Failure of Notched Laminates Under Out-of-Plane Bending

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Motivation, Objective, and Approach

- Motivation and Key Issues

  The need for effective finite element analysis techniques for the design of aircraft structures using notched carbon fiber laminates
- Objective

  Evaluate the effectiveness of currently-used material models in commercial finite element packages in predicting response to damage
- Approach
  - Replace the currently-used and physically-unrealistic matrix compression material model with physically realistic model and evaluate the effect on predictions of damage propagation
  - Investigate the validity of a linear elastic fracture mechanics (LEFM) material model for the fiber tension failure material model

Project Overview

- Current commercial finite element simulation software typically utilize a fiber and matrix LEFM model for tension and compression damage modes
- Existing damage propagation models, while computationally advantageous, may not depict the actual material science
- Little experimental studies focused purely on matrix compression propagation behavior
- Challenges developing a matrix compression test specimen for materials with different matrix tensile/compressive strength ratios

- Goal: Develop a test specimen to characterize the matrix compression damage initiation and propagation
- Goal: Determine the validity of LEFM for fiber tension damage propagation

Today's Topics

- Matrix Compression Damage Overview
- Modified Compact Compression Specimen Development
  - Tapered Testing
  - Layered Version 1 Testing
  - Machined Testing
  - Layered Version 2 Testing
- Fiber Tension Damage
  - Literature Summary

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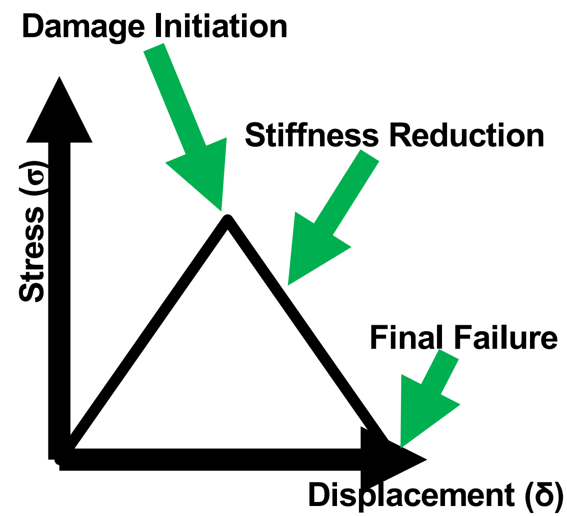
Matrix Compression Damage Overview

- ABAQUS uses continuum damage mechanics model
  - Stiffness degradation occurs post-damage initiation
  - It is believed that a residual stiffness remains after matrix compression damage and continues to carry load
  - How to experimentally demonstrate this?
- ASTM D6641[1] and D3410[2] test methods and specimens don't cover characterizing matrix damage progression
  - Need a test specimen that will accomplish this

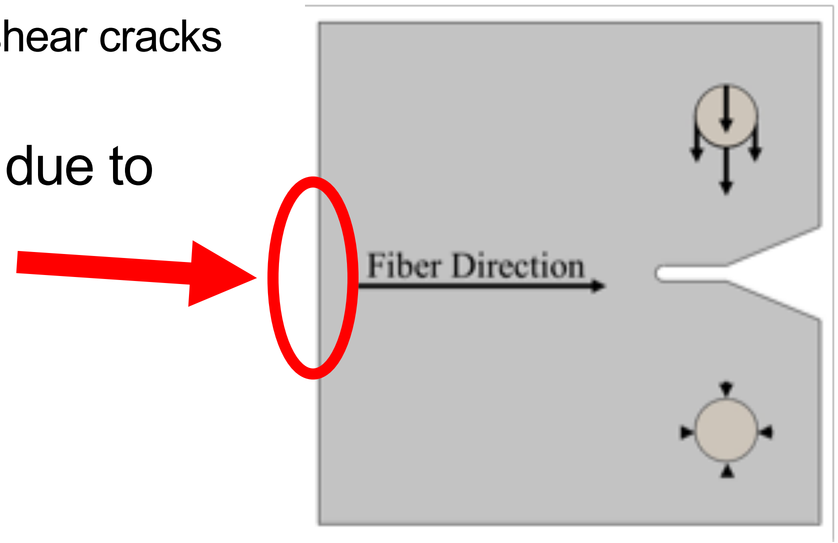


1) Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression Test Fixture
2) Standard Test Method for Compressive Properties of Polymer Matrix composite Materials with Unsupported Gage Section by Shear Loading

Matrix Compression Damage Overview

- Prior work was completed to establish a test specimen to propagate compression damage
  - FEA indicated compact compression (CC) specimens best isolated damage

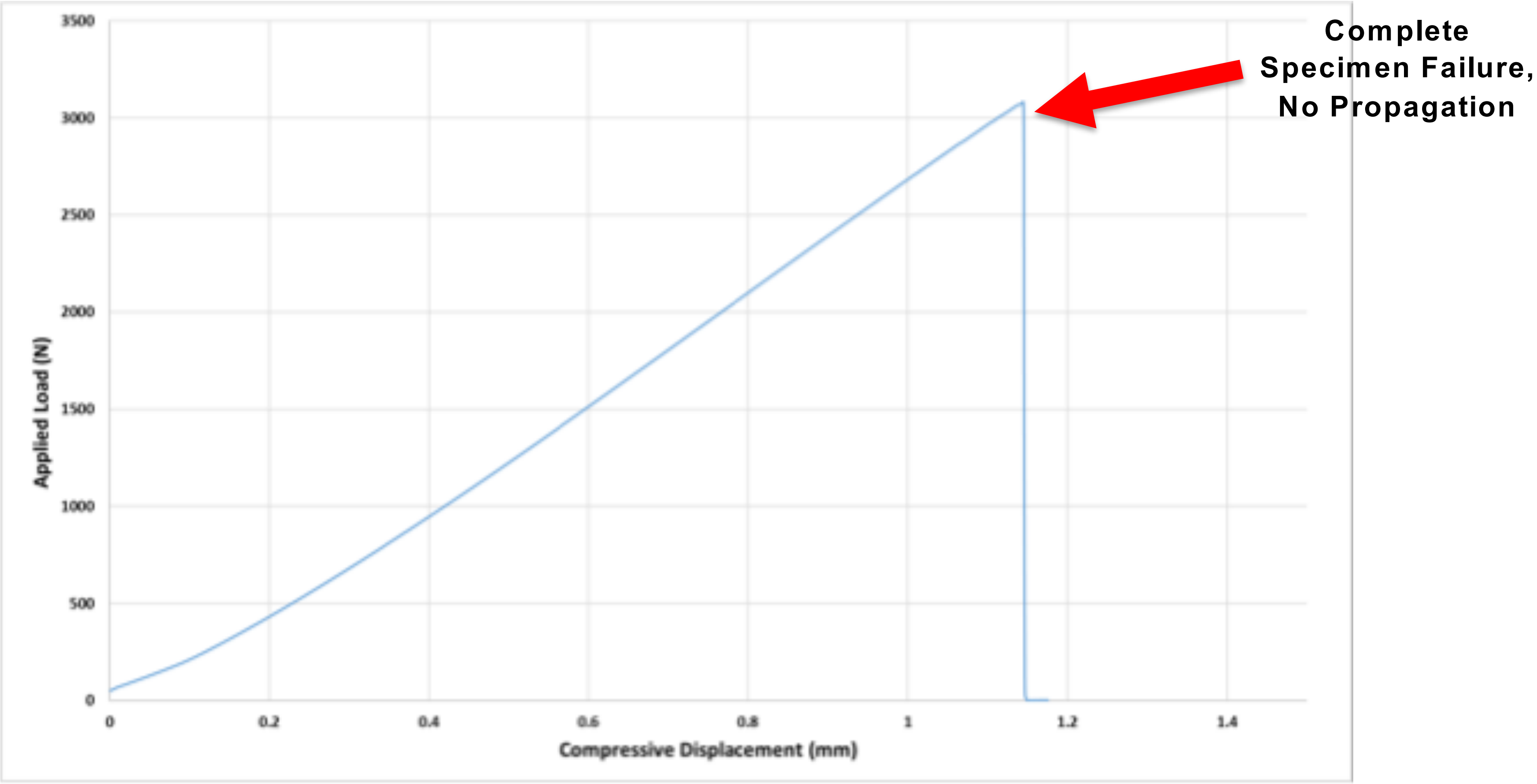
- CC testing with commercially available carbon fiber/epoxy material[1] was successful
  - Damaged primarily from through-thickness shear cracks
  - Parallel to the notch
- Boeing material specimens didn't work due to tensile end failures before the onset of compressive damage



