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

Fall 2017 Meeting

Taylor Rawlings, Kevin Carpenter, Tim McKinley,

& John P. Parmigiani,
Oregon State University

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

- ## Motivation and Key Issues

  Evaluate and develop progressive-damage analysis techniques useful in design of carbon fiber laminate aircraft structures

- ## Objective
  - Determine failure modes and evaluate capabilities of current models to predict failure.
  - Currently investigating damage initiation and propagation for
    - Matrix compression (concluding in 2017-18)
    - Fiber tension (beginning in 2017-18)

- ## Approach

  Conduct experiments to characterize fundamental material behavior, create corresponding finite element models simulating this behavior, and compare to currently-used techniques.

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

- Principal Investigators & Researchers
  - John Parmigiani (PI); OSU faculty
  - T. Rawlings, K. Carpenter, T. McKinley; OSU grad students
- FAA Technical Monitor
  - Ahmet Oztekin
  - Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Kazbek Karayev, Boeing
  - Gerry Mabson, Boeing
  - Tom Walker, NSE Composites

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

- Four modes of damage in carbon fiber composites: Fiber tension, fiber compression, matrix tension, matrix compression
- Matrix compression (concluding in 2017-18)
  - Very little published literature exists for matrix compression damage initiation and propagation behavior
  - Currently simplifying assumptions based on studies of other modes are applied to matrix compression behavior
  - Our goal is to experimentally determine the damage initiation and propagation behavior for matrix compression loading and compare to what is currently used in the commercial finite element package Abaqus
  - Also we will examine the effect of variable notch length and mixed mode loading under matrix compression
- Fiber Tension (beginning in 2017-18)
  - Determine the effectiveness of Abaqus fiber-tension damage initiation and propagation model

Today's Topics

- Experimental Specimens for Compressive Matrix Damage
  - Compact Compression Specimen
  - Bending Specimens
  - Center Notch Compression
  - Edge Notch Compression
- Fiber Tension Damage
  - Literature Review

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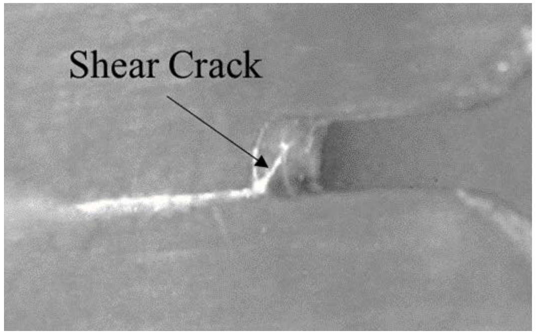
Compact Compression Specimens

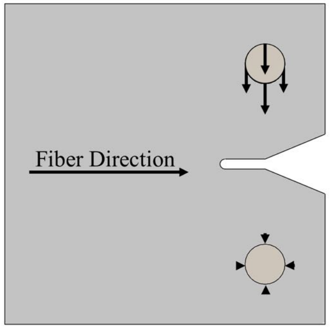
Commercial

- Mitsubishi Rayon TR50S/NB301 $[90]_{20}$
- Damage mechanisms primarily shear cracks through the thickness
- Shear cracks propagate parallel to the notch
- Shear cracks measured between 47° and 54°
- Propagation limited by tensile failure of the opposite end

Sponsor

- Unable to produce compressive damage before tensile splitting
- Maximum failure ratio $\frac{\sigma_{Compression}}{\sigma_{Tension}} = 2$
- Sponsor failure ratio $\frac{\sigma_{Compression}}{\sigma_{Tension}} > 2$



