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College of Engineering

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Evaluation of Parameters used in Progressive Damage Models

JAMS Technical Review
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Presented by:
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Oregon State University

Evaluation of Parameters used in Progressive Damage Models

- 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

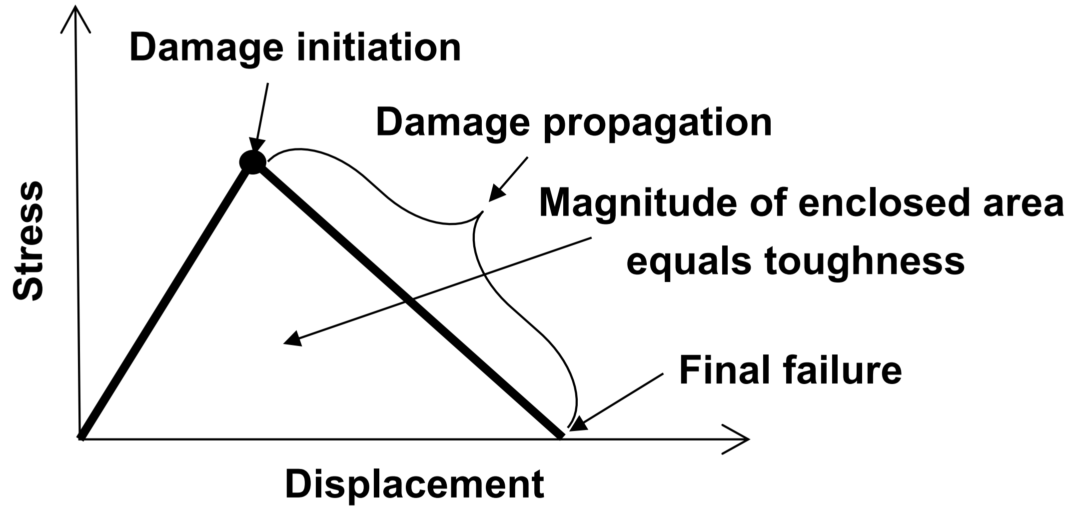
- Principal Investigators & Researchers
  - John Parmigiani (PI); OSU faculty
  - D. Plechaty, S. Solanki, T. Moore; OSU grad students
- FAA Technical Monitor
  - Ahmet Oztekin
  - Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Kazbek Karayev, Boeing
  - Gerry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

Today's Topics

- Background
- Specimen Design
- Specimen Testing
- Data Analysis
- Experimental Results
- Material Model
- Finite Element Results
- Conclusions

Background

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



- This model consists of
  - A linear elastic region ending at the point of maximum load carrying ability at damage initiation
  - A linear plastic region beginning at damage initiation, including all damage propagation, and ending with no load carrying ability
- The use of the same model for both matrix tension and compression is problematic
  - Model parameters such as toughness are likely different for compression than for tension
  - Matrix compression, unlike tension, typically retains load-carrying ability in the crack wake due to debris accumulation
- We began the project with the development of a suitable test specimen to observe and quantify matrix compression damage behavior initiation and propagation.

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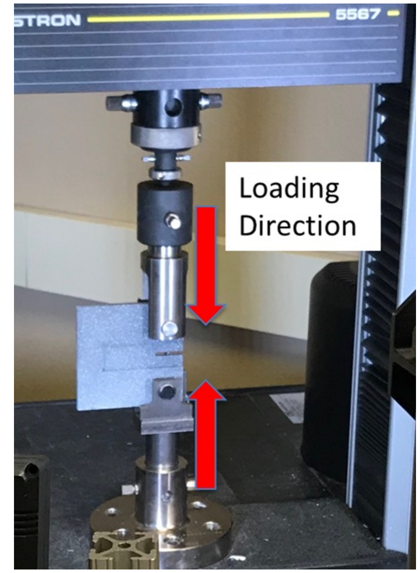
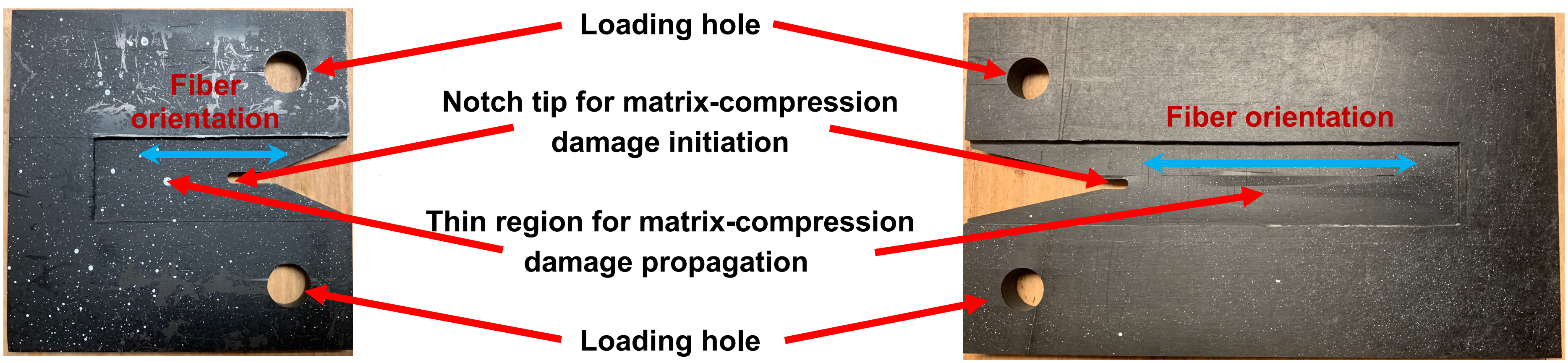
Specimen Design



- Two carbon fiber materials were included in the study
  - Boeing-Proprietary material
  - Commercially-available material (TR50S carbon fiber and NB301 epoxy)
- Differences in the ratio of matrix compressive strength to matrix tensile strength between the two materials necessitated different test specimen geometries
- Key specimen features
  - Notch tip for damage initiation
  - Thin region for damage propagation
  - Loading holes for attachment to mechanical tester