1) TR50S/NB301 manufactured by Mitsubishi Rayon

Matrix Compression Damage Overview

Unsuccessful Load vs. Displacement Plot



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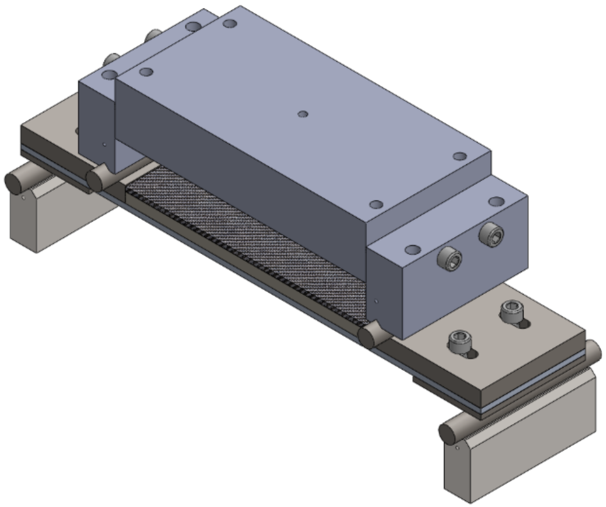
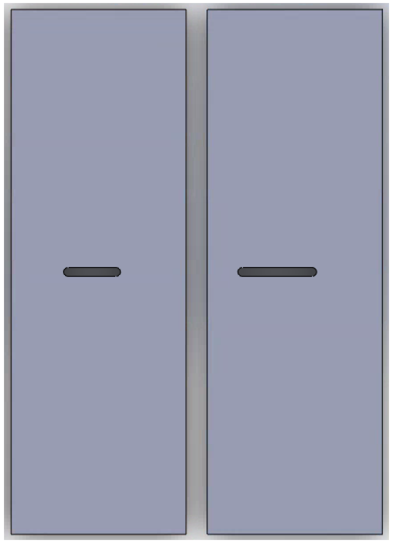
Matrix Compression Damage Overview

- Last Fall these specimens were presented
  - Bending (3 & 4-point) --- Unable to achieve damage propagation
  - Center Notch Compression --- Instant failure, no propagation
  - Edge Notch Compression ---- Minor propagation

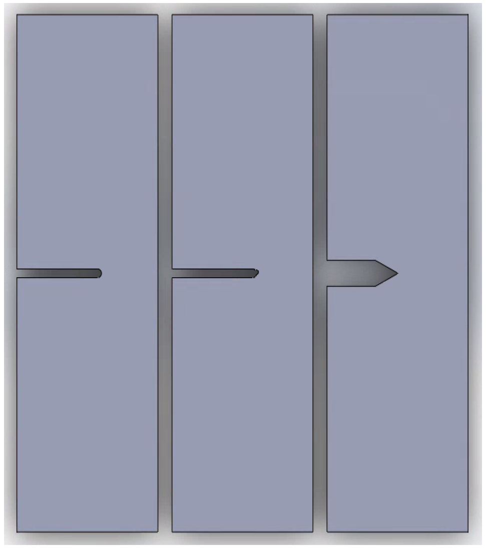
Bending



Center Notch Compression



Edge Notch Compression



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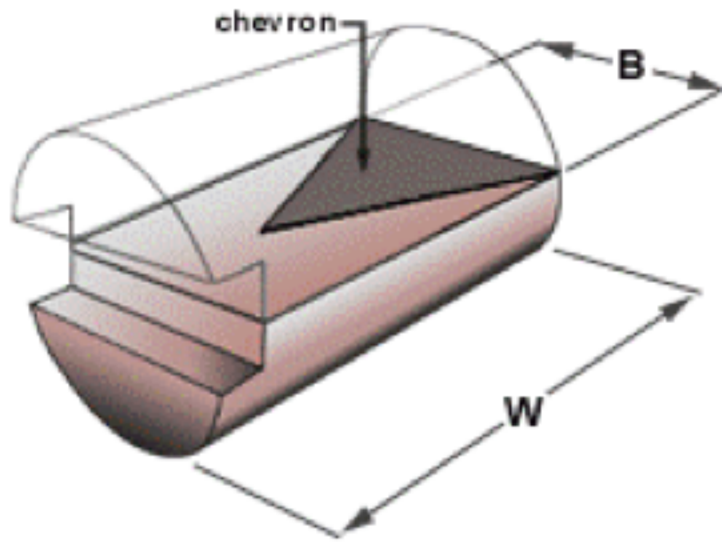
Modified Compact Compression Specimen Development – Tapered Testing

- Prior testing indicated the need for two specimen features:
  1) Slow the rapid/instant crack propagation
  2) Increase resistance to tensile side failure (if present)
- Leveraged a "Short-Rod" fracture toughness test specimen design feature
  - Short-Rod (Chevron) used for variety of materials (e.g. metals, cemented carbides)
  - Behavior is characterized primarily by slow continuously advancing crack growth



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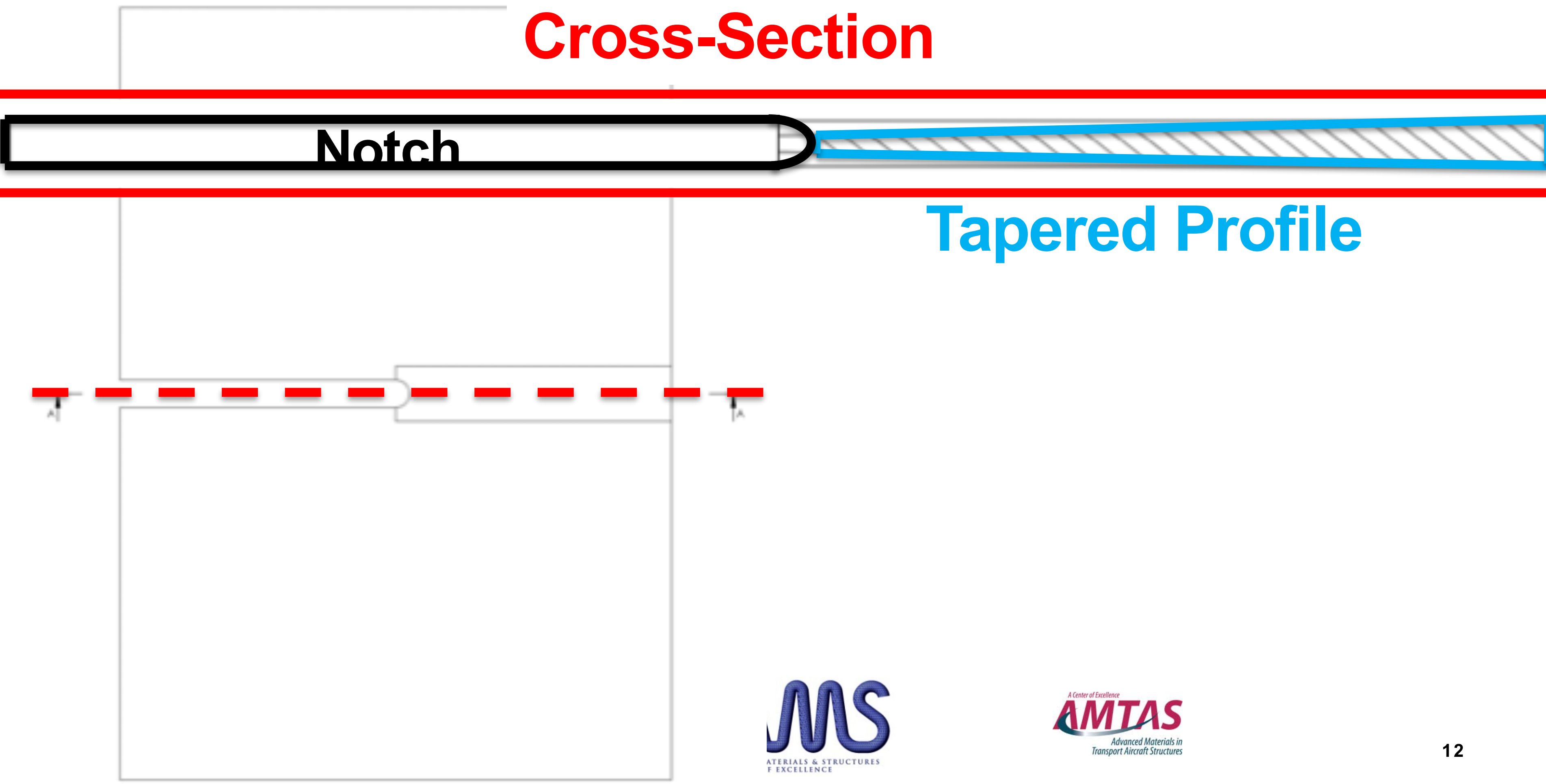
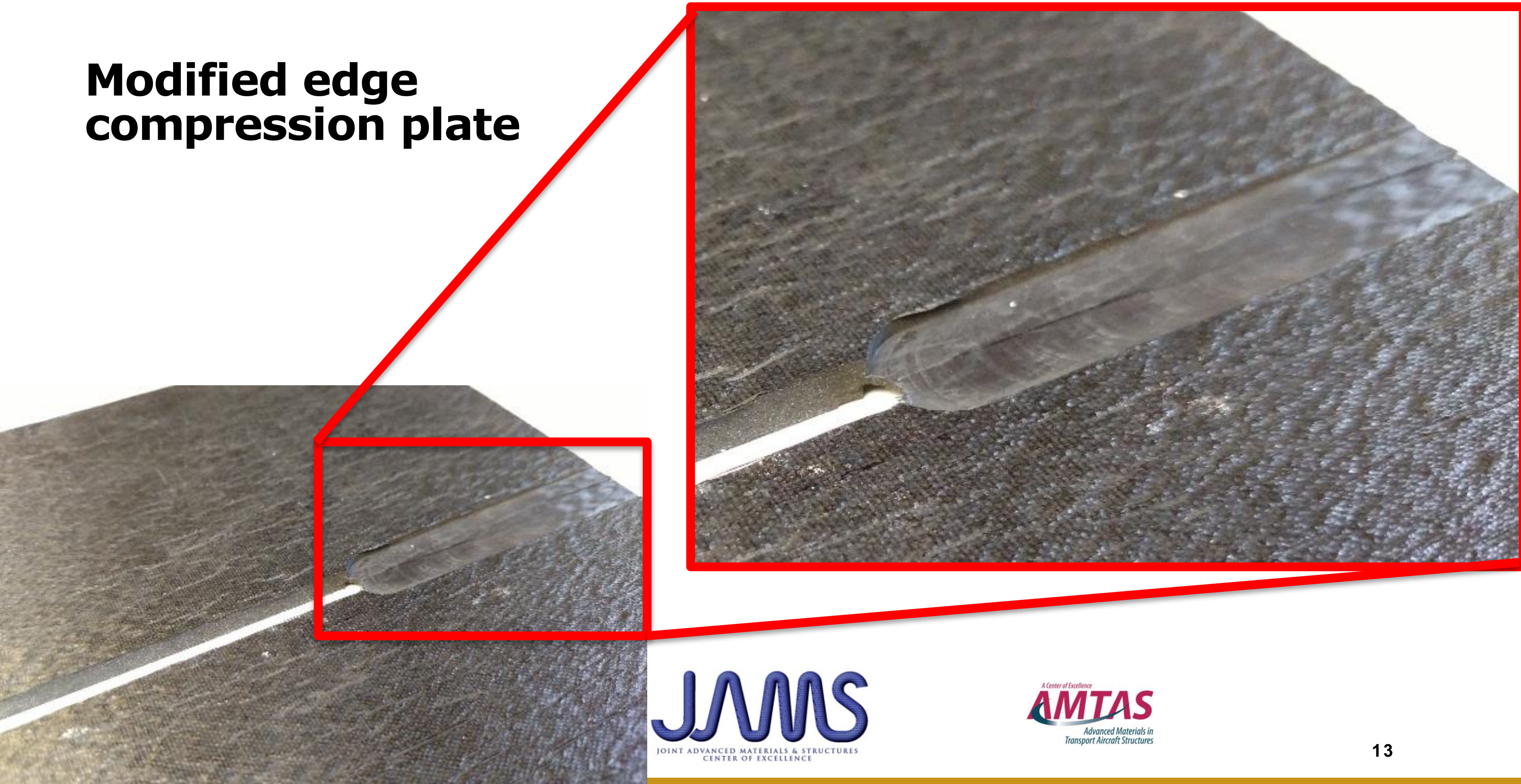
Modified Compact Compression Specimen Development – Tapered Testing

