Å Motivation and Key Issues

- Å The matrix-compression material-model used in A.34444TJuD 1cad center of excellence for composites and advanced materials

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Today’s Topics

- Background (the reason for our work)
- Our Prior work (a useful review of what we have done)
- Todayôs new content
  - Specimen Manufacturing
    - Commercial Material
    - Proprietary Material
  - Specimen Use
    - LEFM determination
    - Propagation Testing Procedures
    - Energy Release rate
- Future plans

- Currently the same simple triangular material model is used for both matrix tension and compression in Abaqus

Our Prior Work

A Compact Compression specimen called the ***Stepped Specimen*** was developed to isolate matrix compression damage initiation and propagation. Geometry consists of:

- 15-plies near the notch tip (thin region), 35 plies elsewhere (thick region).
- 3-inch thin region for crack propagation.

Specimen development has been described in pri

Our Prior Work

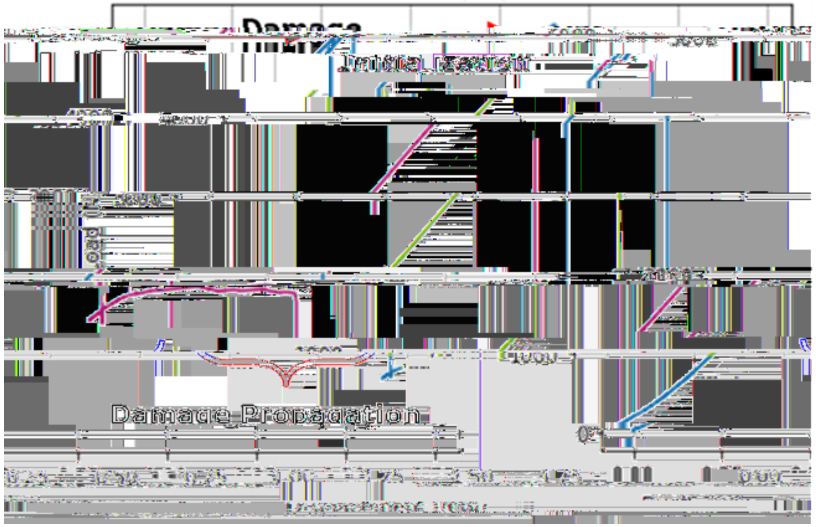
Preliminary testing showed that:

Å **The specimen works well**, creating significant compression damage prior to tensile failure.

Å A simple triangular material model is not physically correct for matrix compression

Å The matrix compression toughness value is significantly different from the matrix tension value.

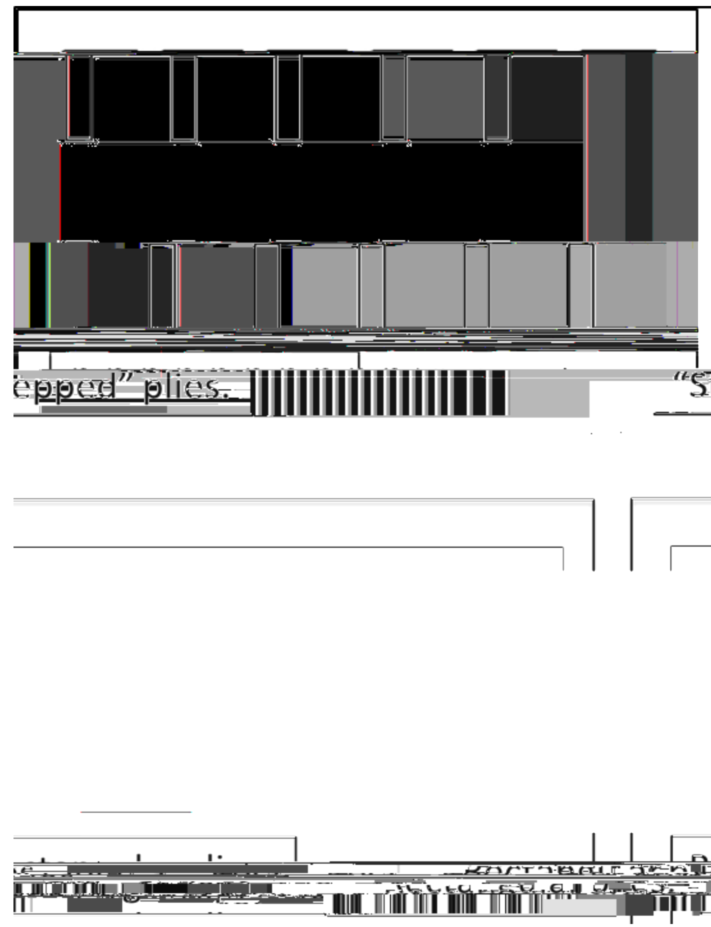
Å Additional testing requires a relatively large number of specimens and improved manufacturing methods



Today's New Content: Specimen Manufacturing

A layup plate was designed for mass manufacturing of Stepped Specimens.