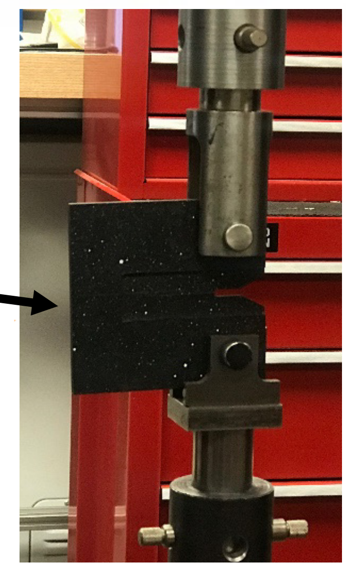


Specimen for Boeing material

Specimen for Commercial material

Specimen Testing

- Testing was conducted on an ADMET eXpert 2653 universal testing machine
  - 45 kN load cell
  - Point Grey FLIR Grasshopper GRAS-50S5M-C Cameras
- Collected data consisted of
  - Load versus displacement at loading holes
  - Images of specimen thin region (where damage occurred)
- Test procedure
  1. Focus camera on thin region and continuously record images
  2. Increase load until damage initiates
  3. Decrease load until displacement equals 0.2 mm
  4. Increase load (i.e. reload) until damage propagation occurs for ~0.1 mm of additional displacement.
  5. Repeat steps 3 and 4 as many times as possible (typically 2) until tensile failure occurs on the back edge of the specimen.



Back edge of the specimen.

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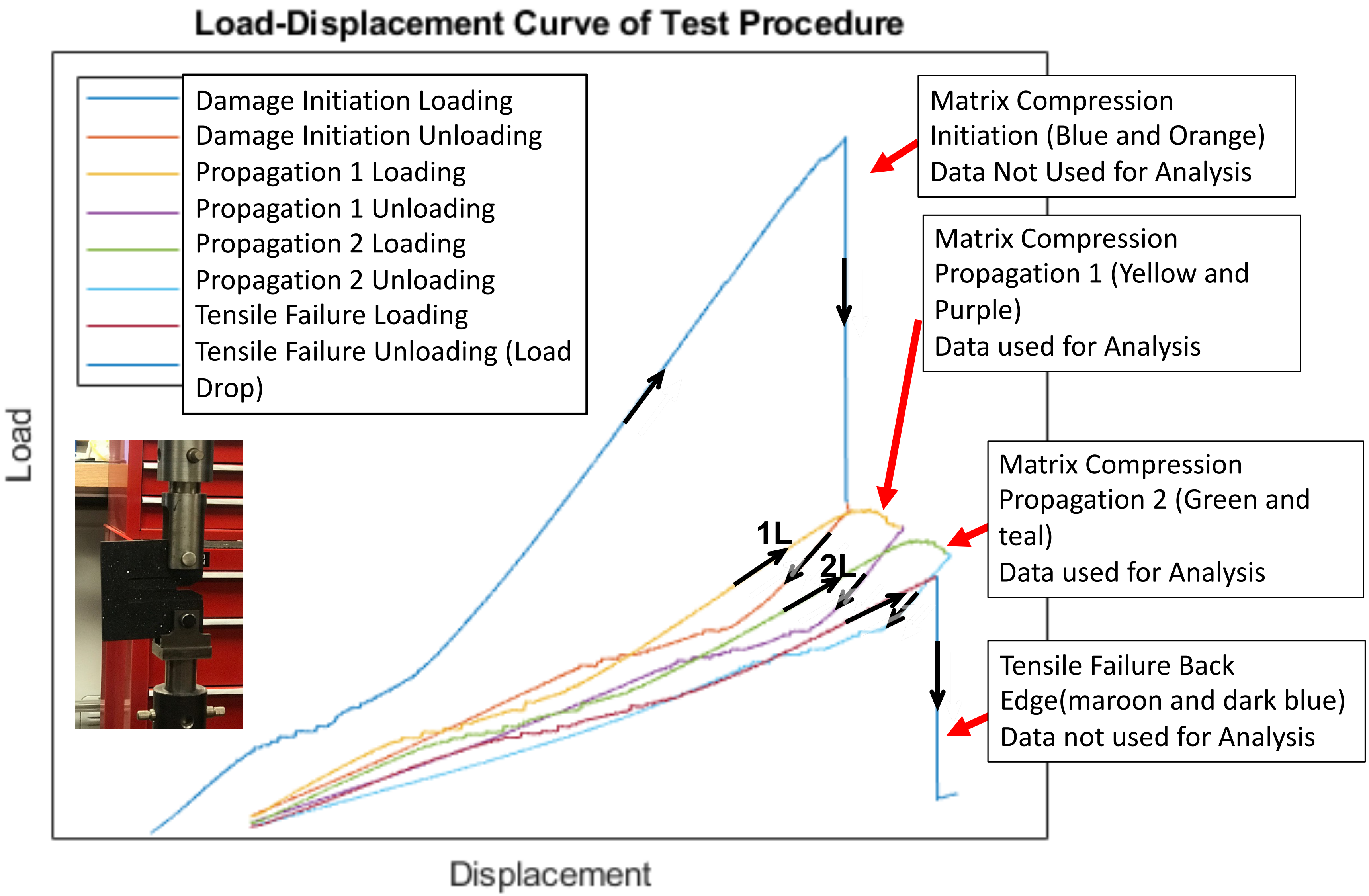
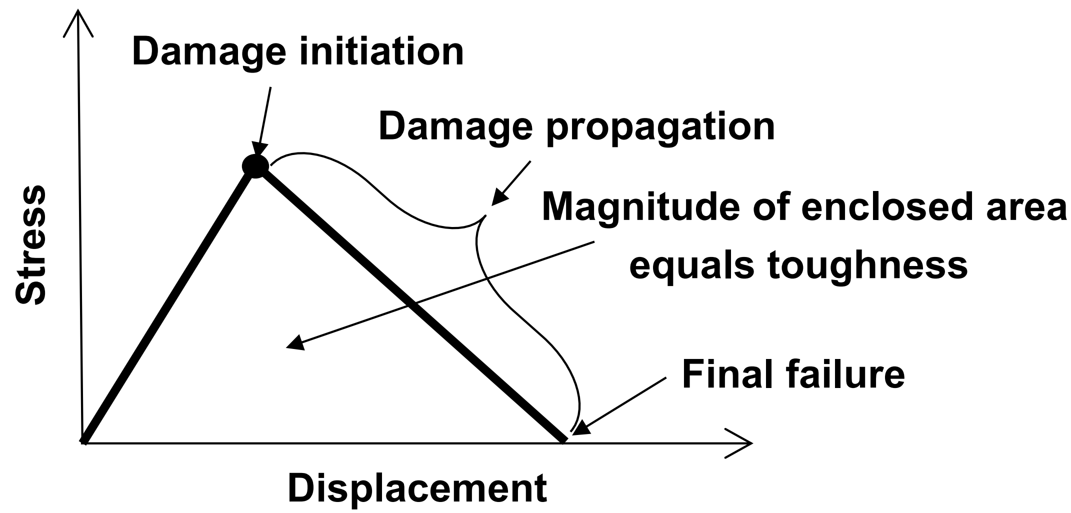
Specimen Testing

