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Failure of Notched Laminates Under Out-of-Plane Bending

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Matrix Compression Damage Model

- Motivation and Key Issues
  - Need to better understand compressive damage mechanisms in carbon fiber matrices
- Objective
  - Create a model that can be used to predict the material response to damage
- Approach
  - Experimental tests to validate continuum damage mechanics model and classify damage behavior

Project Overview

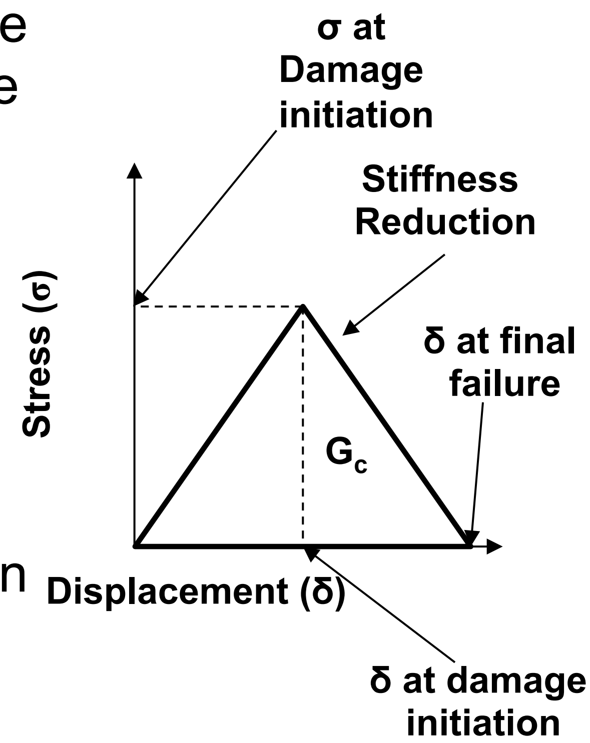
- Out-of-Plane loading
  - Four point bending experiments and simulations showed good agreement (within 10% for max. load)
  - Out-of-plane shear experiments and simulations also showed good agreement (within ~20% for max load, and most strain fields)
- Sensitivity studies to determine effects of FEA inputs
  - Largest effects were longitudinal strengths
  - Larger uncertainty associated with damage propagation values
- Results of previous work showed need for better understanding of damage propagation behavior
- Current study focuses on matrix compression damage propagation

Today's Topics

- Literature Review
  - Damage Models
  - Compression specimens
- Specimen Selection
  - Candidate Specimens
  - Selection study using FEA
  - Selected Specimen
- Proposed Model
- Preliminary Study
  - Un-notched Specimens
  - Compact Compression Specimens
  - Conclusions
- Final Testing Plan
- Looking Forward

Matrix Damage Models Literature

- Compression damage in composites is often modeled with fracture mechanics methods
- Pinho et al. assumed matrix compression can be modelled as a single angled mode II crack in the 90 degree plies
- Abaqus model uses a continuum damage mechanics model
- Net effect of damage modeled by smearing properties over entire damage region
- Strain energy release rate governs the degradation of the stiffness and the overall strain to failure for the material
- Ritter used energy dissipation methods to determine when damage occurred in composites



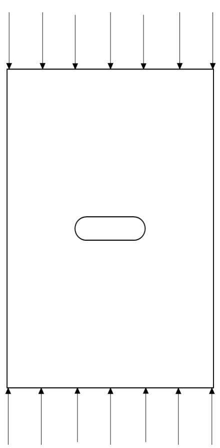
Specimen Literature Review

- All studies found focused on fiber compression not matrix compression
- Similar specimens can be used since similar loading modes desired
- Center Notched Compression (CNC)
  - Used primarily in early studies
  - Isolation of desired failure mechanism achieved in some studies, but specimens showed a tendency to split off axis
  - Require anti-buckling guards: face mounted or edge mounted
- Compact Compression (CC)
  - Modified versions of compact tension specimens
  - Good isolation of desired failure mode until significant damage growth
- Four Point Bending (4PB)
  - Different failure mode: through thickness vs intralaminar failure
  - Able to isolate the fiber compressive mode sufficiently well

