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

- 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 History
- Uniform Compression Specimens
  - Damage Mechanisms
  - Stress Displacement
- Compact Compression Specimens
  - Damage Mechanisms
  - Variable Notch Study

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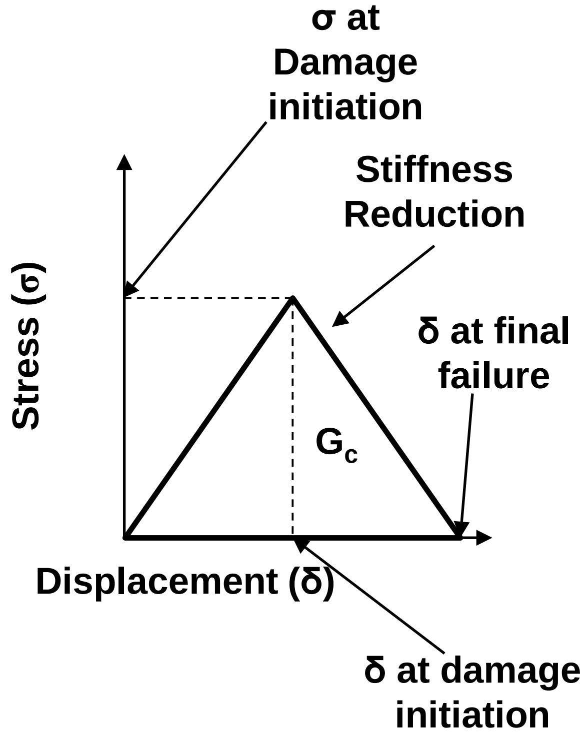
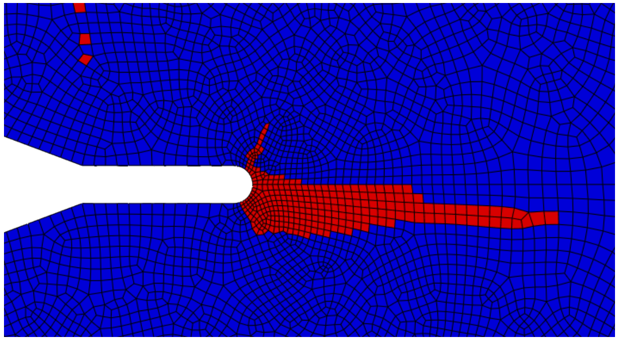
Matrix Compression History

- ABAQUS uses continuum damage mechanics model
- Previously performed a literature review
  - Fracture mechanics methods used to model compression damage
  - Determined possible specimens to isolate compression damage
    - Center Notched Compression (CNC)
    - Compact Compression (CC)
    - 4-Point Bending (4PB)
- ABAQUS modeling to determine best damage isolation
- Preliminary tests to confirm CC selection





Compact Compression (CC)

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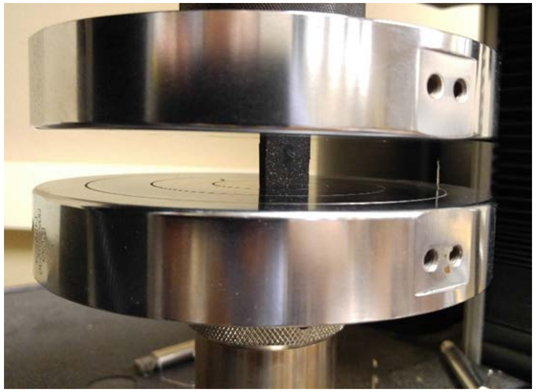
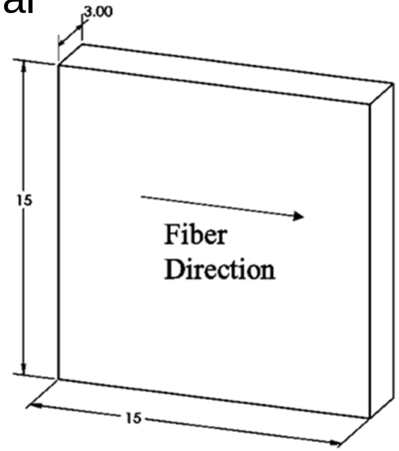
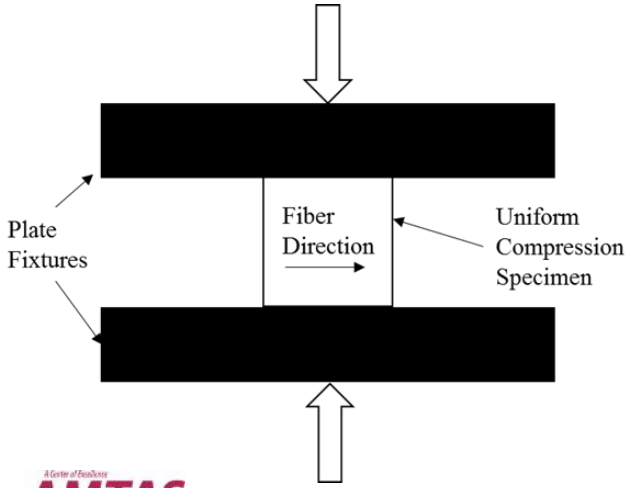
Uniform Compression Specimens