- Typical test results

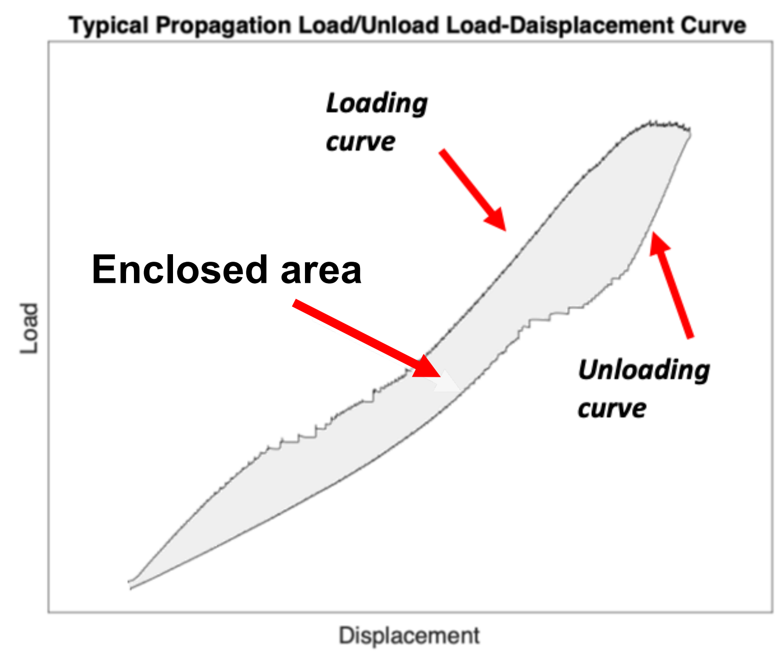


Data Analysis

- Toughness is a key parameter of the material model



- Toughness calculated w/ the Area Method
  - Crack propagation during each load-unload cycle
  - Energy associated with a load-unload cycle equals the magnitude of the enclosed area between the loading curve and the unloading curve.
  - This is the energy of crack propagation
- The Area method requires the following
  - Specimens to be periodically loaded/unloaded
  - Minimal far field damage is present
  - Load-displacement data returns to the origin
- All requirements were sufficiently met



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Data Analysis

- Energy release rate is calculated as

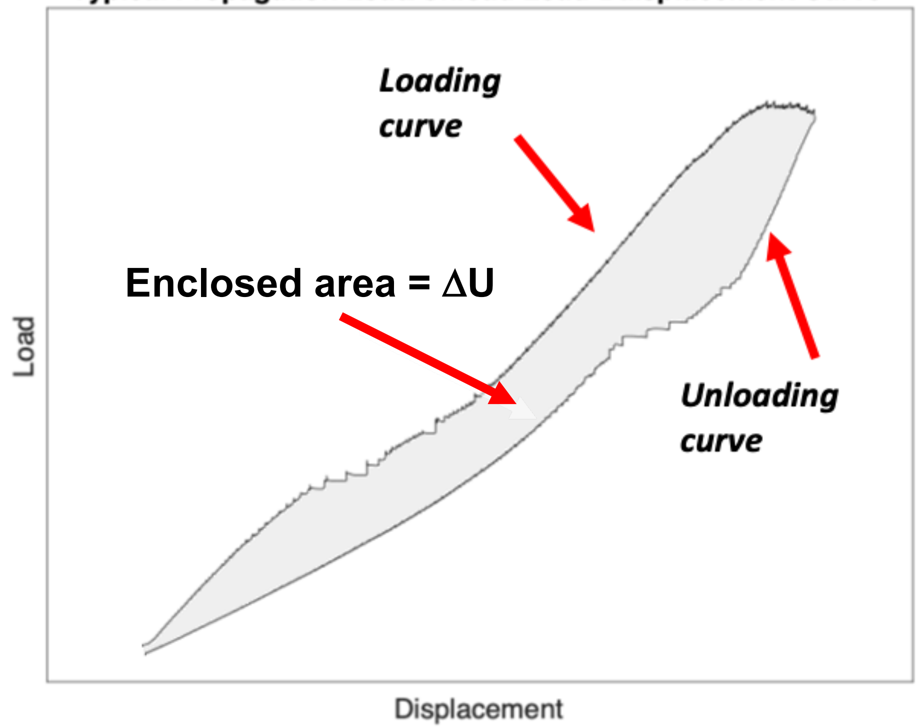
$$G^{MC}_{Observed} = \frac{\Delta U}{\Delta A}$$

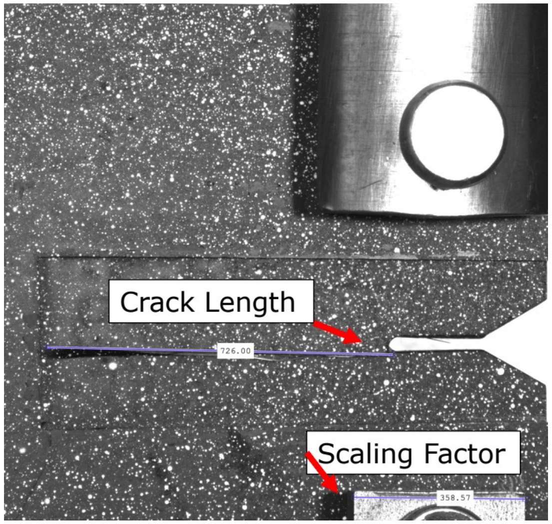
  - ΔU: The energy associated with the crack propagation equal to the enclosed area
  - ΔA: The corresponding area of crack surface created
- ΔA is the product of crack width B and propagation length Δa

$$\Delta A = B\,\Delta a$$

  - **Width B:** Cracks form a "W" shape through thickness. Δa equals the sum total length of segments of the "W"
  - **Δa:** Crack length is measured from images using fixture length as scaling factor

