Evaluation of Parameters Used in Progressive Damage Models

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Evaluation of Parameters used in Progressive Damage Models

Key Aspects

Motivation and Key Issues

- The matrix-compression material-model used in Abaqus for carbon fiber laminates is computationally efficient but is physically unrealistic and does not correspond to actual material behavior.

Objective

- Determine the conditions under which the use of this unrealistic material model causes significant errors in predictions of carbon fiber laminate response to load and load-carrying ability.

Approach

- Conduct experimentation to determine a physically-correct matrix-compression material model
- Implement this material model in Abaqus and compare its predictions with those of the currently-used material model

Personnel

- Principal Investigators & Researchers
  - John Parmigiani (PI); OSU faculty
  - K. Carpenter, D. Plechaty; OSU grad students
- FAA Technical Monitor
  - Ahmet Oztekin
  - Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Kazbek Karayev, Boeing
  - Gerry Mabson, Boeing
  - Sangwook (Simon) Lee, Boeing

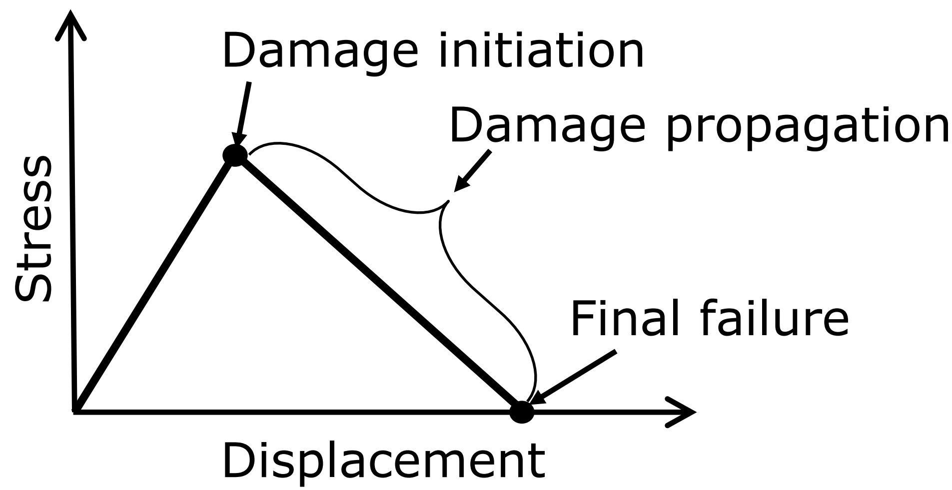
Today's topics

- Background (The reason for our work)
- Our Prior work (a useful review of what we have done)
- Today's new content
  - Specimen selection
    - Tapered-layup specimen
    - Zero-Degree-support specimen
    - Stepped specimen
  - Specimen Manufacturing
  - Specimen Use
    - LEFM determination
    - Energy release rate
  - Future plans

Evaluation of Parameters used in Progressive Damage Models

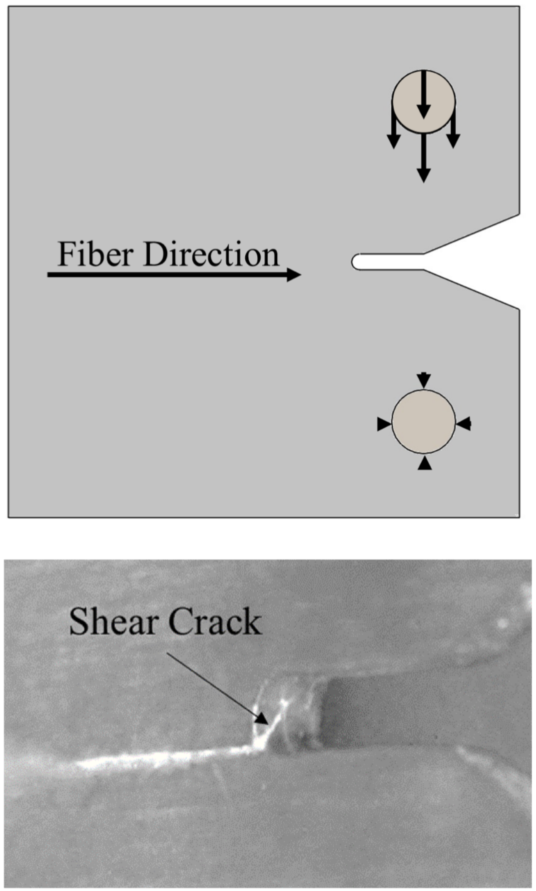
Background

- Currently the same simple-triangular material model is used for both matrix tension and compression in Abaqus
- During damage propagation, load-carrying ability decreases at a constant rate until final failure occurs
- This model is computationally convenient and is appropriate for matrix tension
- Our thinking from this project’s beginning was that this model is not accurate for matrix compression



Our prior work

- Prior to our work, very little research had been conducted on matrix compression
- Work that had been done assumed matrix compression was dominated by the shear properties of the matrix
- Our research, using constant-thickness compact compression specimens, supports this claim and shows shear angles of ~ 50° for commercially-available* carbon fiber material
- However …

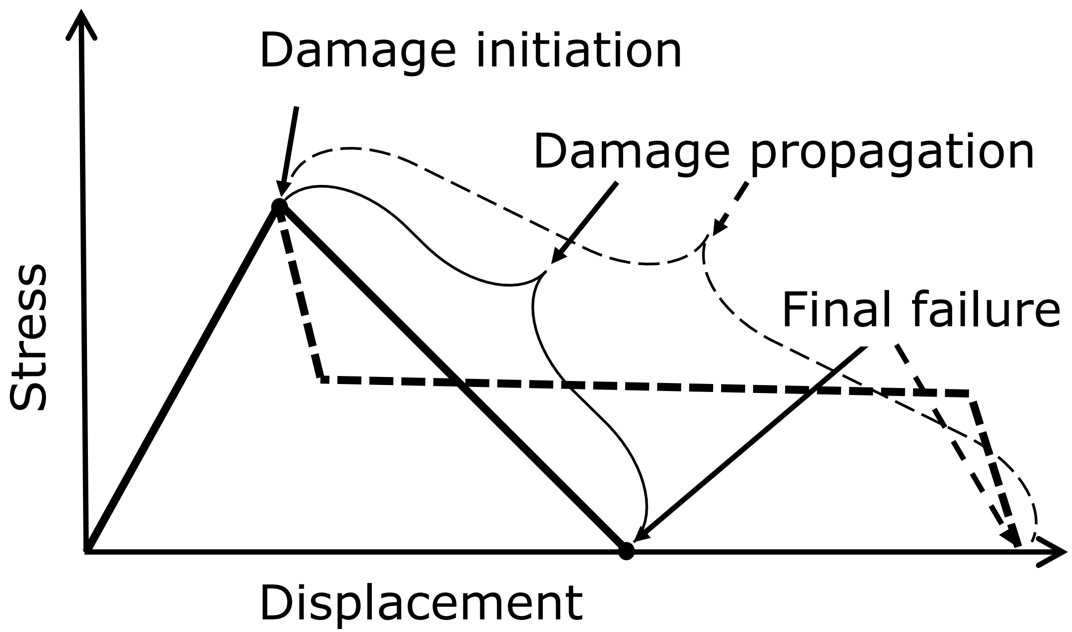


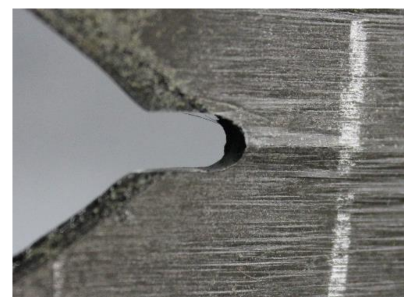
* TR50S/NB301 manufactured by Mitsubishi Rayon

