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Advanced Materials in
Transport Aircraft Structures

Failure of Notched Laminates Under Out-of-Plane Bending
Phase X

Fall 2016 Meeting

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Failure of Notched Laminates Under Out-of-Plane Bending. Phase X

- 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

Failure of Notched Laminates Under Out-of-Plane Bending. Phase X

- Principal Investigators & Researchers
  - John Parmigiani (PI); OSU faculty
  - M. Daniels, T. Rawlings; OSU grad students
- FAA Technical Monitor
  - Curt Davies
  - Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Gerry Mabson, Boeing (technical advisor)
  - Kazbek Karayev, Boeing (technical advisor)

Project Overview

Phase I (2007-08)

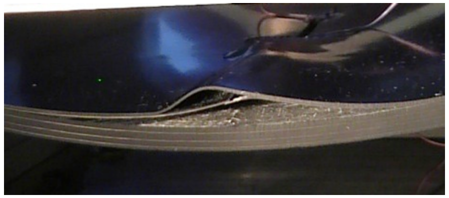
- Out-of-plane bending experiments w/composite plates
- Abaqus modeling with progressive damage

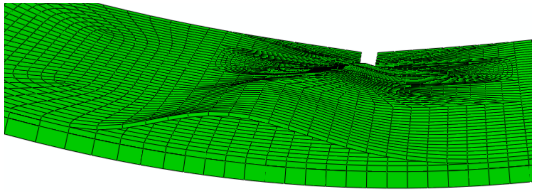
Phase II (2008-09)

- Abaqus modeling with buckling delamination added
- Sensitivity study of (generic) material property values

Phase III (2009-10)

- Abaqus modeling w/ more delamination interfaces





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Project Overview

Phase IV (2010-11)

- Further study of additional delamination interfaces
- Sensitivity study using Boeing mat’l property values

Phase V (2011-12)

- Out-of-plane shear (mode III) experiments
- Evaluate the Abaqus plug-in Helius for out-of-plane bending

Phase VI (2012-13)

- Out-of-plane shear modeling with Abaqus Standard/Explicit
- Evaluation of plug-in Helius: MCT for out-of-plane shear

Project Overview

Phase VII (2013-14)

- Improvement to Abaqus Explicit models
- Explore damage softening parameters in Helius: MCT
- Explore possible inaccuracies in material properties

Phase VIII (2014-15)

- Explore significance of damage propagation material properties, i.e. when do energy parameters matter?
- Begin work on modeling matrix compression damage

Phase IX (2015-16)

- Mode III Wrap up
- Matrix compression damage modeling and testing

Project Overview

Phase X (2016)

- Compression testing
- Energy dissipation calculations

Failure of Notched Laminates Under Out-of-Plane Bending: Phase X Overview

- Damage propagation in composites is broken up into four modes: Fiber tension, fiber compression, matrix tension, matrix compression
- Extensive experimental studies have been done to directly classify the propagation behavior of the former three modes
- No experimental studies have focused purely on matrix compression propagation behavior
- Instead, simplifying assumptions based on initiation studies are applied to matrix compression propagation behavior
- The often complex behavior of composite materials makes direct experimental observation desirable
- Goal: Design and test specimens to determine the damaged material behavior due to matrix compression loading

Today’s Topics

Matrix Compression Specimens

- Uniform Compression Specimens
  - Damage Mechanisms
  - Stress Displacement
- Compact Compression Specimens
  - Damage Mechanisms
  - J-Integral

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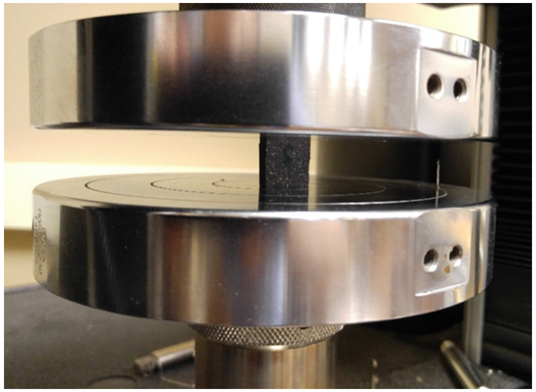
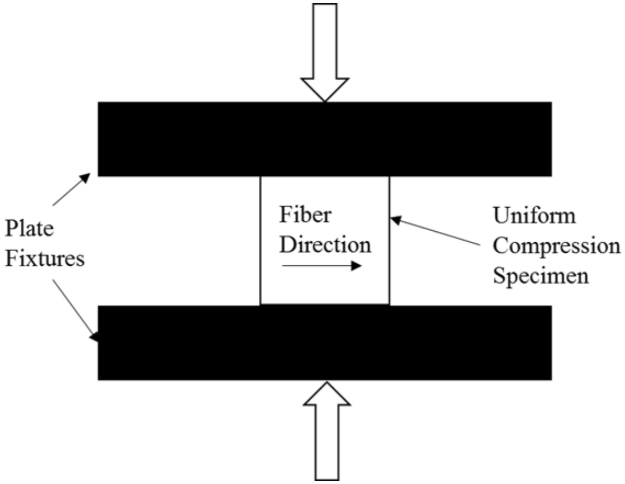
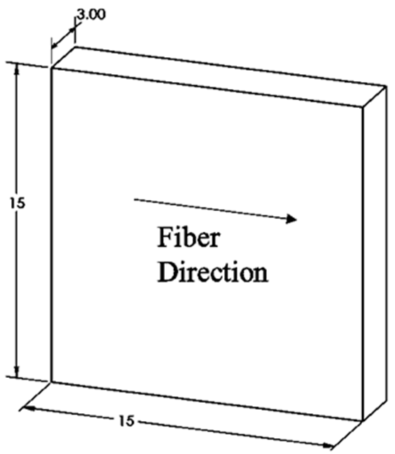
Uniform Compression Specimens

- Measure the matrix compression stress-displacement behavior directly
- Rectangular specimens from commercial material (Mitsubishi Rayon TR50S/NB301, ~60% FV)
- Range of dimensions used
  - Average dimensions shown in mm for general scale
- Dimensions selected to create matrix compression damage before buckling
- Monotonic and unloading tests to classify range of behavior