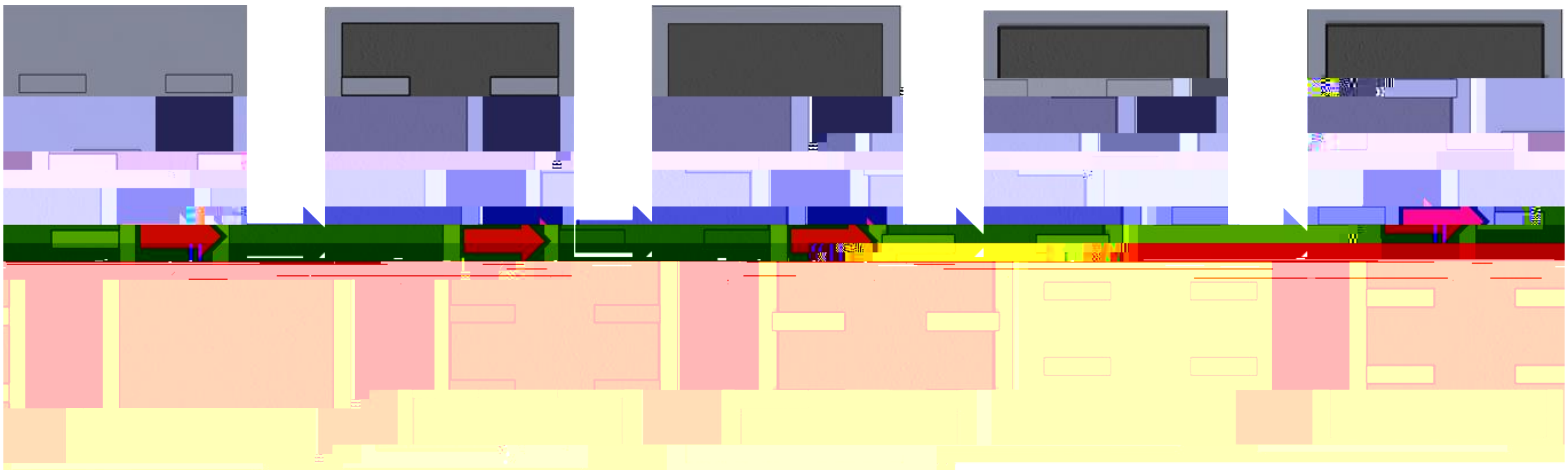
- Plate consisted of 10 steps machined into the plate and made a total of 10 specimens per a layup. This plate was called the ***Machined Step Plate***.



- Layup Procedure consisted of 20 stepped plies and 15 rectangular plies. Layup procedure is detailed in the following text.
  - 10 stepped plies are laid on top of the machined step plate.
  - 15 rectangular plies are then laid on top of the 10 stepped plies.
  - 10 steel shims are then placed in line with the machined steps on top of the rectangular plies. After the shims are placed, 10 stepped plies are laid in-between the steel shims to complete the layup procedure.

Images of this process are shown on the following slide.

Today's New Content: Specimen Manufacturing



Layup Procedure for the Compact Compression Specimen

Today's New Content: Specimen Manufacturing

Manufacturing defects with the

Today’s New Content: Specimen Manufacturing

Additional Manufacturing problem:

- Additional manufacturing problem occurred with the Machined Step Plate (with commercial material).
- The cracks along the edges of the thin region as shown.

Cause:

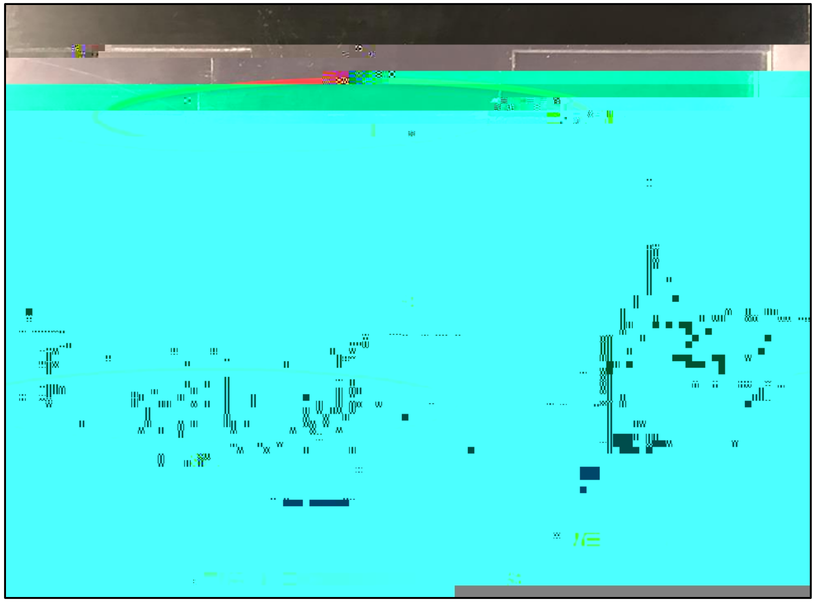
- Cracks appeared during separation of cured laminate from the aluminum plate (large amount of bending).

Solution:

- Layup method was changed by altering ply geometry, switching fiber release agent and the separation tool.

Today's New Content: Specimen Manufacturing

- The revised manufacturing methods prevented the damage from occurring in commercial material.



Manufacturing problem with Proprietary Material

- However Proprietary material still had cracking. Also surface delaminations occurred.

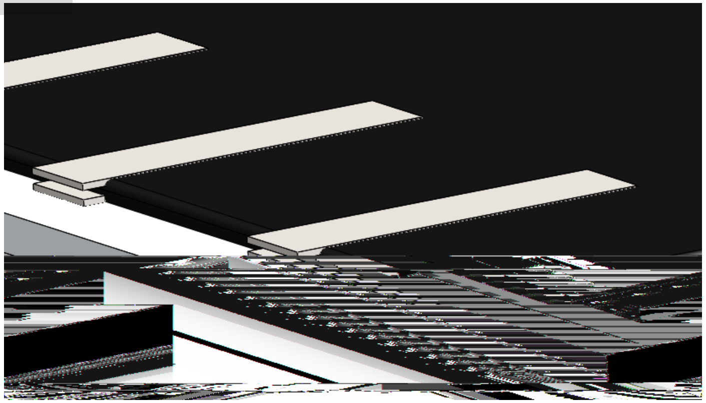
Cause:

- 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

Solution:

- To reduce cracks from occurring to the material a the 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 shims on the top of thin region.
- Caul plate was used to reduce delaminations.
- Result: No cracking was induced, and Proprietary-material specimens made with this method had a **~90% success rate** in matrix compression damage initiation and propagation.



- A primary use of the specimens is to determine the correct matrix

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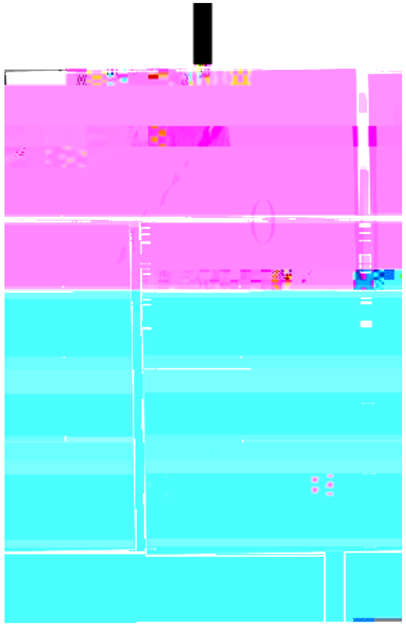
Today's New Content: Propagation Testing Procedures

- To focus on this region of interest, compact tension specimen literature was explored.
- It was found that most compact tension specimens have a sharp starter crack placed into the specimen with either a diamond wire, razor saw, or a razor blade to get fracture toughness values for tension. With this in mind it was decided to introduce starter cracks into the specimens to see if these will help the focus on matrix compression propagation.
- Matrix compression tests were conducted at displacement rate of 1 mm/min using specimens with either
  - a 0° fracture-angle starter crack
  - a 45° fracture-angle starter crack
  - no starter crack (baseline). Baseline specimens were tested to have a direct comparison.
- All starter cracks were made with a diamond wire.



Fracture surface with fracture angle shown as .

- The 0° fracture angle cracks failed in tension, similar to specimens with a long notch length (1.875”), which were too long for the specimen geometry.

- 45° fracture angle cracked specimens had compression damage occur before tensile failure. But this compressive damage had a large crack jump (Nonstable propagation) similar to the initiation from a blunt crack tip (notch tip) .

