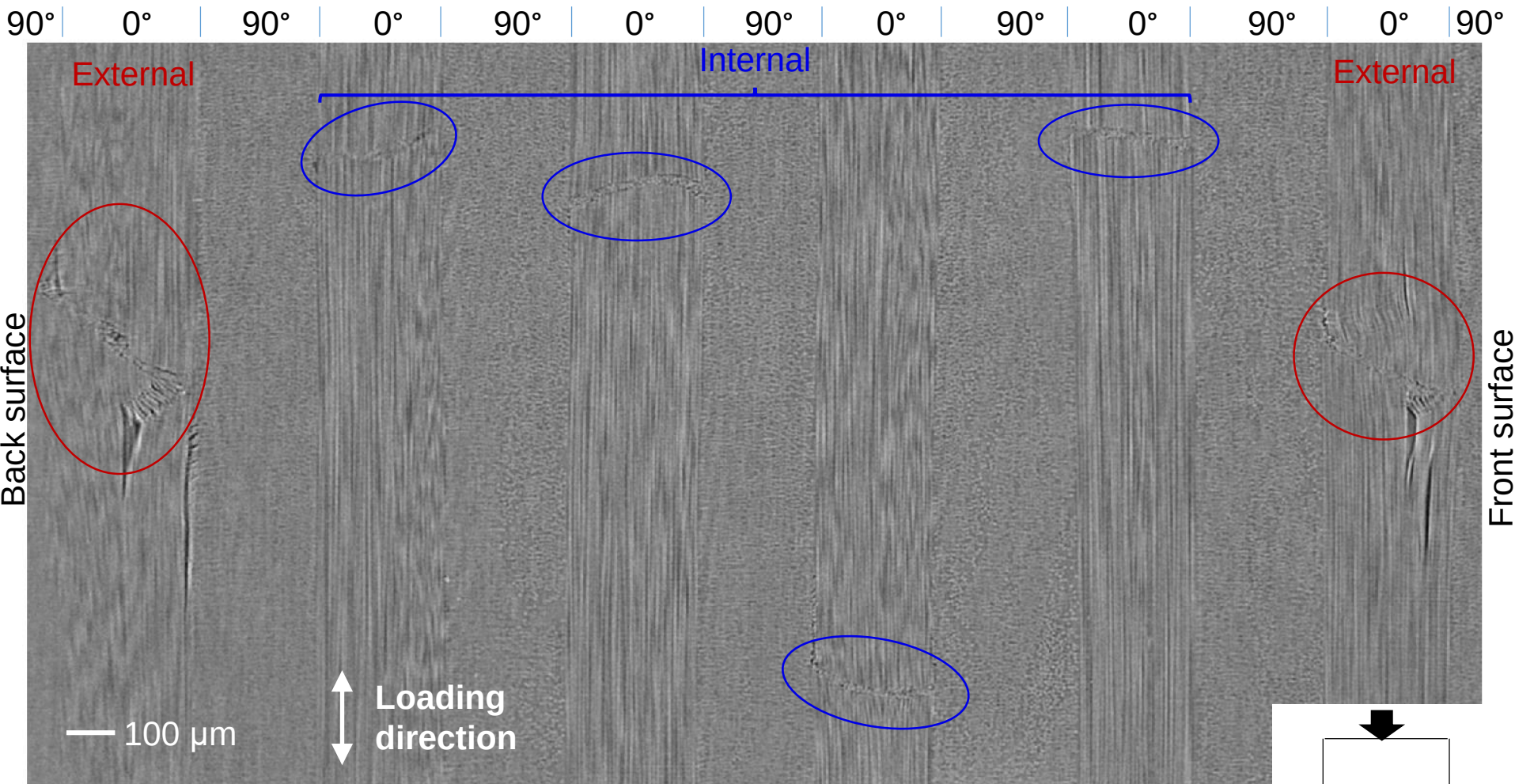


- Kink bands may occur in any plane, given by ψ
- As a simplifying assumption, focus on limiting cases: **in-plane** and **out-of-plane** kinking

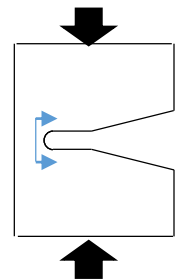
Limiting cases



Motivation



- Image shows damage just before collapse
- Exterior most 0° plies kinked **out-of-plane**; interior kinked **in-plane**
- **How do in-plane kinks and out-of-plane kinks contribute to collapse?**



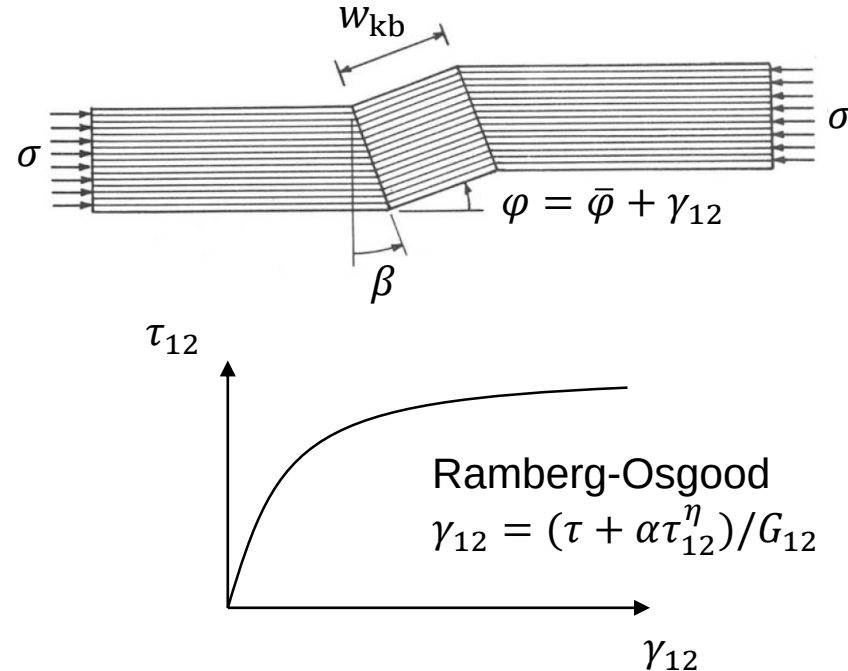
Outline

- Fiber kinking model
 - Review previous 2-D kinking model
 - New 3-D formulation
- Verification
 - Single element studies
 - Unnotched compression
- Validation: Double edge notched compression
 - Comparison of results from 2-D and 3-D kinking models
 - Predictions using measured initial fiber misalignments
- Concluding remarks

Fiber Kinking Theory (FKT)

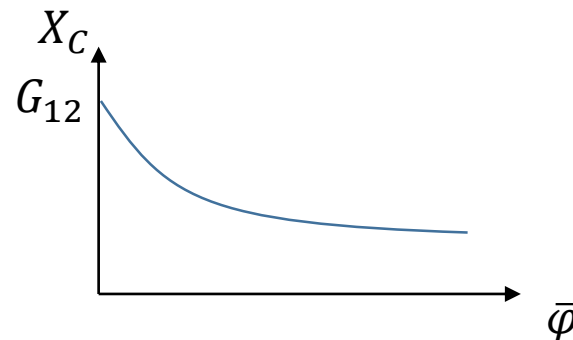
- Budiansky proposed that kink bands are a result of:

- An initial (infinitely wide) band of misaligned fibers, $\bar{\varphi}$
- Nonlinear material behavior under shear loading
- Accounting for large rotations of the fibers



- Imperfection sensitivity

$$X_C = \frac{G_{12}}{1 + \eta \alpha^{1/\eta} \left(\frac{G_{12} \bar{\varphi}}{\eta - 1} \right)^{\frac{\eta-1}{\eta}}}$$



Previous 2-D Fiber Kinking Model

CompDam is a NASA Langley CDM code that uses the deformation gradient

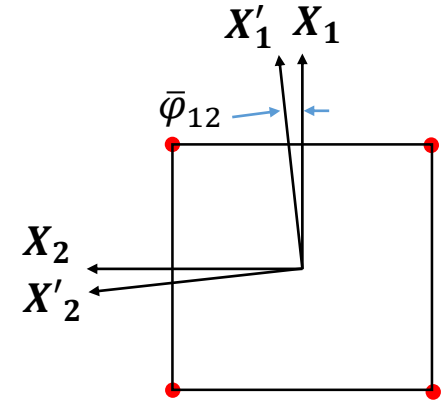
- Particular attention paid to kinematics of cracking

$$\mathbf{E}_{GL} = \frac{1}{2}(\mathbf{F}^T \mathbf{F} - \mathbf{I})$$

$$\mathbf{E}'_{GL} = \mathbf{R}^T \mathbf{E}_{GL} \mathbf{R}$$

$$\bar{\varphi}_{12} \leq |\varphi_c| = \frac{\eta - 1}{G_{12}} \left(\frac{G_{12} - X_C}{X_C \eta \alpha^{1/\eta}} \right)^{\frac{\eta}{\eta-1}}$$

$$\mathbf{R} = \begin{bmatrix} \cos \bar{\varphi}_{12} & -\sin \bar{\varphi}_{12} & 0 \\ \sin \bar{\varphi}_{12} & \cos \bar{\varphi}_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



$$\mathbf{E}'_{GL} = \mathbf{E}'_{GL} - \frac{\gamma_{PL}}{2} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\gamma_{12} = \frac{1}{G_{12}} [\tau_{12} + \text{sign}(\tau_{12}) \alpha |\tau_{12}|^\eta] \quad (\text{Ramberg-Osgood})$$

$$\gamma_{12}^{PL} = \gamma_{12} - \gamma_{12}^{EL}$$

$$\mathbf{S}' = \mathbf{C} : \mathbf{E}'_{GL}$$

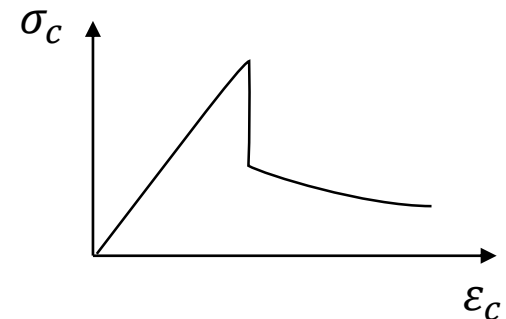
$$E_1 = E_1^0 (1 + c_l \varepsilon_{11})$$

$$\mathbf{S} = \mathbf{R} \mathbf{S}' \mathbf{R}^T$$

$$\boldsymbol{\sigma} = \mathbf{F} \mathbf{S} \mathbf{F}^T |\mathbf{F}|^{-1}$$

Highlights

- Captures characteristics of FKT
- Tracks fiber rotation
- Constitutive response is an outcome of the model; not prescribed directly



New 3-D Fiber Kinking Model

CompDam is a NASA Langley CDM code that uses the deformation gradient

- Particular attention paid to kinematics of cracking

$$\mathbf{E}_{GL} = \frac{1}{2}(\mathbf{F}^T \mathbf{F} - \mathbf{I})$$

$$\mathbf{E}'_{GL} = \mathbf{R}^T \mathbf{E}_{GL} \mathbf{R}$$

$$\left\{ \begin{array}{l} \bar{\varphi}_{1i} \leq \frac{\eta - 1}{G_{LT}} \left(\frac{G_{LT} - X_C}{X_C \eta \alpha^{1/\eta}} \right)^{\frac{\eta}{\eta-1}} \\ \mathbf{R} = \begin{bmatrix} \cos \bar{\varphi}_{12} & -\sin \bar{\varphi}_{12} & 0 \\ \sin \bar{\varphi}_{12} & \cos \bar{\varphi}_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \bar{\varphi}_{13} & 0 & -\sin \bar{\varphi}_{13} \\ 0 & 1 & \cos \bar{\varphi}_{13} \\ \sin \bar{\varphi}_{13} & 0 & 0 \end{bmatrix} \end{array} \right. \begin{array}{l} G_{LT} = G_{12} = G_{13} \\ \alpha = \alpha_{12} = \alpha_{13} \\ \eta = \eta_{12} = \eta_{13} \end{array}$$

$$\mathbf{E}'_{GL} = \mathbf{E}'_{GL} - \frac{\gamma_{12}^{PL}}{2} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} - \frac{\gamma_{13}^{PL}}{2} \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

$$\left\{ \begin{array}{l} \gamma_{1i} = \frac{1}{G_{LT}} [\tau_{1i} + \text{sign}(\tau_{1i}) \alpha |\tau_{1i}|^\eta] \\ \gamma_{1i}^{PL} = \gamma_{1i} - \gamma_{1i}^{EL} \end{array} \right.$$