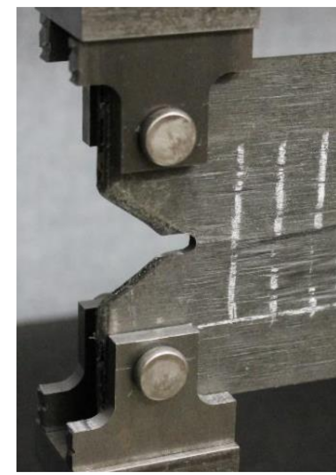
Evaluation of Parameters used in Progressive Damage Models

Our prior work

- Our testing w/ constant-thickness compact compression specimens suggested a material model for compression different from tension
- We found load-carrying ability rapidly dropped, then changed slope, then again rapidly dropped to final failure at a much greater displacement
- However, we had a problem …







Matrix Tension

Matrix Compression

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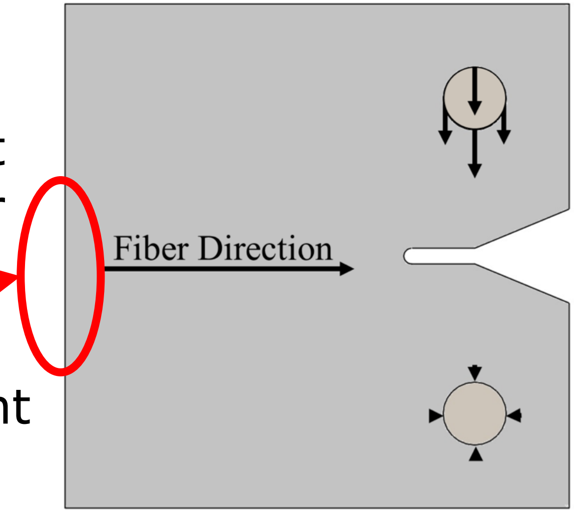
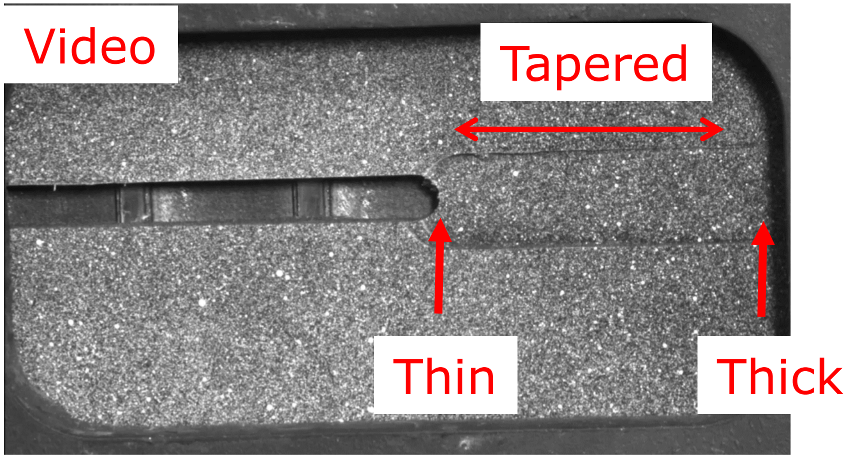
Our prior work

- Our constant-thickness compact compression specimen only gave consistent results for the commercially-available* carbon fiber material. It did not work for Boeing-proprietary carbon-fiber material
- The problem was tensile failure occurred on the back-side of the specimen prior to any significant compressive damage propagation



- A number of alternatives (see our AMTAS 2017 slides) were considered. We found machining (milling) a thin-to-thick taper ahead of the notch resulted in excellent matrix compression damage initiation and propagation



* TR50S/NB301 manufactured by Mitsubishi Rayon

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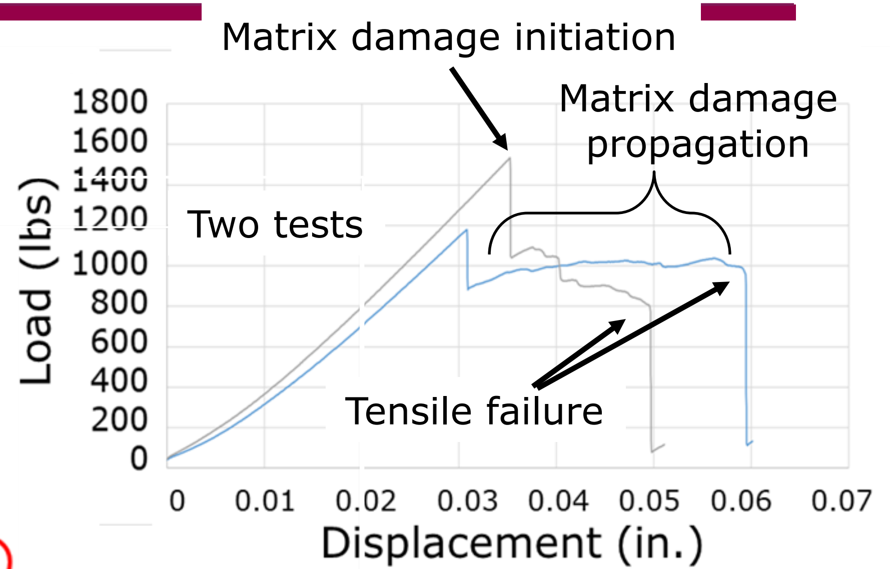
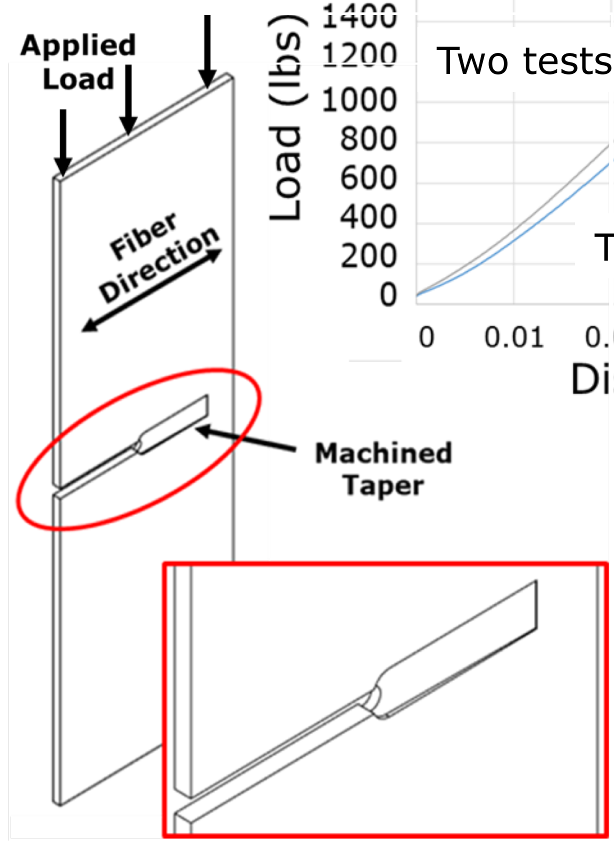
Our prior work

- This "tapered" specimen causes compression damage at thin notch tip prior to tensile failure at the thick side.
- Load-displacement behavior is as we expect
    - Rapid drop as the initial shear crack forms
    - Approximately horizontal as debris is compressed and crack propagates
    - Sudden tensile failure





Today's new content: Specimen selection

- The tapered specimen was thus shown to produce the desired matrix-compression behavior.
- However, to avoid machining variability and machining-induced damage it was necessary to create a variable-thickness specimen using ply layup
- A number of options were considered.