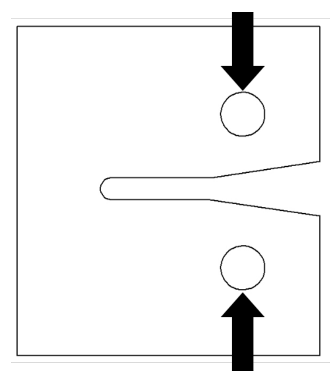
Candidate Specimens and Procedures

- Based on the literature Center Notched Compression, Compact Compression and Four point bending specimens were selected for evaluation
- The goal of these specimens is to be able to isolate compressive damage in a specific region
- Allow for tracking of the damage propagation through the specimen
- Varied boundary conditions in models to test fixture types

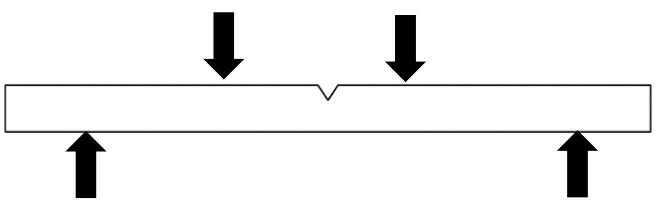
Center Notched Compression (CNC)



Compact Compression (CC)