$$\mathbf{S}' = \mathbf{C} : \mathbf{E}'_{GL}$$

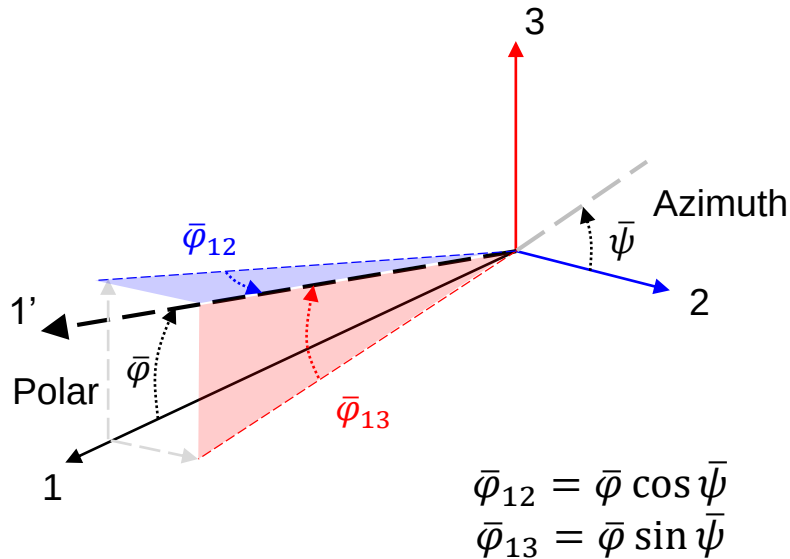
$$\left\{ \begin{array}{l} E_1 = E_1^0 (1 + c_l \varepsilon_{11}) \end{array} \right.$$

$$\mathbf{S} = \mathbf{R} \mathbf{S}' \mathbf{R}^T$$

$$\boldsymbol{\sigma} = \mathbf{F} \mathbf{S} \mathbf{F}^T |\mathbf{F}|^{-1}$$

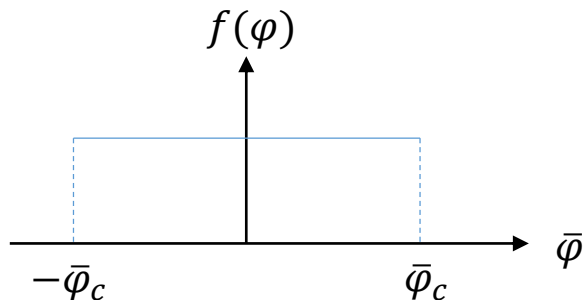
Initial Fiber Misalignment

Based on X_c



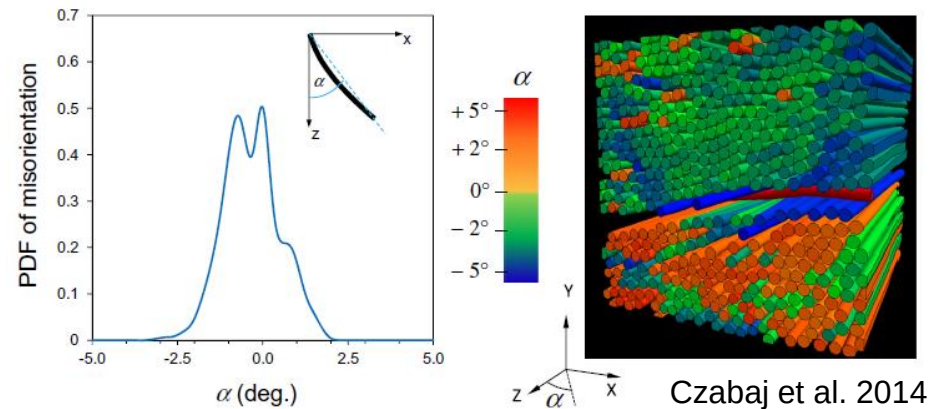
$$\bar{\varphi}_c = \frac{\eta - 1}{G_{LT}} \left(\frac{G_{LT} - X_C}{X_C \eta \alpha^{1/\eta}} \right)^{\frac{\eta}{\eta-1}} \quad \begin{array}{l} \bar{\varphi} \in [0, \bar{\varphi}_c) \\ \bar{\psi} \in [-\pi, \pi) \end{array}$$

Assume random uniform distribution:



Based on Measurements

- Published measurements of $\bar{\varphi}$ based on optical microscopy or X-ray computed tomography images are available



- Few include both $\bar{\varphi}$ and $\bar{\psi}$
- Most are for small volume ($2 \mu\text{m}^3$)
- Generally expect differences based on material architecture and manufacturing process

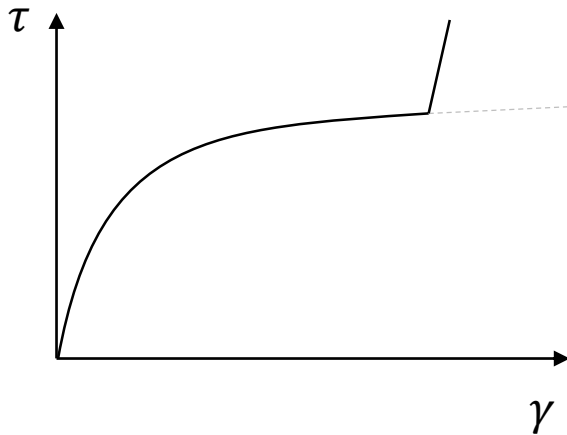
Approach:

- Given likelihood of occurrence data for $\bar{\varphi}$ and $\bar{\psi}$, fit with a probability density function
- Sample $\bar{\varphi}$ and $\bar{\psi}$ following the distribution

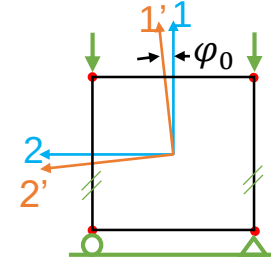
Fiber Failure

- Assume that fiber failure occurs when $\varphi = \varphi_{ff}$
- Hold γ_{PL} constant

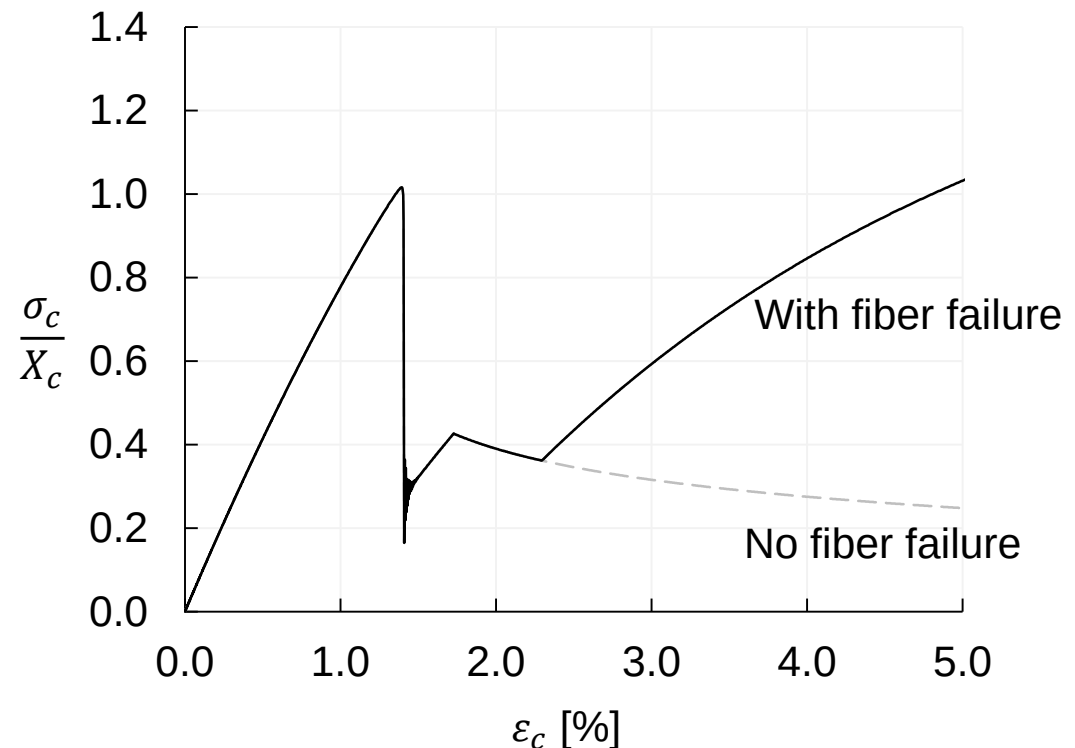
Modified Shear Stress-Strain



Single Element Demonstration



Assume $\varphi_{ff} = 10^\circ$

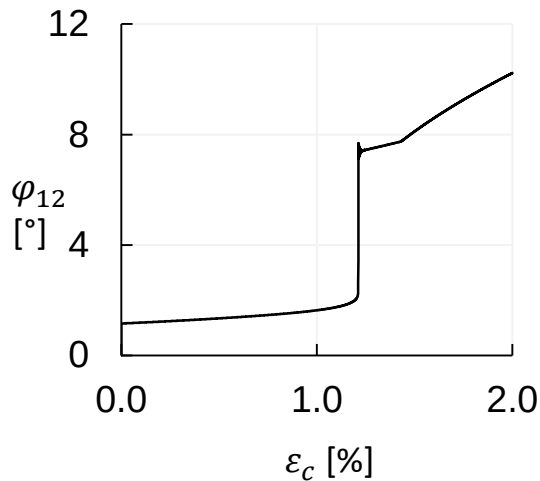


Outline

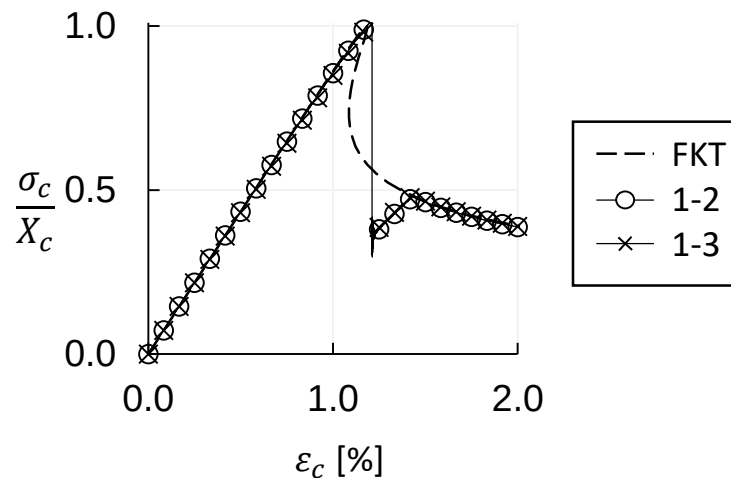
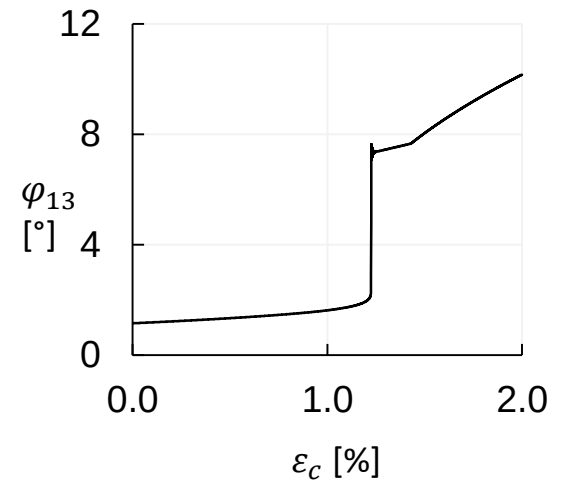
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Single Element: In-Plane vs. Out-of-Plane Kinking

In-Plane kinking $\bar{\varphi} = \bar{\varphi}_c$
 $\bar{\psi} = 0$



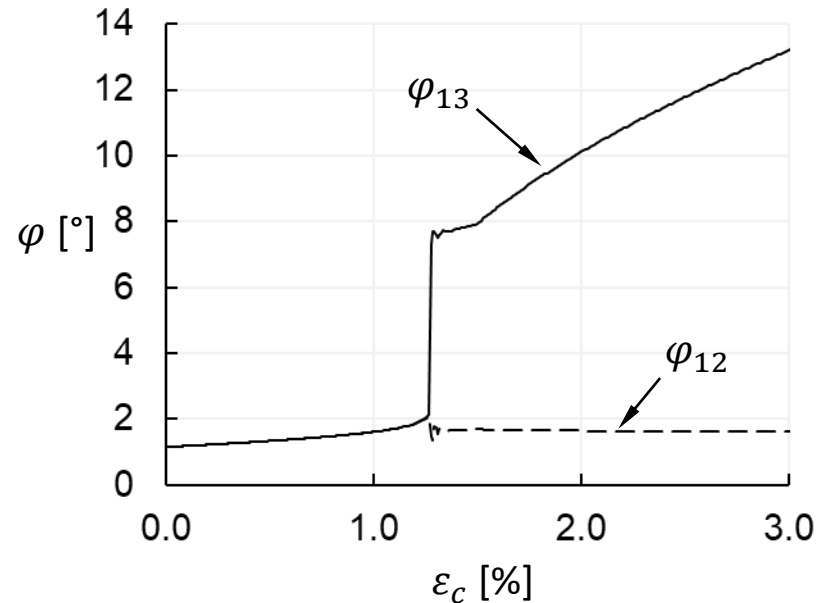
Out-of-plane kinking $\bar{\varphi} = \bar{\varphi}_c$
 $\bar{\psi} = \pi/2$