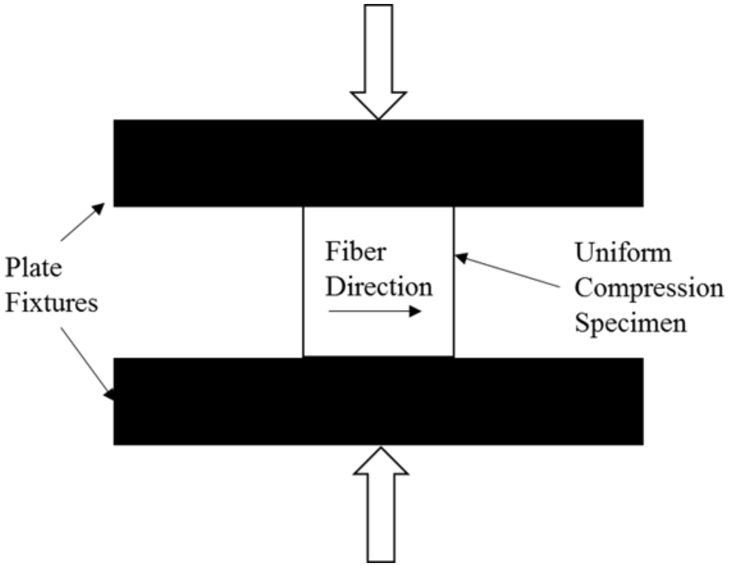


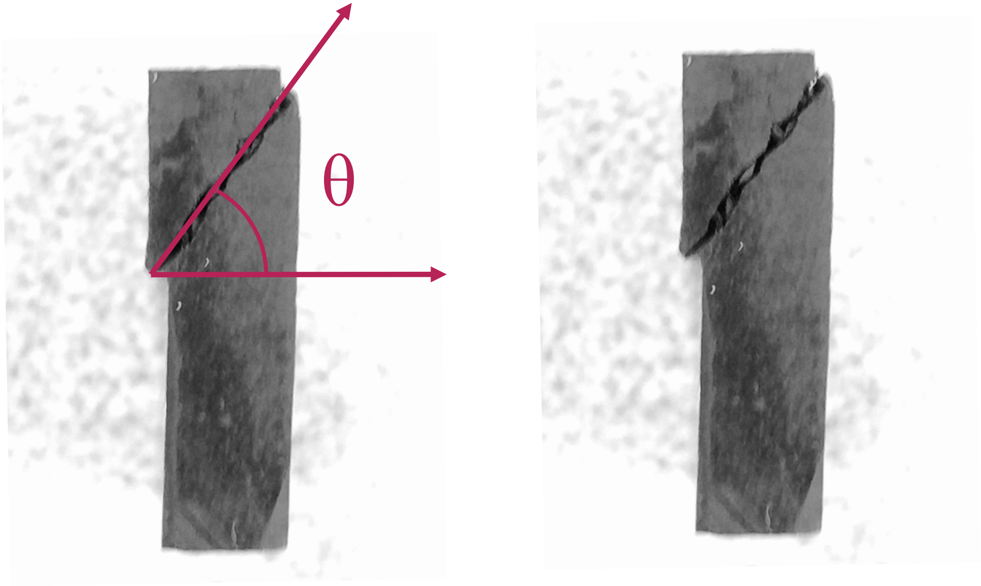
Today's Topics

- Uniform Compression Specimens
  - Damage Mechanisms
  - Stress Displacement
- Compact Compression Specimens
  - Damage Mechanisms
  - J-Integral

Uniform Compression:
Damage Mechanisms

- Shear cracks through the thickness were observed
- Large range of angles observed (52° to 73°)
- Trapped material is present in the wake of the crack
- Fiber bridging also present





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Uniform Compression: Stress Displacement

- Stress-Displacement Behavior can be split into three zones:

  Zone 1 Elastic:

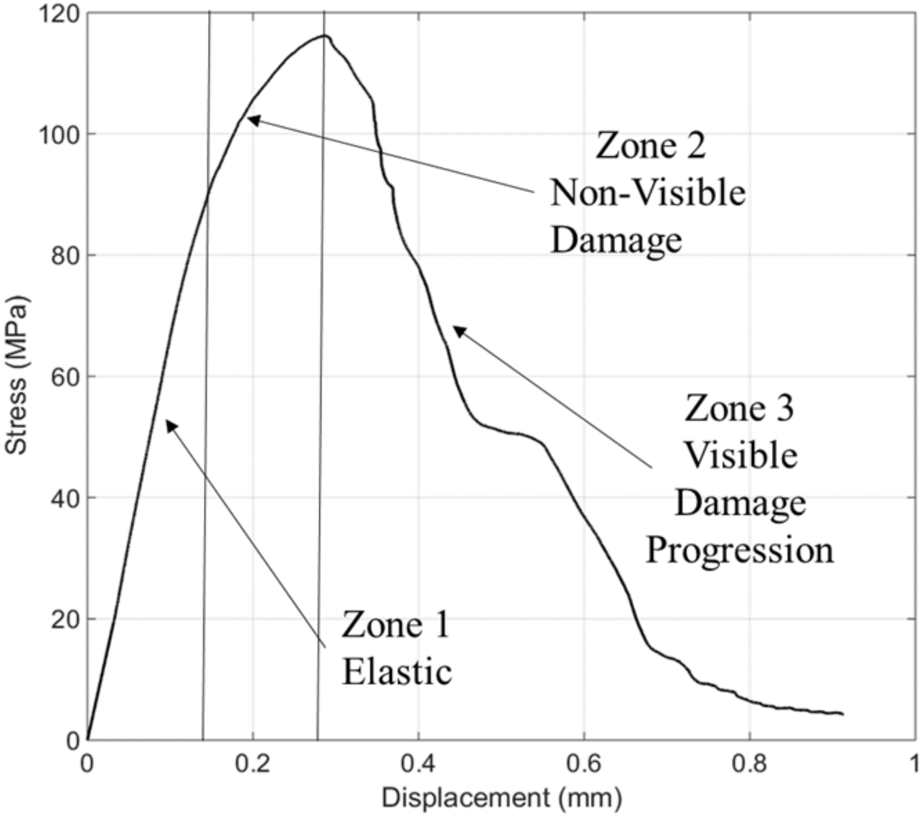
  Unloading traces back over loading curve