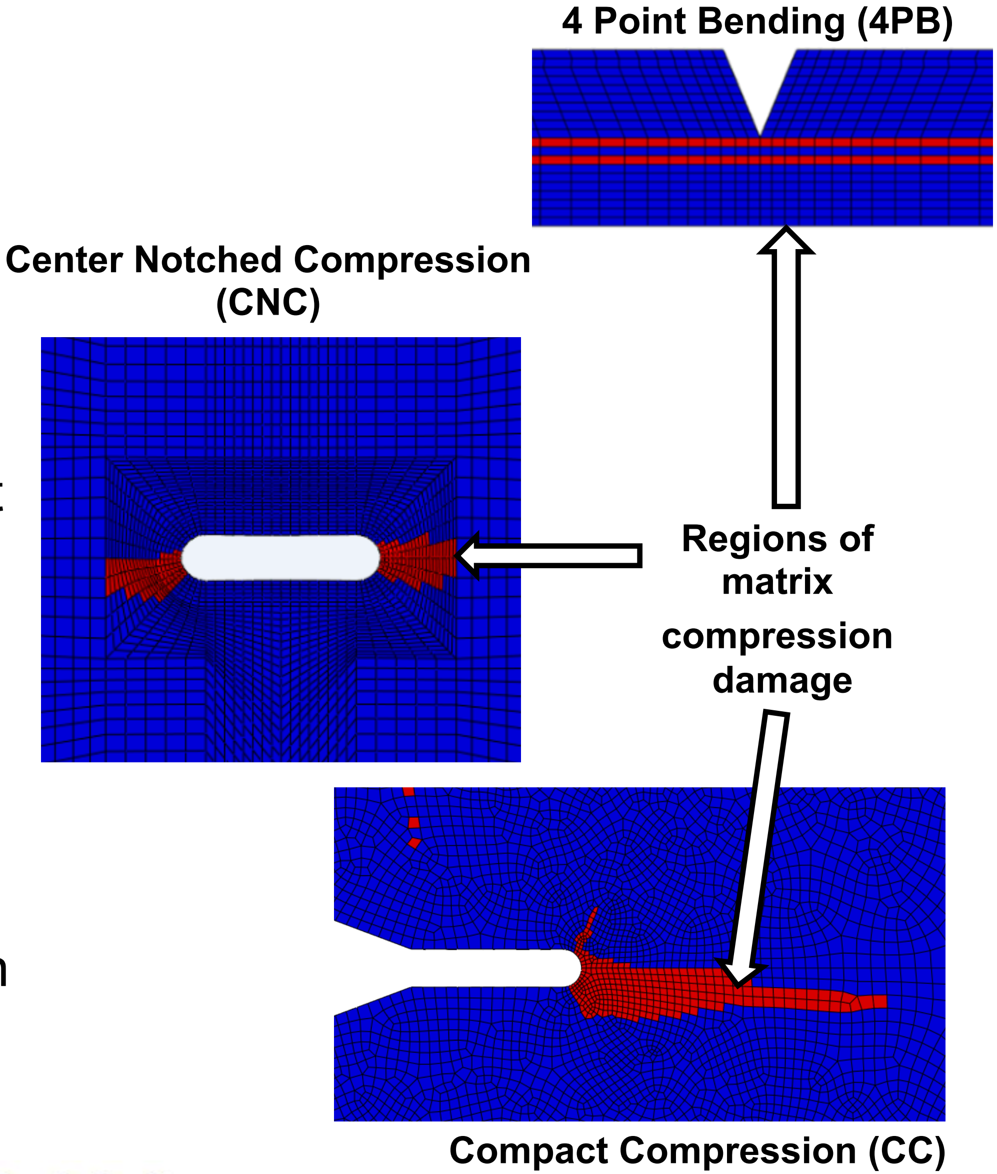


4 Point Bending (4PB)



Specimen Selection-FEA Results

- Specimens using the current Abaqus Damage Model
- Compared predicted damage region sizes to evaluate specimens
- 4PB mostly showed damage at load points
- CNC had a tendency to split perpendicular to the notch
- CC showed best isolation of compressive damage- tensile splitting only occurred after significant damage propagation



Final Specimen Selection

- Based on the results the CC specimens were chosen for the preliminary tests
- CC specimens showed the best isolation of compressive damage, despite some tensile splitting after significant damage propagation
- CC specimens require simple pin fixtures and no buckling guards as long as the specimen is sufficiently thick
- CNC showed fairly good isolation of compressive damage but is dependent on complex fixtures and boundary conditions
- 4PB did not show isolation of the desired damage modes

Proposed Model

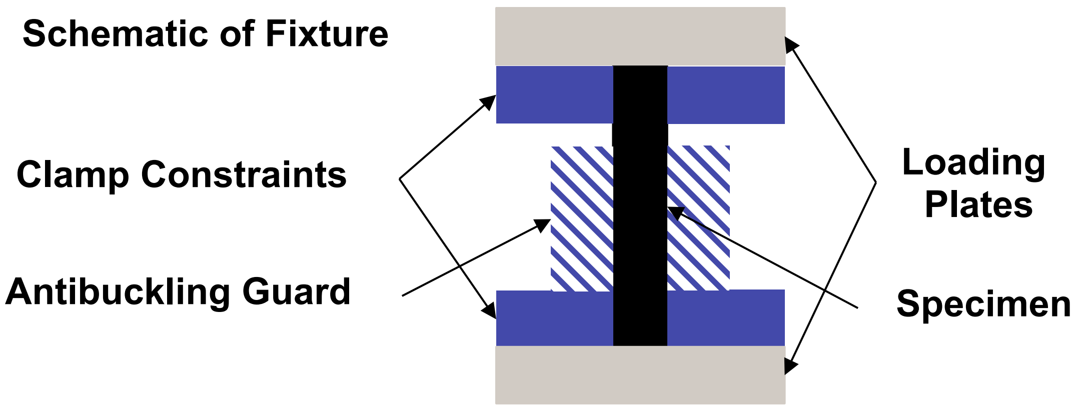
- Continuum damage mechanics models use the energy dissipated by a damage region to degrade the stiffness of that region
- Since all damage is irreversible and the model does not explicitly model damage mechanisms, continuum damage mechanics can be applied relatively generally
- Useful computational model for FEA programs
- Need accurate energy dissipation and degradation of stiffness
- Abaqus model currently continuum damage mechanics based, but degrades stiffness linearly to zero stress
- May not be accurate for matrix compression (possibility of residual stress in material after fully damaged, non-linear stiffness effects)
- Once damage behavior in understood:
  - Refinements to stiffness degradation in computational model as needed
  - Model can be developed to predict energy dissipated based on damage mechanisms