Verified fiber kinking response in 1-2 and 1-3 planes independently

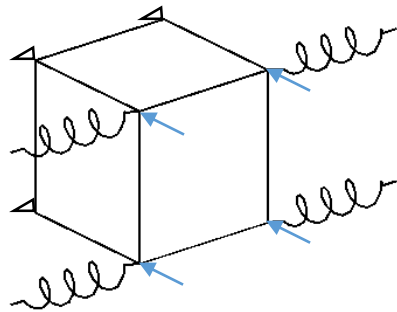
Single Element: Perturbation of Initial Misalignment

- Start with: $\bar{\varphi}_{12} = \bar{\varphi}_{13} = \bar{\varphi}_c$
- Adding a small perturbation $\bar{\varphi}_{13} = \varphi_c(1 + \delta_\varphi)$ where $\delta_\varphi = 0.001$ results in out-of-plane kinking
- Small perturbation to $\bar{\varphi}_{12}$ produces an in-plane kink
- When $\bar{\varphi}_{12} = \bar{\varphi}_{13} = \bar{\varphi}_c$ the model predicts either $\psi = 0^\circ$ or $\psi = 90^\circ$ (numerical sensitivity)
- The model is predisposed to predict in-plane, $\psi = 0^\circ$, or out-of-plane kinking, $\psi = 90^\circ$ (instead of an intermediate kinking plane $0^\circ < \psi < 90^\circ$) since:
 - Formulated in the principal material planes
 - Shear non-linearity is uncoupled between the two planes

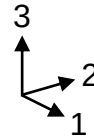
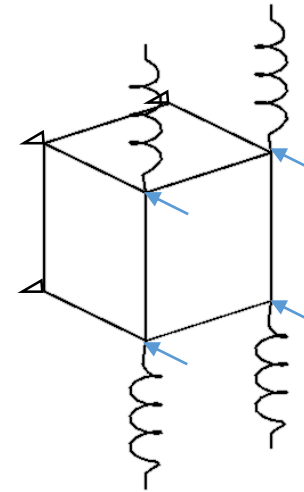


Single Element: Effect of Constraint on Kinking Plane

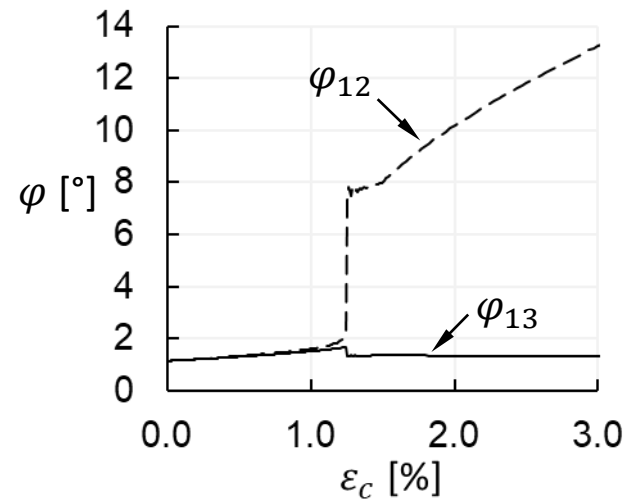
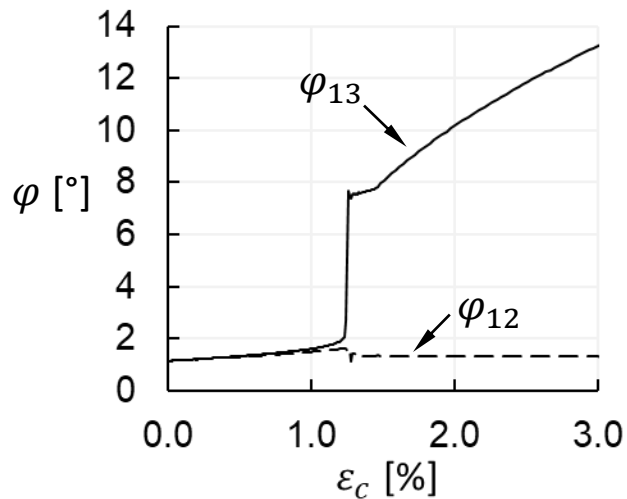
Simulated in-plane constraint



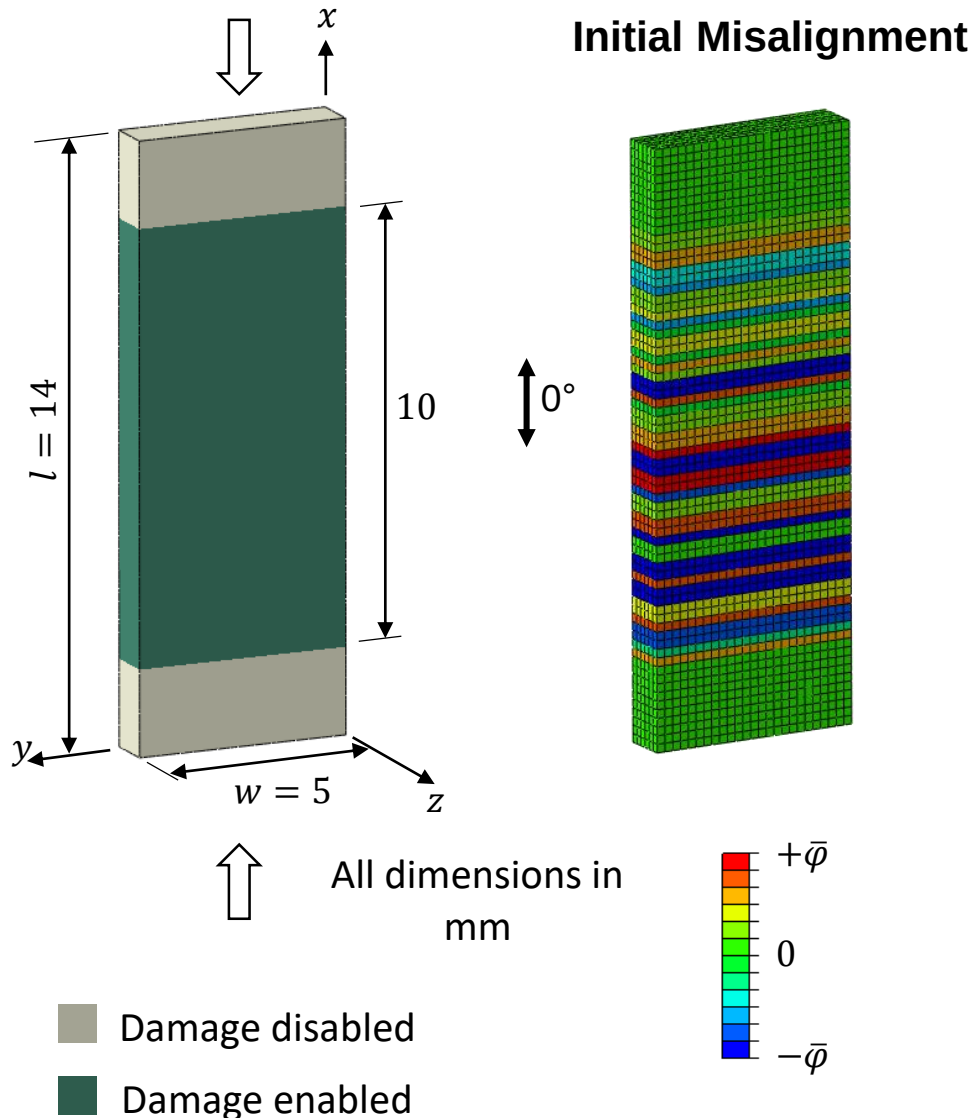
Simulated out-of-plane constraint



$$\bar{\varphi}_{12} = \bar{\varphi}_{13} = \bar{\varphi}_c$$



Unnotched Compression

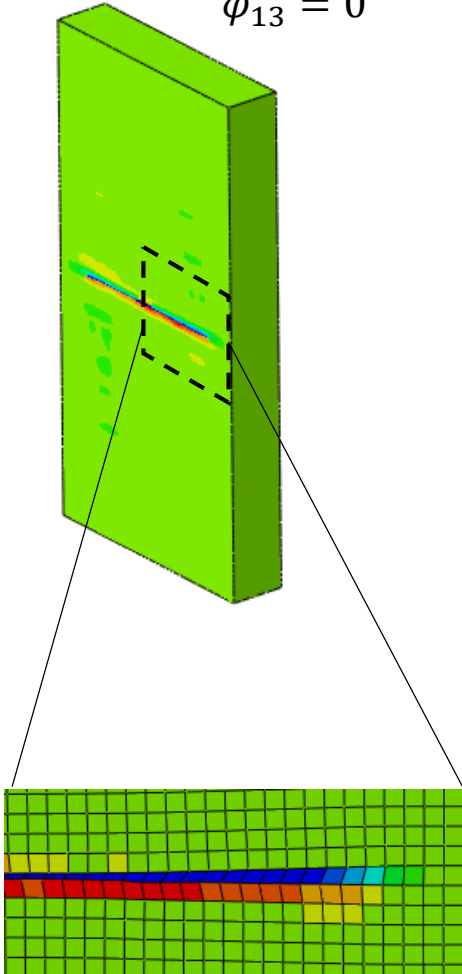


- Geometry and boundary conditions chosen to resemble a typical unnotched compression test specimen
- Initial misalignment serves as a perturbation to trigger damage localization (uniform random distribution)
- Material: IM7/8552, unidirectional [Wanthal 2017]
- Considered three cases for initial misalignments
- Automatic mass scaling