- Measure the matrix compression stress-displacement behavior directly
- 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
- Two different materials tested
  - Mitsubishi Rayon TR50S/NB301
  - Boeing provided material







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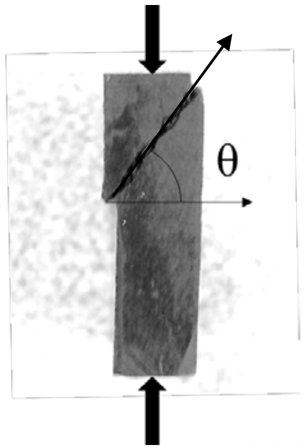
Uniform Compression: Damage Mechanisms

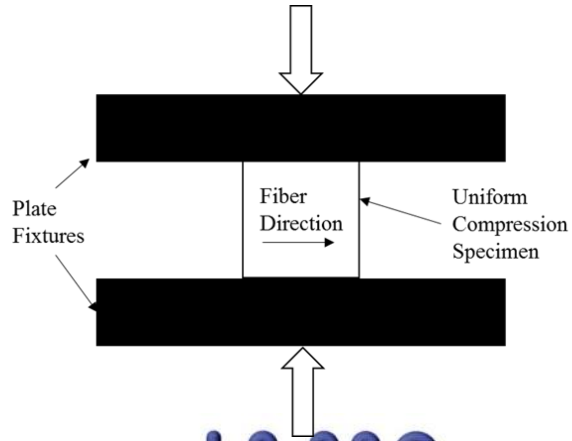
Commercial Material

- Shear cracks through the thickness
- Angles between 52° to 73°
- Trapped material in crack wake
- Fiber Bridging