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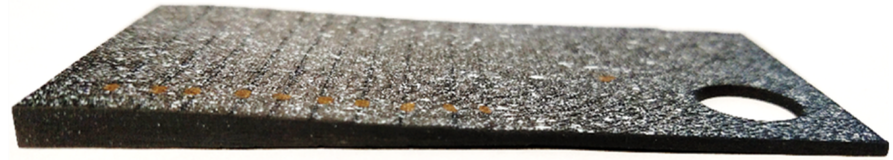
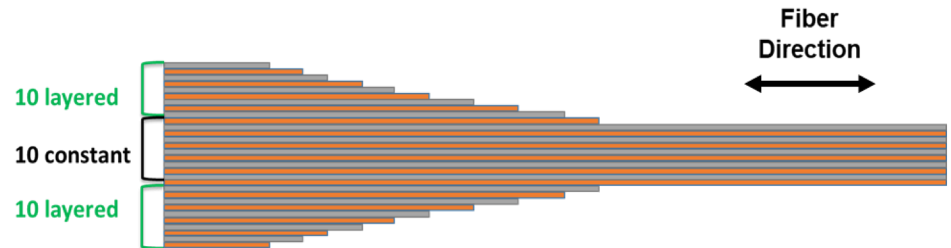
Today's new content: Specimen selection

Tapered-layup specimen

- The machined taper was replaced with a taper created by varying the ply layup throughout the specimen
- 10-to-30 plies were used.
- The specimen did not work.
- Tensile failure occurred in the specimen near the loading pin holes prior to significant notch-tip compression damage





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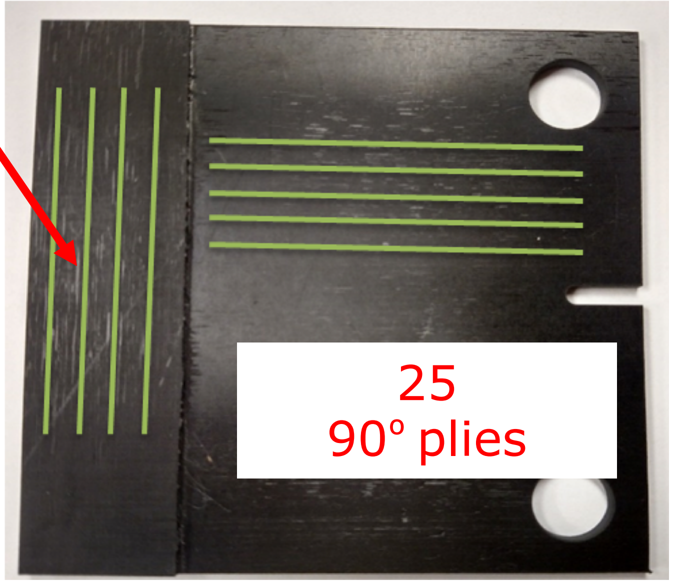
Today's new content: Specimen selection

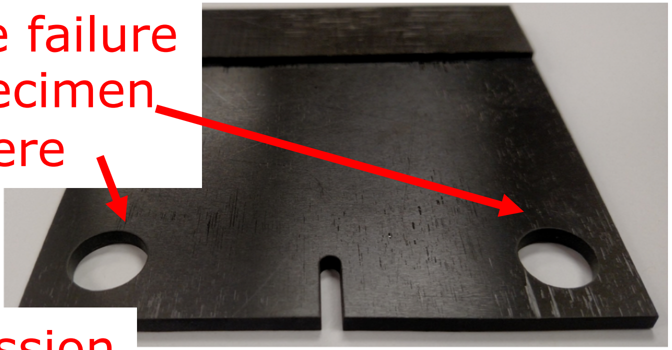
0°-support specimen

- 25-ply 90° constant-thickness region
- 10-ply above-and-below 0° reinforcement to prevent premature tensile failure
- The specimen did not work.
- Tensile failure again occurred in the specimen near the loading pin holes prior to significant notch-tip compression damage

10
0° plies
above and
10 below



Tensile failure
in specimen
here



Little compression
damage

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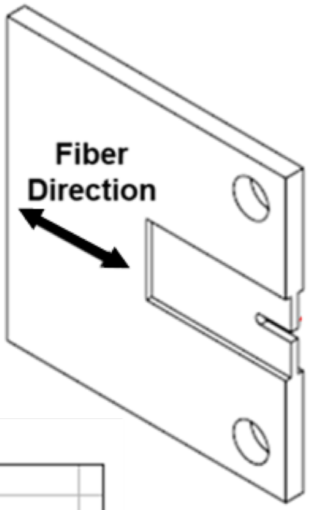
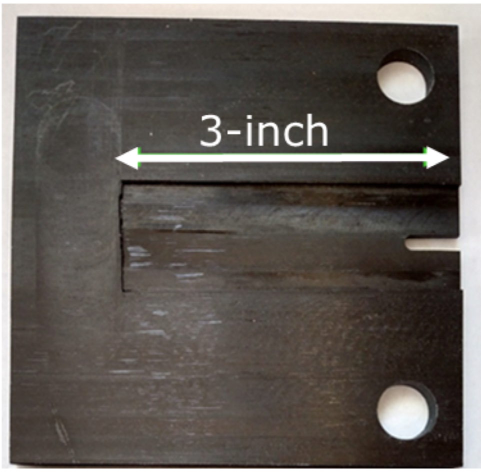
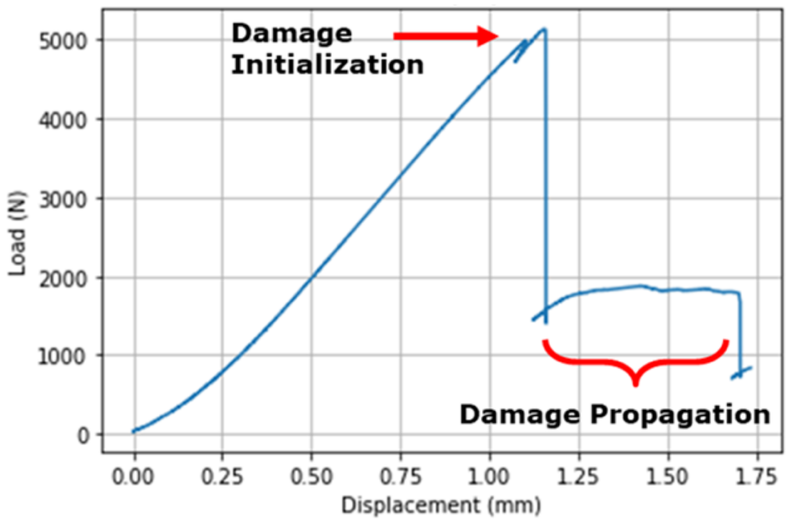
Today's new content: Specimen selection