Typical Propagation Load/Unload Load-Daisplacement Curve





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Data Analysis

- The "W" shaped through-thickness crack path indicates the fracture is a combination of mode I and mode II
- Thus the toughness can be decomposed into two components.

$$G_{Observed}^{MC} = G_I^{MC} + G_{II}^{MC}$$

- The relative magnitude of mode I and mode II is given by the phase angle (ψ)

$$\psi = arctan\left(\frac{G_{II}^{MC}}{G_I^{MC}}\right)$$

- Giving

$$G_I^{MC} = G_{Observed}^{MC}\left[1 - \frac{(tan\psi)^2}{[1+(tan\psi)^2]}\right]$$

$$G_{II}^{MC} = \frac{G_{Observed}^{MC}(tan\psi)^2}{[1+(tan\psi)^2]}$$

Phase angle was calculated as the average of each leg of the "W"

Experimental Results

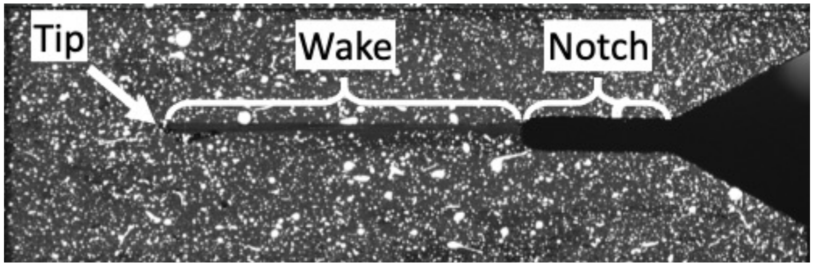
- Results showed
  - The matrix compression toughness be significantly greater than the currently-used tensile toughness value
  - Significant variation
- The matrix tension value was calculated to validate the testing procedure

	Parameter	Symbol	Boeing Material *		Commercial Material	
			50 specimens tested for matrix compression		Due to manufacturing defects and the project conclusion no final testing was performed.	
			Mean Value	Standard Deviation	Mean Value	Standard Deviation
Matrix Tension	Total Toughness	G^{MT}_{Total}	1.2 X	0.39 X	-	-
Matrix Compression	Total Toughness	G^{MC}_{Total}	15.3 X	6.0 X	-	-
	Mode I Toughness	G^{MC}_{I}	3.4 X	1.7 X	-	-
	Mode II Toughness	G^{MC}_{II}	11.9 X	2.1 X	-	-
	Phase Angle	ψ	62.1°	4.2°	-	-

* Boeing-material values given as a multiple of the currently-used matrix tensile toughness

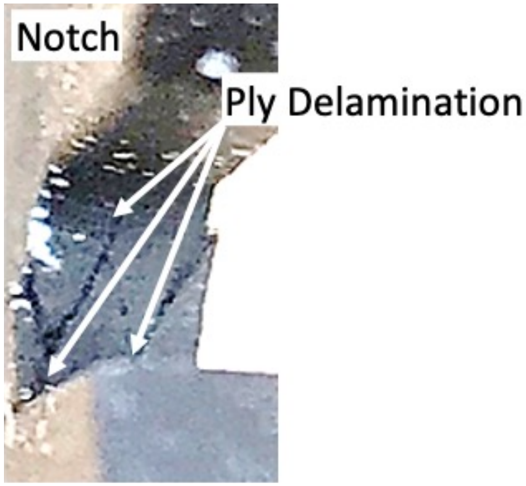
Material Model

- A key consideration is the ability of the material behind the advancing crack to carry load.
  - The material behind the advancing crack remains in contact with reduced capability to support load.
  - "Tip" is the leading edge of the crack, "Wake" is the material behind this leading edge through which the crack has passed but retains a reduced capability to support load.
  - Toughness of the propagating crack can be partitioned into tip and wake contributions.



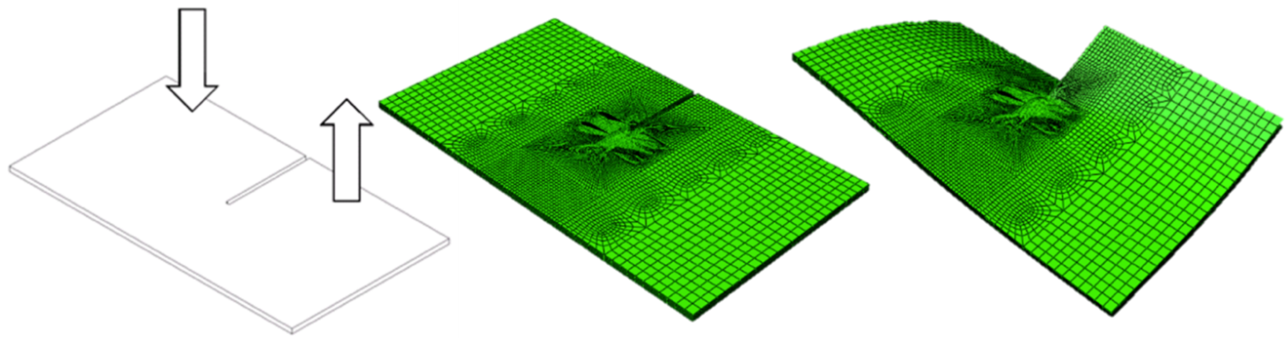
$$G_{Total}^{MC} = G_{\mathrm{Tip}}^{MC} + G_{\mathrm{Wake}}^{MC}$$