Sponsor Material

- Sudden specimen failure
- Multiple cracks

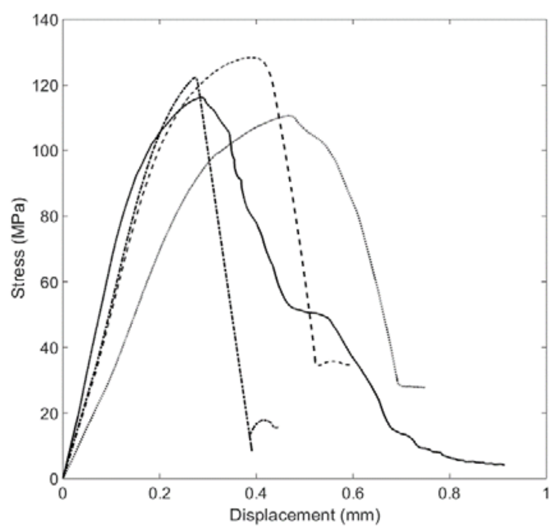




Uniform Compression: Stress Displacement

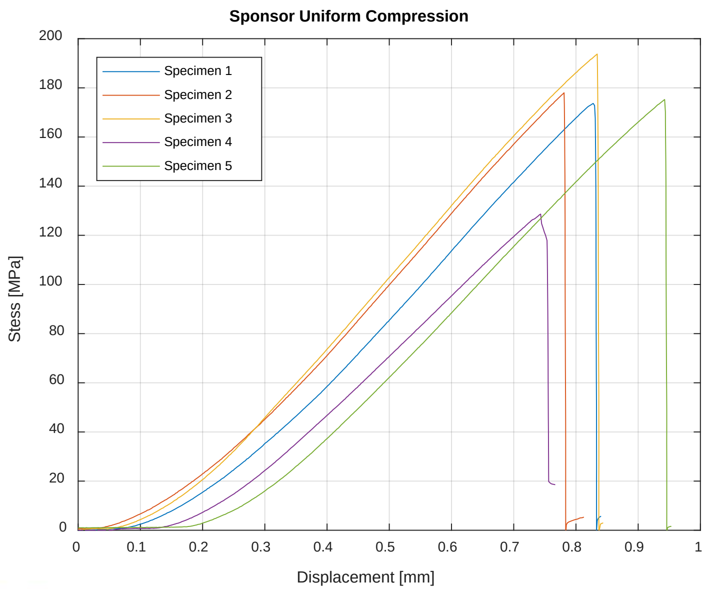
Commercial

- Three behavior zones
- Variable propagation speed
- Typically retains some stress



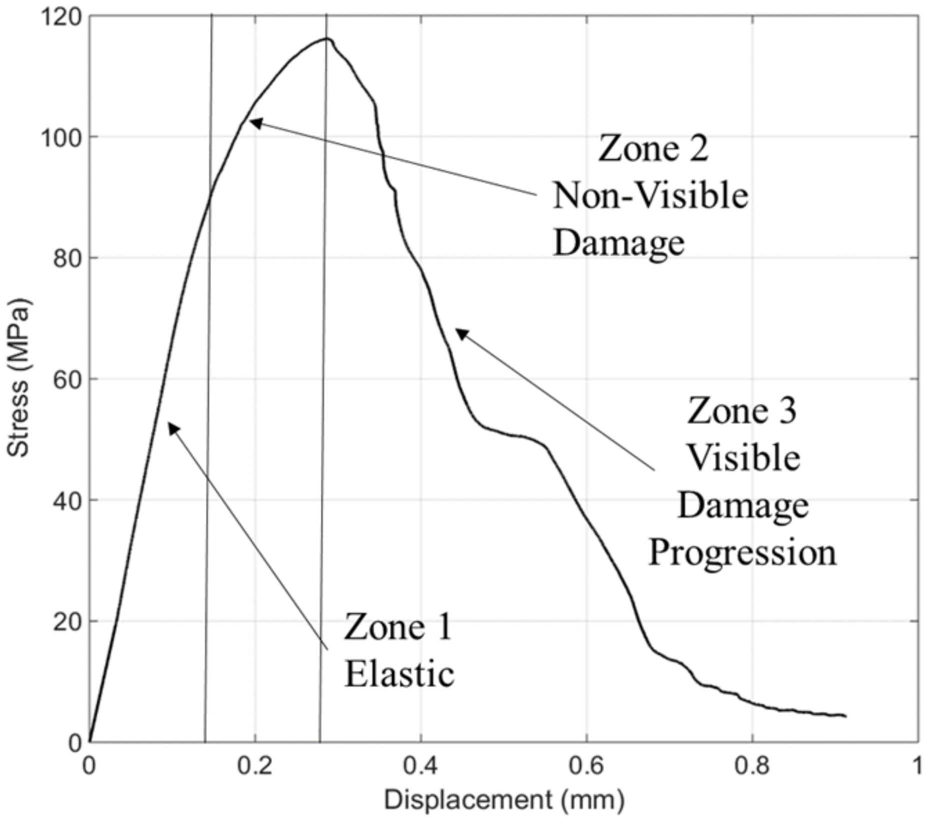
Sponsor

- One behavior zone
- Sudden specimen failure
- Little to no load carrying ability after fracture



Uniform Compression: Behavior Zones (Commercial)