  Zone 2 Non-Visible Damage:

  Nonlinearity caused by plasticity and possibly micro cracking

  Zone 3 Visible Damage Progression:

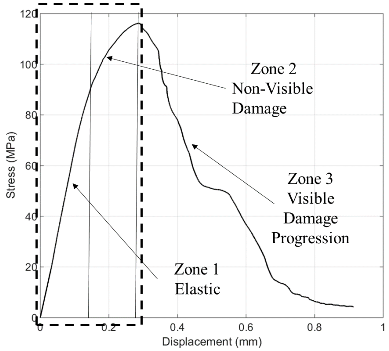
  Stiffness significantly degrades
- Figure shows slow propagation of damage
- Faster propagation shows more linear decrease
- Typically retains some stress after decrease

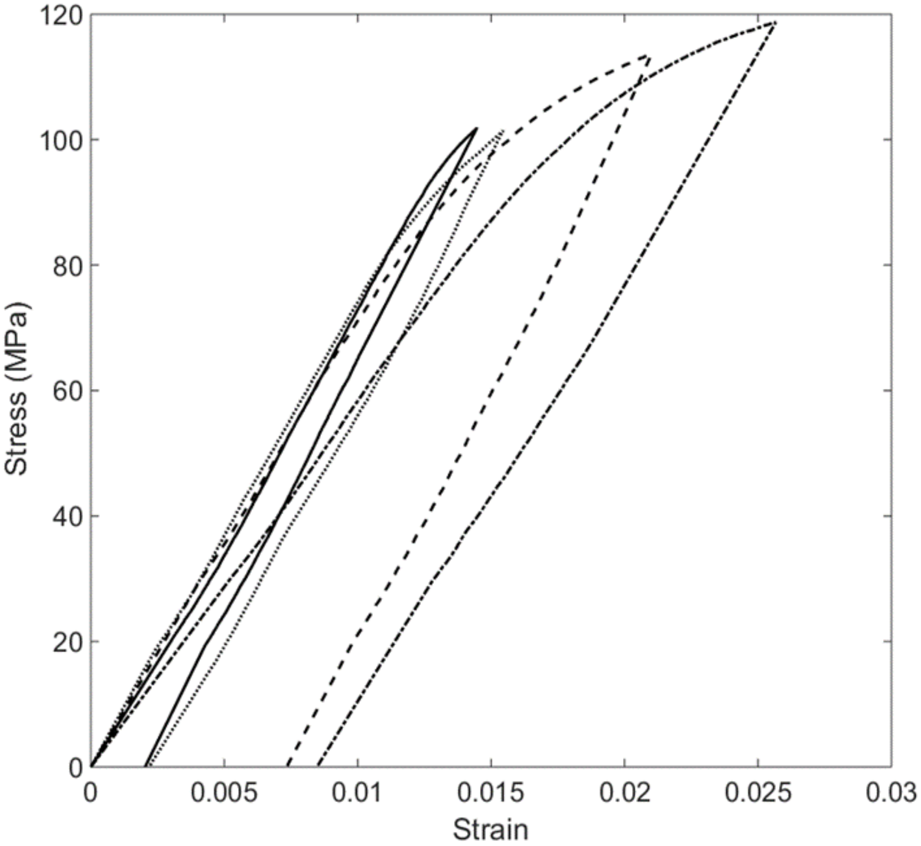


Note: Curve is one trial that is representative of population failure.

Uniform Compression: Nonvisible Damage Region

- Unloading tests used to determine behavior
- Hysteresis in unloading was observed
- Offset in displacement suggests plasticity
- Nonlinearity generally observed around a strain of 0.0125

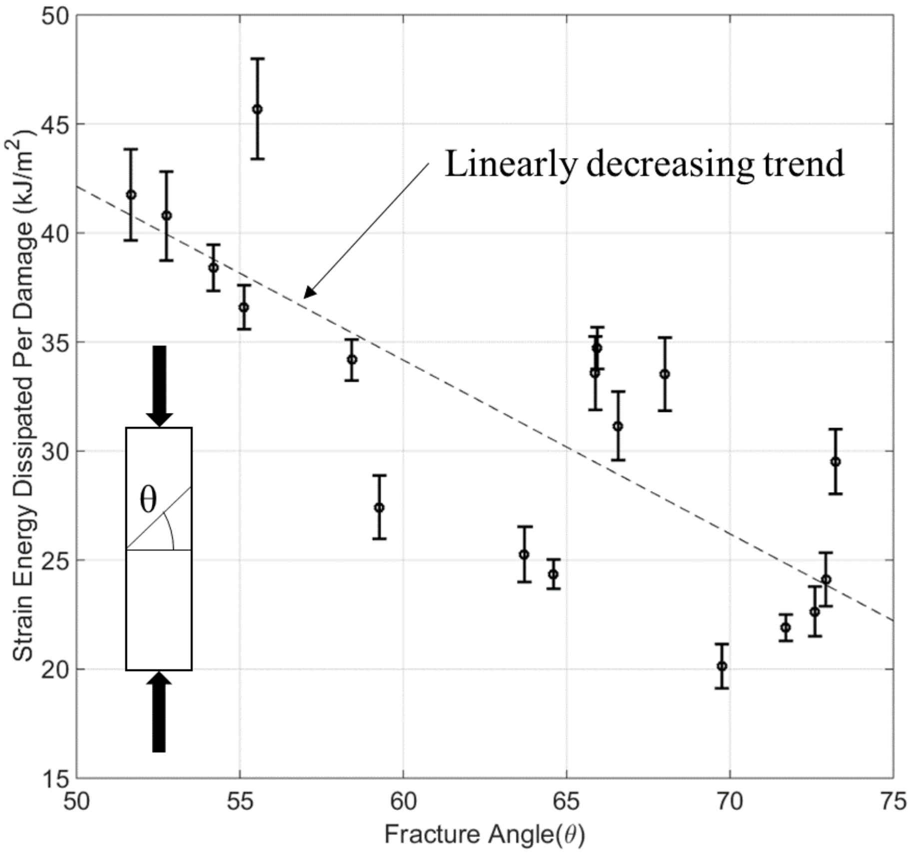




Note: Curve shows a few representative specimens. All other specimens tested showed similar behaviors