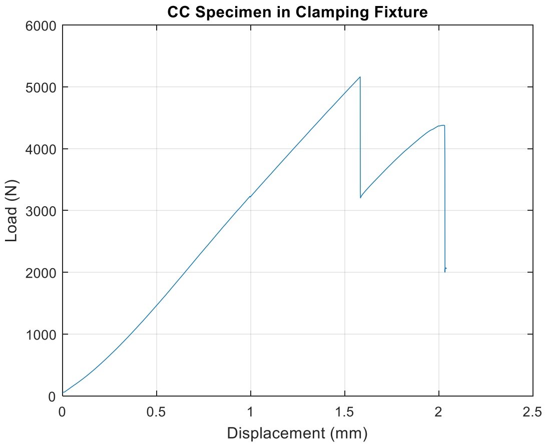


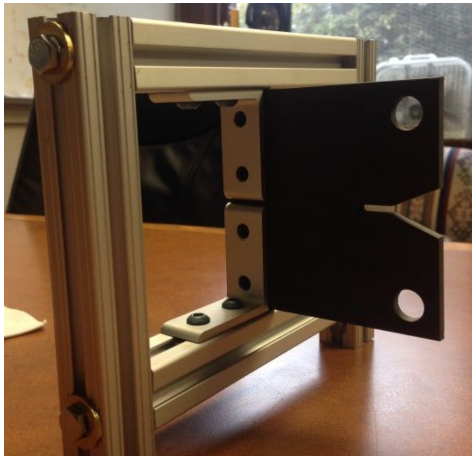
Commercial Compact Compression Specimen

Splitting Fixtures

- Various fixtures tested to delay tensile failure in sponsor material
  - None delayed tensile failure long enough
- New specimen needed that can handle failure ratios above two

$$\frac{\sigma_{Compression}}{\sigma_{Tension}} > 2$$





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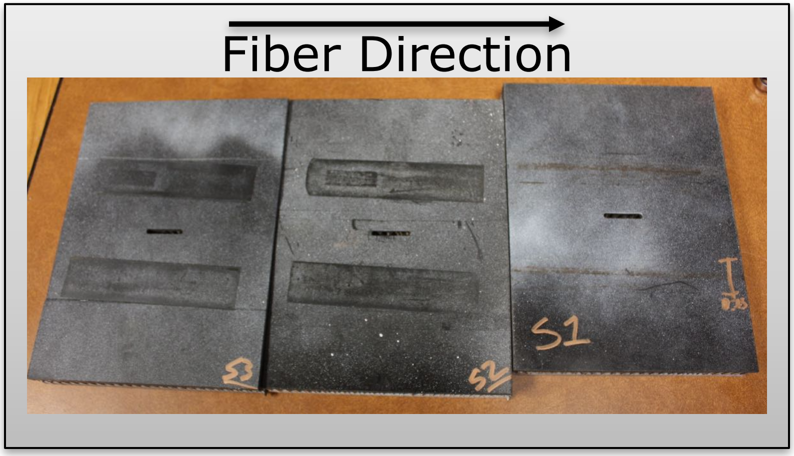
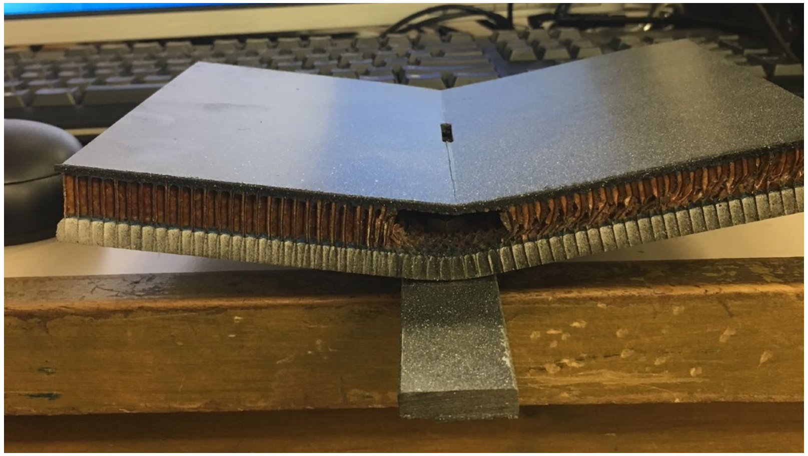
Bending Specimens