- 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



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

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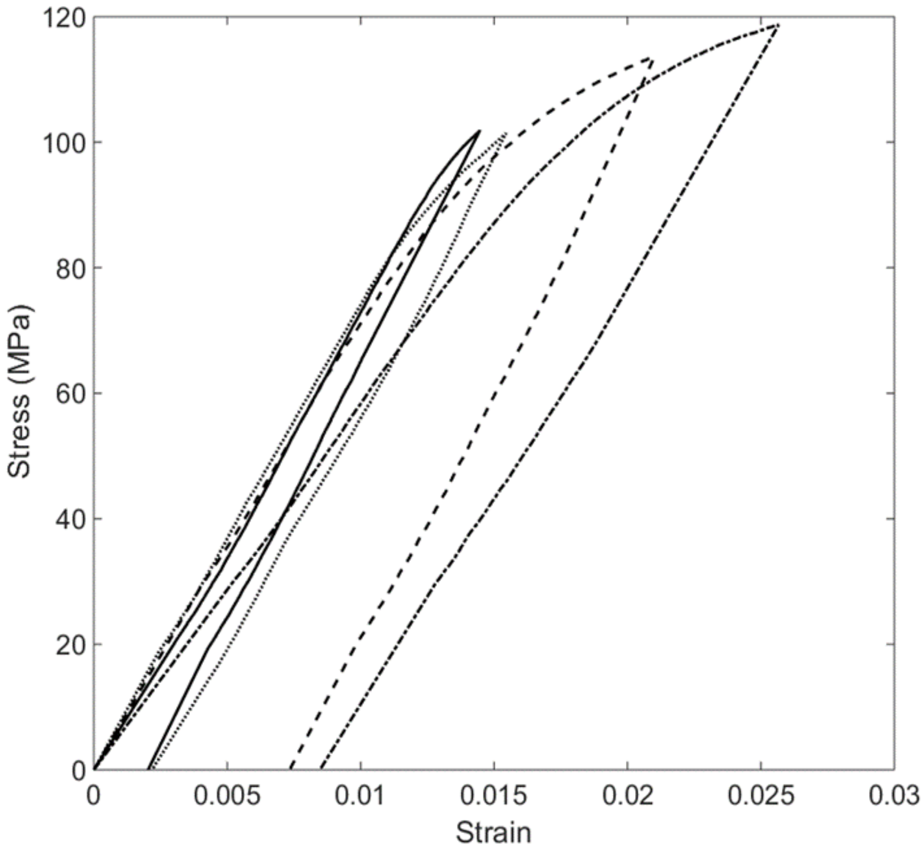
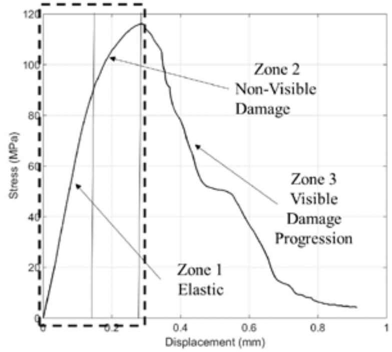
Uniform Compression: Commercial Nonvisible Damage

- 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





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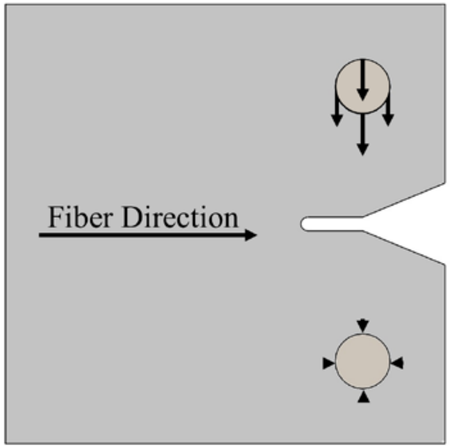
Compact Compression Specimens

- 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 can be used to calculate strain energy release rate
- Notch length can be changed to vary crack length