Uniform Compression: Energy Dissipation

- Calculated energy dissipation from area under stress-displacement curve
- Energy dissipation decr. w/ incr. fracture angle
- Larger angles correspond to more efficient fracture
  - Less energy lost to mode I compression.
- Energy dissipation much higher than single mode II crack assumption
  - Due to bridging, friction, and other mechanisms



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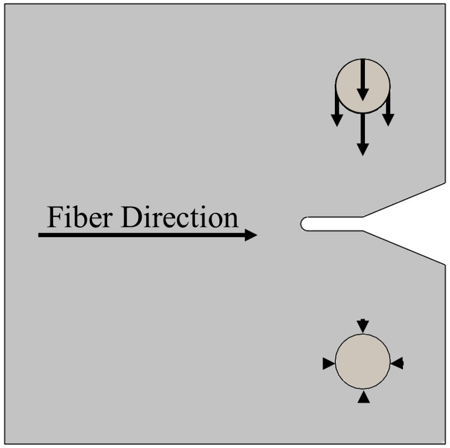
Compression Specimens

- Compact compression (CC) specimens to propagate compression damage in a controlled way
  - Crack propagates further than UC
- Presents a more complex case for comparison of models
- J-integral used to calculate strain energy release rate



Today's Topics

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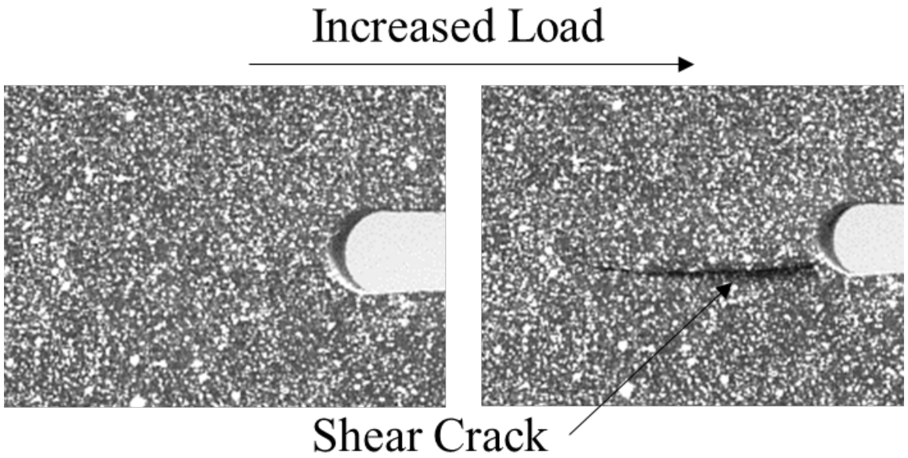
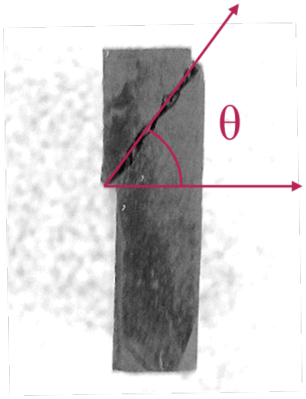
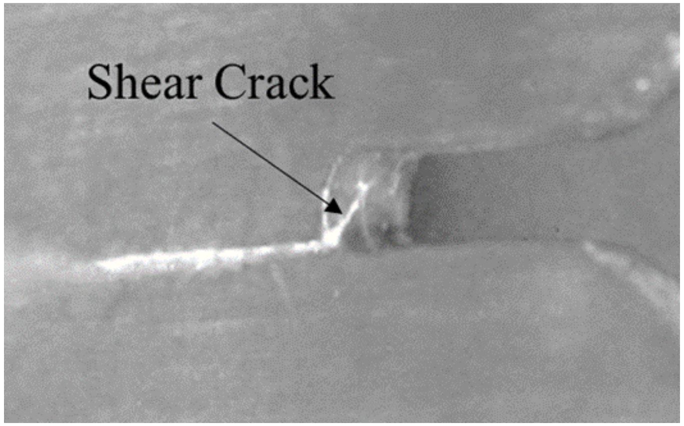
Compression Specimens: Damage Mechanisms

- Damage mechanisms primarily shear cracks through the thickness
  - Same as UC Specimens
- Shear cracks propagate parallel to the notch
- Shear cracks measured between 47° and 54°
  - UC showed 52° to 73°
- Propagation limited by tensile failure of the opposite end