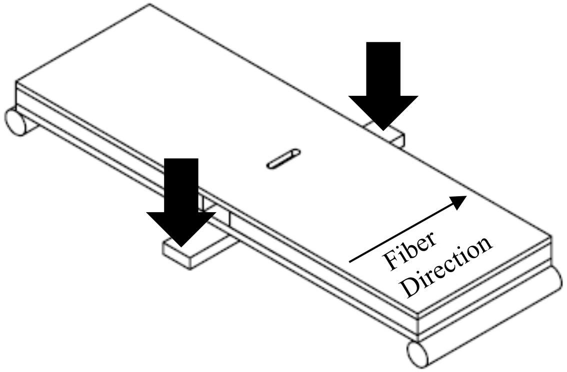
- 4 Point bending specimens carbon face loading
  - Loaded with roller
  - Loaded with washer
    - To distribute load over larger area
- Both failed by cracking in the carbon face at the loading point
- Crushing in honeycomb below the loading application location
- No strain concentration around notch tip when face cracked



Bending Specimens

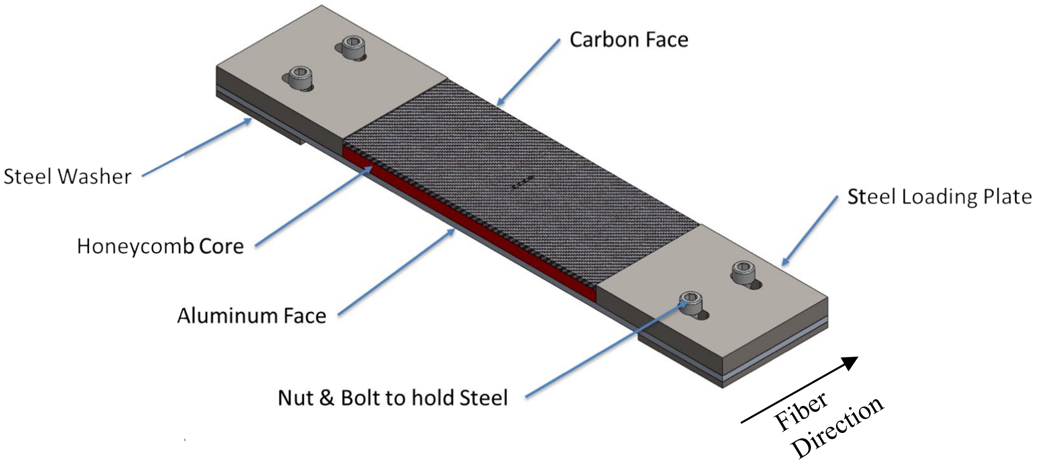
- 3-Point being specimen made from untested 4-point specimens
  - Used to load the specimen through aluminum face rather than carbon face
- A crack in the carbon occurred from the notch
- Significant plastic deformation occurred
- Shear failure also occurred in the core