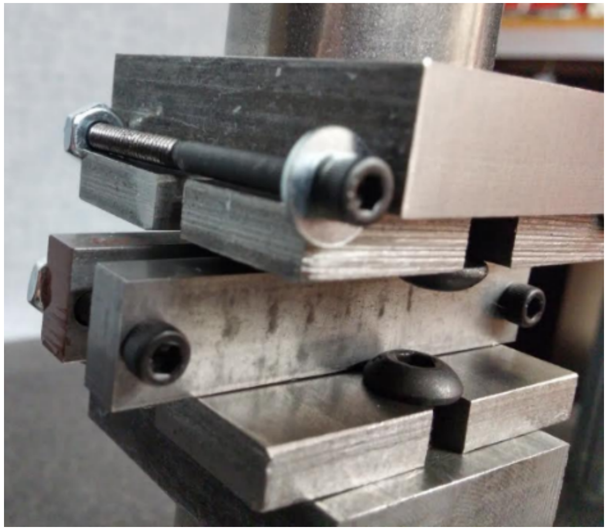
Preliminary Testing Overview

- Sourced materials to manufacture preliminary carbon fiber specimens at Oregon State
- Un-notched specimens used to classify the failure mechanisms in the damaged region due to compressive loading
- CC specimens used to validate specimen design and testing concepts
- Goal: Classify damage mechanisms and measure a preliminary strain energy release rate using simple procedures to proof the concepts
- Use results to inform final testing procedure design

Preliminary Testing-Un-notched Specimens

- Several different sizes of unidirectional un-notched specimens manufactured with vacuum bagging techniques
- Edges machined to create a flat surface to load
- Very difficult to suppress buckling despite guards
- Compression loading very unstable
- Requires tight tolerances to prevent any loading eccentricity
- Unable to isolate desired failure with current set up





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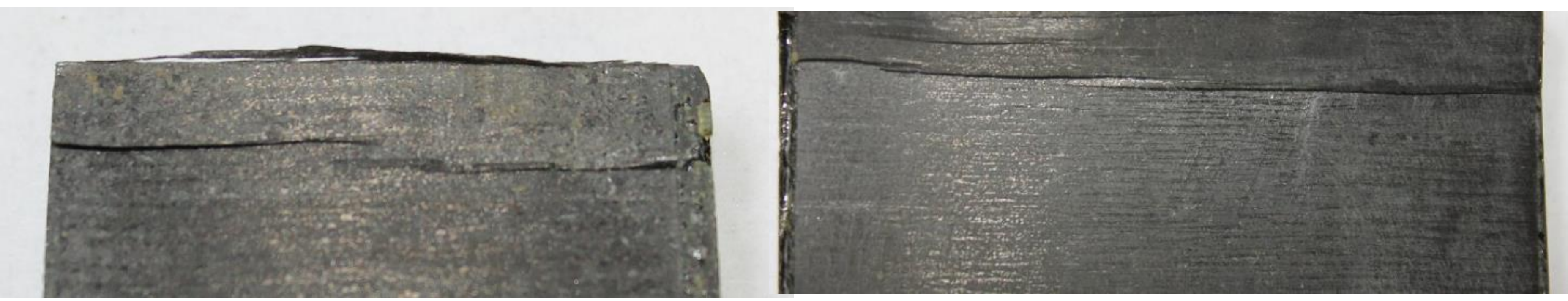
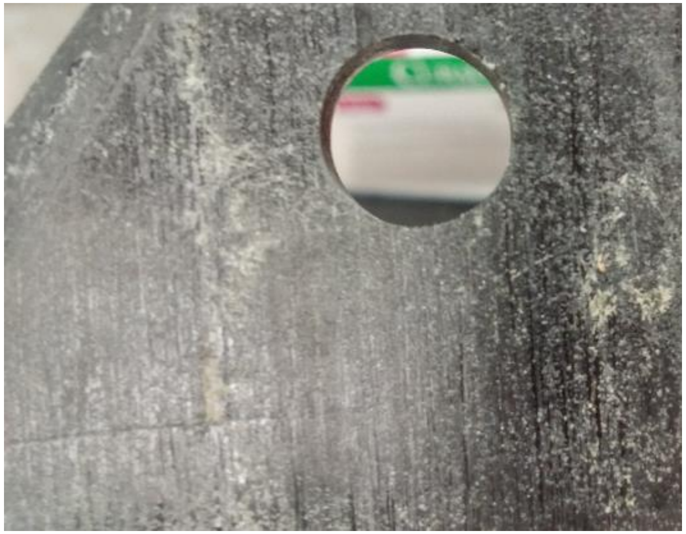
Preliminary Testing-Un-notched Specimens