Modified a Boeing material edge compression specimen by machining a tapered profile in front of the notch



Modified Compact Compression Specimen Development – Tapered Testing

Modified edge compression plate

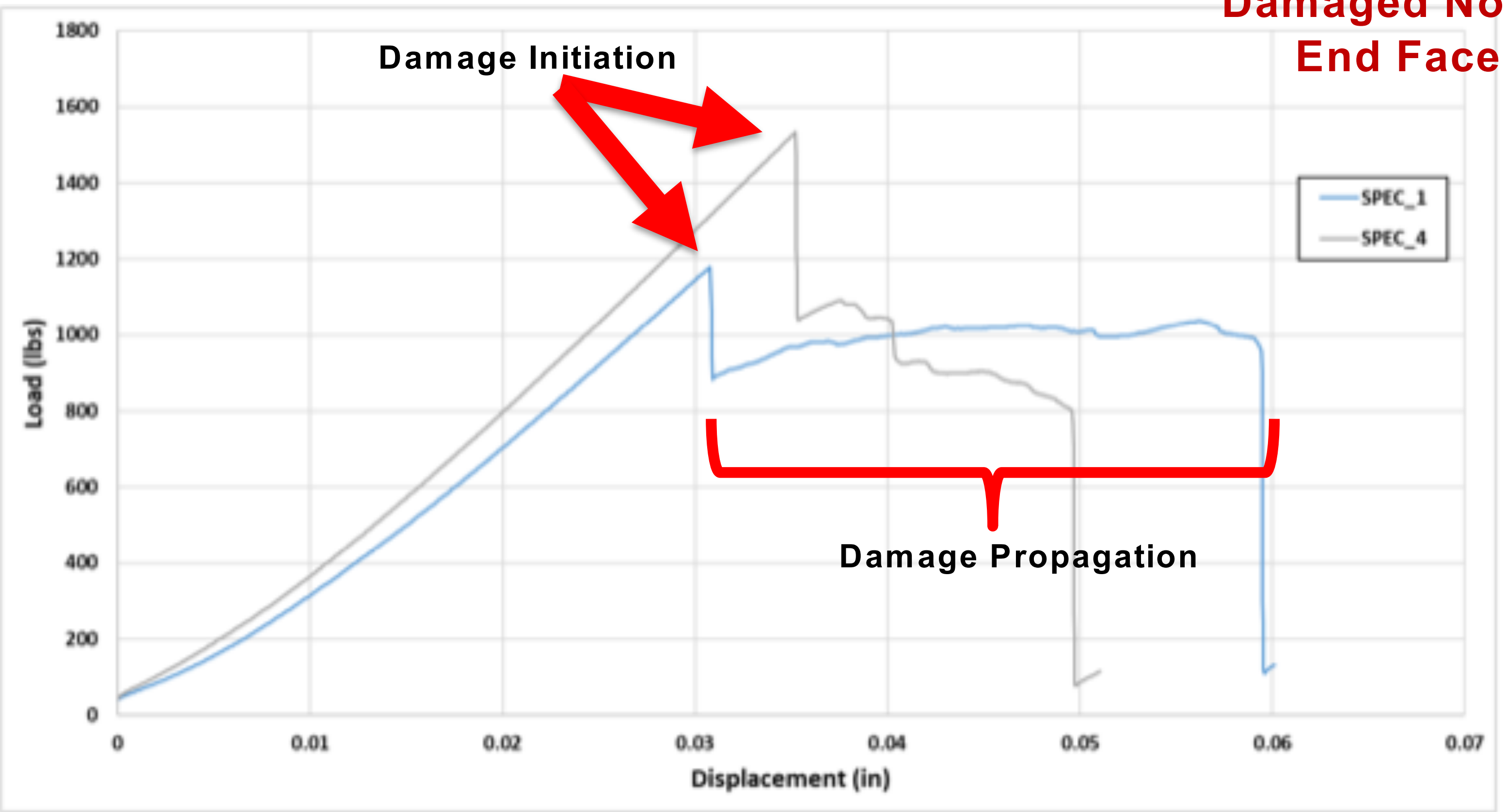


Modified Compact Compression Specimen Development – Tapered Testing

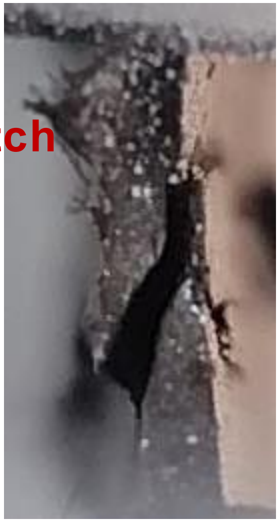
Modified edge compression plate

Modified Compact Compression Specimen Development – Tapered Testing

Machined edge compression specimens, even though crude, gave us the damage initiation and propagation we wanted