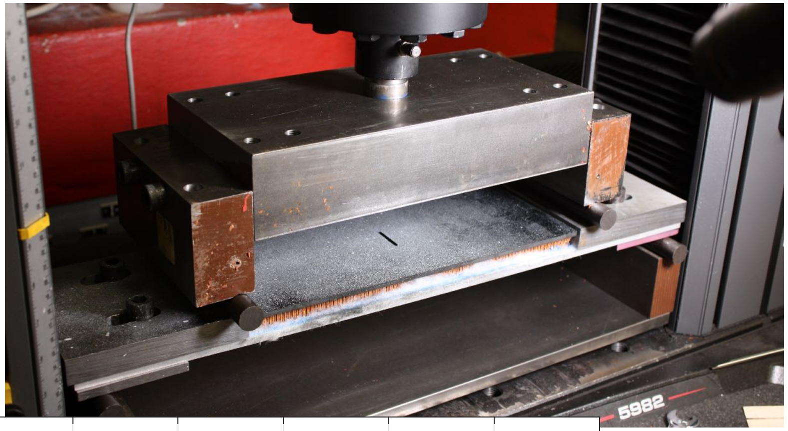
Bending Specimens

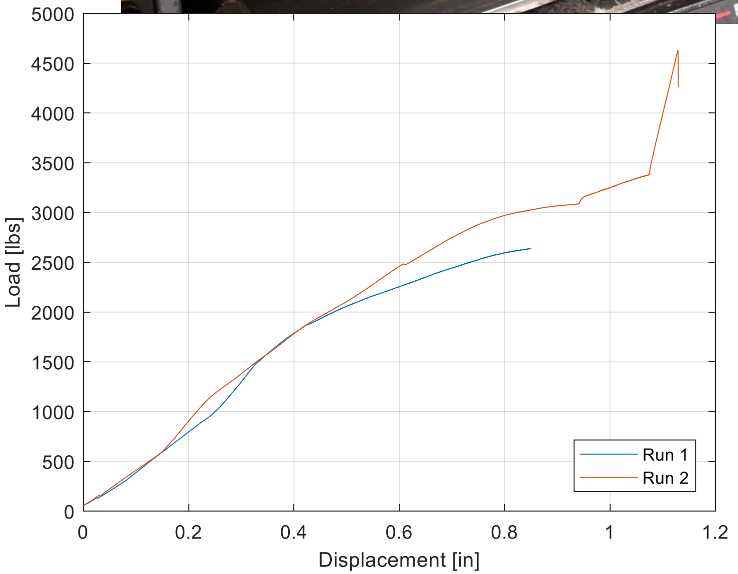
- Created new 4-point bend specimen to load the specimen without applying load to the carbon face
  - Steel washers used to prevent damage on the aluminum load application site
  - Also used to support the honeycomb and prevent shear failure



Bending Specimens

- Experienced significant deflection
- Cracks occurred at Carbon-Steel interface
- Aluminum experienced plastic deformation
- No crack occurred at the notch
- Large spike in loading occurred due to contact with test fixture after large deformation
- 4-PB specimens don produce necessary cracks





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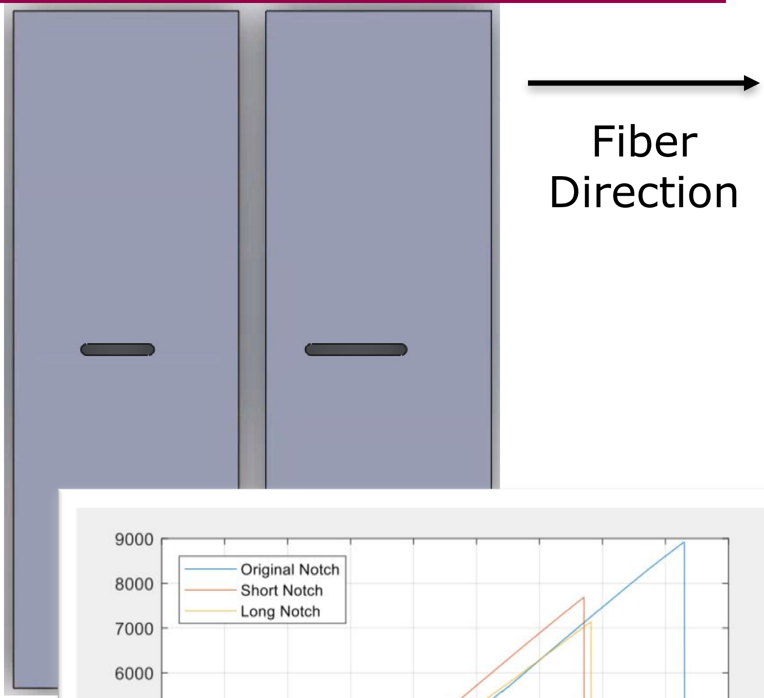
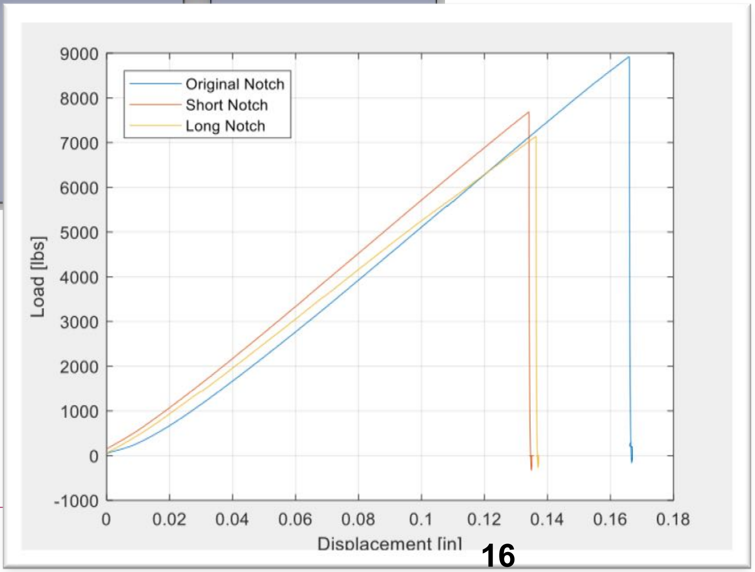
Center Notch