Uniform Compression Specimen



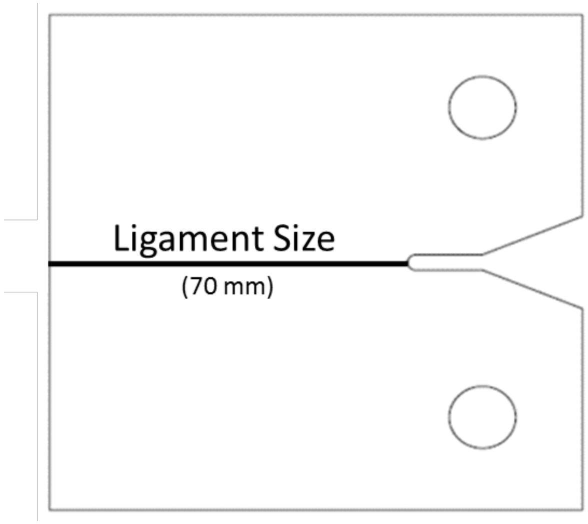
Compact Compression Specimen

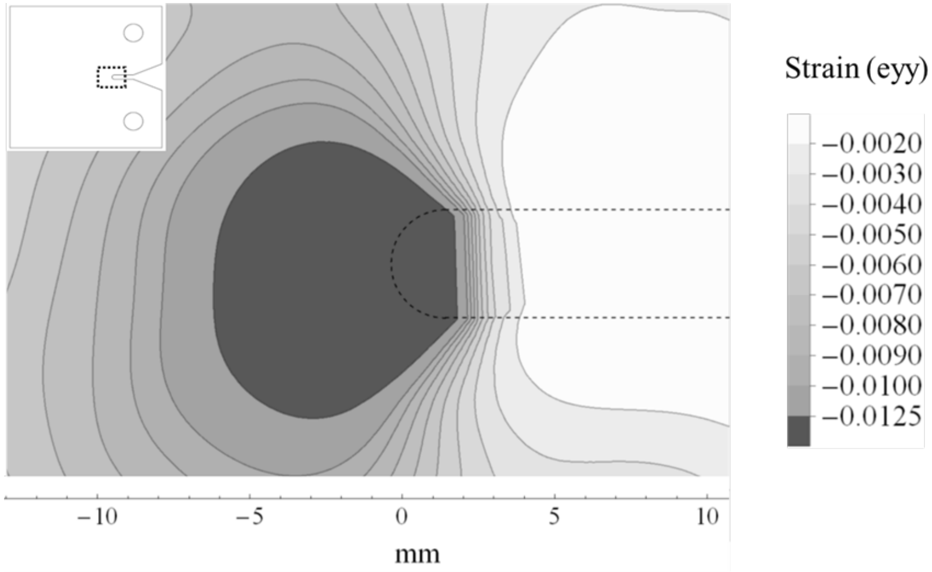
Today’s Topics

- Uniform Compression Specimens
  - Damage Mechanisms
  - Stress Displacement
- Compact Compression Specimens
  - Damage Mechanisms
  - J-Integral

Compression Specimens: J-Integral Validity

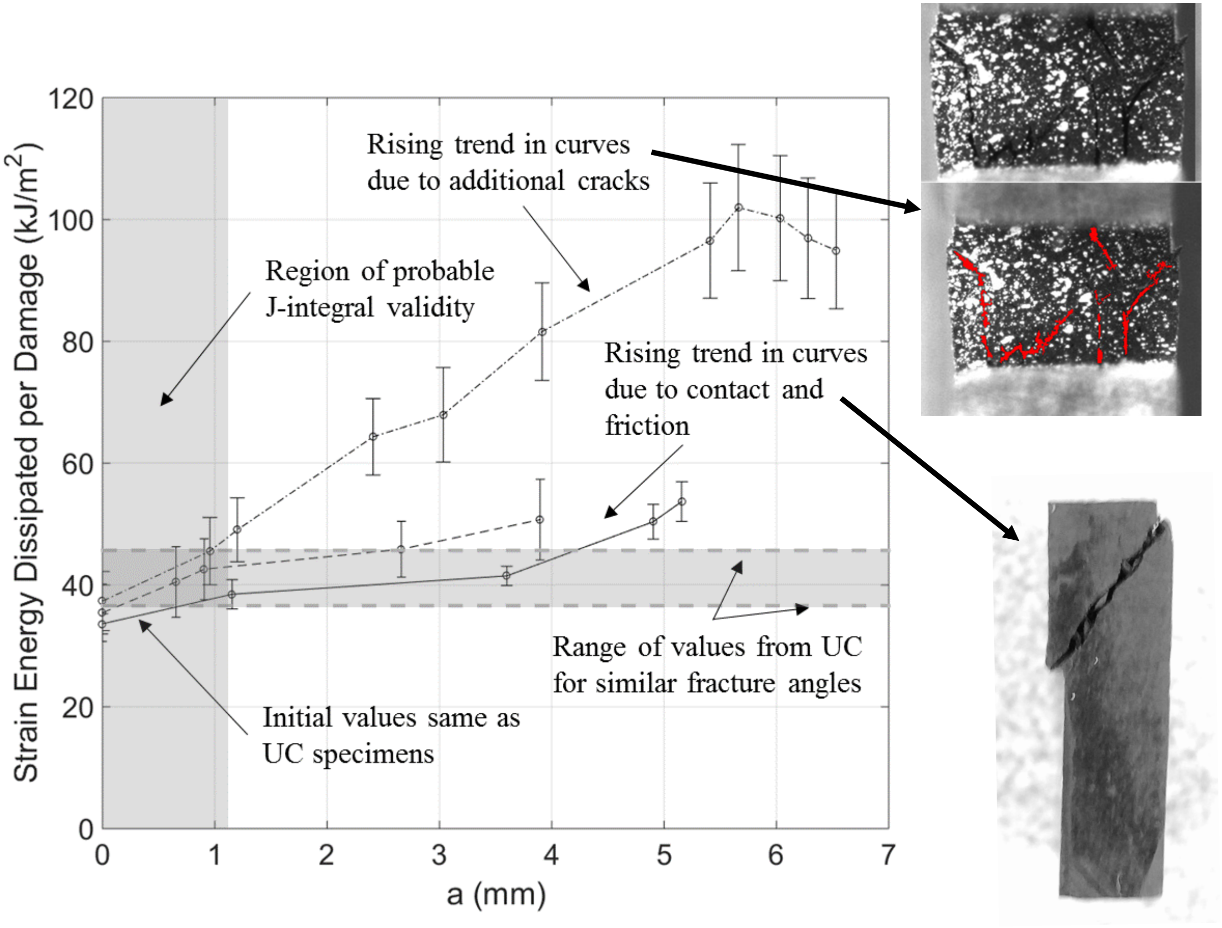
- J-integral derived from energy balance and damage extension
- Valid with plasticity (damage) if confined to a small region and contour does not cross plastic zone
- In our work with the compact compression specimens
  - Plastic zone is order of magnitude smaller than ligament size
  - Contour was selected to avoid plastic zone