Stepped specimen

- 15-plies near the notch tip, 35 plies elsewhere.
- 3-inch thin region for crack propagation.
- **Specimen works well**, creating significant compression damage prior to tensile failure







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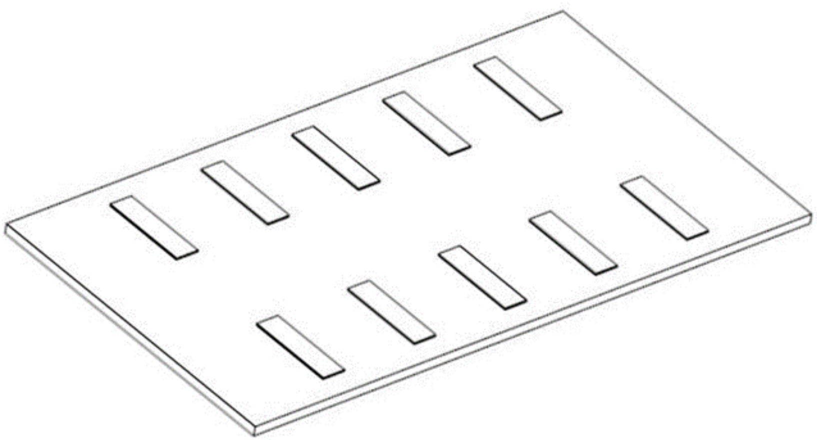
Today's new content: Specimen Manufacturing

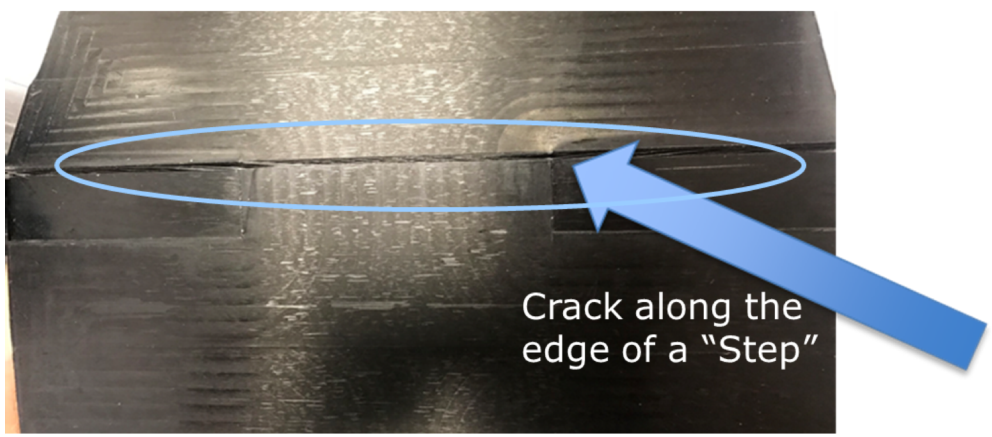
Layup plate was designed for mass manufacturing of Stepped Specimens.

- 10 specimens per plate with steel shims on top of thin region to maintain symmetry above and below the mid-section.

Initial layup (with commercial material) resulted in cracks along the edges of the thin region.

- Cracks created during separation of carbon fiber and the aluminum plate (large amount of bending).
- Layup method was changed by altering ply geometry, switching fiber release agent and the separation tool.

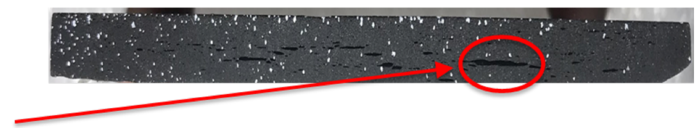


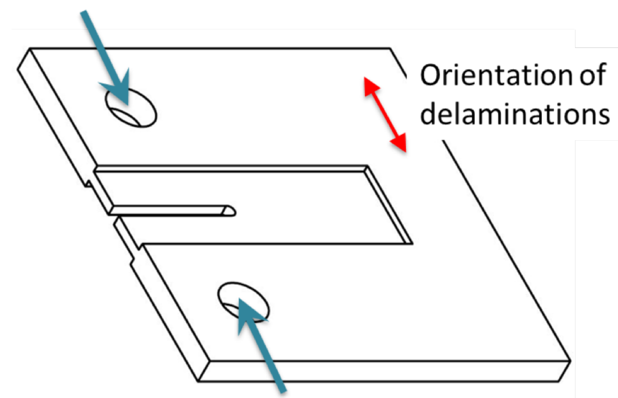


Evaluation of Parameters used in Progressive Damage Models

Today's new content: Specimen Manufacturing

- Other manufacturing issues that occurred throughout the commercial material specimens were delaminations between the plies in the 'thick' region
  - Subsequent testing has confirmed that the delaminations were caused by high moisture content, low applied pressure, and a low debulking time.
  - Adjusted processing parameters resulted in minimal delaminations.





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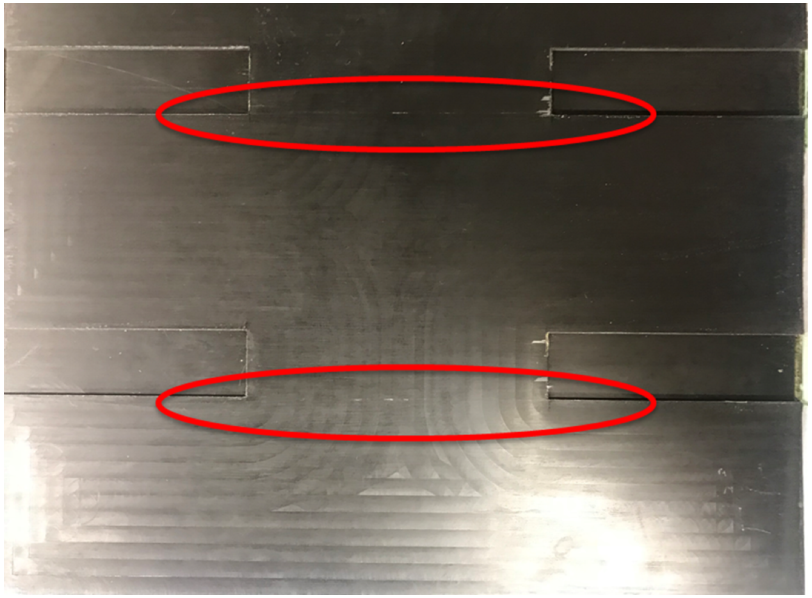
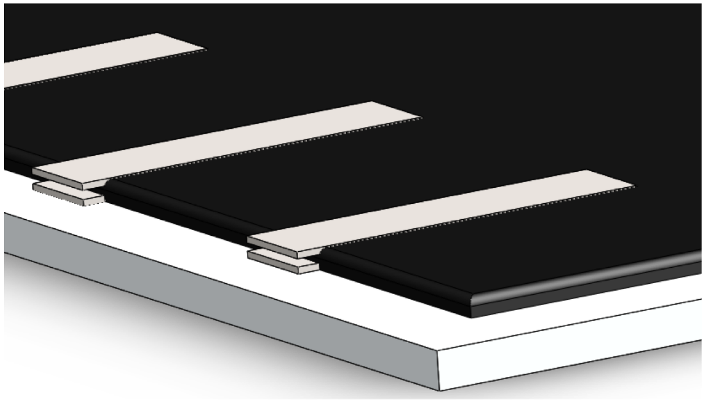
Today’s new content: Specimen Manufacturing