- Anti-buckling guard with a window to allow for DIC
- Strain gauges on specimens to ensure uniform compression loading
- Steel shims to align specimen
- Flat platen to apply load
- ¼″ x 1″ slot in the center of the specimen (5″x15″)
- Specimens failed suddenly
  - No crack progression

Center Notch

- Variable notch length to use short side as a method to slow the crack propagation
  - Break the short side first then break the long side
- Failure occurred suddenly with no crack propagation





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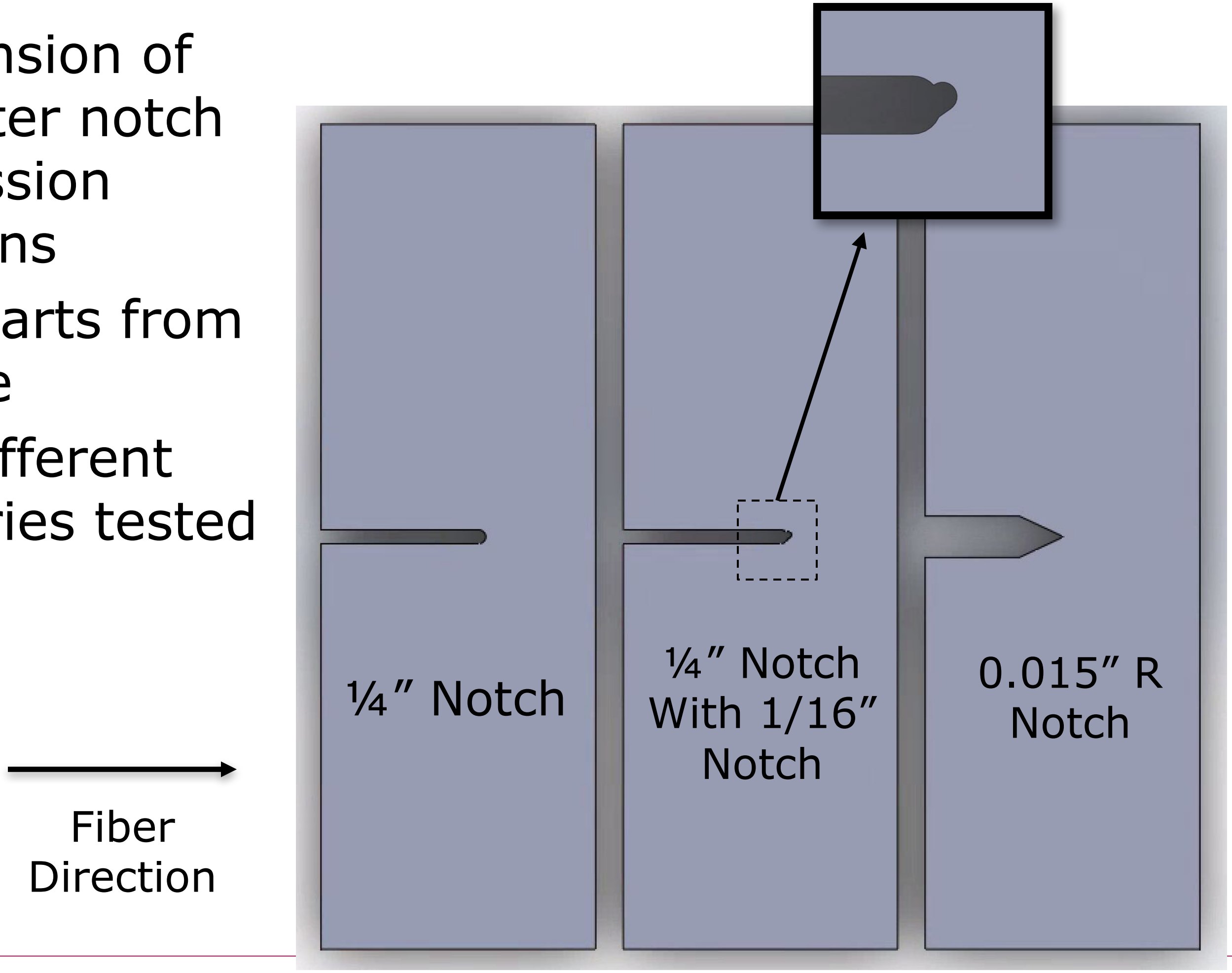
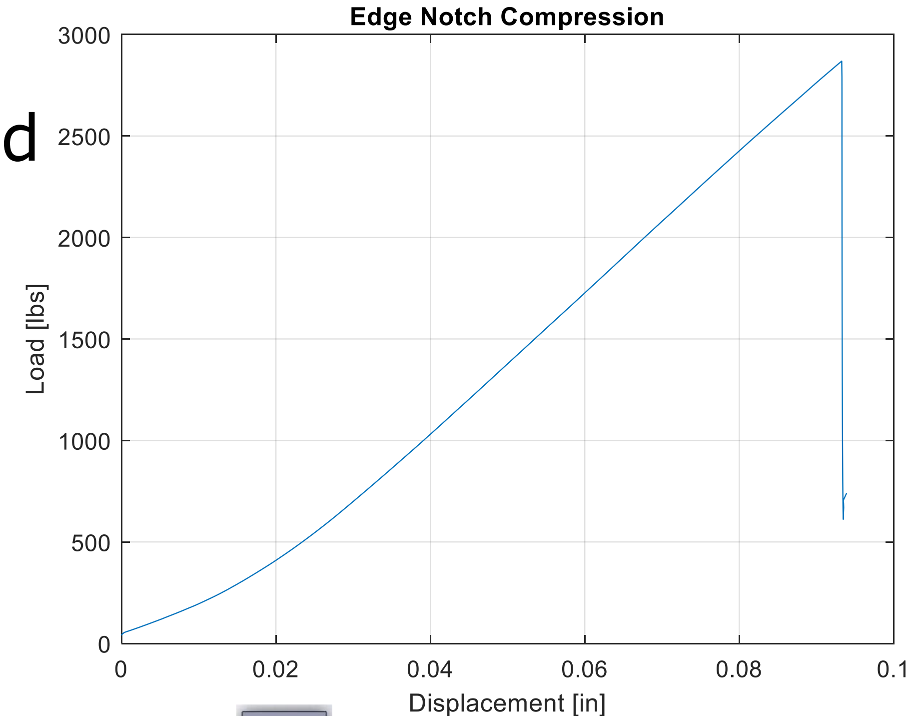
Edge Notch