- Fracture in the wake consists primarily of ply delamination
- Through analysis using Boeing-provided ply delamination toughness values and experimental measurements, G_{Wake}^{MC} was calculated to be just 2.5% of G_{Total}^{MC}
- Thus $G_{Total}^{MC} \sim G_{\mathrm{Tip}}^{MC}$ and the material model is simply to use G_{Total}^{MC} in place of G_{Total}^{MT} and disregard load-carrying ability in the crack wake

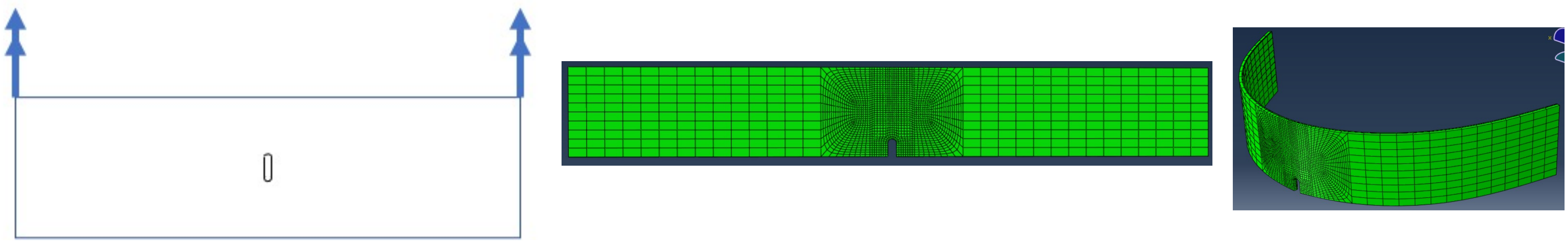


Finite Element Results

- The effect of implementing the new matrix compression toughness values was explored through finite element simulations of
  - Out-of-plane shear of notched carbon-fiber laminate panels



  - Out-of-plane bending of notched carbon-fiber laminate panels



Note: The FEA models consist of 8 node, reduced integration continuum shell elements (Abaqus SC8R) with mesh density of 20 elements around the notch (element size of approximately 0.545 mm by 0.737 mm). Element size increased with increasing distance from the notch tip. Loading was displacement controlled. Details of modeling can be found in publications associated with the AMTAS project "Failure of notched laminates under out-of-plane bending".

Finite Element Results

- For both out-of-plane shear and out-of-plane bending six layups were studied
  - 40 plies, 10% zero-degree plies
  - 40 plies, 30% zero-degree plies
  - 40 plies, 50% zero-degree plies
  - 20 plies, 10% zero-degree plies
  - 20 plies, 30% zero-degree plies
  - 20 plies, 50% zero-degree plies
- For each layup, comparisons of
  - Mises stress
  - Fiber-tension damage
  - Fiber-compression damage
  - Matrix-compression damage
  - Matrix-tension damage
  - Shear damage

  were made using the currently-used value of matrix-compression toughness and the value determined in this project.
- Loading was displacement controlled and held equal in all comparisons

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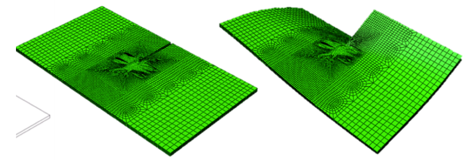
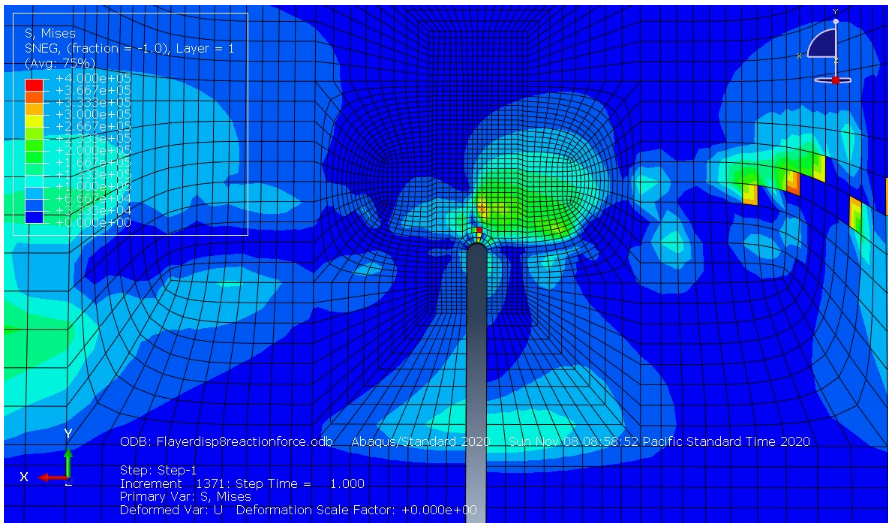
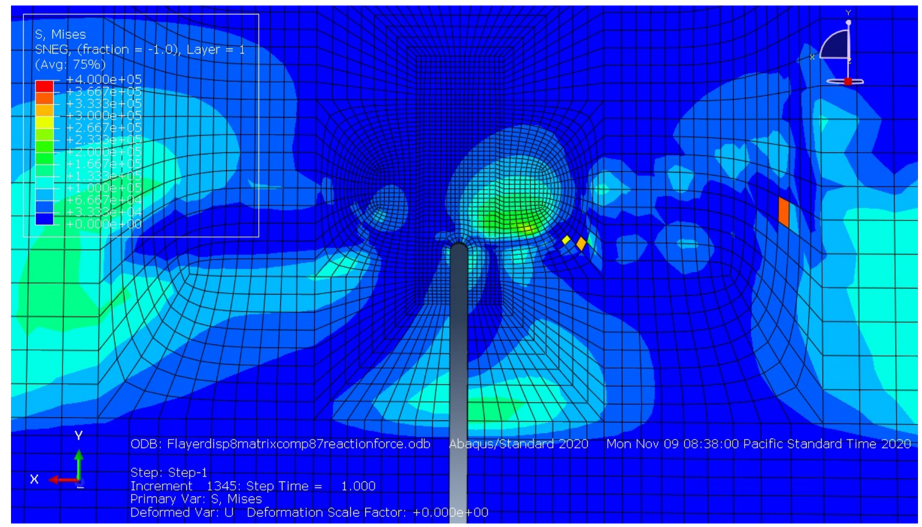
Finite Element Results, Out-of-Plane Shear: Mises Stress



- Shown is a typical result for all layups
- Red ➔ Blue corresponds to Greater ➔ Lesser values



G^{MC} currently used



G^{MC} from this project

- The change in energy release rate does not significantly change maximum magnitude but does affect the distribution.