Damaged Notch End Face



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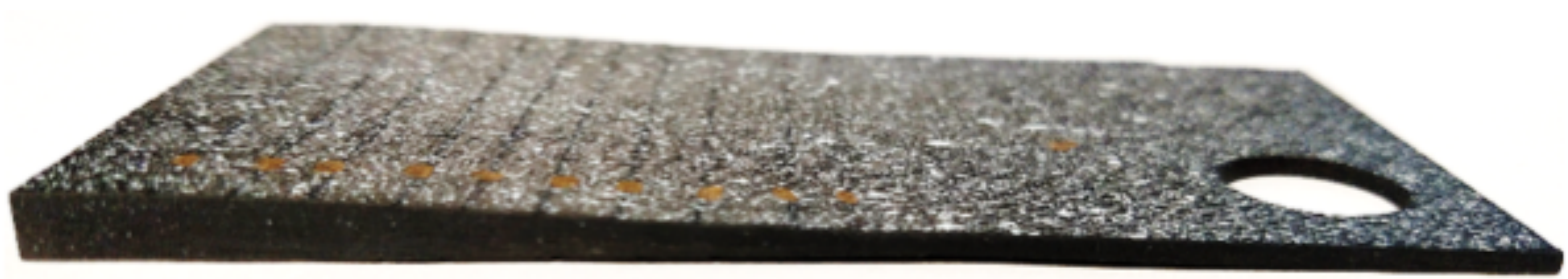
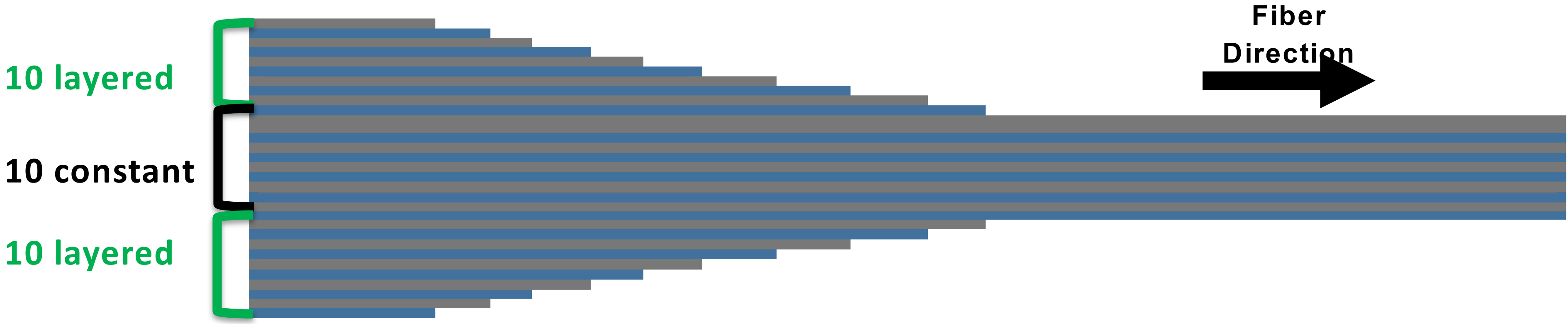
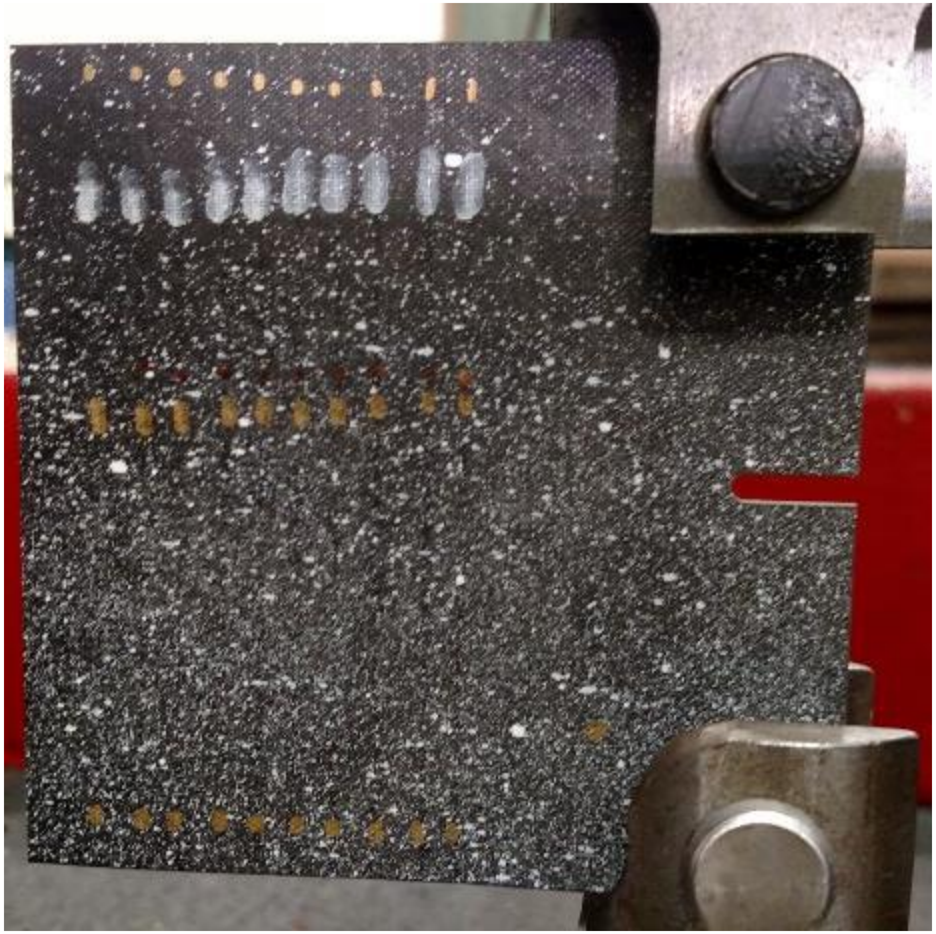
Modified Compact Compression Specimen Development – Layered Version 1 Testing

In an effort to avoid machining variability and machining induced impacts, a layered CC specimen was built by using different width layers





Modified Compact Compression Specimen Development – Layered Version 1 Testing



- This CC design:
  - Suppressed tensile side failure
  - Enabled compression damage initiation and propagation
- Unwanted load hole tensile failure and buckling occurred
  - Needed to resolve

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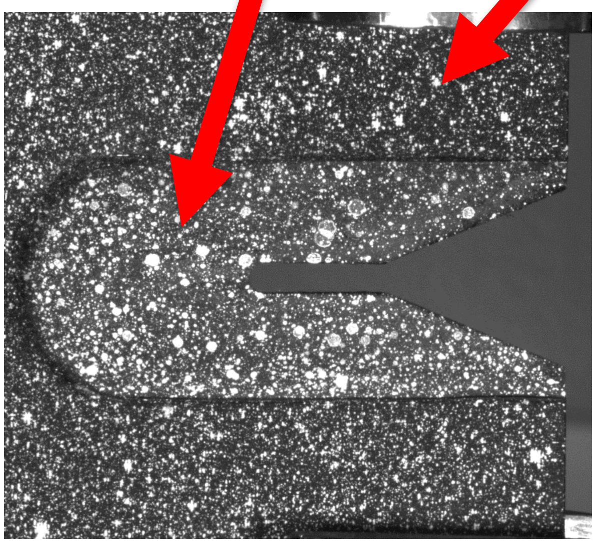
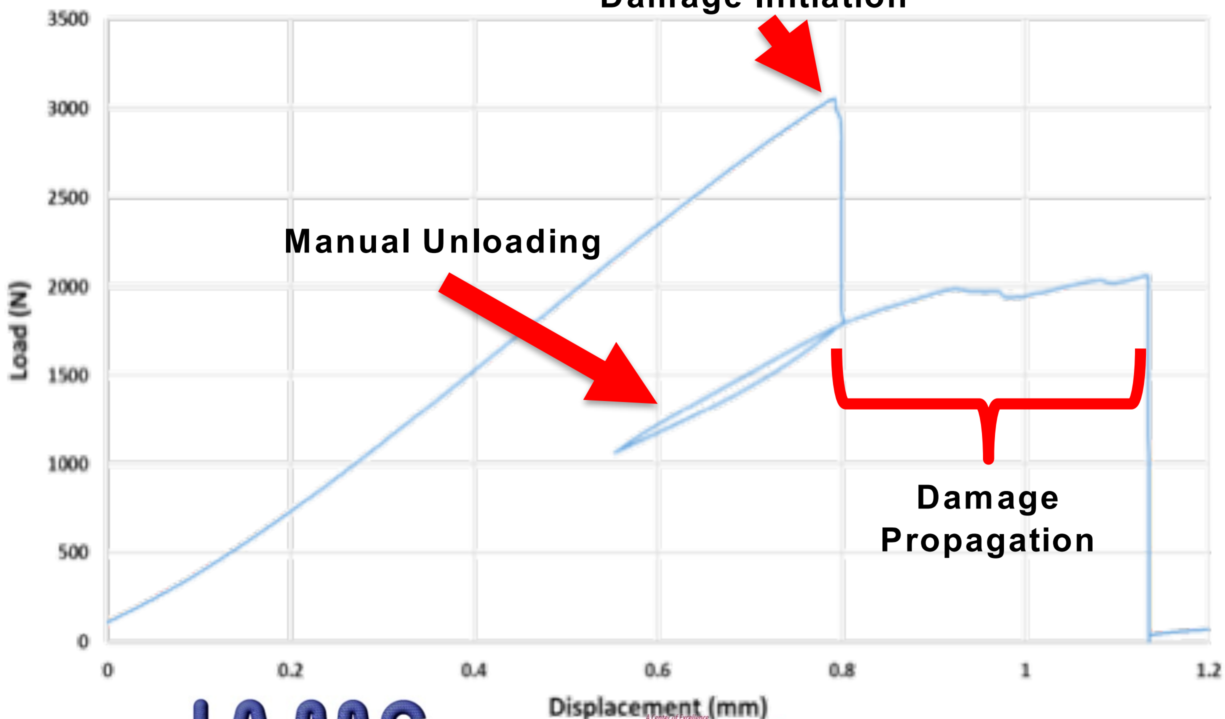
Modified Compact Compression Specimen Development – Machined Testing

Mitigating the load hole failures was explored by machining existing Boeing CC material specimens to have a step-down thickness section

Thicker at loading holes (0.18”), thin at notch tip (0.07”)



Resolved load hole failure issues and produced damage initiation and propagation



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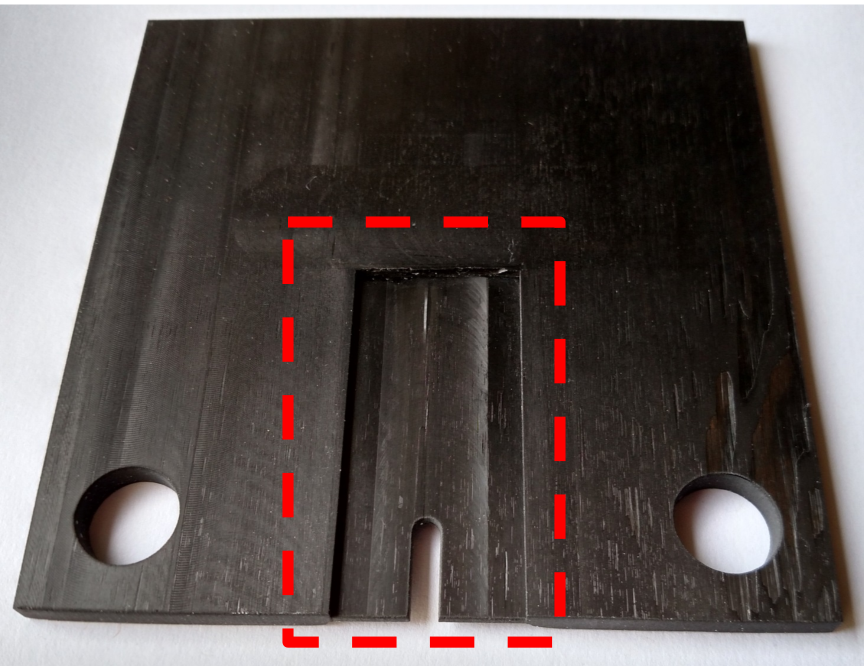
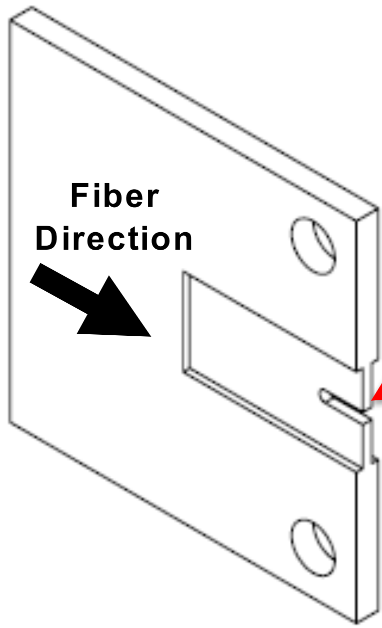
Modified Compact Compression Specimen Development – Layered Version 2 Testing