- An extension of the Center notch compression specimens
- Notch starts from the edge
- Three different geometries tested



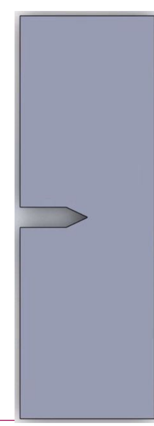
Edge Notch

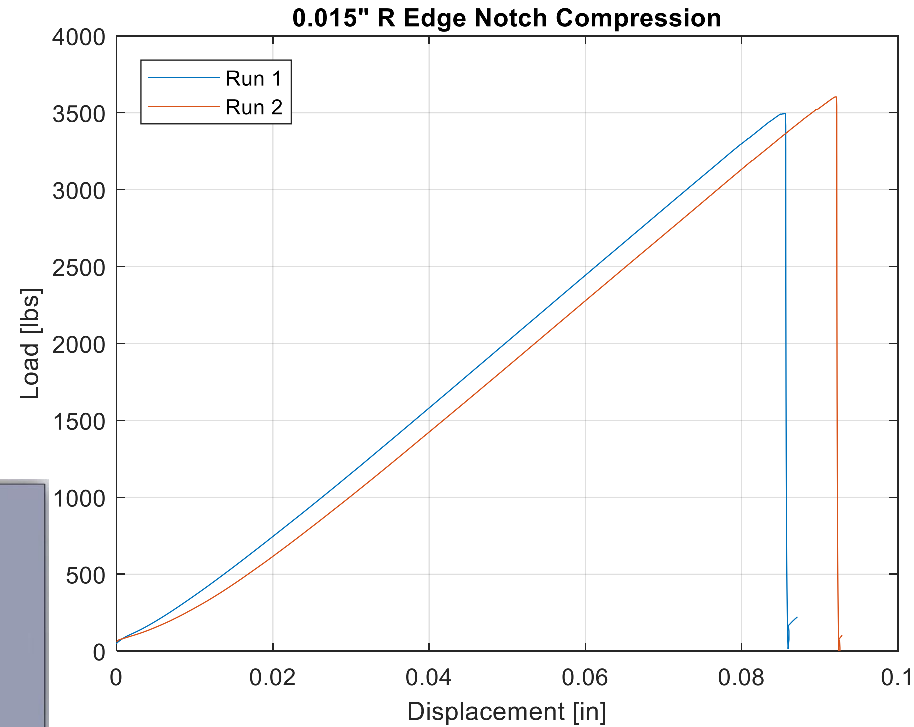
- Failure occurred suddenly at a lower load than the side notch specimens
- Straight load drop, indicating no crack propagation before specimen failure
- Failure method was consistent with center notch compression specimens



Edge Notch (0.015″ R)