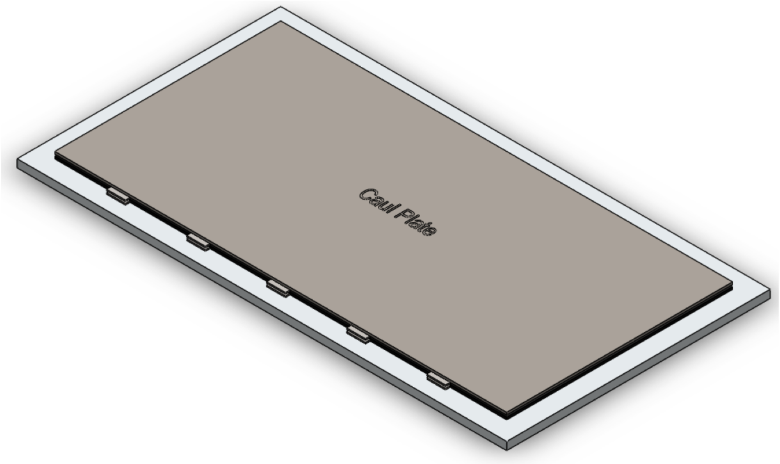
- The revised manufacturing methods **prevented the damage from occurring in commercial material.**
- However Boeing material still had cracking. Also surface delaminations occurred.
- Industry partners concluded that the material contracts during the cure cycle. The rigid steps in the aluminum plate are damaging the carbon fiber during cure.



Today's new content: Specimen Manufacturing

- A new layup method was used that introduced an additional degree of freedom.
- By using shims that were not fixed to the plate, they were free to move with the carbon fiber as it contracted.
- 10 shims for the bottom thin region, and 10 on the top.
- Caul plate was used to reduce delaminations.
- Result: No cracking was induced, and **specimens ready for final manufacturing process**.





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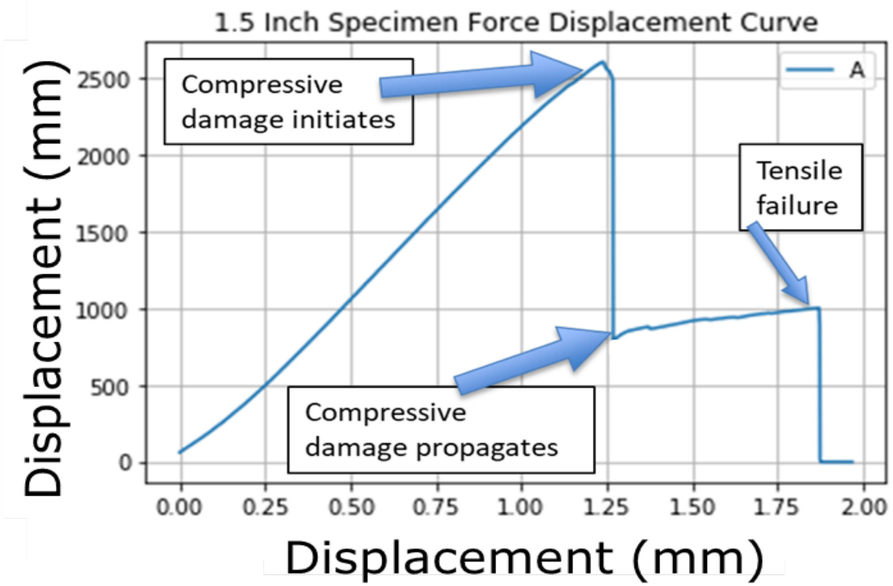
Today's new content: Specimen Use

- Having successfully developed a suitable specimen, testing was conducted.
- Load-displacement curves showing correct material response were consistently observed.
- Strain energy release rates were estimated from the load-displacement curves.
  - Many researchers and industry professionals use the same value for Compression as for Tension.
  - An average of the estimated Matrix Compression energy release rate was about **G_{MC} = 10.1 N/mm!**



Typical Load-displacement curve.

G_{MT} [N/mm]	G_{MC} [N/mm]
0.33	0.33
Wong *et al.* (2011)	

Today's new content: LEFM Determination

Continuum damage mechanics models in FEA software use strain energy release rates to degrade the stiffness of a material. With composites, there are four: Fiber Tension, Fiber Compression, Matrix Tension, and Matrix Compression.

Matrix Compression has not been investigated thoroughly, and there is no direct method to measure it's energy release rate. It is often assumed to be equal to the Matrix Tension value (not correct), or approximated from Mode II loading (assumed to follow Linear Elastic Fracture Mechanics).

For Tension, carbon fiber has been shown to be linear elastic, but not for compression, which makes the assumption unsupported.

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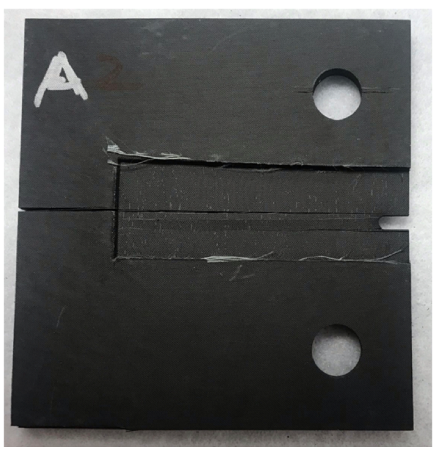
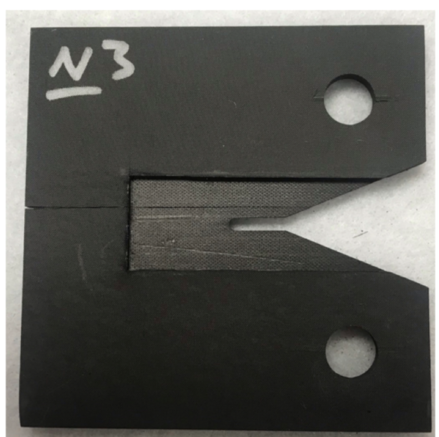
Today's new content: LEFM Determination

In linear elastic fracture mechanics, for a specimen with a notch, the failure load is directly related to the notch length. On a log-log plot of failure load vs. notch length, the slope will be linear and have a slope of −(1/2).

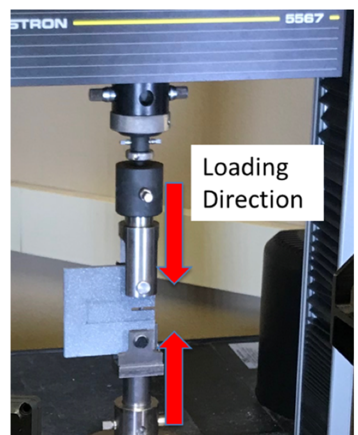
Varying the notch length of multiple specimens (1/4″ – 1 7/8″), and measuring the peak (failure) load, such a plot can be generated, and the trend will reveal LEFM behavior.