Unnotched Compression: Plastic Strain

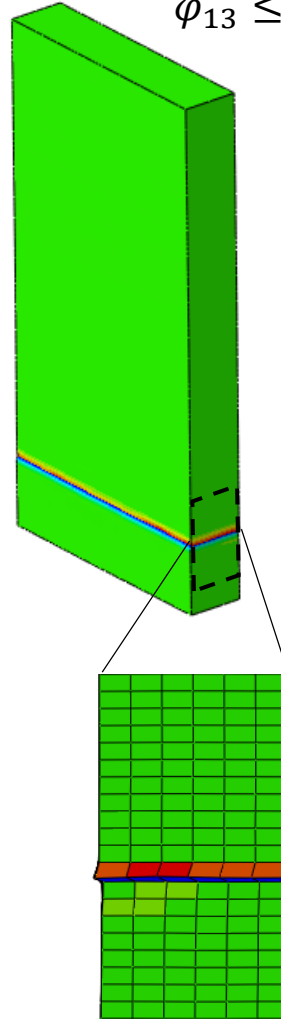
In-Plane kinking

$$\bar{\varphi}_{12} \leq \bar{\varphi}_c$$
$$\bar{\varphi}_{13} = 0$$



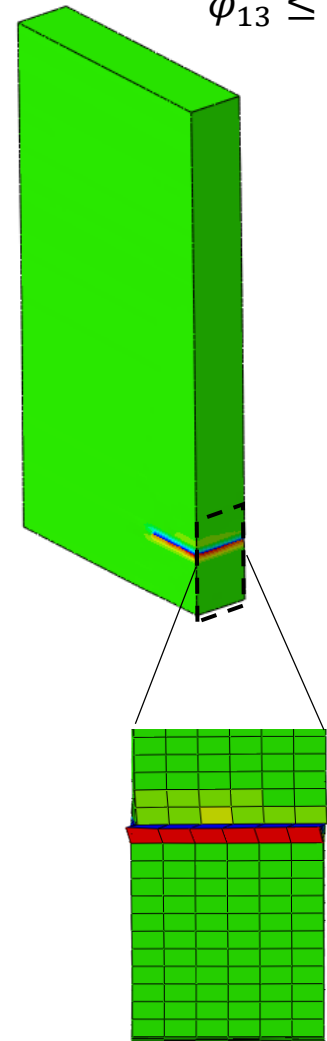
Out-of-Plane kinking

$$\bar{\varphi}_{12} = 0$$
$$\bar{\varphi}_{13} \leq \bar{\varphi}_c$$



3-D kinking

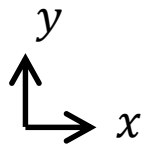
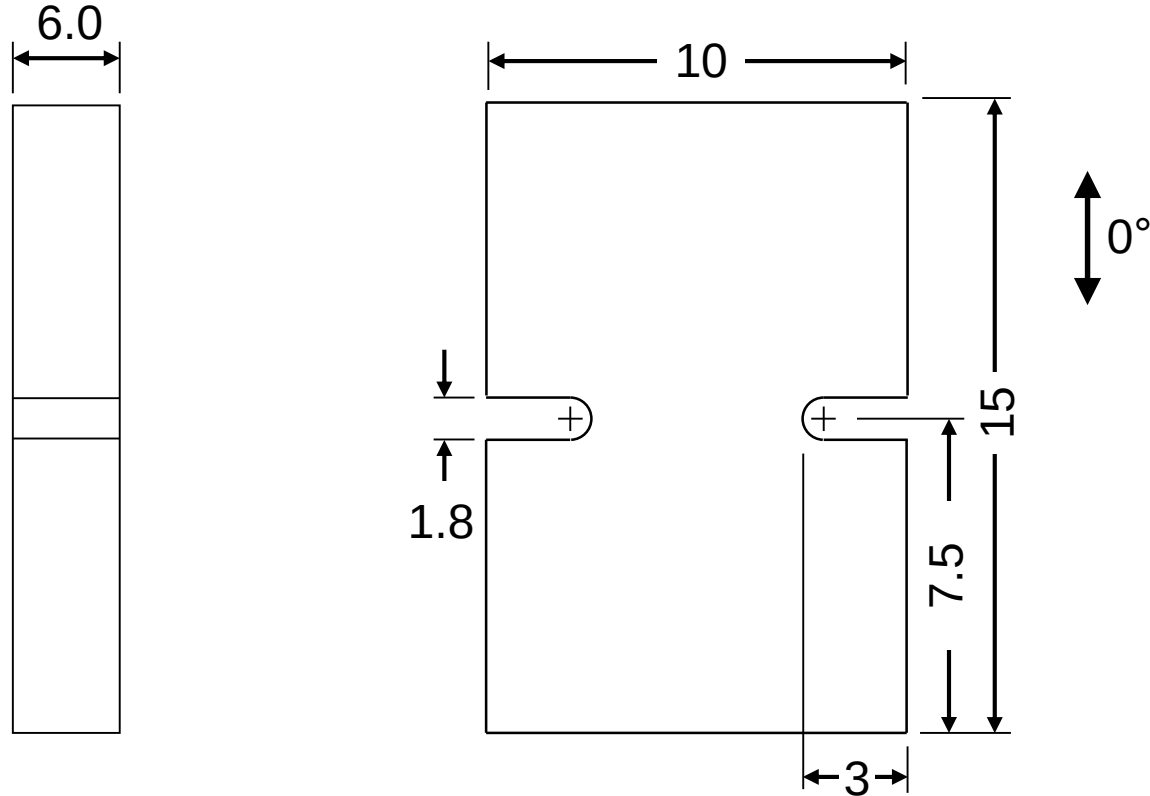
$$\bar{\varphi}_{12} \leq \bar{\varphi}_c$$
$$\bar{\varphi}_{13} \leq \bar{\varphi}_c$$



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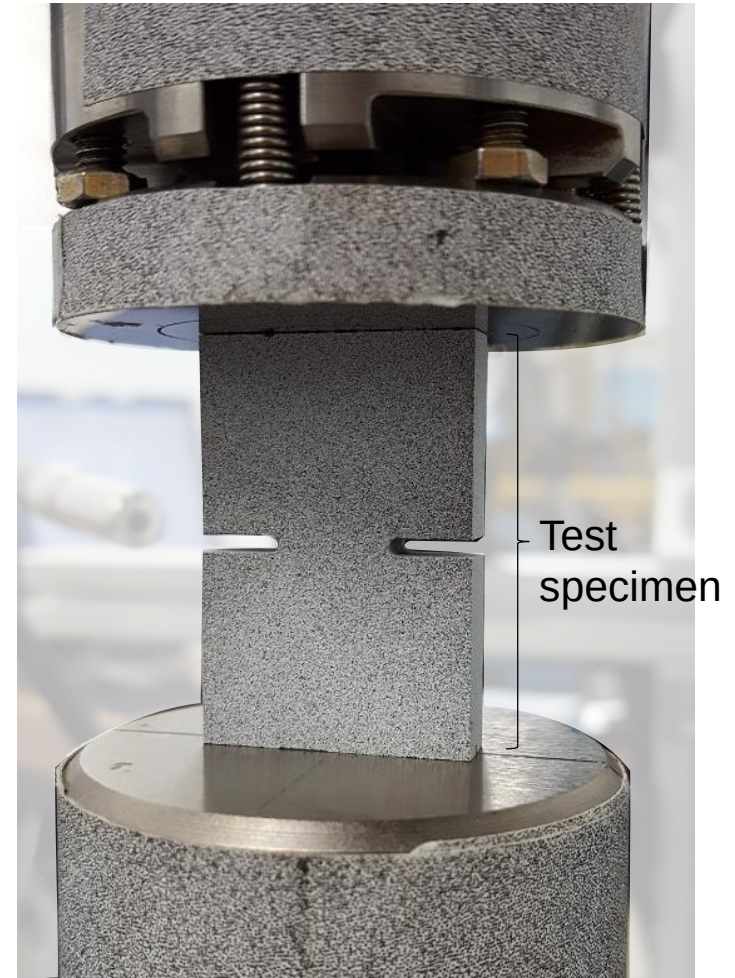
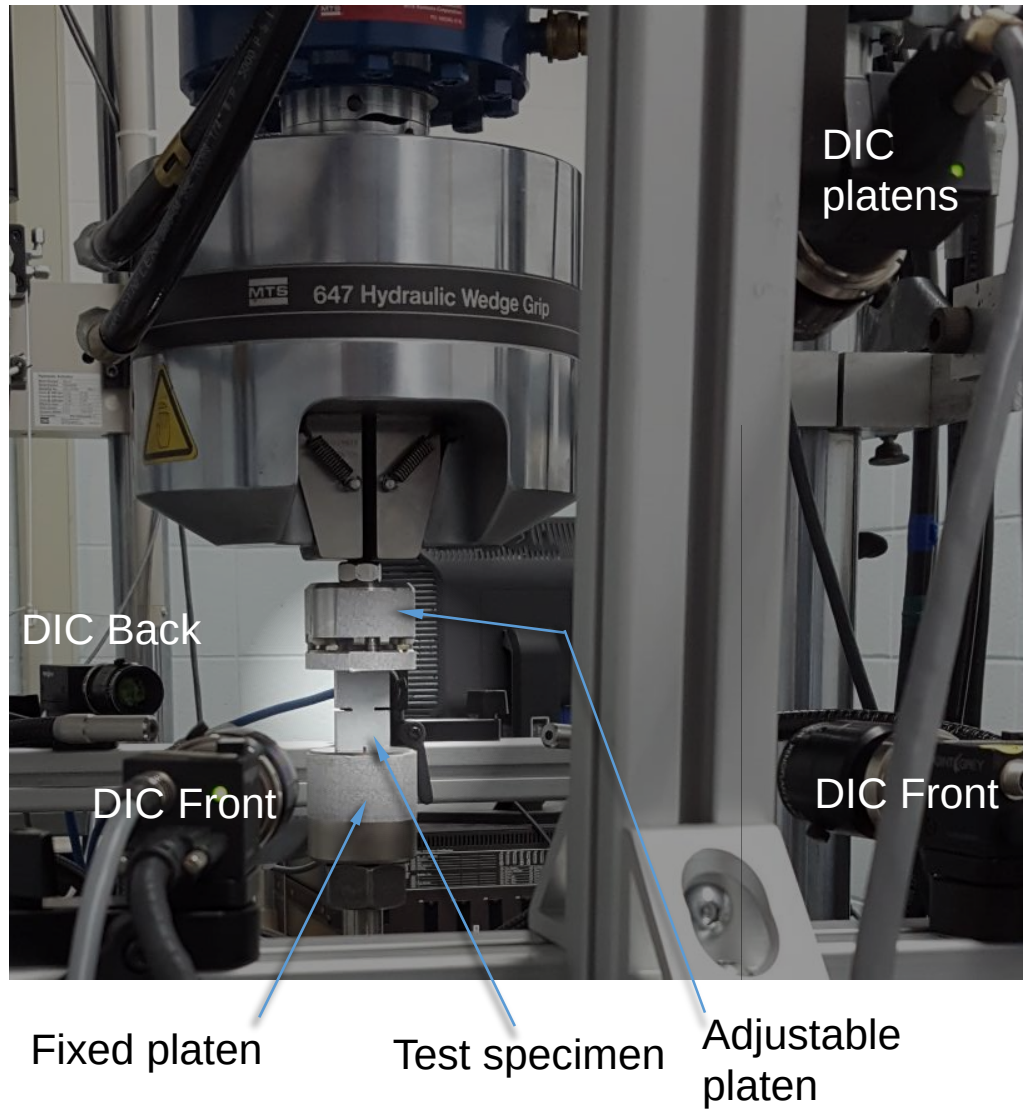
Double Edge Notch Compression (DENC) Specimen Configuration



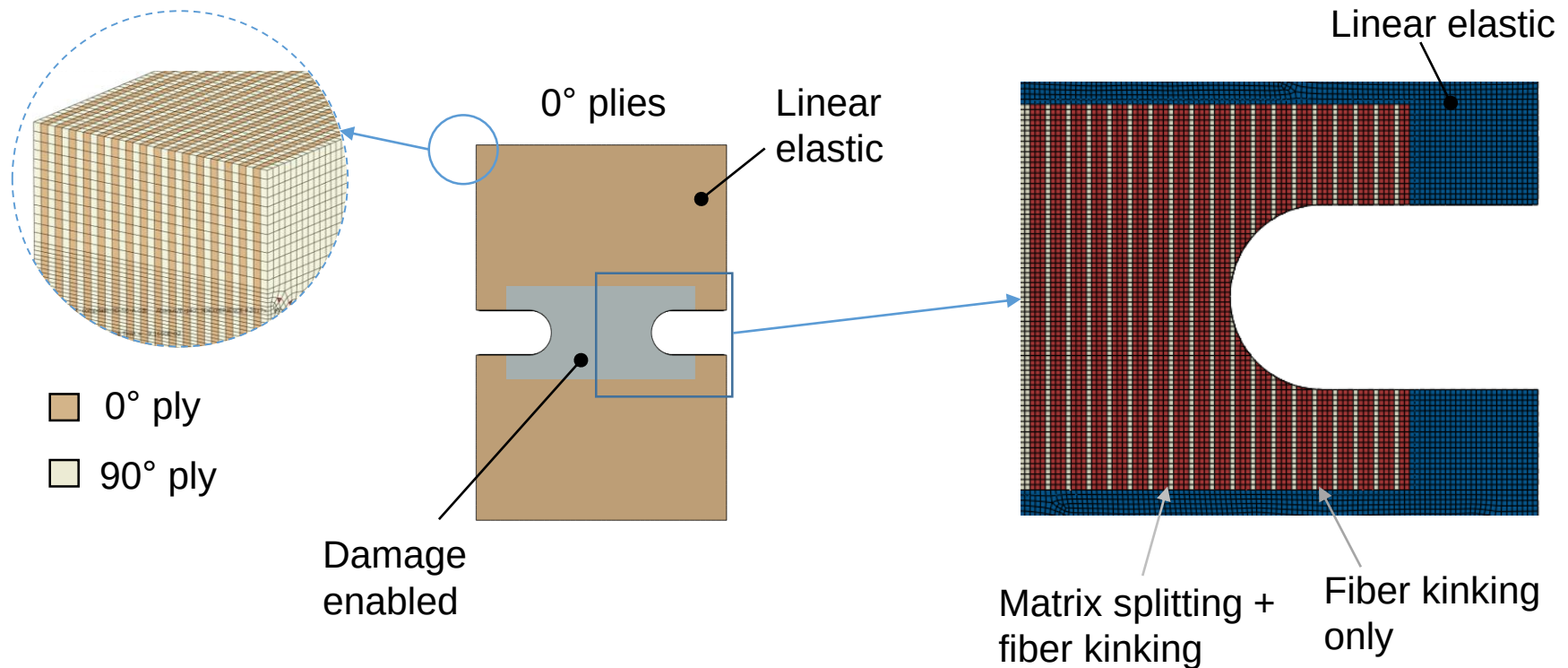
Notes:

1. All dimensions in mm
2. 33 ply Layup $[(90/0)_8/90/(0/90)_8]$
3. $a/w = 0.6$
4. Four replicates of each size

Test Setup



Model Overview



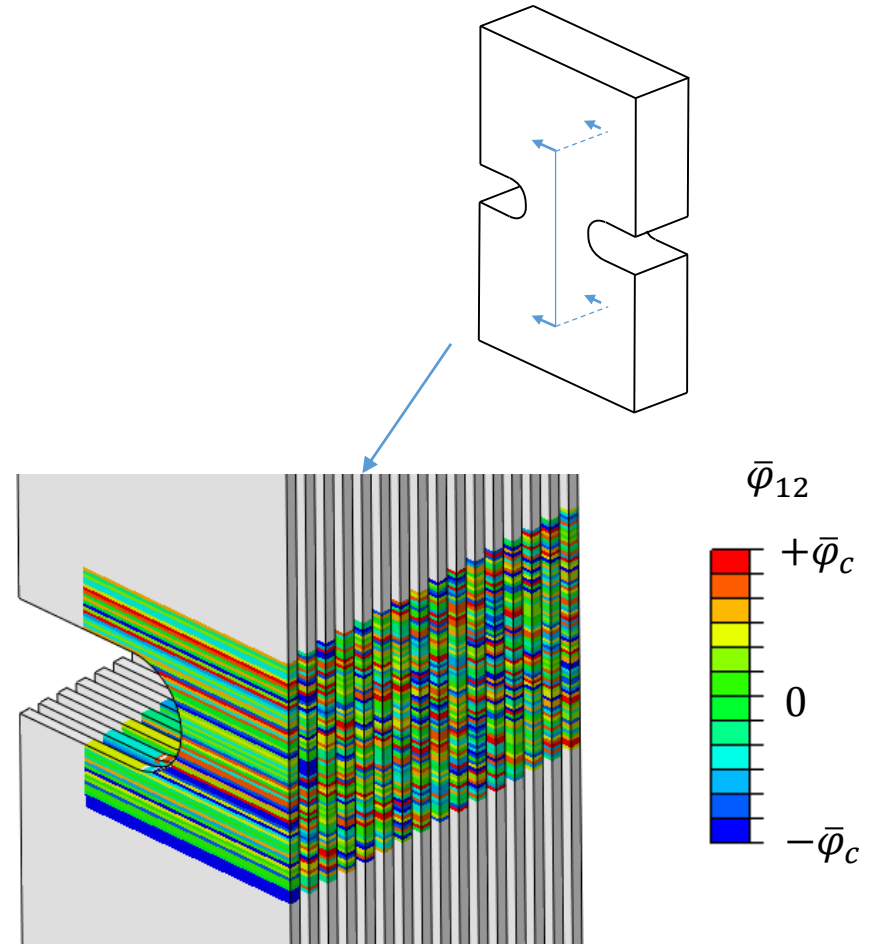
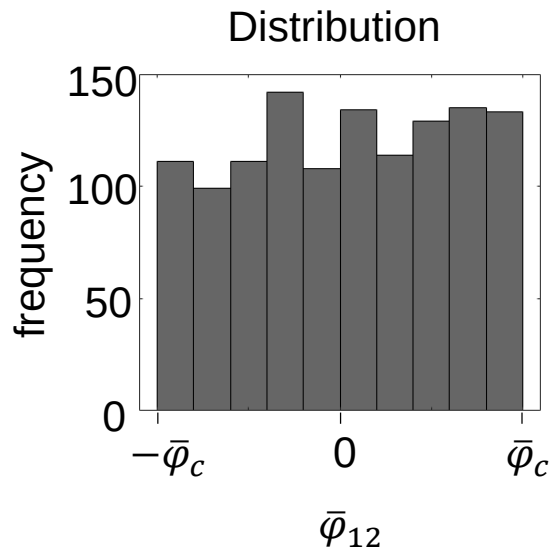
Notes:

1. IM7/8552; material properties from Wanthal et al. 2017
2. Aligned mesh, min element size = 0.05 mm, C3D8R
3. No damage allowed in the 90° plies
4. Cohesive elements at all ply interfaces

Initial Fiber Misalignments: 2-D (in-plane) kinking

$$\bar{\varphi}_{12} = \bar{\varphi} = \bar{\varphi}_c$$
$$\bar{\psi} = 0$$

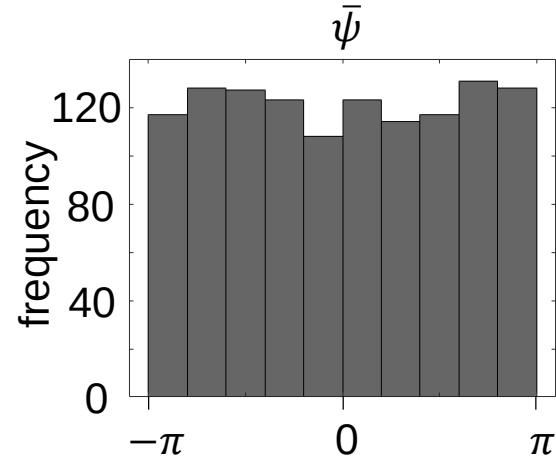
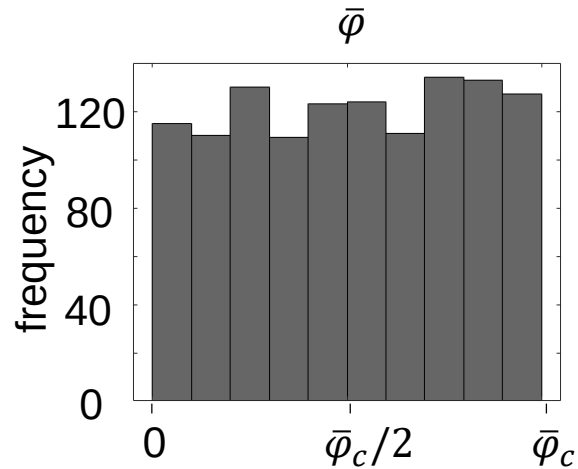
- Random uniform distribution for $\bar{\varphi}$
- 1-D spatial variation in $\bar{\varphi}$; each ply has different realization of $\bar{\varphi}$



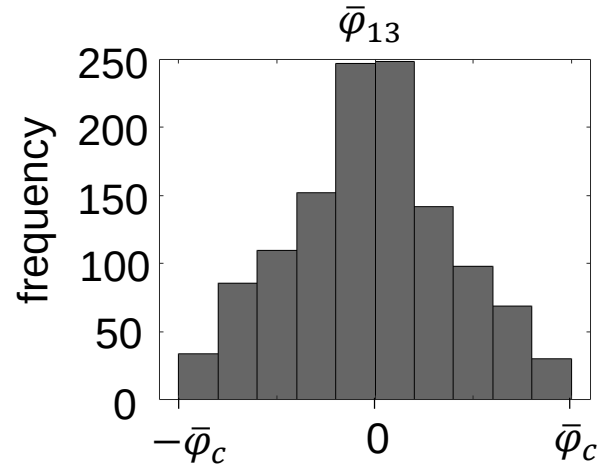
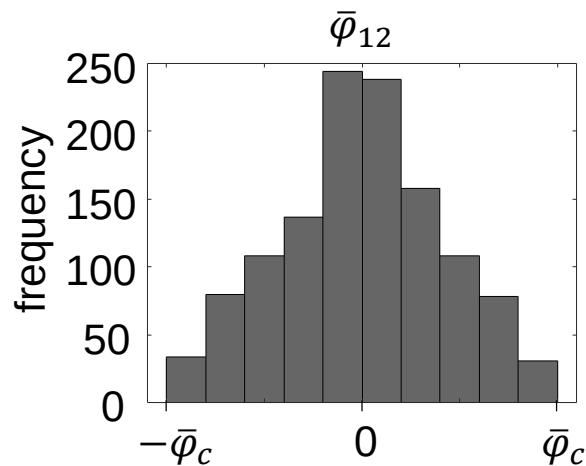
Realization of $\bar{\varphi}_{12}$
(only 0° plies shown)

Initial Fiber Misalignments: 3-D kinking

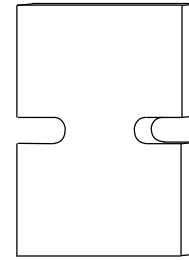
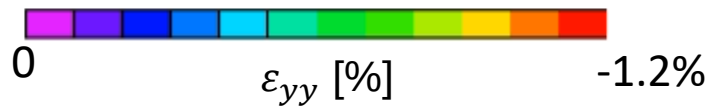
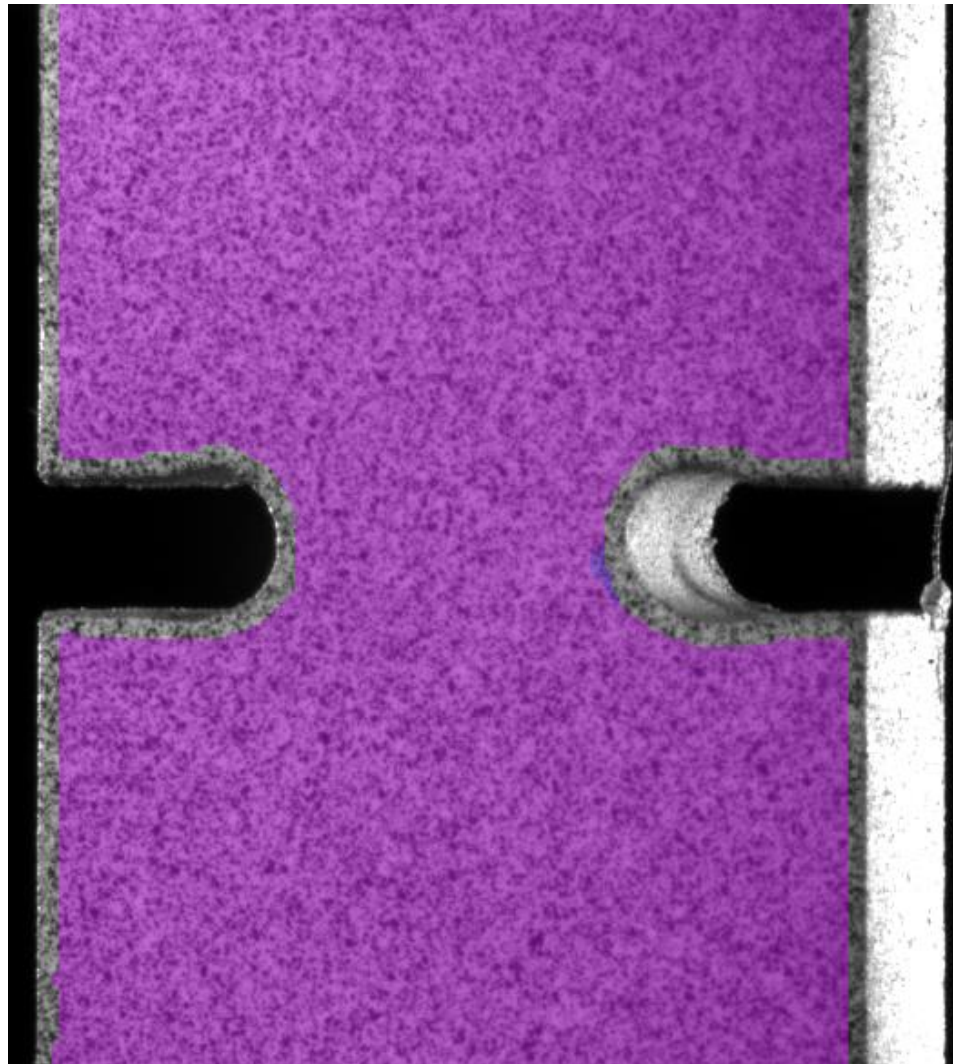
- Random uniform distribution for $\bar{\varphi}$ and $\bar{\psi}$



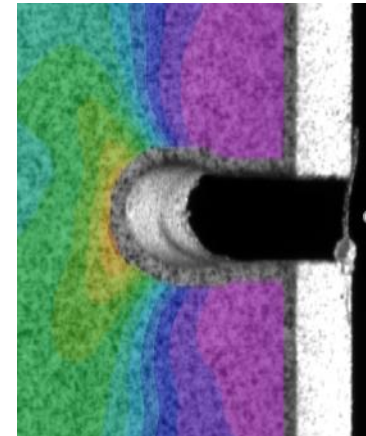
- Transforming to principal material planes:



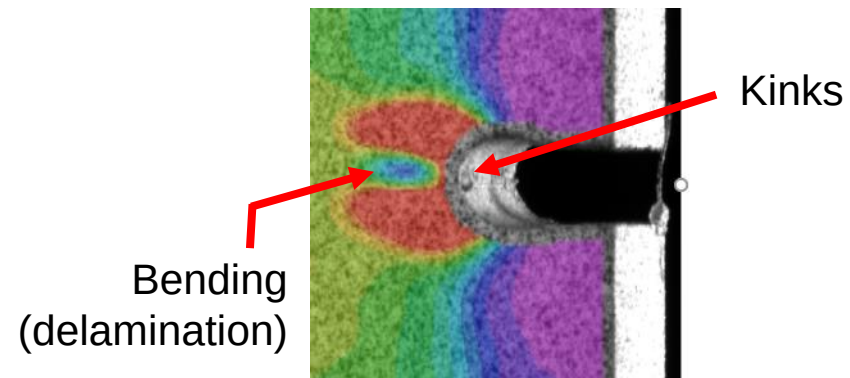
Typical Test Result



Before visible damage

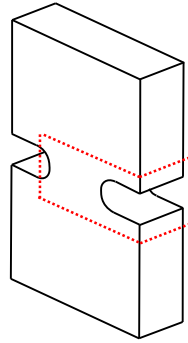


Before collapse

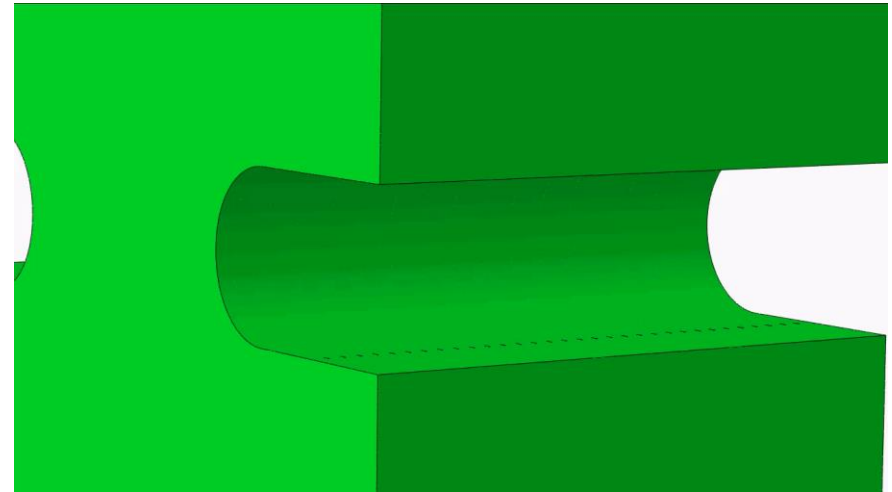
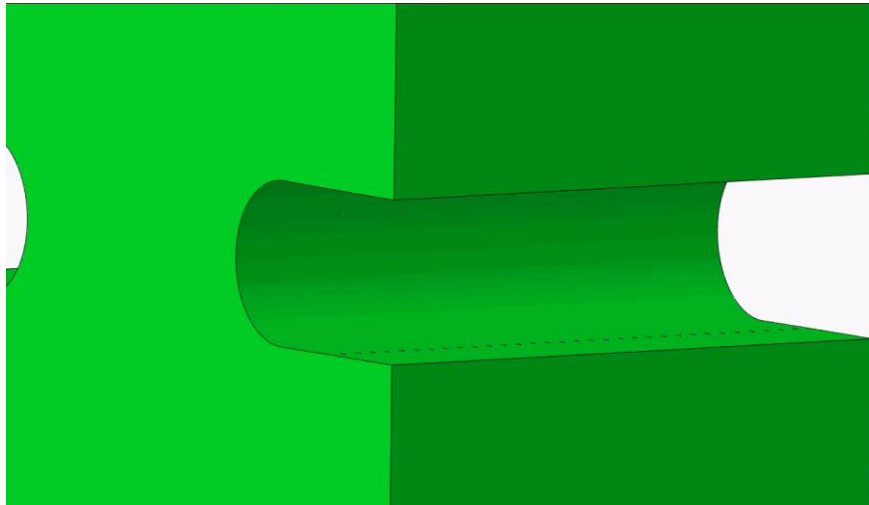


2-D Kinking vs. 3-D Kinking: Animated Collapse

2-D (in-plane) kinking

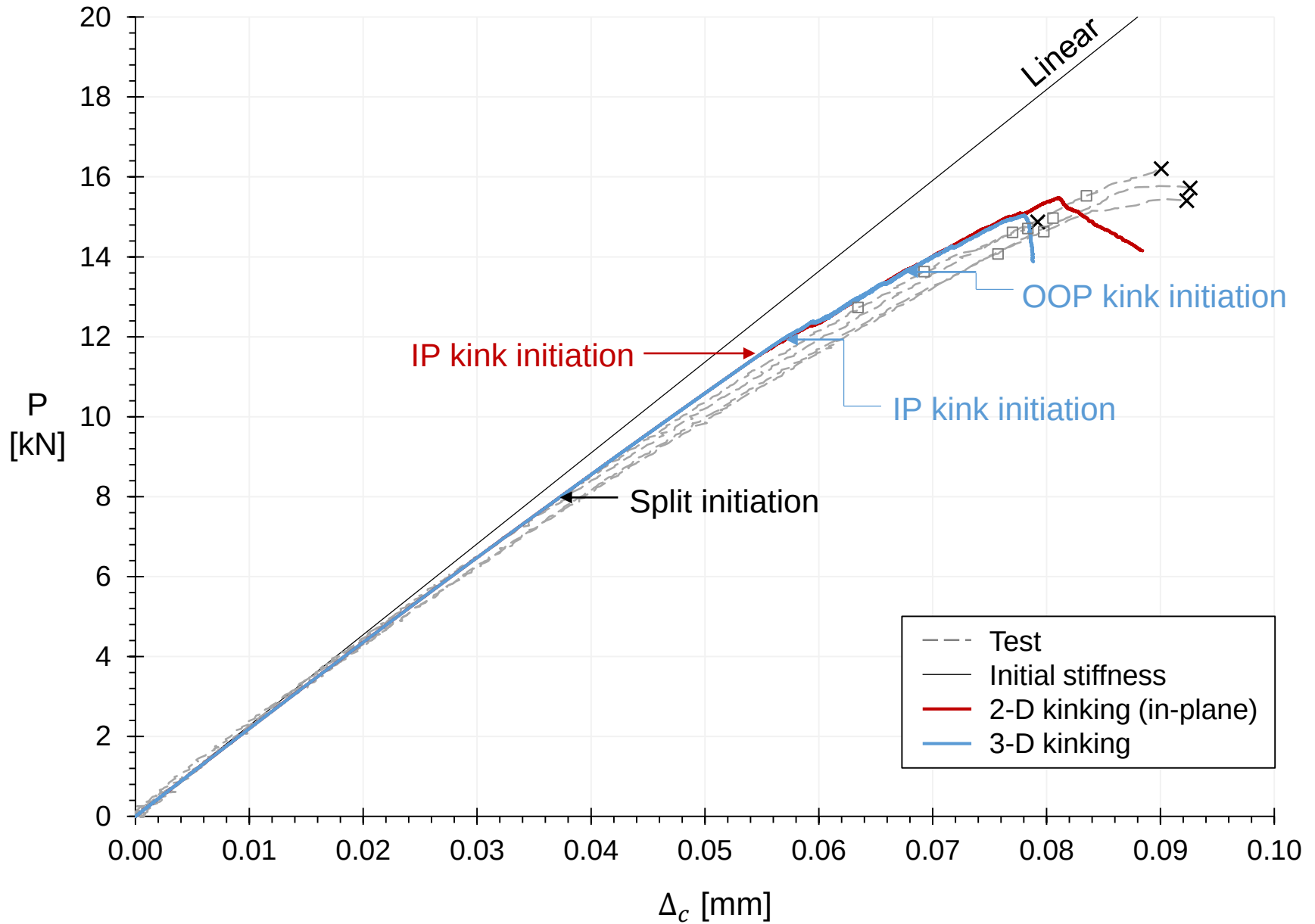


3-D kinking

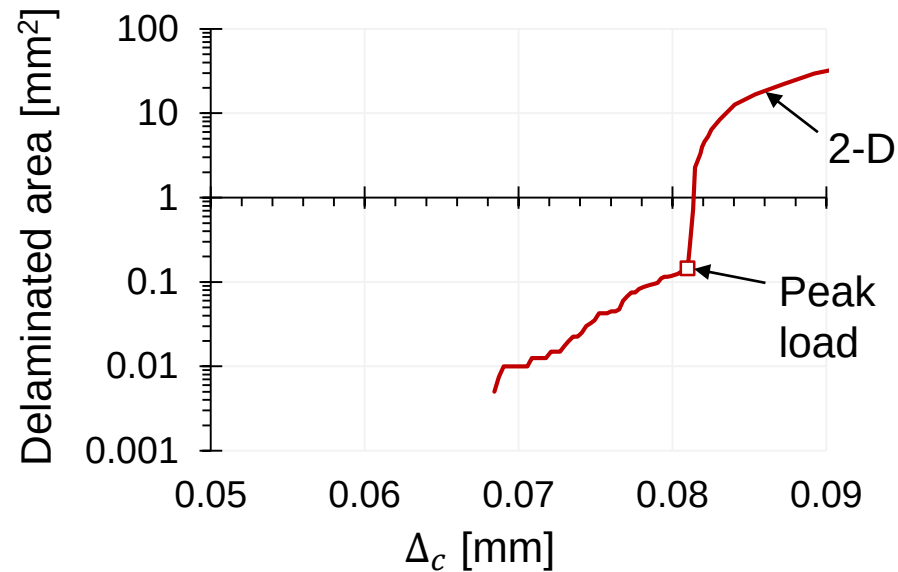


- 2-D kinking model predicts slightly higher failure load
- Otherwise, two model results look nearly identical
- Transverse compressive cracks in 90° plies are omitted so deformed shape of 90° plies appears unrealistic

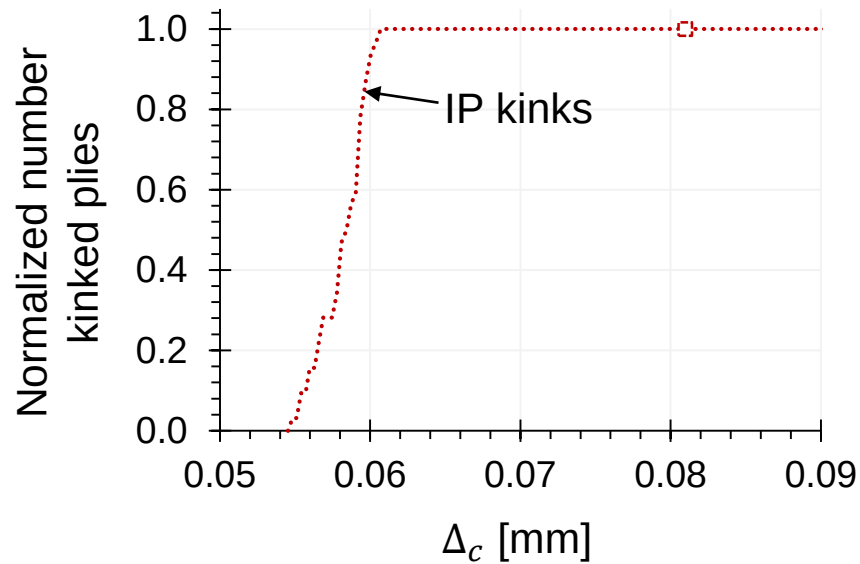
Load vs. Displacement



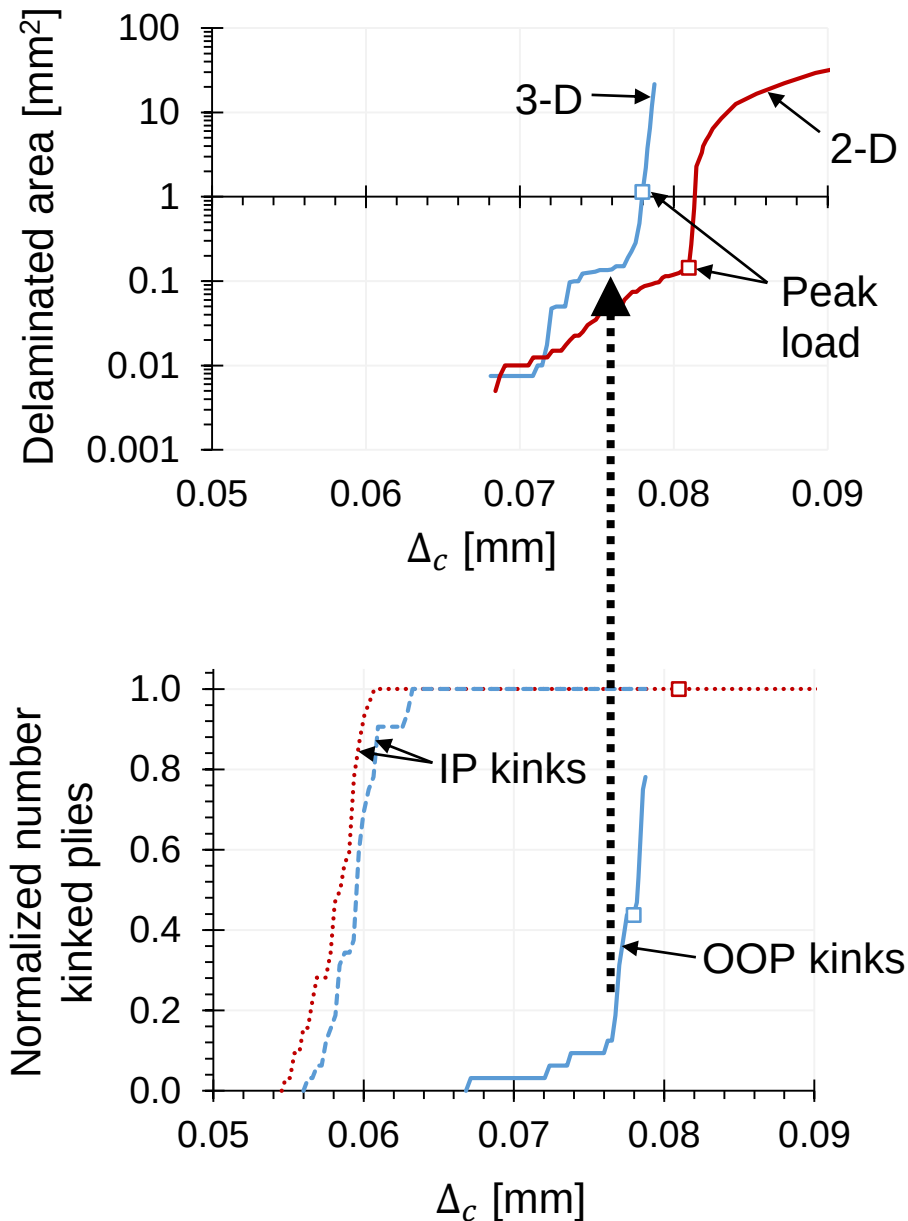
2-D Kinking vs. 3-D Kinking: Key Differences