- Represented the machined specimen features with a layered geometry
  - Utilized a single step layered CC specimen
  - Conducted a study to establish the minimum ply thickness threshold

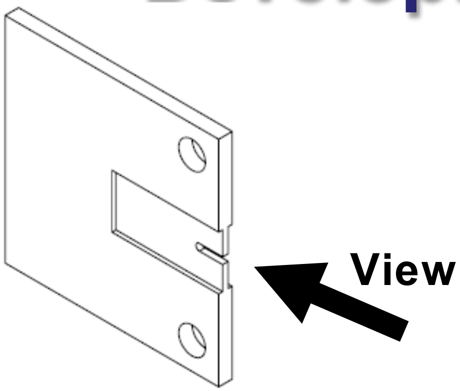




Tested specimens with the following step thickness

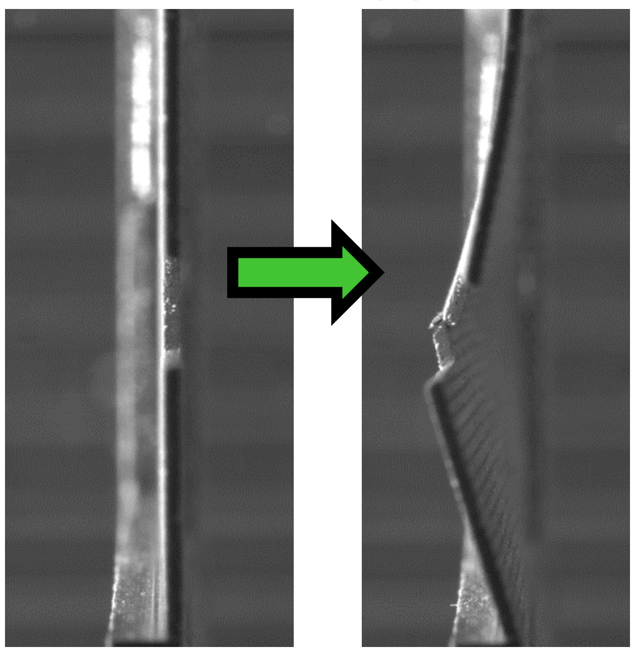
- 4 Plies
- 5 Plies
- 10 Plies
- 15 Plies

Modified Compact Compression Specimen Development – Layered Version 2 Testing

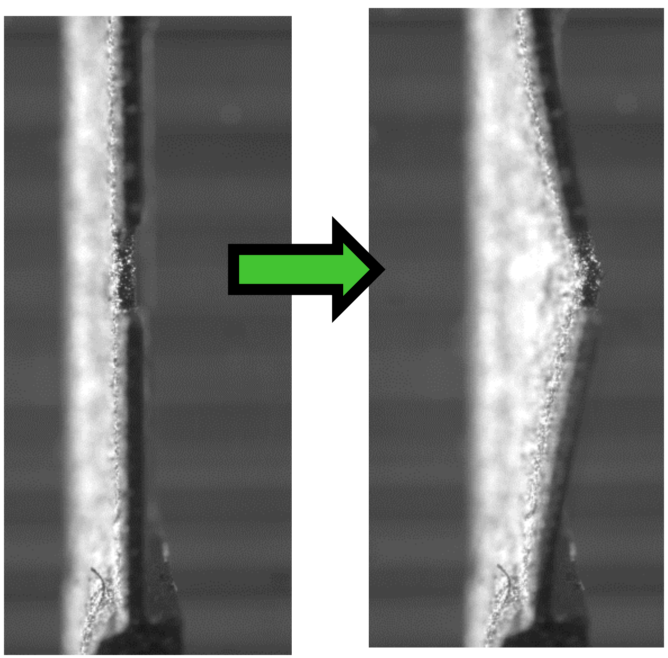


Both 4 & 5 ply layered modified CC specimens were susceptible to localized buckling

4 Plies

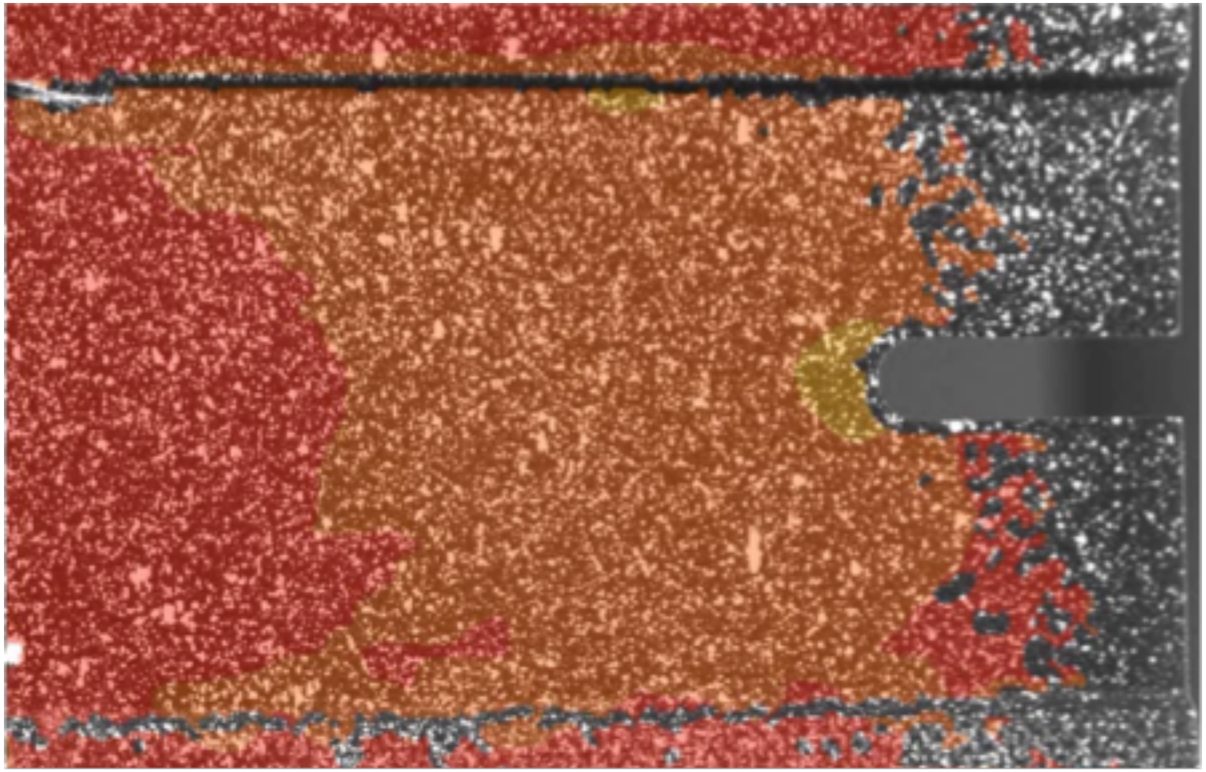


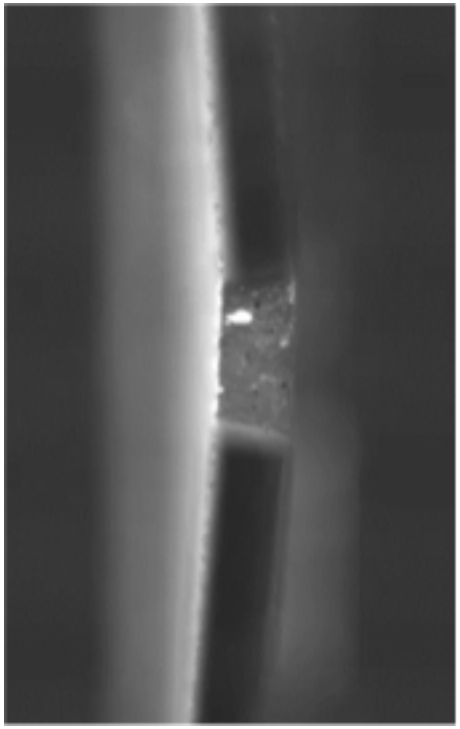
5 Plies



Modified Compact Compression Specimen Development – Layered Version 2 Testing

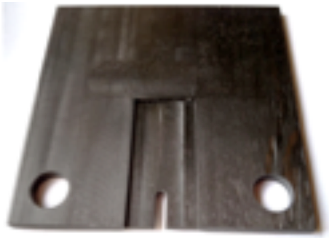
- **10 Ply layered modified CC specimen results**