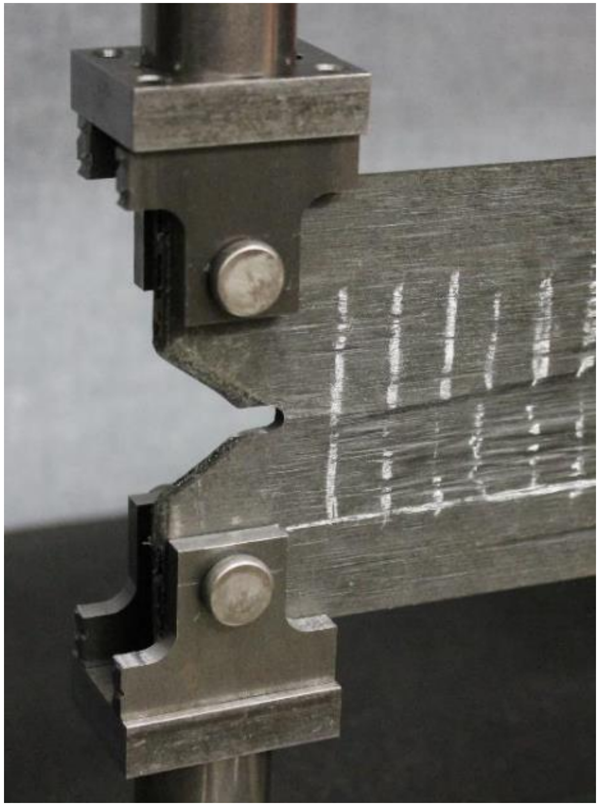
- Global buckling generally caused a large crack towards the middle of the specimen
- With anti-buckling guards the specimen would still often buckle at a lower wave length
- Clear from lack of symmetry in failures
- Examples of buckling failures:



Preliminary Testing-Compact Compression Specimens

- Specimens made with unidirectional plies with fiber direction parallel to the notch
- Notch and Pin holes machined after curing
- Specimens Loaded using custom clevis fixture
- Load-Displacement recorded and tests filmed





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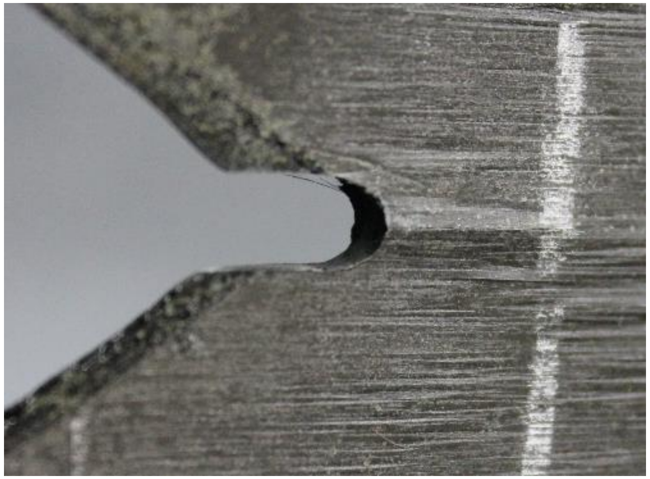
Preliminary Testing-Compact Compression Specimens

- CC specimens showed good isolation of compressive damage without global buckling
- Evident in symmetry of damaged material
- Failure mechanisms show evidence of plastic deformation, shear cracks, localized delamination, and local buckling
- Ultimate failure due to tensile splitting, after a significant amount of compressive damage