Compression Specimens: J-Integral Results

- Same initial values as UC specimens
- Rising trends in J-integral
  - Due to additional cracks, contact stresses, increased plasticity and friction
- J-integral may be invalid after damage advances



Rising trend in curves due to additional cracks

Region of probable J-integral validity

Rising trend in curves due to contact and friction

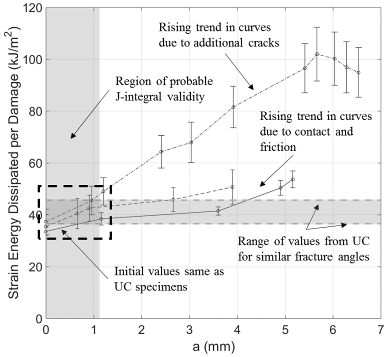
Range of values from UC for similar fracture angles

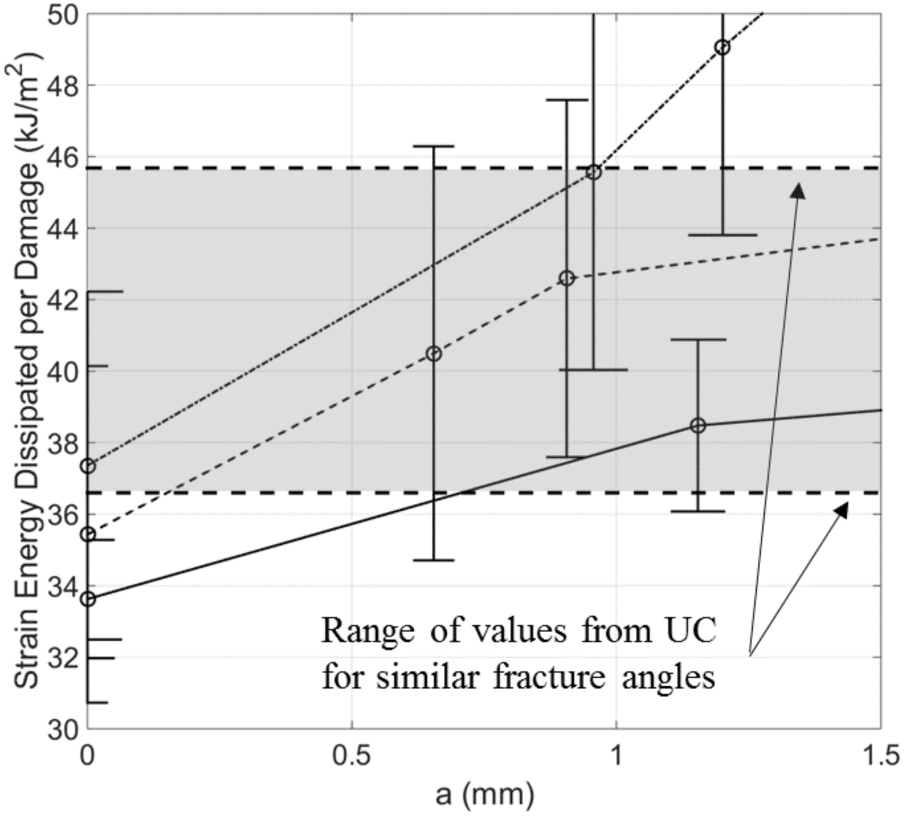
Initial values same as UC specimens

Compression Specimens:

Energy Dissipation Agreement

- Energy dissipation rate at initiation agrees with UC
- Calculated J-integral values using CC ranged from 33.6 kJ/m² to 45.6 kJ/m²
    - UC energy dissipation ranged from 36.6 kJ/m² to 45.69 kJ/m² for similar angles





Conclusions

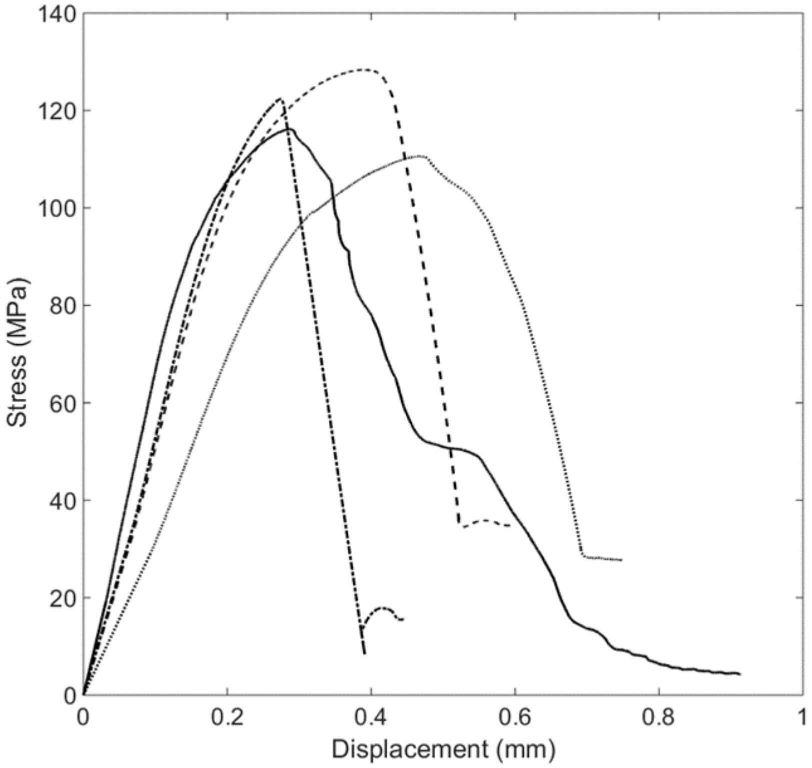
- Damage propagates as shear cracks
- Plasticity occurs before visible damage
- Energy dissipation rate dependent on fracture angle
- J-integral in CC specimens and area under stress-displacement show fairly good agreement for similar fracture angles
- Energy dissipation much higher than is commonly reported based on simple mode II crack assumption (1 kJ/m^2 for similar materials)
- J-integral becomes inaccurate during damage growth as evidenced by the rising energy dissipation values
- Single strain energy release rate not capable of fully capturing the damage behavior as it would need to be adjusted for fracture angle, plastic nonlinearity, and residual stiffness

Next Steps

1. Implement the new matrix-compression damage model into Abaqus.
2. Determine the effect of the new matrix compression material model using a Design-of-Experiments sensitivity study.
3. Determine the role of matrix compressive loading in mixed-mode damage and failure.
4. Create a written report, to be submitted to the FAA, describing the work completed in this project.