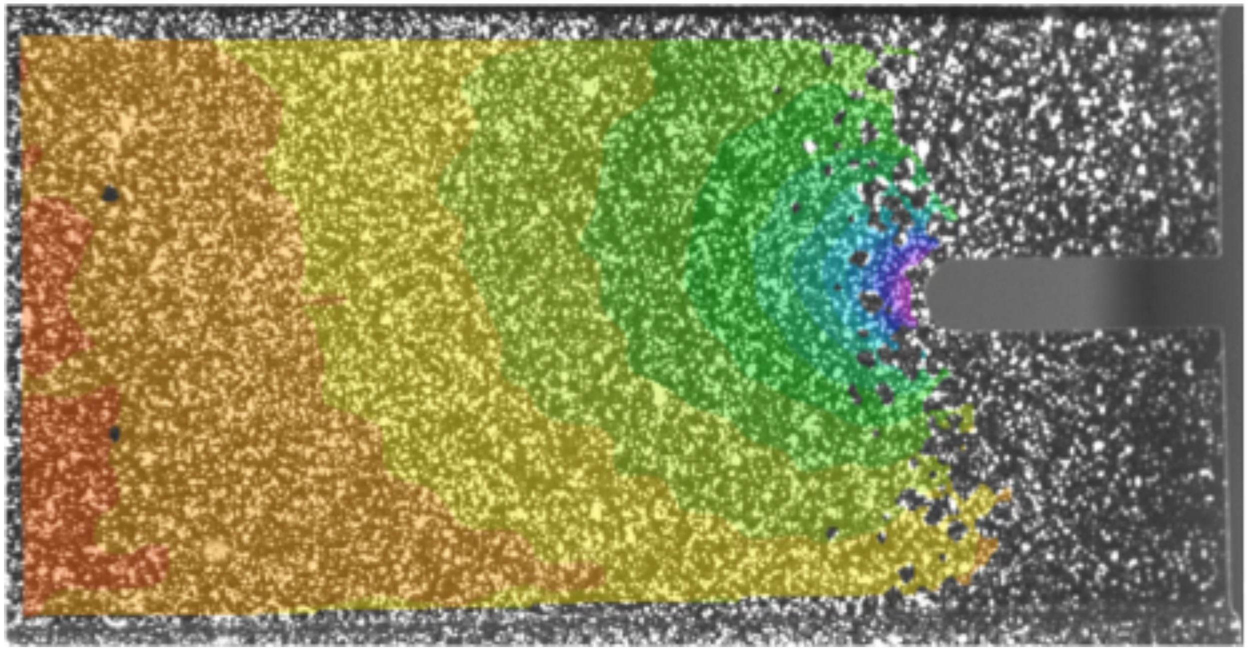


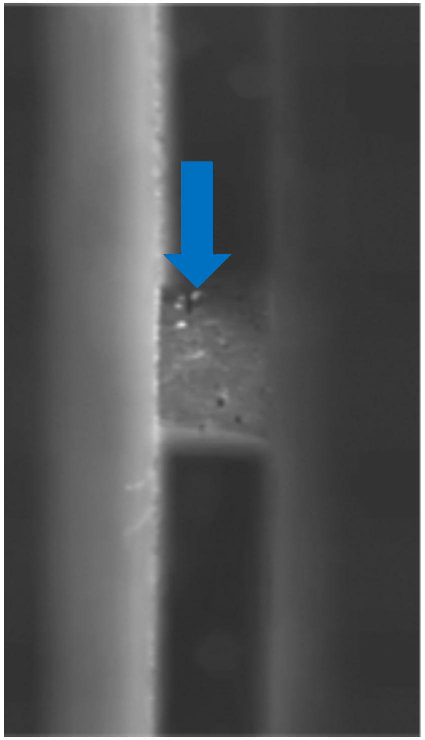


Modified Compact Compression Specimen Development – Layered Version 2 Testing

- **15 Ply layered modified CC specimen results**





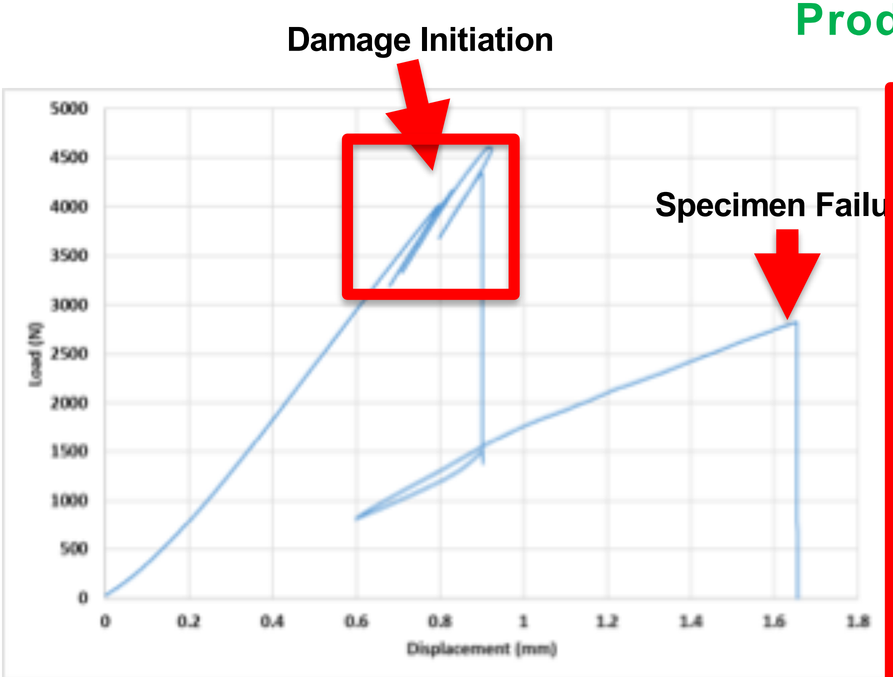


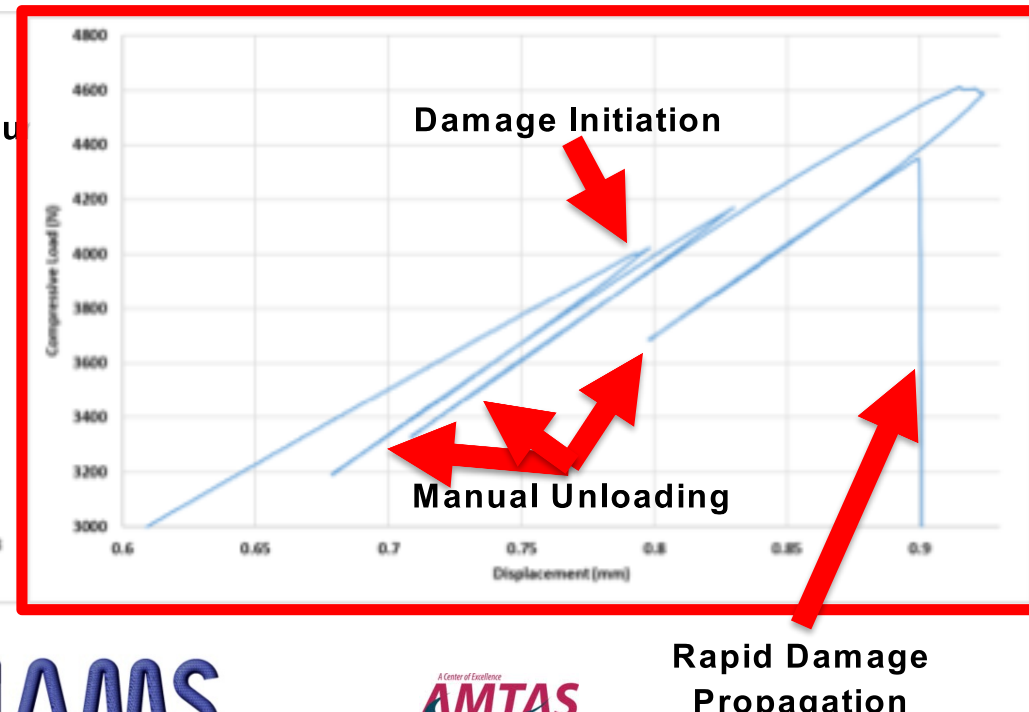
Modified Compact Compression Specimen Development – Layered Version 2 Testing