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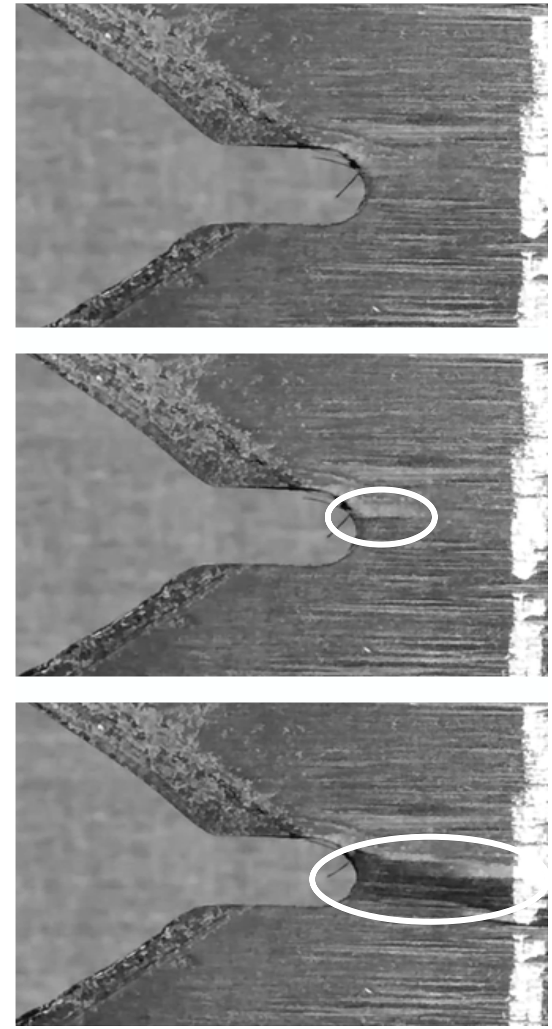
Preliminary Testing-Compact Compression Specimens

- Damage able to be tracked visually
- Damage region size measured using simple visual processing

Increasing Load

Increasing Load



Preliminary Testing-Compact Compression Specimens

- Load displacement curves showed drops in load due to damage
- Drops in load correspond to compressive damage propagation from video
- Able to be used to measure change in compliance
- Change in compliance can be used to calculate strain energy release rate:

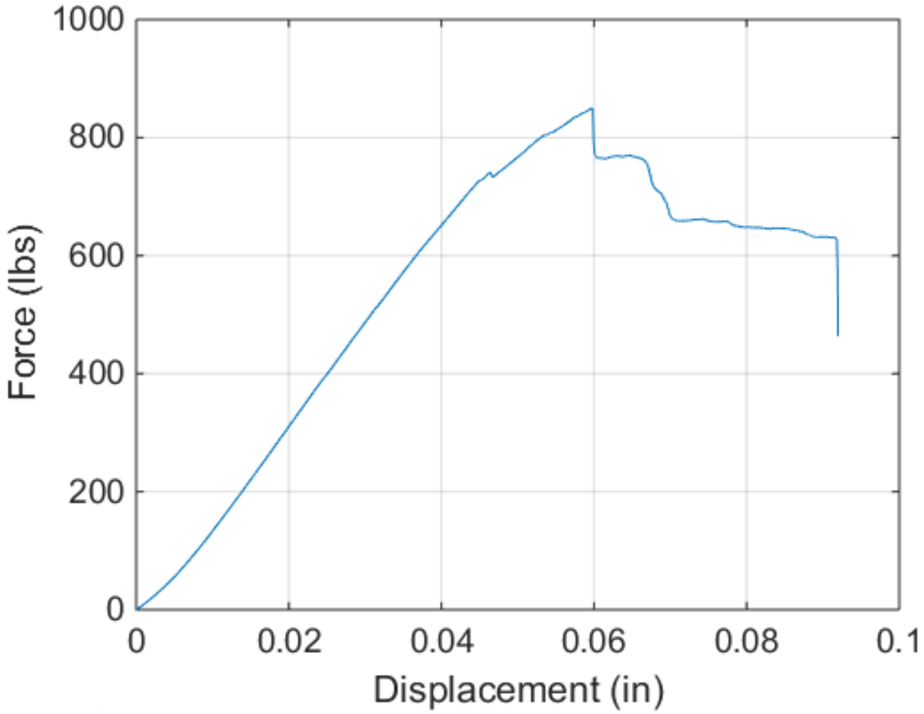
$$G = \frac{P^2}{2B} \frac{dC}{da}$$

P=Load

B=Thickness

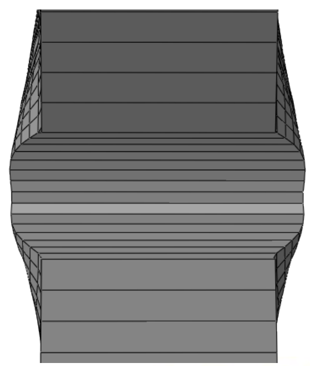
C=Compliance

a=Length of Damage Region



Important Lessons and Conclusions

- Special care is required in compression to prevent instabilities
- CC specimens allow compressive damage to occur without global buckling
- Careful design of CC specimen required to delay tensile splitting as long as possible
- Compressive damage can be seen visually from test footage
- Preliminary measurement of strain energy release in range of expected
- Preliminary testing validates basic concepts of test plan
- Abaqus model showed similar deformation of damage as experiments