- 2-D kinking model (red)
 - Steady accumulation of kinks and delamination up to peak load
 - Significant delamination at peak load
 - Peak load coincides with artificial strain energy increase; apparent numeric instability



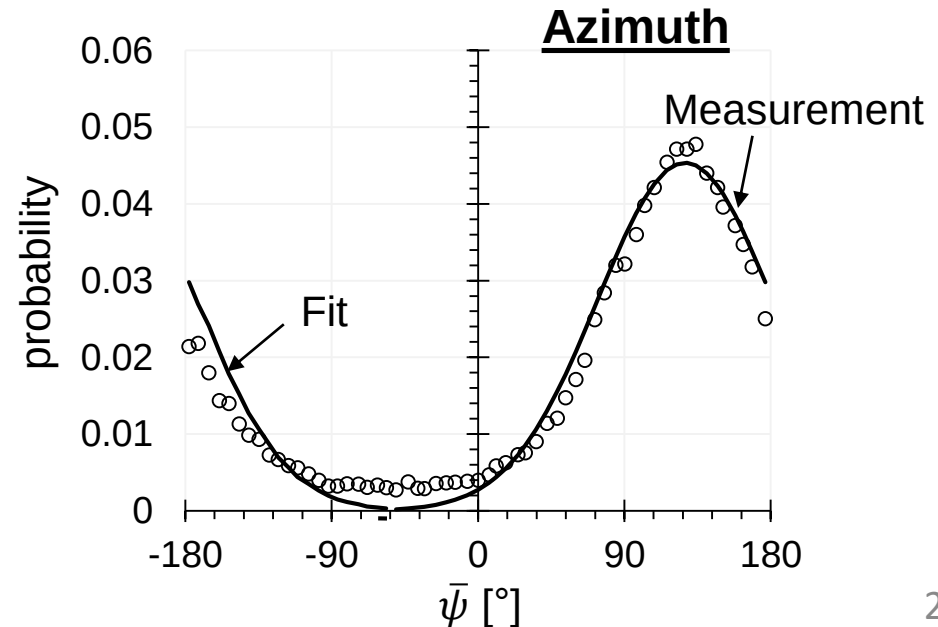
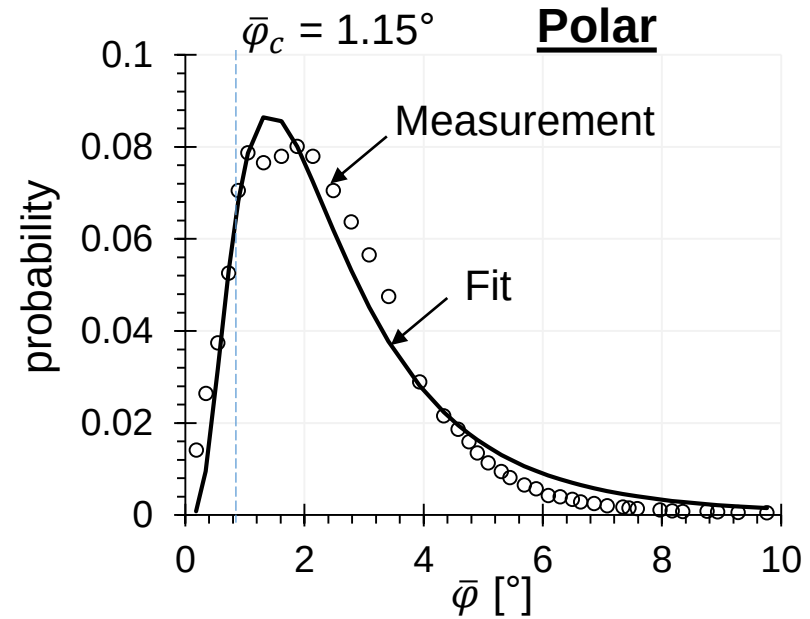
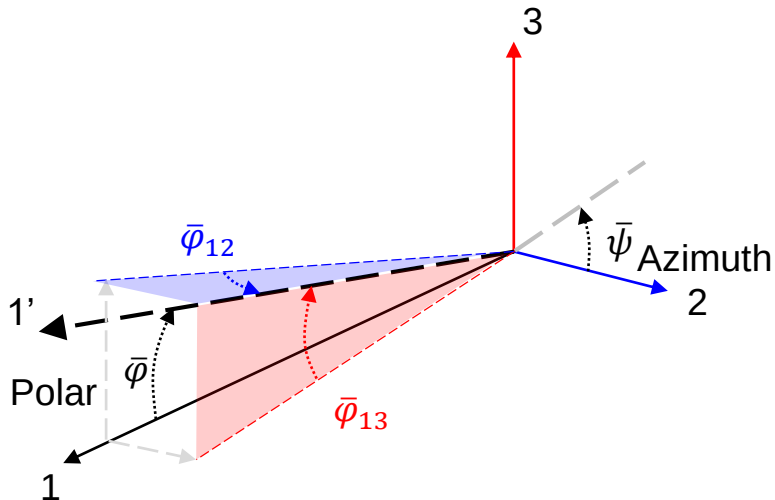
2-D Kinking vs. 3-D Kinking: Key Differences



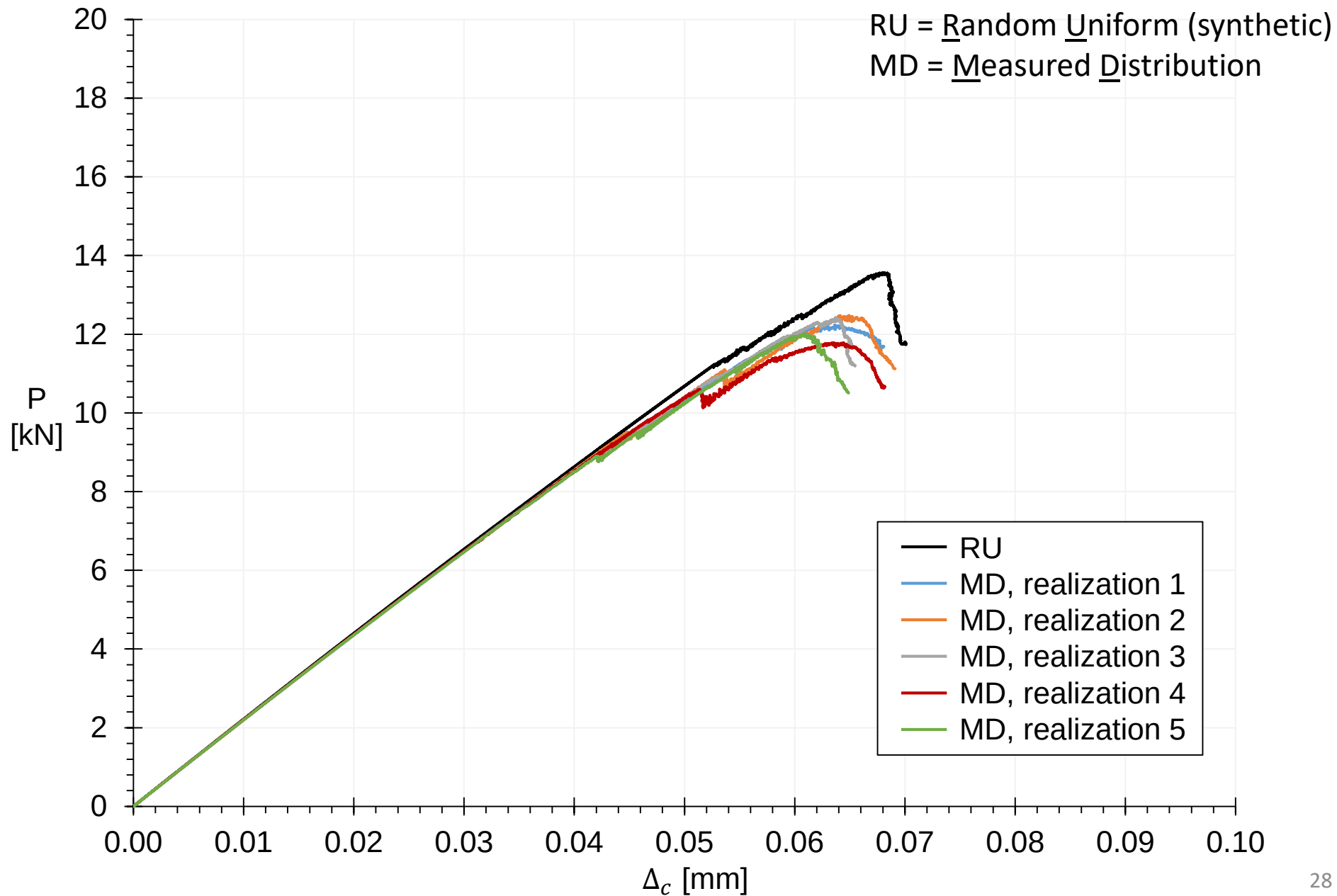
- 2-D kinking model (red)
 - Steady accumulation of kinks and delamination up to peak load
 - Significant delamination at peak load
 - Peak load coincides with artificial strain energy increase; apparent numeric instability
- 3-D kinking model (blue)
 - Two spurts of delamination growth
 - 1st delamination growth coincides with initiation of out-of-plane kinks
 - 2nd delamination growth occurs when out-of-plane kinks are rapidly accumulating
- Conclusion: collapse is governed by interaction of out-of-plane kinking and delamination

Measured Distribution (MD) of Fiber Misalignments

- Experimental measurements by Requena et al. 2009
- Polar angle $\bar{\varphi}$ fit with lognormal distribution
- Azimuth angle fit with Gaussian distribution
- Five realizations analyzed with $\bar{\varphi}$ and $\bar{\psi}$ sampled from these measured distributions



Load vs. Displacement Results Using a Measured Imperfection



Concluding Remarks

1. New model was developed for predicting in-plane and out-of-plane kinking
 - Uncoupled shear nonlinearity in the 1-2 and 1-3 planes
 - Includes a fiber failure criterion
 - Implemented in CompDam
2. Verifications demonstrate capability and sensitivity of the model
 - Good agreement with fiber kinking theory
 - Favors in-plane or out-of-plane but not an intermediate plane due to uncouple shear nonlinearity
3. Comparison of the 3-D kinking model with the previous 2-D model predictions for a double edge notch specimen shows the necessity of the 3-D kinking model
 - Final collapse is governed by interaction of delamination and out-of-plane kinking
 - Measured imperfections appear as a promising alternative to X_C

Thank You!

Questions?