¼″ Specimen



1 7/8″ Specimen



Specimen in loading fixture

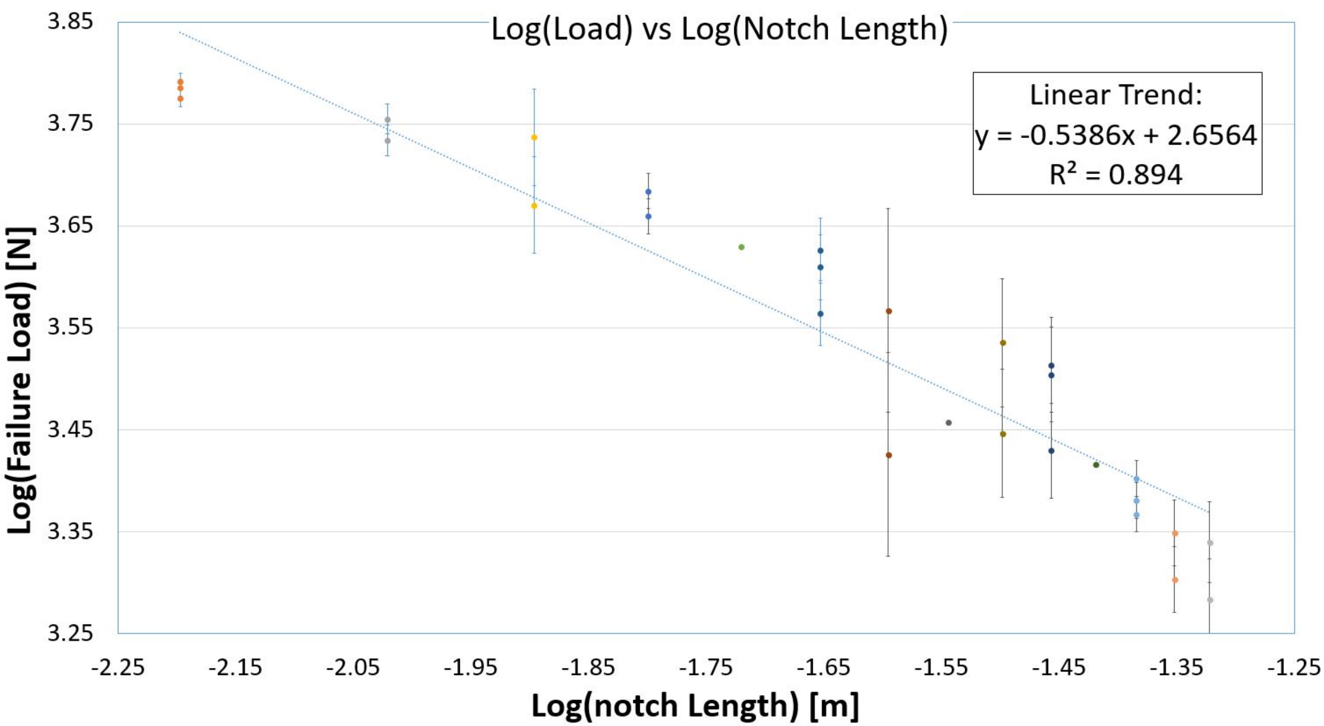
- ¼″ – 1 7/8″ (at 1/8″ increments)
- 3 Specimens per notch length.
- 1 mm/min compression test

Today's new content: LEFM Determination

The commercial specimens exhibited a decrease in peak load as the notch length was increased.

The log-log plot of the data on the right follows a linear trend with an R^2 value of 0.89, and a slope of -0.54.

The matrix in compression has been experimentally shown to follow the laws of LEFM.



Evaluation of Parameters used in Progressive Damage Models

Today's new content: Future plans

With a specimen that isolates matrix compression damage, we can start to develop and implement a physically accurate material model for FEA software.

- Develop the model. The key difference between matrix tension and matrix compression is that after initiation, there is damaged material in the wake of the crack.
  - The Energy associated with the material after damage initiation will be divided into an initiation component (to advance the crack), and a propagation component (absorbed by the wake of the crack).
- Implement this material model in Abaqus and compare its predictions with those currently used—evaluate under what conditions the current model gives significant error.

Industry Partners

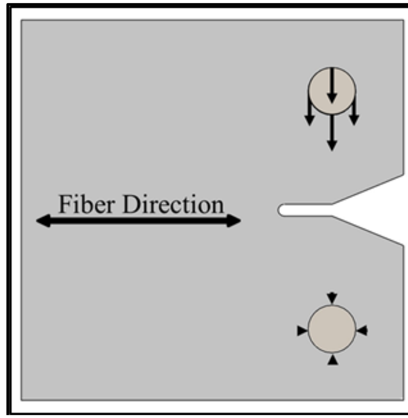
We would like to thank the following companies for letting us use their services.

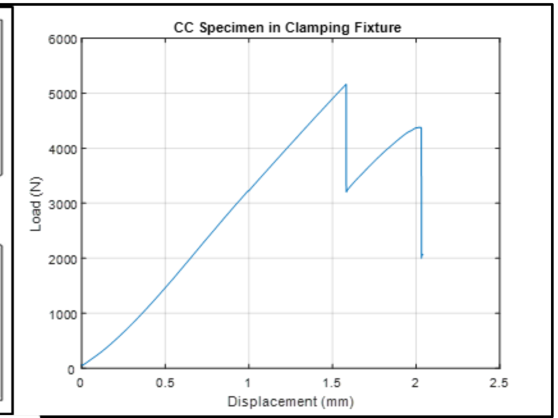
Questions?

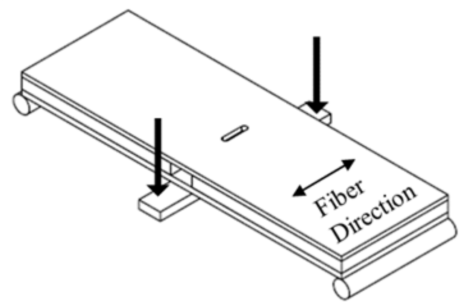
Uniform-Thickness Specimens

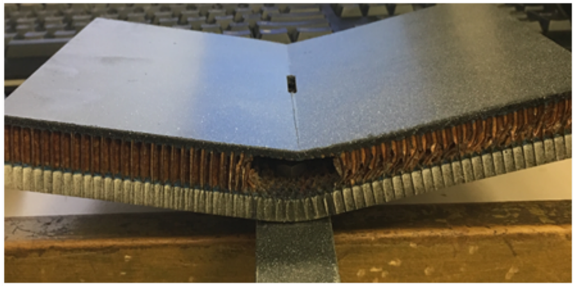
Specimens of constant thickness were designed based on ASTM standards:

- Compact Compression (Modified ASTM E399)
  - Failed in tension on side opposite the compressive load.
- 4- and 3-Point Bend (Modified ASTM D5467/D5467M)
  - Specimen damage due to testing procedures