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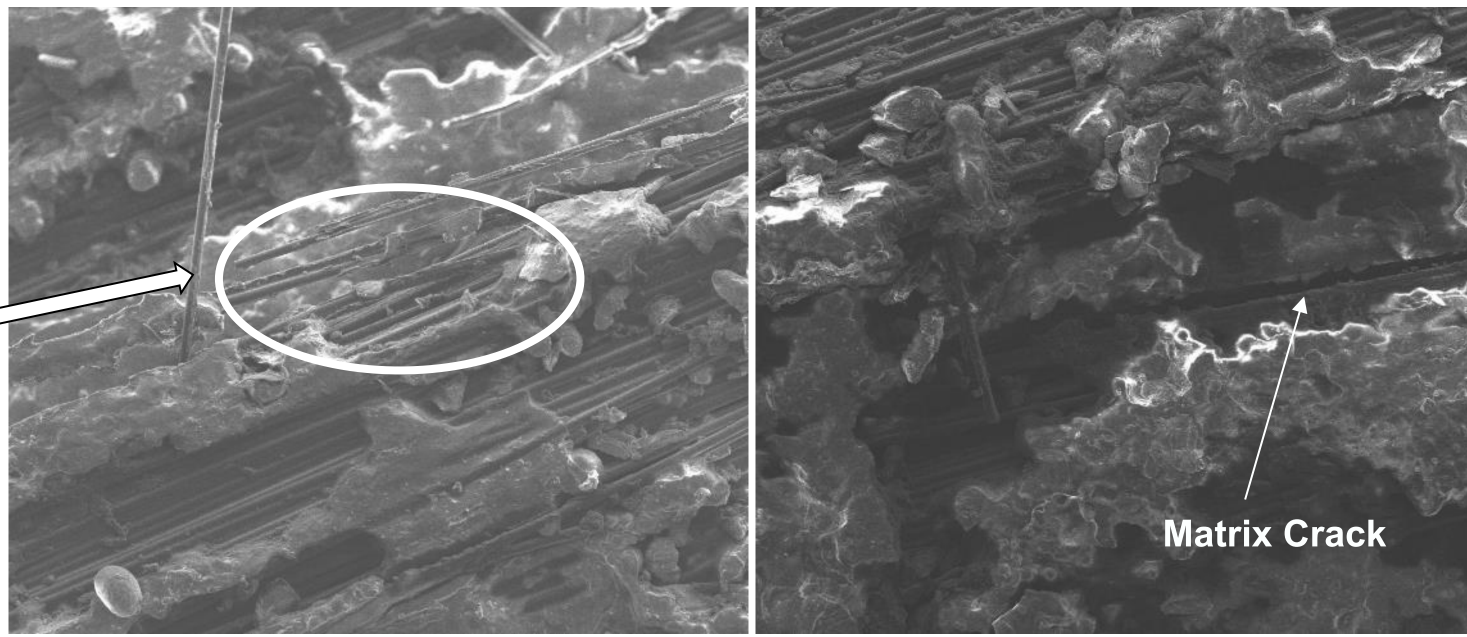
Carbon Fiber Fractography