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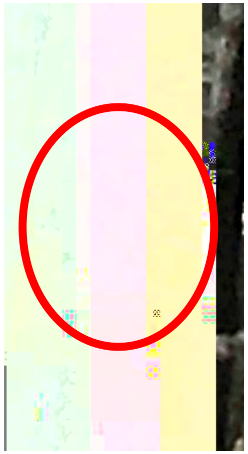
Today's New Content: Propagation Testing Procedures

Å The reason starter cracks do not work with matrix compression is due to compressive crack having a complex fracture surface. A compressive fracture surface creates a ñVòor ñWòcrack shape unlike tension damage which creates a straight (0°) fracture surface through the thickness of the specimen (Crack Surfaces shown below).



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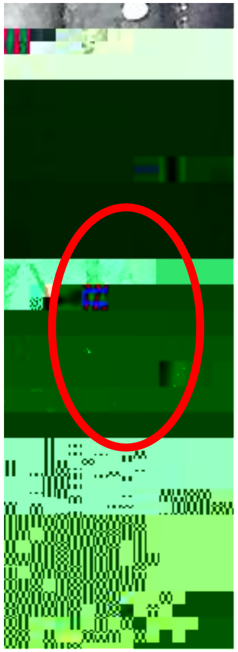

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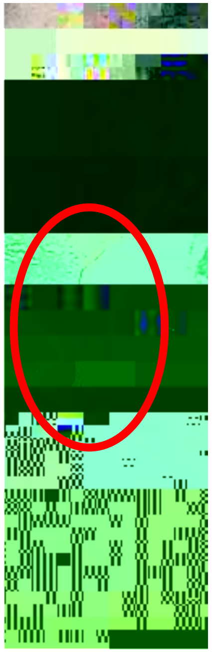

C

A: Fracture surface of the starter crack (0°) with a compression crack surface forming afterwards ("W") .

B: "V" fracture surface that occurs with a compression crack.

C: "W" fracture surface that occurs with a compression crack.

Today's New Content: Propagation Testing Procedures

- Although this method works for our propagation focus, there are still a few concerns with this method:
  - Fully unloading the specimen results in specimen not loaded in the same orientation.
  - Specimens have to be preloaded twice (1 for initiation, 1 for propagation).

- To minimize these concerns, it was suggested that instead of unloading the specimen fully we unload the specimen back to the original pre-load. This would allow the specimen to be unloaded while also not allowing the specimen to change orientation during the two tests.

Today's New Content: Energy Release Rate

- With testing procedures in place our focus changed to calculating the strain energy release rate due to matrix compression. Multiple methods were explored as there was little literature on the compression energy release rate.
- Further research in energy release rate methods used for tension showed ASTM E399, Area method, Compliance Calibration (CC), Modified Compliance Calibration Method (MCC), and J- Integral were used.
- Due to the nature of compression damage and orthotropic materials certain analysis methods were ruled out. These consisted of ASTM E399 as it is strictly for isotropic materials and the MCC method as it relied on machining starter cracks. This reduced the methods that could be explored.
- Of the methods left the Compliance Calibration method, Area method, J-integral method were explored further.

Compliance Calibration Method:

- This method was used to calculate strain energy by taking the inverse slope of the load displacement data right after crack propagation and before tensile failure.

$$= \frac{\quad^{2}}{2}\,\frac{\quad}{\quad}$$

- P = Peak Load
- B = Fracture Surface Width
- dC = C_1 - C_2
- da =crack extension (measured optically)

- As with crack length, the fracture surface were measured following the same method as previously stated.
- The reason for this is because the crack occurred at angles such as the ñVòor ñWòformations shown. So the specimen thickness, alone,

Area Method:

Å To have a direct comparison to the CC method the area method was used. This method is very similar to the CC method but instead of using the inverse of the slope it uses the area under the load displacement data (Energy released). To get the energy released due to compression a sloped line must

Today's New Content: Energy Release Rate

Å Using the crack measurement method stated, the compliance calibration method and area method were able to be used.

Å **Preliminary results** with these methods (in the following table) show that the currently assumed strain energy release rate value used for matrix compression is not correct as the calculated value is ~7 to 8 times bigger. This shows that the currently assumed value is incorrect.

Å Between the two methods there was about a 12% difference in the calculated energy release rate. With this in mind more specimens need to be tested to verify these methods.

Method Used	$\frac{G_{MC\ Calculated}}{G_{MC\ Assumed}}$
CC	7.82
Area	6.90

Conclusions

ÅWe have developed

ï An effective matrix-compression test specimen

ï Corresponding manufacturing procedures

ï Corresponding test procedures

ï Corresponding data analysis procedures

ÅWork is proceeding on

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