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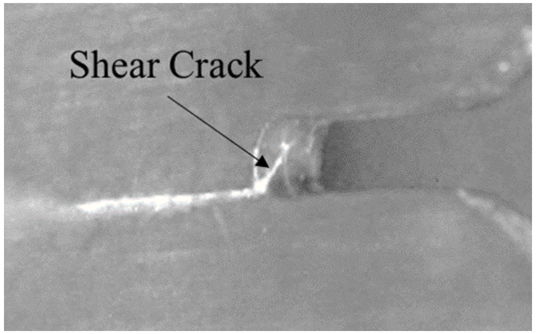
Compression Specimens: Damage Mechanisms

Commercial

- 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

Sponsor

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

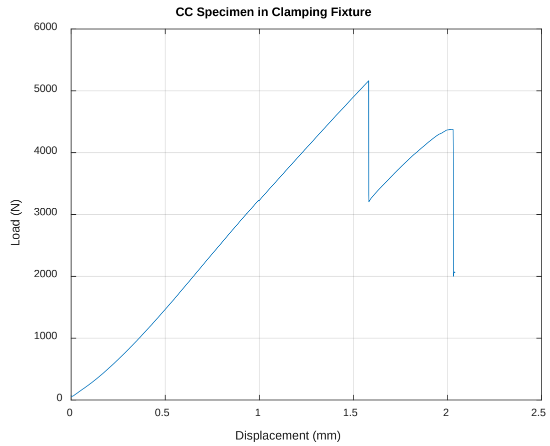


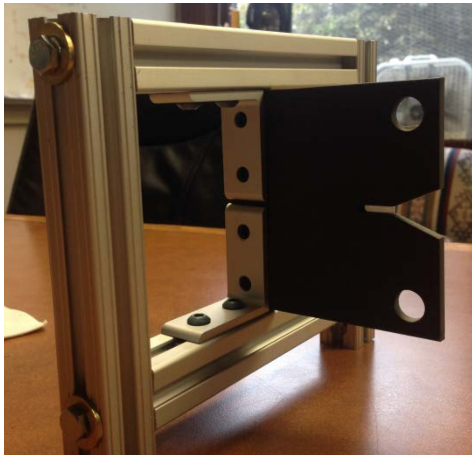
Commercial Compact Compression Specimen

Sponsor 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

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

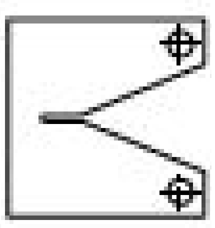




Compact Specimen: Variable Notch Study

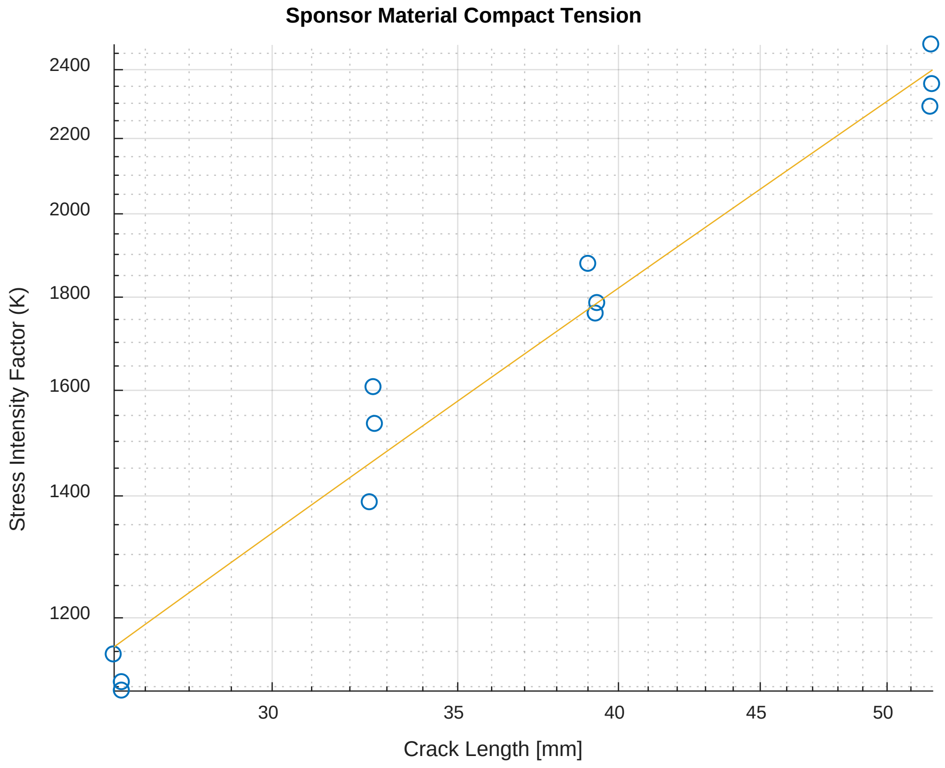
- Compact Compression specimens with varying notch lengths
  - Used to determine the stress intensity factor
  - Used to determine if LEFM relationship exists at initiation
- Stress at crack imitation used for stress intensity factor calculation
- If LEFM relationship shown
  - Damage propagation studies