Uniform Compression: Stress Displacement

- Faster propagation is more linear
- Has residual stress carrying with continued displacement



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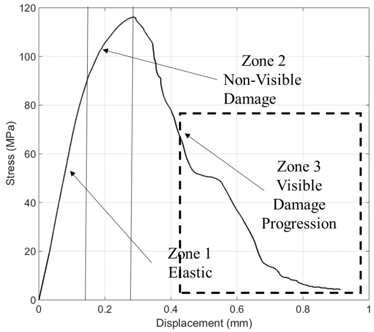
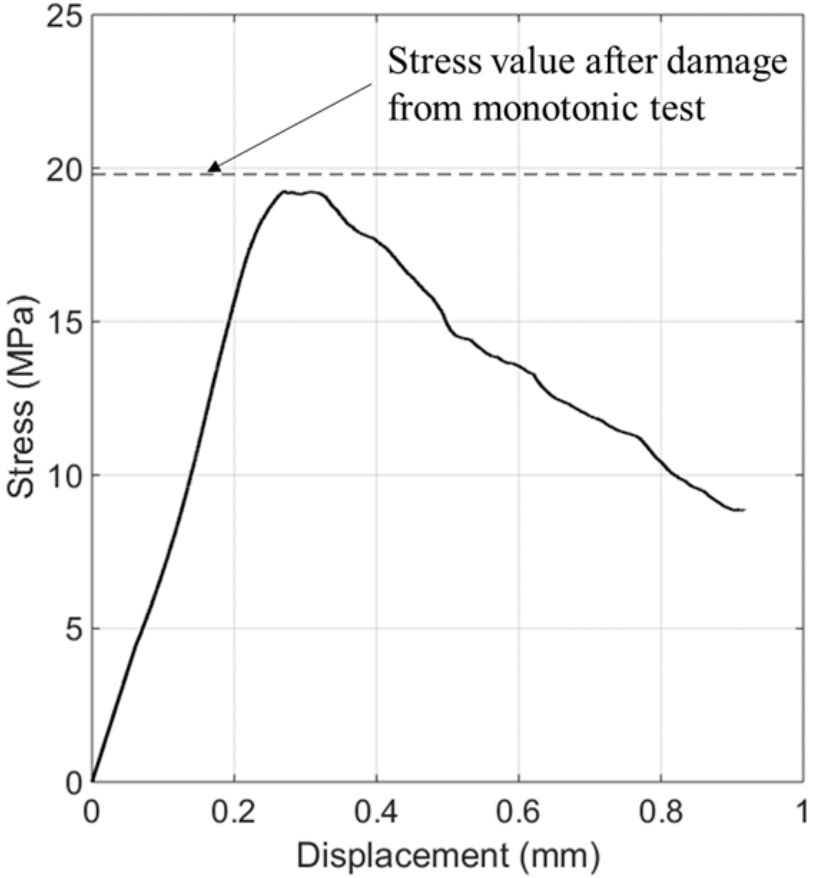
Uniform Compression: Visible Damage Reloading

- Specimen reloaded after fracture occurred
- Linear stress increase to stress value after monotonic test
- Slow degradation of stress with continued displacement.





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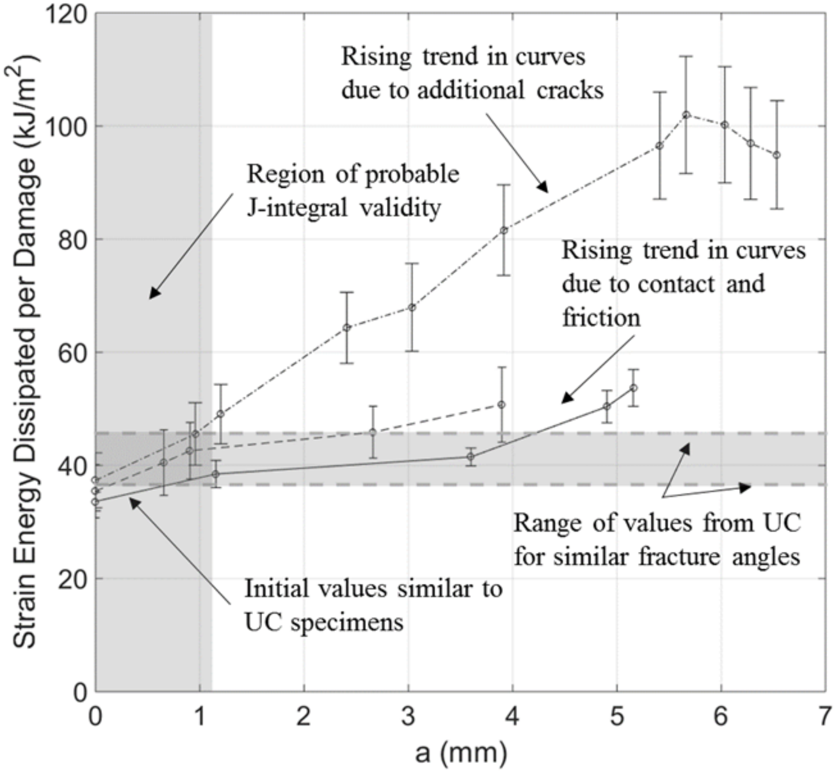
Propagation vs Initiation Energy