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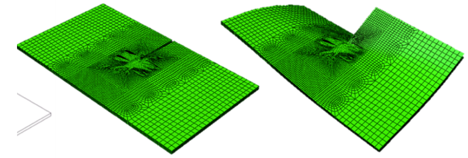
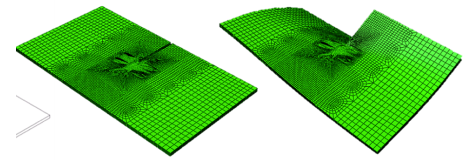
Finite Element Results, Out-of-Plane Shear: Fiber Tension and Fiber Compression Damage



- As might be expected, the fiber-tension damage and fiber-compression damage were in general not significantly affected for any of the layups by the change in energy release rate value.

Finite Element Results, Out-of-Plane Shear: Matrix Compression Damage



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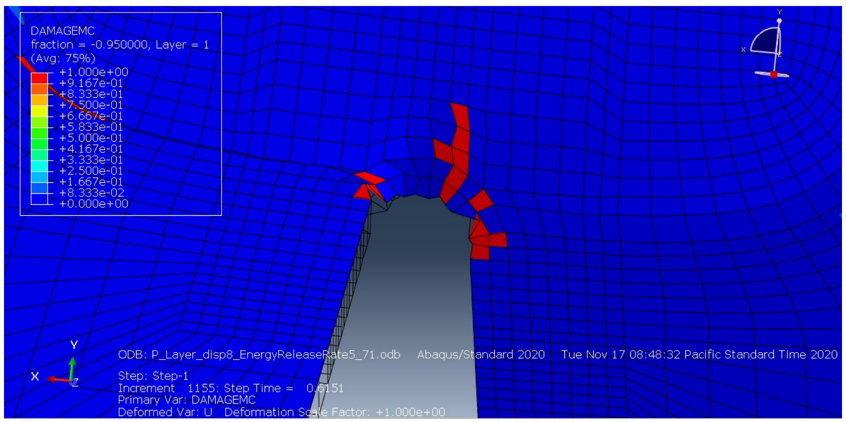
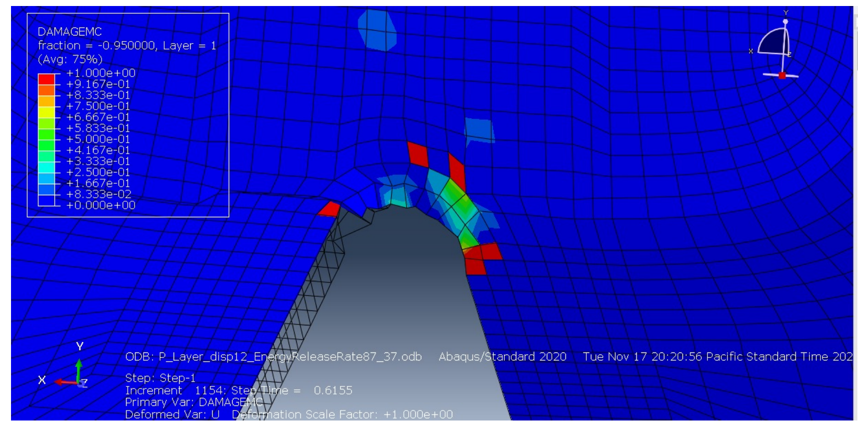


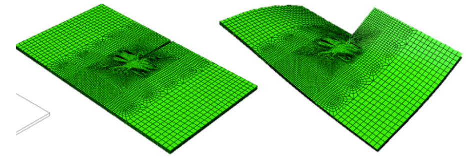
G^{MC} currently used



G^{MC} from this project

- As expected, the greater value of the matrix-compression energy-release rate resulted in a decrease in matrix damage.

Finite Element Results, Out-of-Plane Shear: Matrix Tension Damage



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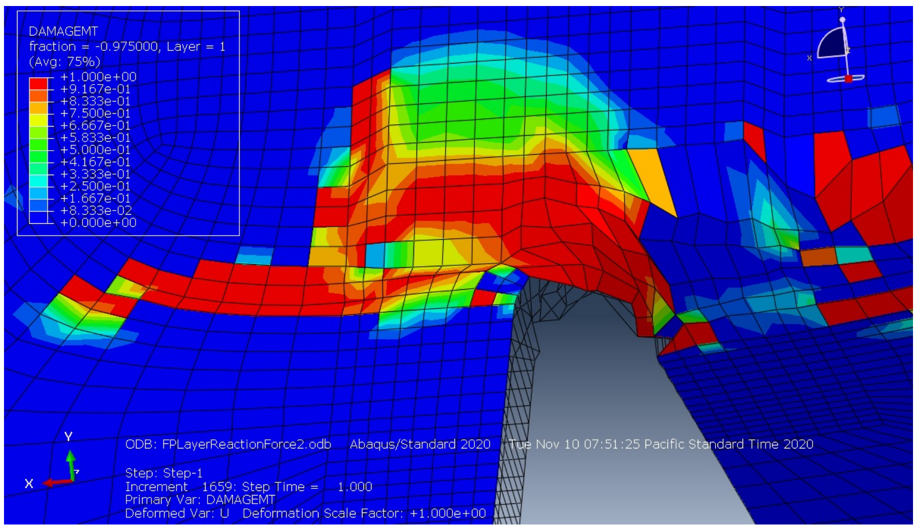
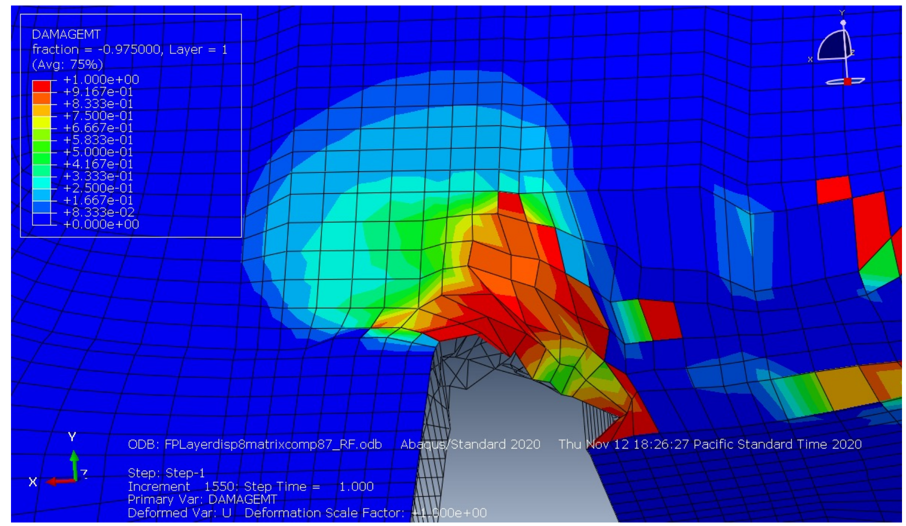