- **15 Ply layered modified CC specimen results**

Specimen works, gives us what we wanted

Produces damage initiation and propagation





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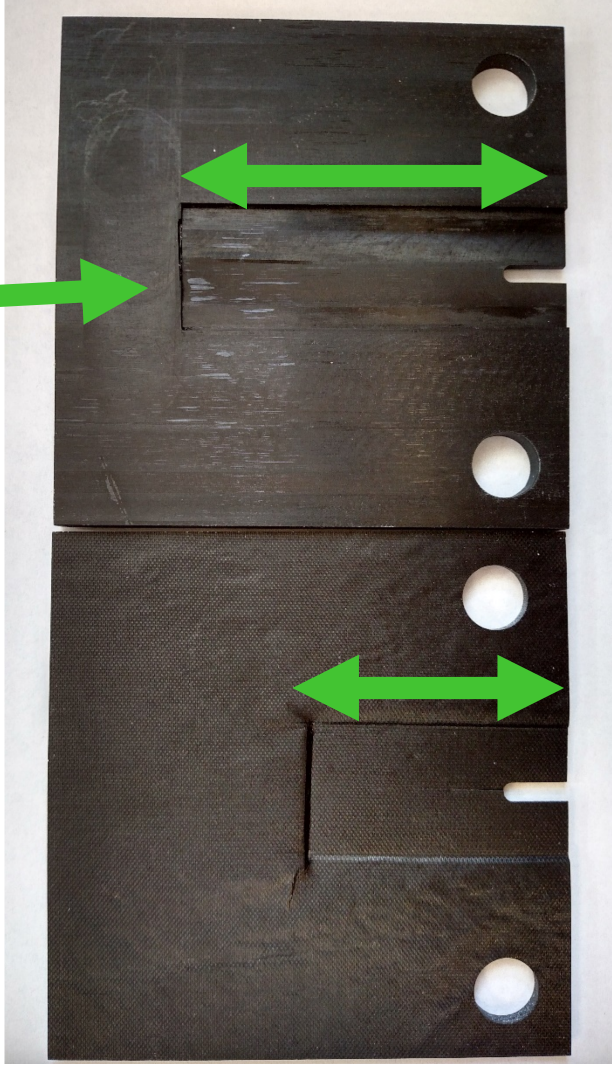
Modified Compact Compression Specimen Development – Layered Version 2 Testing

- Explored increasing the damage propagation length
  - Extended step length (+50%)



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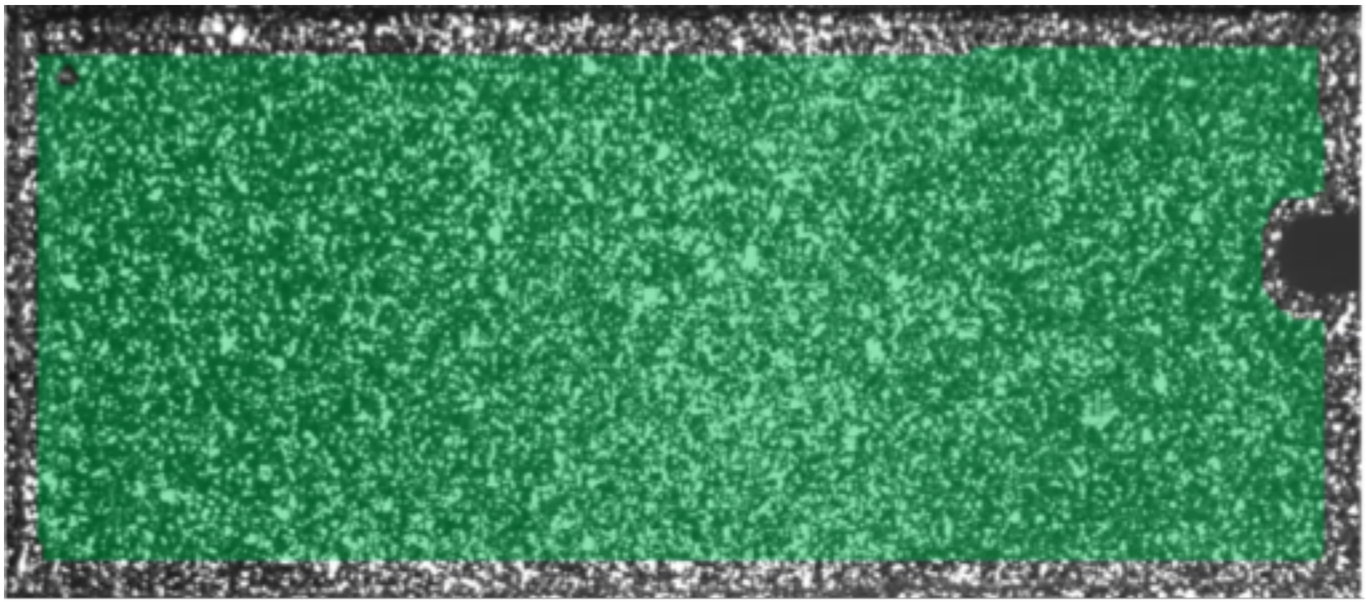
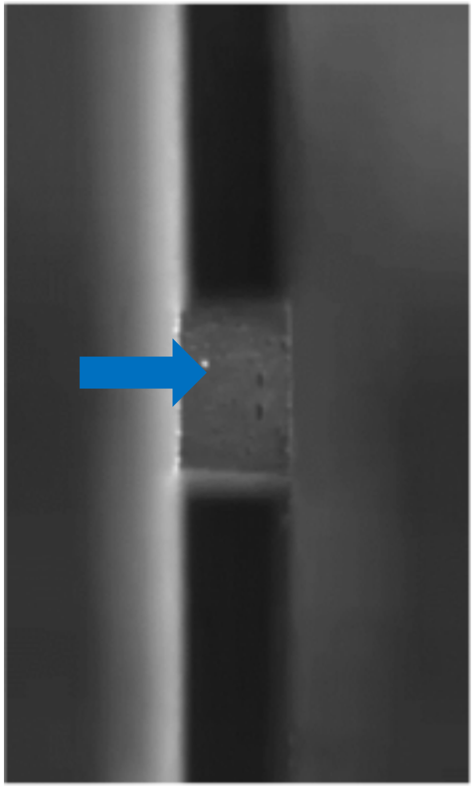
Modified Compact Compression Specimen Development – Layered Version 2 Testing

- **15 Ply extended step layered modified CC specimen results**





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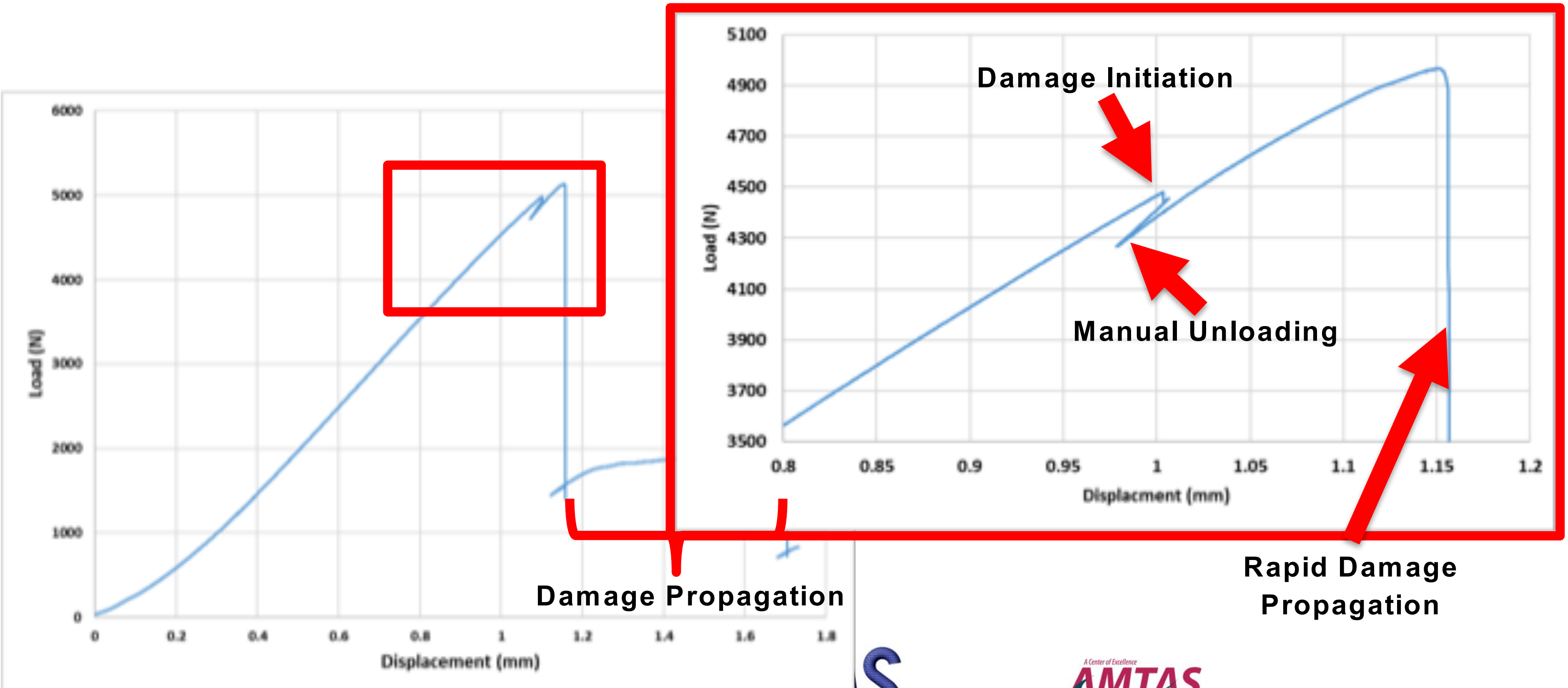
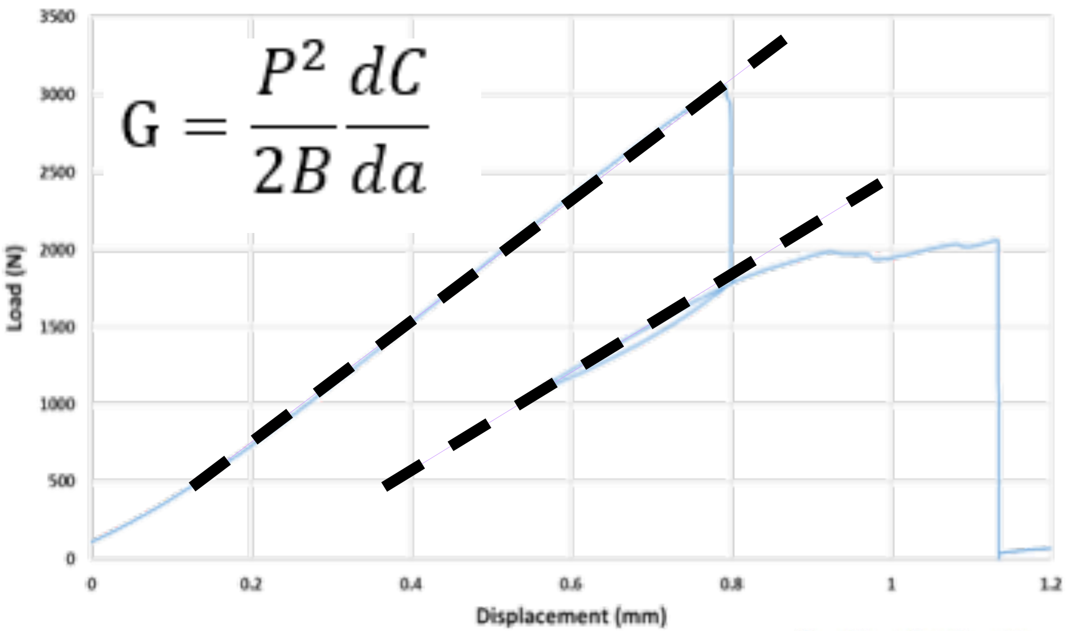
Modified Compact Compression Specimen Development – Layered Version 2 Testing