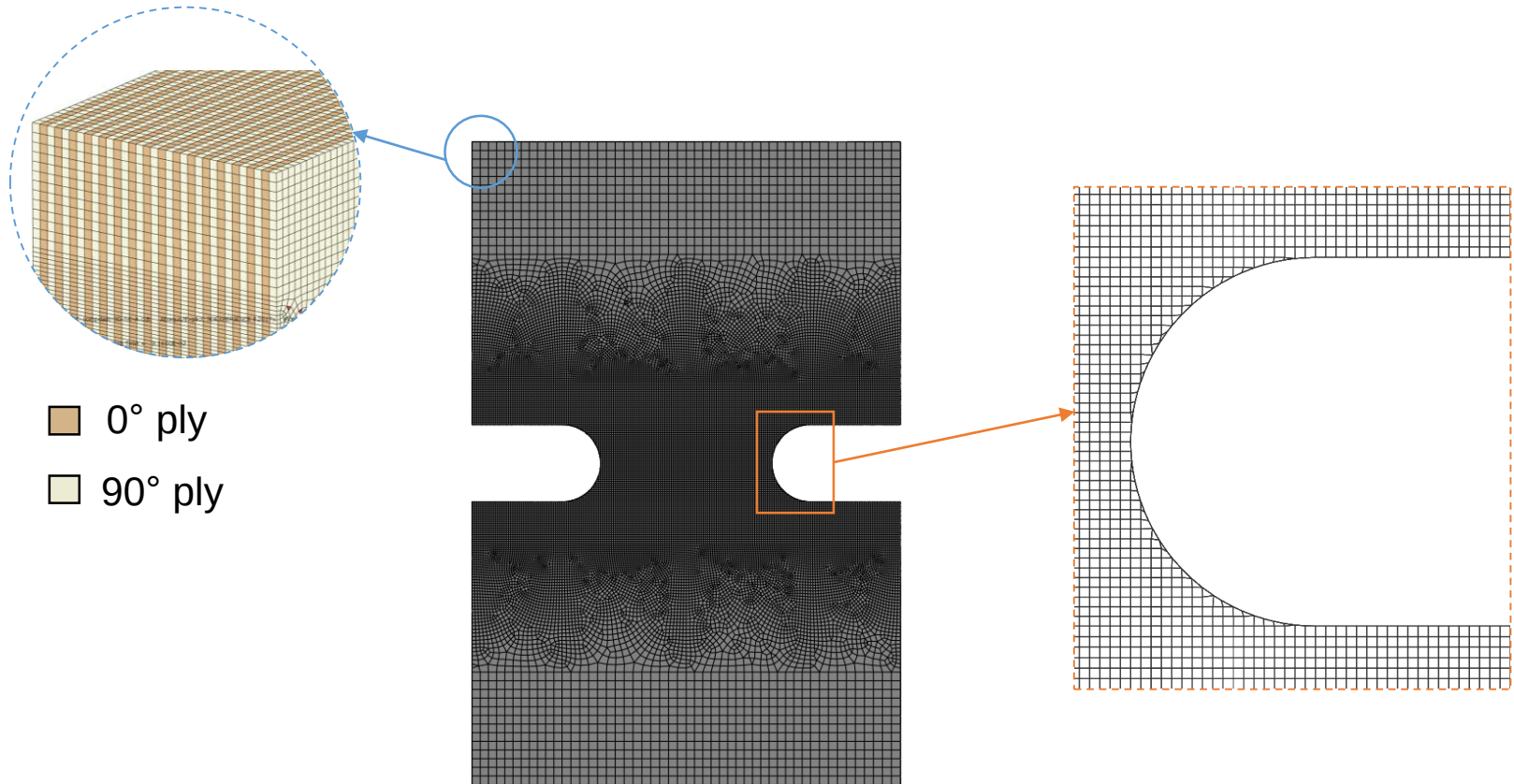
https://github.com/nasa/CompDam_DGD

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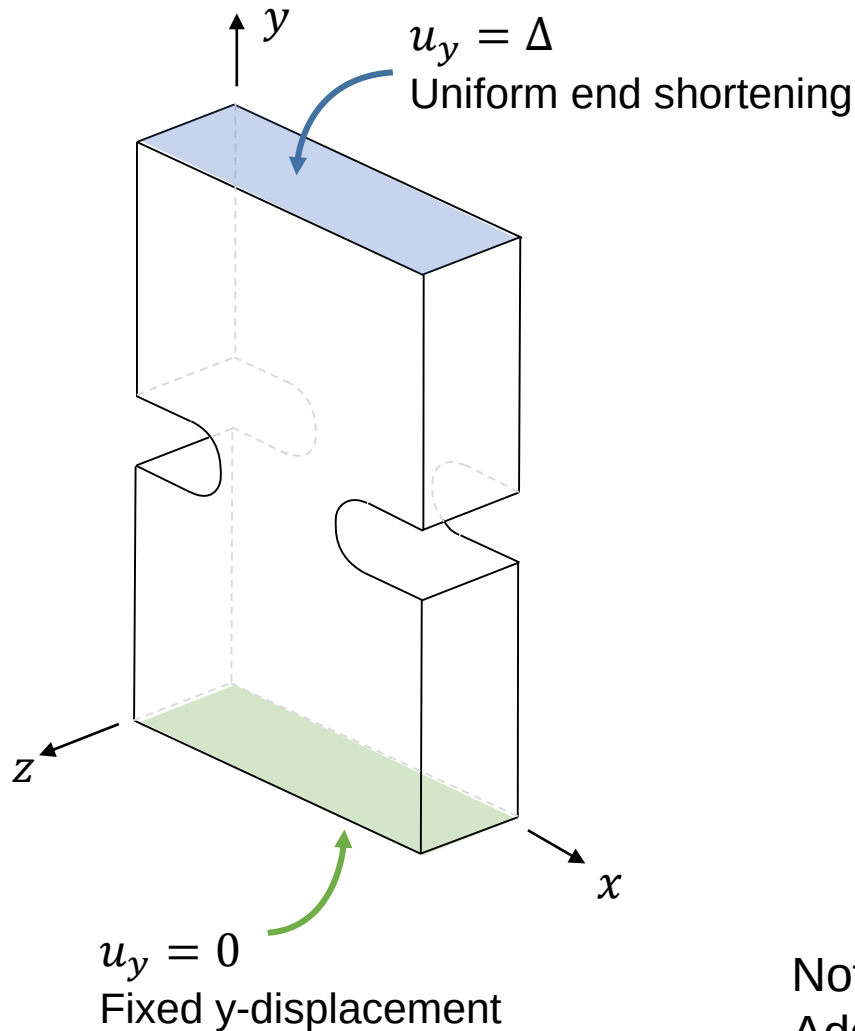
Model Overview



Notes:

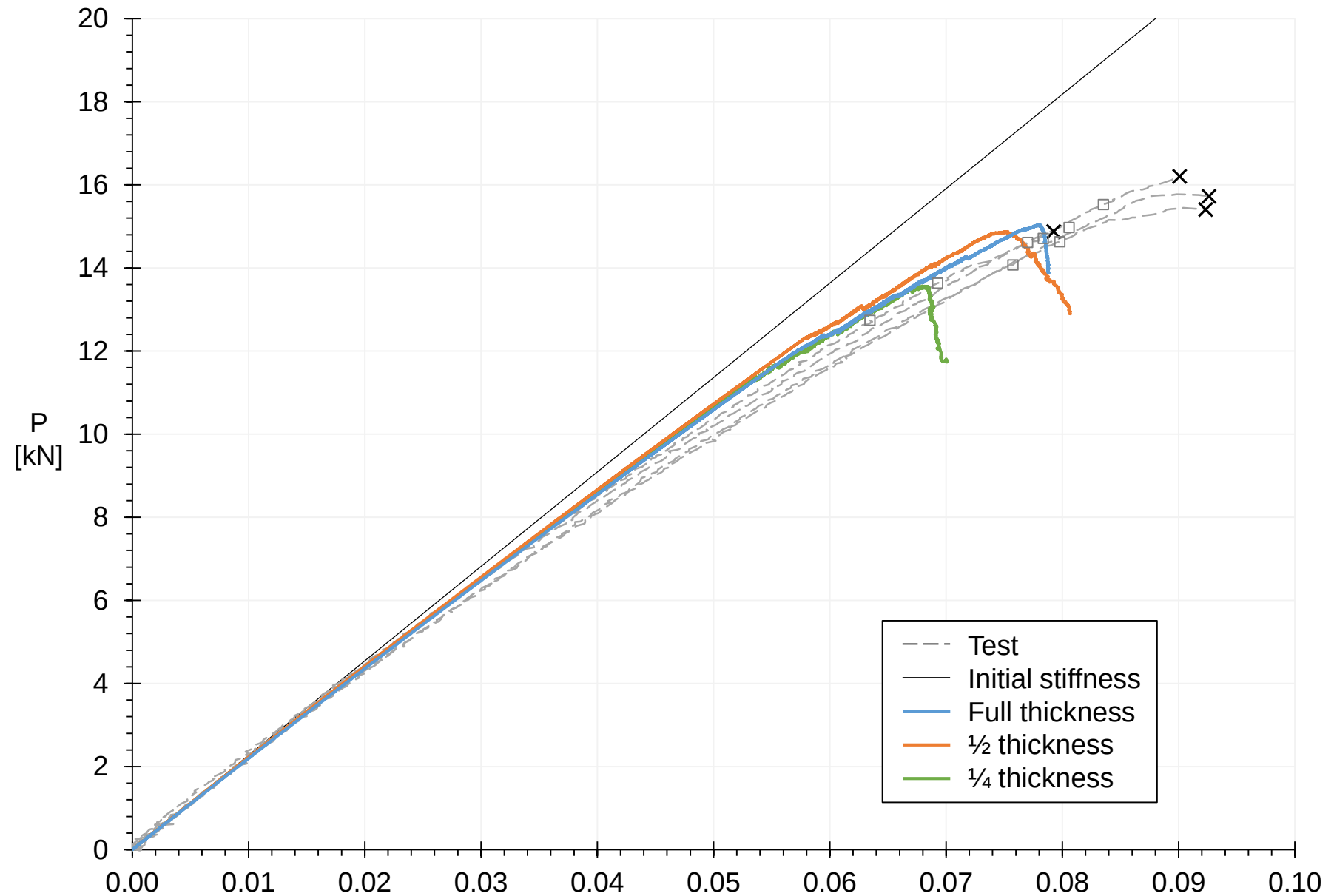
1. Aligned mesh, min element size = 0.05 mm, C3D8R
2. Abaqus 2017, two explicit dynamic steps
3. Automatic mass scaling, step time = 0.1, target inc = $2e-7$

Boundary Conditions

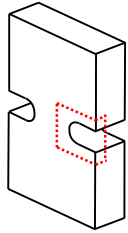


Not shown:
Additional boundary conditions
to prevent rigid body motion

Fractional Thickness Models



2-D Kinking vs. 3-D Kinking: Failure Process



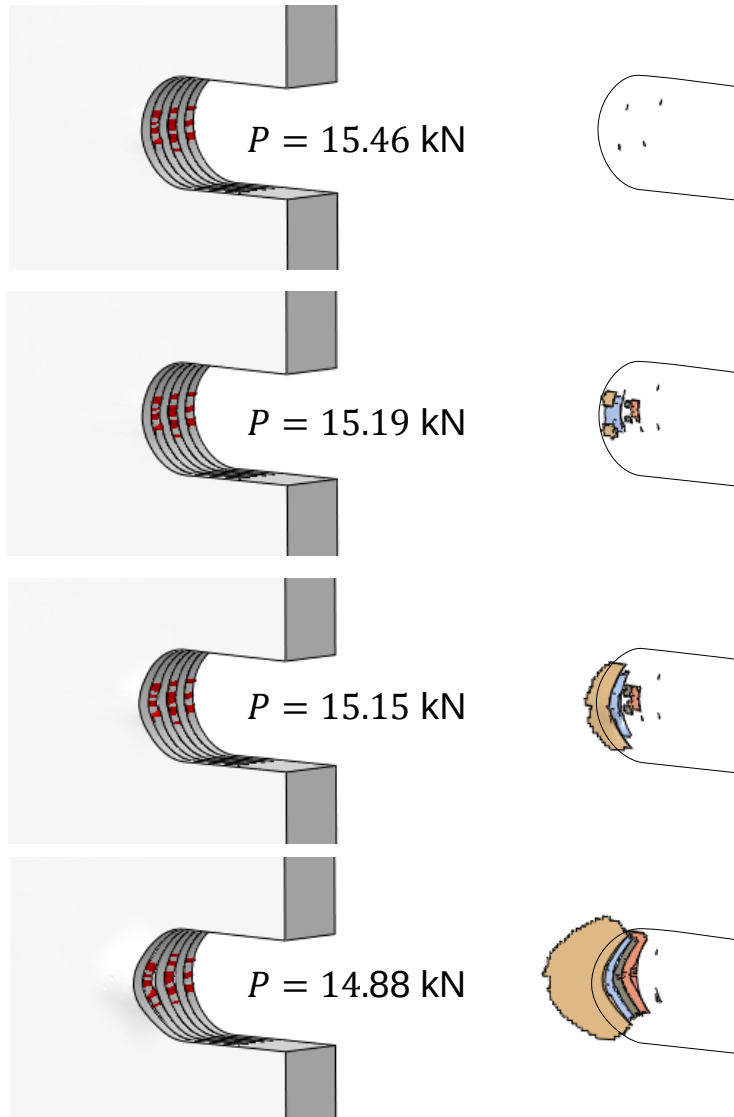
Interface

- 1st
- 2nd
- 3rd
- 4th
- 5th

2-D (in-plane) kinking only

In-plane kinks

Delamination



3-D kinking

Out-of-plane kinks

Delamination