- Initiation energy is defined as the energy dissipated when damage first occurs
- Used because it represents the dissipation due to damage without other cracks or other dissipation mechanisms
- After once damage begins to advance crack face contact and additional damage in the crack wake may invalidate J-integral calculation
- Evidenced by rising trend
- Initiation energy from J-integral and Stress-Displacement curves still represent damage propagation as it provides information of behavior after damage occurs



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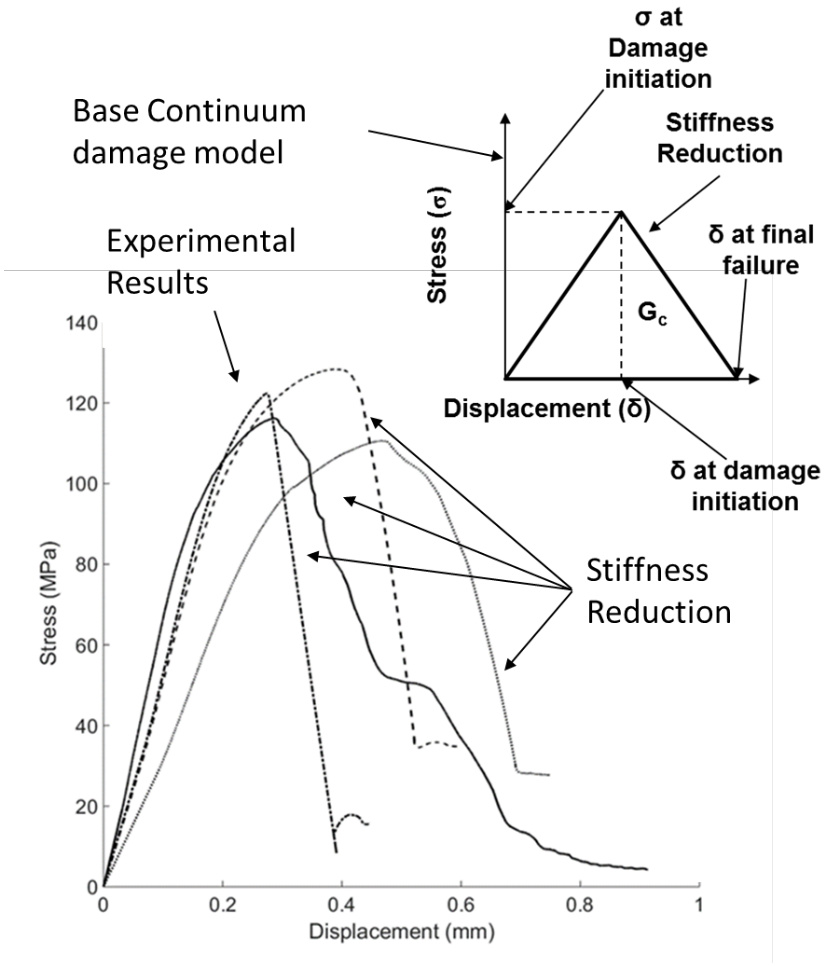
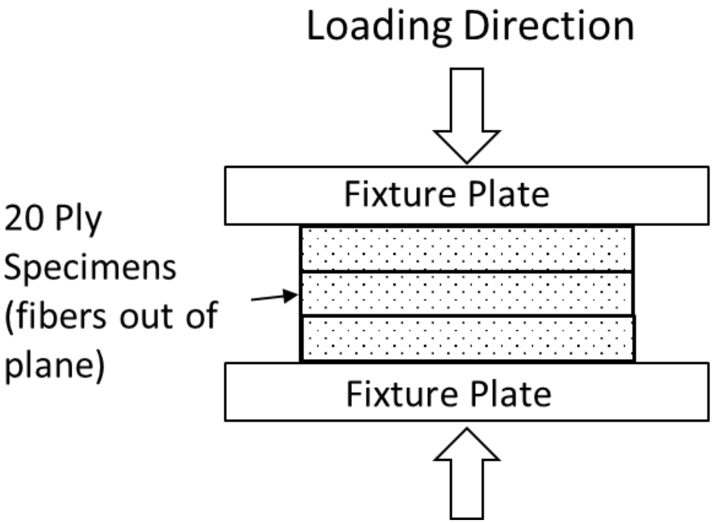
Propagation vs Initiation Energy

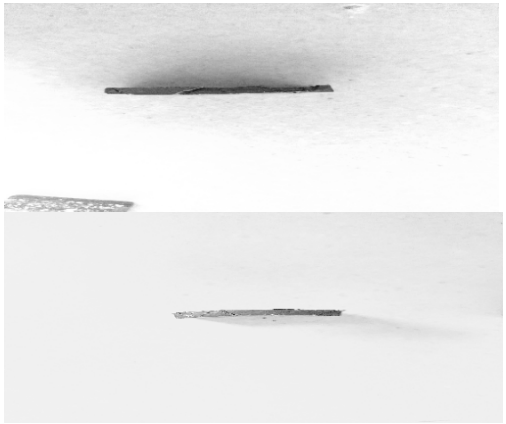
- Energy dissipation governs the propagation of damage by reducing the stiffness
- The energy dissipated due to onset of damage is applied to the elements
- Propagation of damage is modeled by initiating and degrading element properties in damage advancement direction
- Elements can be thought of as region of undamaged material where damage initiates
- Therefore initiation energy can be used to model damage propagation



Uniform Compression: Through Thickness Stack

- Tested stacks of one, two, and three 20 ply specimens
- Crushed specimens by loading through the thickness
- Displayed matrix compression failure mechanisms (shear cracks)
- Crushing caused several additional cracks as undamaged material was loaded leading to:
  - Many shear cracks in series
  - Network of small cracks at varying angles, i.e. crushed material





Uniform Compression: Through Thickness Stack

- Load-Displacement behavior determined by stack size
- 2-3 specimen stack:
  - Load drops due to initial crack
  - Load continues to drop as more material is crushed
  - Load increases due to loading crushed material and interaction with grips
- 4+ specimen stacks:
  - Load decreases due to initial cracks
  - Load increases and decreases around a roughly constant value as material is crushed and loaded
  - Similar to uniform compression tests where a relatively constant stress was observed before the crack faces slipped past each other