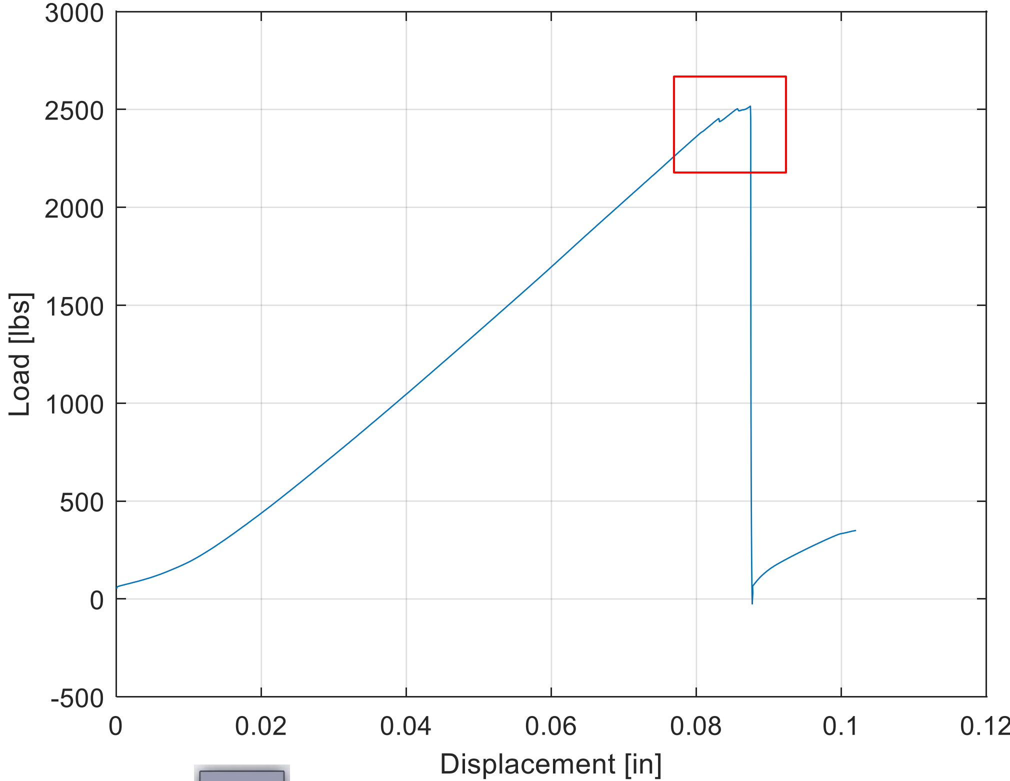
- Designed to have a high stress intensity factor to produce a small stable crack prior to specimen failure
  - 1/16″ radius produced a small crack propagation
- Failure occurred suddenly at a load higher than the ¼″ edge notch compression specimen

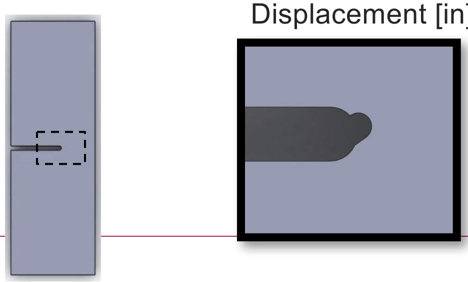




Edge Notch (1/16”)

- Increase the stress intensity factor
- Non-linearity before drop suggests crack propagation
- DIC showed some crack growth
- Continued experimentation on edge notch specimens to increase crack propagation prior to specimen failure





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Fiber Tension Damage

The fiber-tension-damage study will consist of:

I. A thorough literature review to determine the current practice
II. Developing, as needed, suitable testing fixtures, specimens, and procedures to identify an effective fiber-tension-damage model
III. Measuring the associated material properties for both Boeing and commercial materials

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Fiber Tension Damage

Investigation into currently available fiber tension damage models included the following commercial software companies:

ANSYS®
3DS SIMULIA Abaqus
LMS® A Siemens Business
MSC Nastran™
AUTODESK® HELIUS COMPOSITE
AlphaSTAR GENOA
LS-DYNA
AnalySwift™
GLOBAL ENGINEERING & MATERIALS, INC. Engineering and Innovative Solutions
Altair

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[1] 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**

1: Tensile Properties of Polymer Matrix Composite Materials

Tensile Fiber Failure Progression

- Most software packages use one of two failure theories for the progression of fiber tension damage.
- These failure theories require the fracture toughness in the progression of fiber tensile damage.
- ASTM-D5528[2] was cited as the testing procedure to obtain the fracture toughness parameter.

> - **Energy dissipation with material softening**
> - **Energy based cohesive law with material softening**

2: Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites

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Questions?