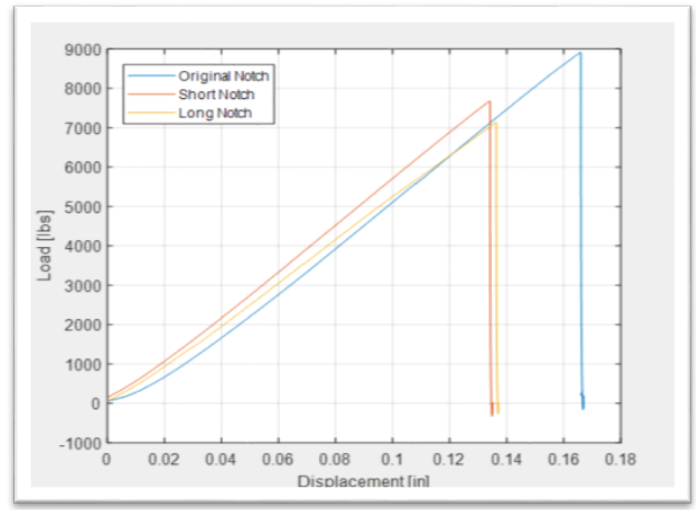


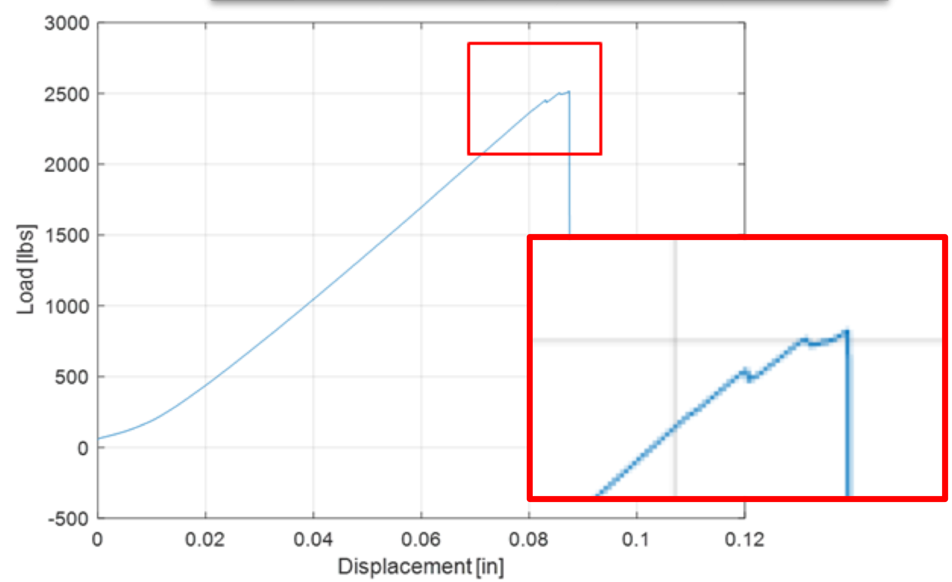


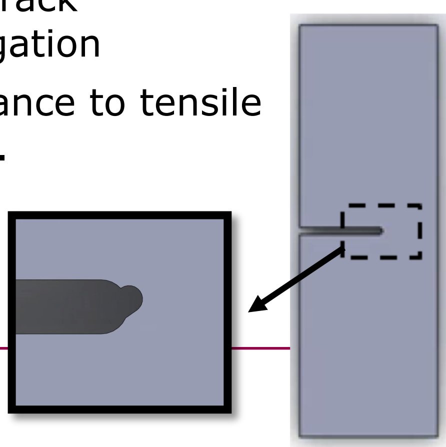


Uniform-Thickness Specimens

- Uniform Compression (ASTM D3410)
  - Compressive crack was instant, and across the width of entire specimen.
  - Edge Notch suggested crack propagation.
- For success, we needed:
  1. Slow crack propagation
  2. Resistance to tensile failure.



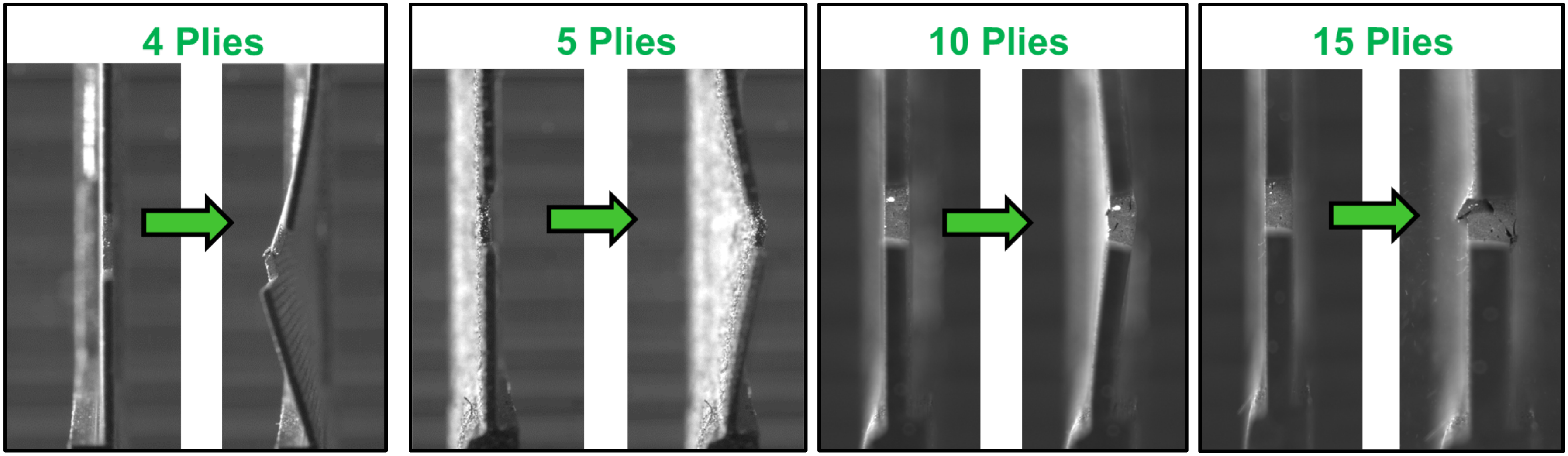




Stepped Specimen

Testing results:

- Both 4 and 5 ply thin region resulted in failure do to buckling before compressive damage occurred.
- 10 ply thin region resulted in some bucking before compressive damage could occur.
- 15 ply in thin region resulted in no bucking before compressive damage occurred.



Mass Manufacturing

- New layup method resulted in no cracking along the thin region. This means successful specimens were made and ready to be cut and tested.