$$k_I = \sigma Y \sqrt{\pi a}$$



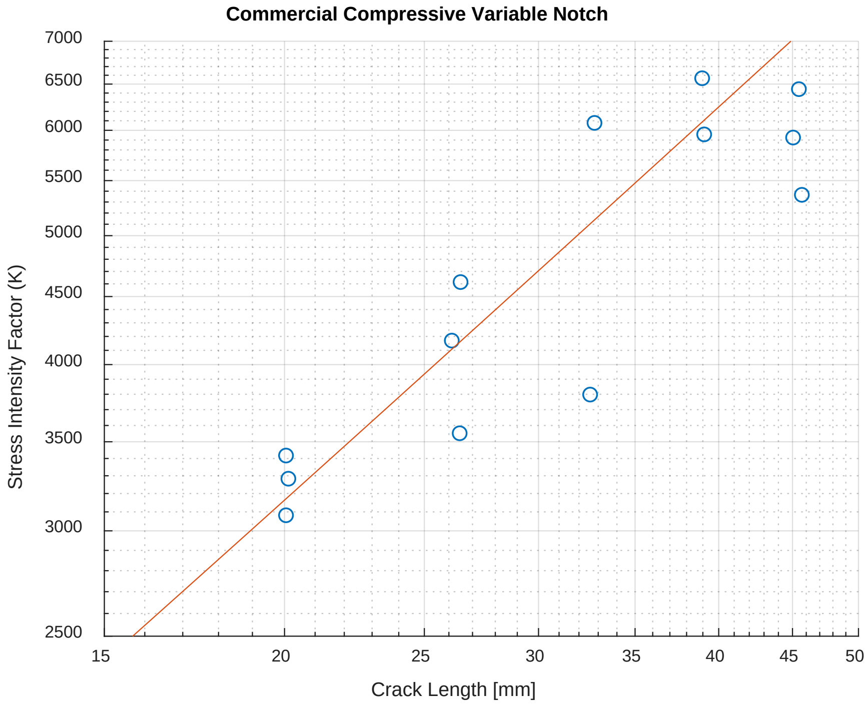
Compact Specimens: Variable Notch Length (Tension)

- Tension study performed on sponsor material to evaluate testing method
- Linear relationship between crack length and stress intensity factor is expected
  - Linear relationship is observed



Compact Specimens: Variable Notch Length (Compression)

- Conducted to determine if LEFM is appropriate model for compressive crack initiation
- Notch length range: 19-63.5 mm
- Large notches fail in tension before compressive damage



Conclusions

- Significant difference is material properties and behaviors observed between commercial material and sponsor material
- Compact compression specimens isolate compressive damage when the failure ratio is less than two
- New specimen is needed for failure ratios greater than two
- Sponsor material shows a linear relationship between stress intensity factor and crack length when loaded in tension
- Commercial material shows a linear relationship between stress intensity factor and crack length when loaded in tension when compressive damage occurs prior to tensile failure

Looking forward

- Benefit to Aviation
  - Better understanding of damage mechanisms to refine models to increase accuracy
- Future Work
  - Further testing to classify range of damage behavior
  - Further testing with notches smaller than 19 mm
  - Mixed mode damage testing
  - Refine material model as needed

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