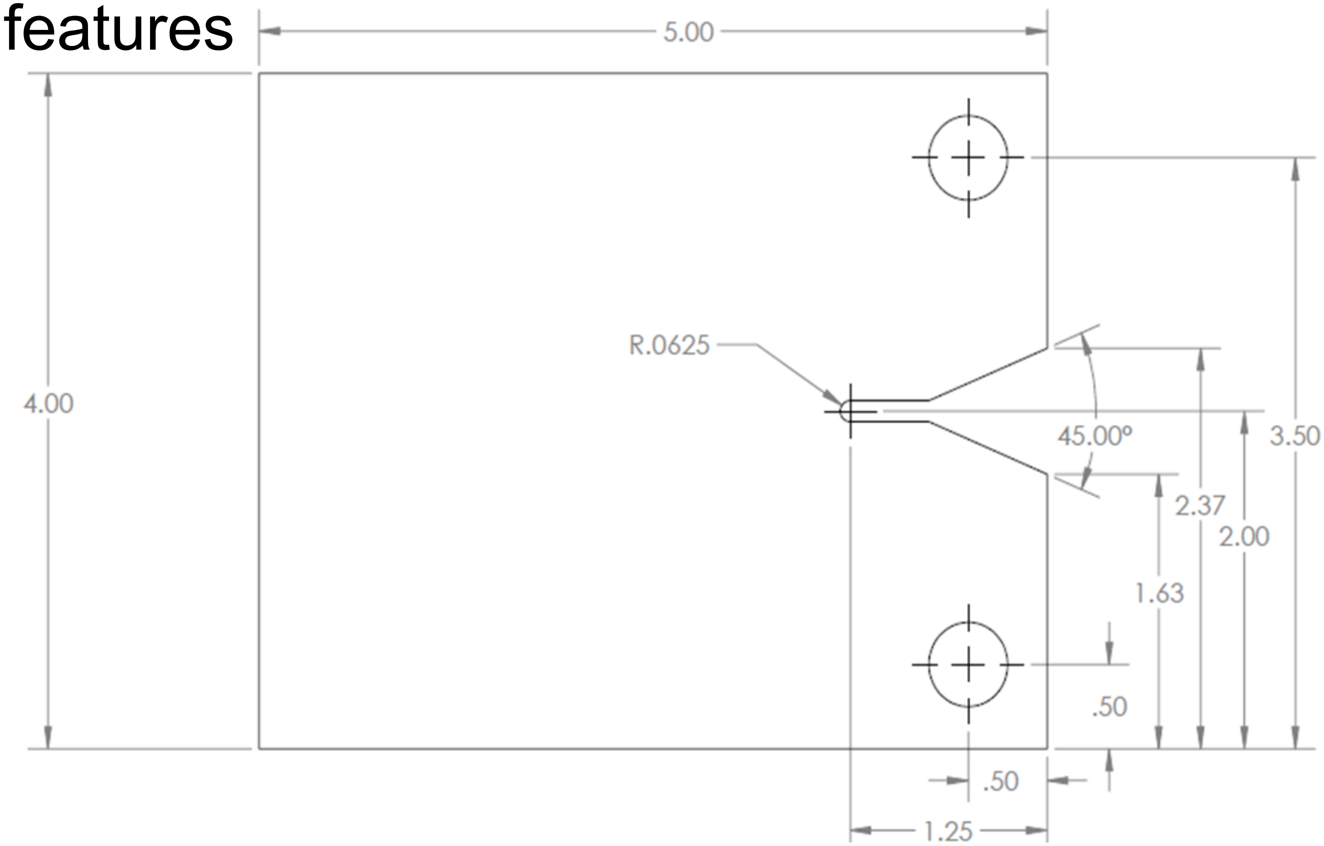
- SEM evidence shows primarily matrix damage
- In the majority of samples the exposed fibers in the fractured regions show matrix still attached
- Shows evidence for mainly matrix failure instead of interface (bare fibers) or fiber (broken fibers) failures

Exposed Fiber due to matrix crack Showing matrix still attached



Final Testing Plan

- The preliminary testing and Abaqus model were used to inform the final geometry of the specimens
- Goal is to delay tensile splitting as long as possible with geometric features



Final Testing Plan

- DIC can be used to calculate the strain energy release rate
- J-integral can be calculated numerically from the strain field and be used to calculate strain energy release rate
- Able to achieve better accuracy then load-displacement based methods
- Displacement fields can be used to track damage based on discontinuities in the fields
- Use system at OSU that was used in Mode III experiments
- Consistent loading rate tests to measure strain energy release rate
- Cyclic loading tests to determine the material behavior and stiffness reduction due to damage
- Varying notch length of specimens compare stress ahead of the crack tip to LEFM solutions to undamaged and damaged specimens

Looking forward

- Benefit to Aviation
  – Experimental methods for measuring energy dissipated due to matrix compression damage
  – Better understanding of damage mechanisms to refine models to increase accuracy
- Future needs
  – Further testing to classify range of damage behavior
  – Validate proposed model
  – Refine material model as needed

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