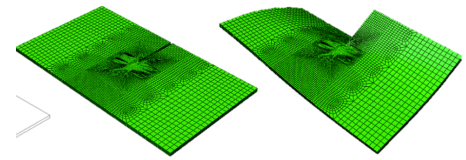
G^{MC} currently used



G^{MC} from this project

- Use of the current G^{MC} value overestimates the extent of matrix tension damage

Finite Element Results, Out-of-Plane Shear: Shear Damage



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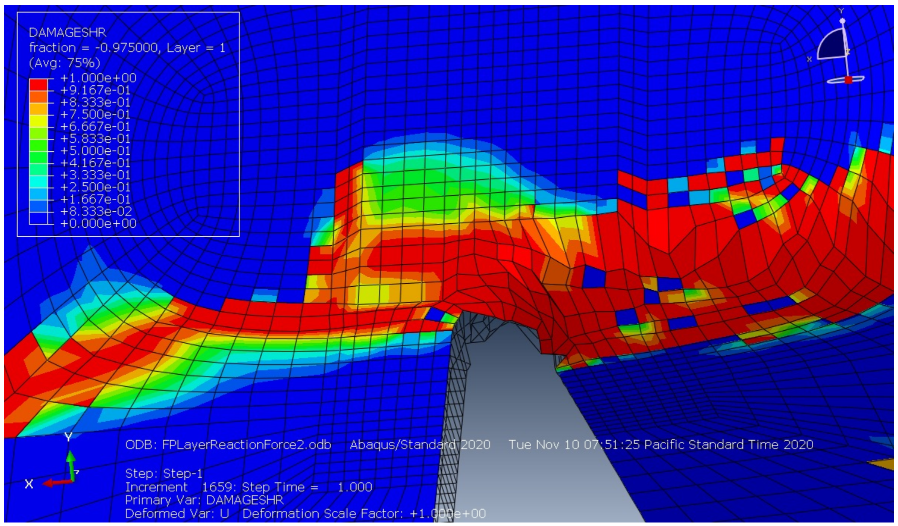
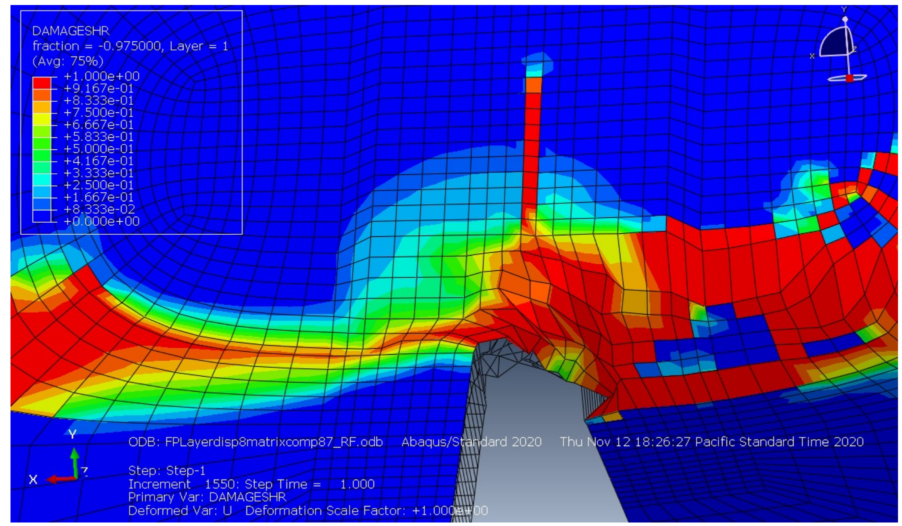


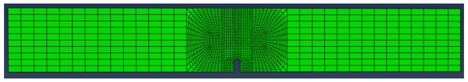
G^{MC} currently used

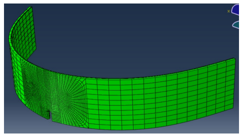


G^{MC} from this project

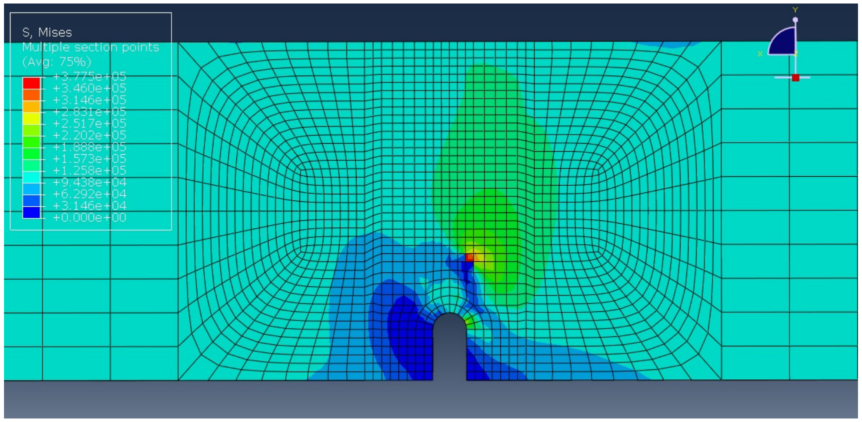
- Use of the current G^{MC} value overestimates the extent of shear damage. .