- **Extended step layered modified CC testing results**
  - For the specimen design, 15 ply is the minimum thickness



Modified Compact Compression Specimen Development

- Comment
  - The modified CC specimen is used in determining material parameters for analytical models
    - Matrix compression energy release rate



- **Commercial material values calculated to be ~ 35 in-lb/in^2**
- **Boeing values have also been calculated but are proprietary**

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Fiber Tension Damage – Literature Summary

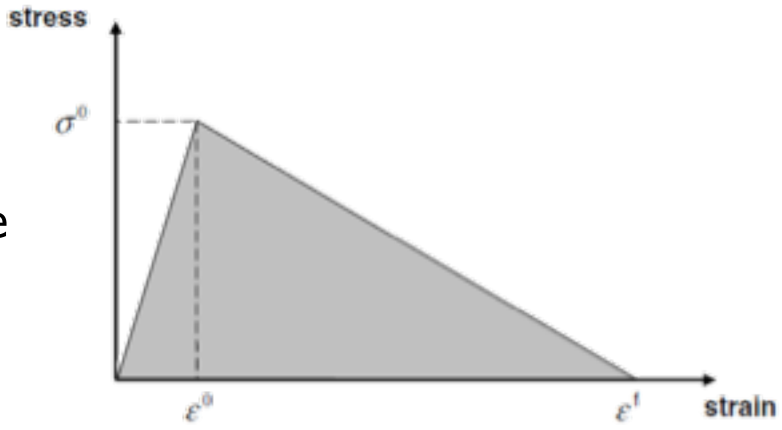
- Tensile Fiber Failure Onset Model
  - 13 failure theories were identified for the onset of fiber tension damage
  - A lot of failure theories, all boil down to two parameters. Either the tensile stress or strain limit are needed to establish the onset of fiber tension damage
  - ASTM-D3039[3] was occasionally cited as the testing procedure to obtain these tensile parameters

- **Maximum Stress**
- **Tsai-Hill**
- **Tsi-Wu**
- **Azzi-Tsai-Hill**
- **Maximum Strain**
- **Hashin**
- **Puck**
- **LaRc02**
- **LaRc03**
- **LaRc04**
- **Christensen**
- **Modified Distortion Energy**
- **Von Mises**

3) Tensile Properties of Polymer Matrix Composite Materials

Fiber Tension Damage – Literature Summary

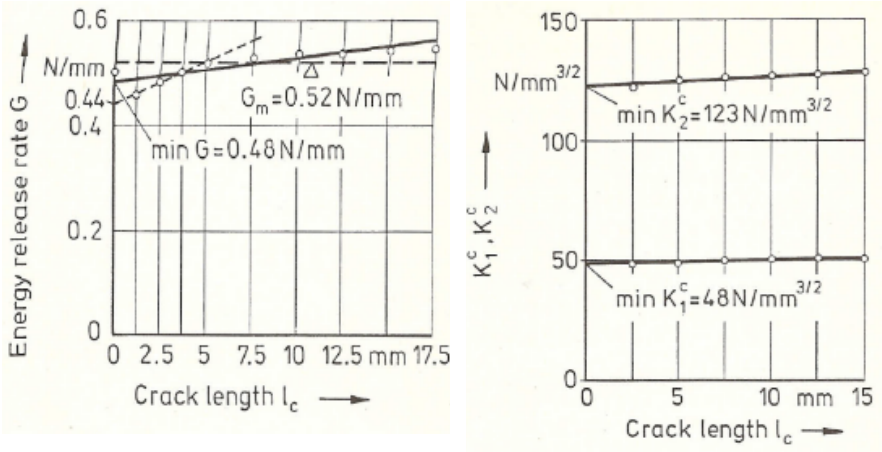
- Tensile Fiber Failure Progression
  - Most software packages use failure theories that require a fracture toughness for the progression of fiber tensile damage
  - ASTM E1922-04[4] (translaminar fracture toughness) is indicated as a possible test method to generate fiber tension fracture toughness values
  - Is LEFM a valid approach?



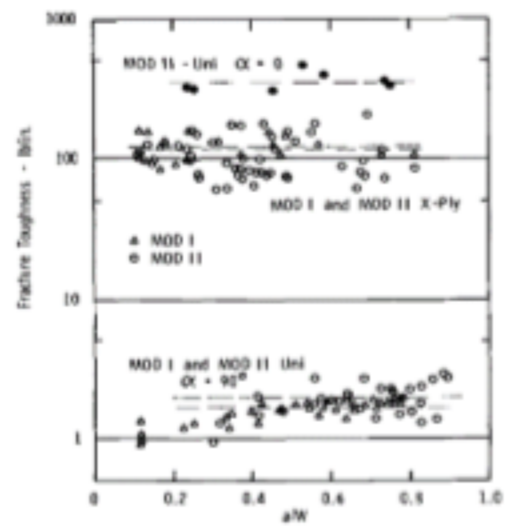
4) Standard Test Method for Translaminar Fracture Toughness of Laminated and Pultruded Polymer Matrix composite Materials

Fiber Tension Damage – Literature Summary

- Experimental evidence exists establishing that LEFM can be applied to characterize the initiation and propagation of reinforcing fibers in composite materials
- Energy release rates and fracture toughness values were generated for several composite materials (including carbon fiber)
- The difficulties in generating only fiber tension failures (longitudinal splitting/delamination) while testing likely contributed to the use of [90/0] cross ply layups in subsequent work
  - Either subtract 90° contribution or neglect it



Eggers, H. et al. Initiation and Propagation of Cracks in Notched Unidirectional Laminates of Carbonfiber-Reinforced Epoxy under Static Tensile Load; 86-30). Köln: DFVLR. 1986.



Slepetz, J. and Carlson, L. Fracture of Composite Compact Tension Specimens, Fracture Mechanics of Composites, ASTM STP 593, 143-162, 1975.

Fiber Tension Damage – Literature Summary

- Recent work suggests determining the fiber-tension fracture toughness using compact tension specimens with:
  - Cross-ply lay up
  - 90° outer plies
- Can follow this method to generate a valid fiber tension fracture toughness for use in the fiber tension damage progression models
- LEFM is a valid approach

Conclusions

- Matrix compression damage initiation and propagation characterization necessitates a unique specimen
  - Modified compact compression specimen accomplishes this
- Experimental matrix compression damage results
  - Shear dominate failure, can originate from manufacturing defects/flaws
  - Clear evidence of load carrying capacity after damage
- Several theories exists for fiber tension onset
  - Tensile stress or strain limit from testing
- Fiber tension propagation theories exists but are experimentally challenging to conduct
  - Common method utilizes cross-ply specimen and removes matrix tension contribution

Looking forward

- Benefit to Aviation
  - Better understanding of damage mechanisms to refine models to increase accuracy
- Future needs
  - Further testing to classify range of damage behavior
  - Mixed mode damage testing
  - Refine material model as needed

Questions?

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Back-Up

- ABAQUS uses continuum damage mechanics model
  - Stiffness degradation post-damage initiation
  - Damaged Elasticity Matrix

$$\mathbf{C_d} = \frac{1}{D}\begin{bmatrix} (1-d_f)E_1 & (1-d_f)(1-d_m)\nu_{21}E_1 & 0 \\ (1-d_f)(1-d_m)\nu_{12}E_2 & (1-d_m)E_2 & 0 \\ 0 & 0 & (1-d_s)GD \end{bmatrix}$$

  - Upper bound to "d" variable is 1.0 (which would reduce the stiffness to zero) and subsequent element deletion is optional
  - It is believed that a residual stiffness remains after matrix compression damage (doesn't go to zero) and continues to carry load