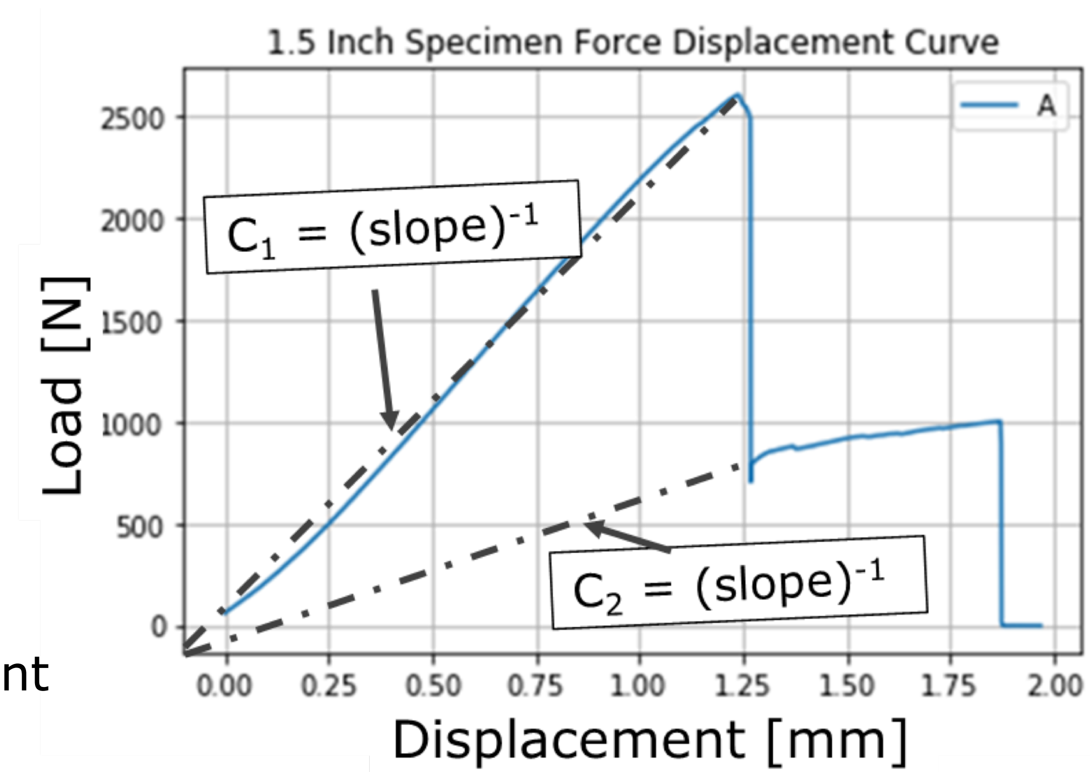
Evaluation of Parameters used in Progressive Damage Models

Estimation of Energy Release Rate

Followed previous student's work (Daniels) and used the Compliance Calibration Equation for Strain Energy Release Rate:

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

P = Peak Load
B = Specimen width (thickness)
dC = C_1-C_2
da = Initial crack advancement (measured optically)



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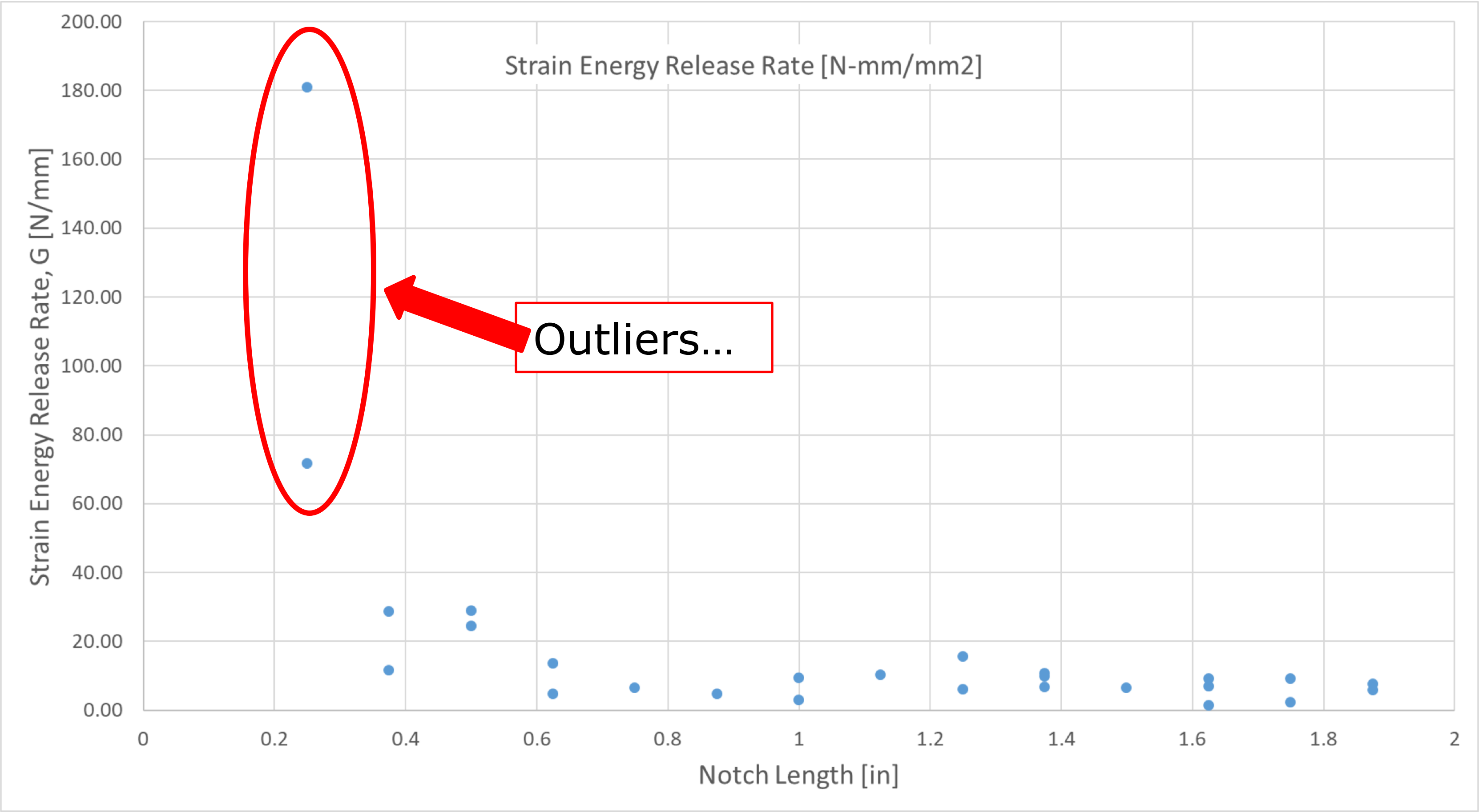
Estimations of Energy Release Rate

Notch Length [in]	Strain Energy Release Rate [N-mm/mm^2]	Strain Energy Release Rate [lb-in/in^2]
0.25	71.50	408.27
0.25	180.89	1032.94
0.375	11.62	66.35
0.375	28.59	163.26
0.5	24.39	139.29
0.5	28.74	164.13
0.625	4.70	26.84
0.625	13.45	76.82
0.75	6.45	36.85
0.875	4.78	27.29
1	9.27	52.91
1	2.88	16.47
1.125	10.20	58.22
1.25	15.47	88.35
1.25	6.03	34.46
1.375	10.60	60.53
1.375	6.60	37.66
1.375	9.85	56.26
1.5	6.48	37.03
1.625	6.90	39.40
1.625	1.36	7.75
1.625	9.13	52.13
1.75	9.02	51.53
1.75	2.30	13.14
1.875	5.77	32.94
1.875	7.55	43.11

Evaluation of Parameters used in Progressive Damage Models

Estimation of Energy Release Rate



Evaluation of Parameters used in Progressive Damage Models

Estimation of Energy Release Rate