Finite Element Results, Out-of-Plane Bending: Mises Stress

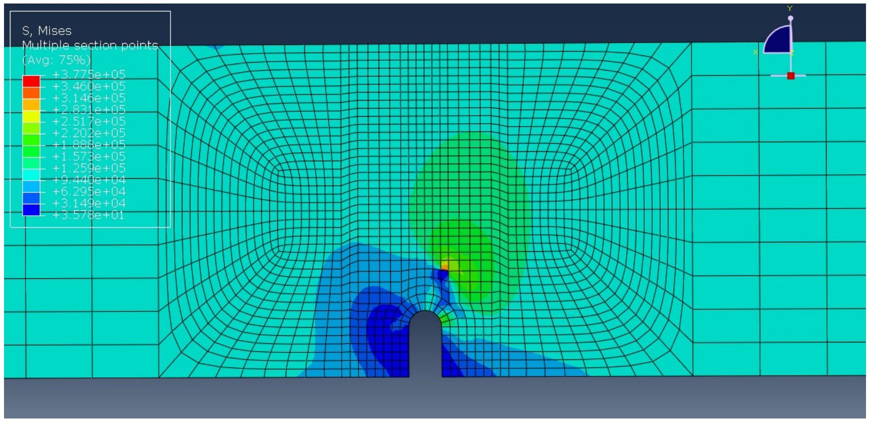




- Shown is a typical result for all layups on tensile side
- Red ➔ Blue corresponds to Greater ➔ Lesser values



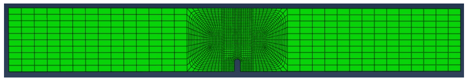
G^{MC} currently used

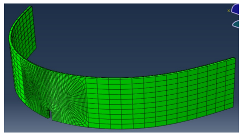


G^{MC} from this project

- The change in energy release rate does not significantly change magnitude or distribution.

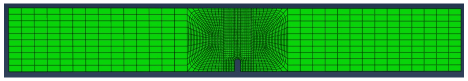
Finite Element Results, Out-of-Plane Bending: Fiber Tension and Fiber Compression Damage

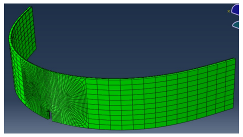




- As might be expected, the fiber-tension damage and fiber-compression damage were in general not significantly affected for any of the layups by the change in energy release rate value.

Finite Element Results, Out-of-Plane Bending: Matrix Compression Damage





- Shown is a typical result for all layups on compressive side
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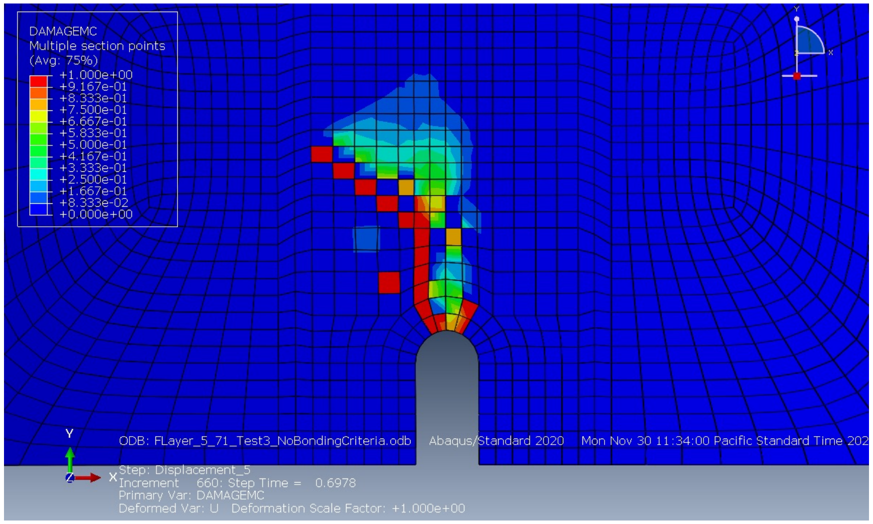
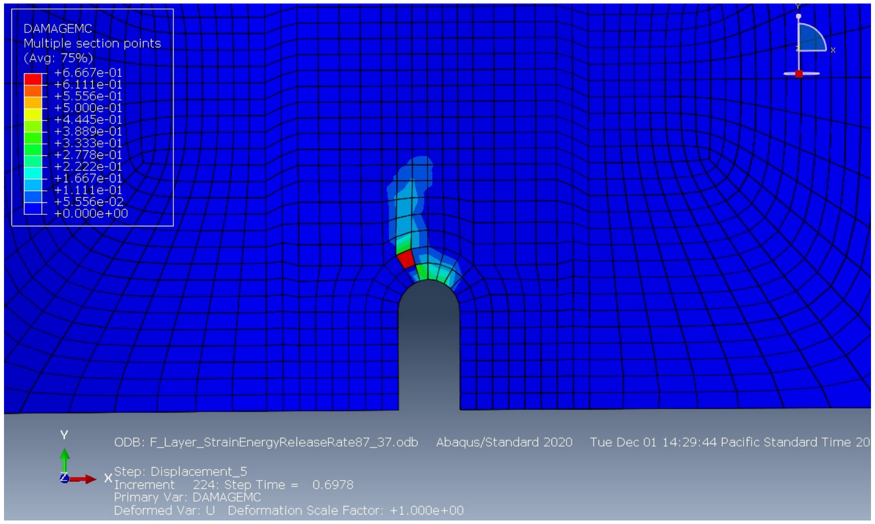


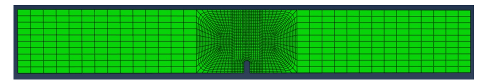
G^{MC} currently used

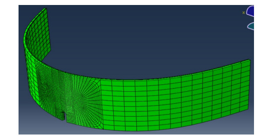


G^{MC} from this project

- Use of the current G^{MC} value overestimates the extent of matrix compression damage.

Finite Element Results, Out-of-Plane Bending: Matrix Tension Damage





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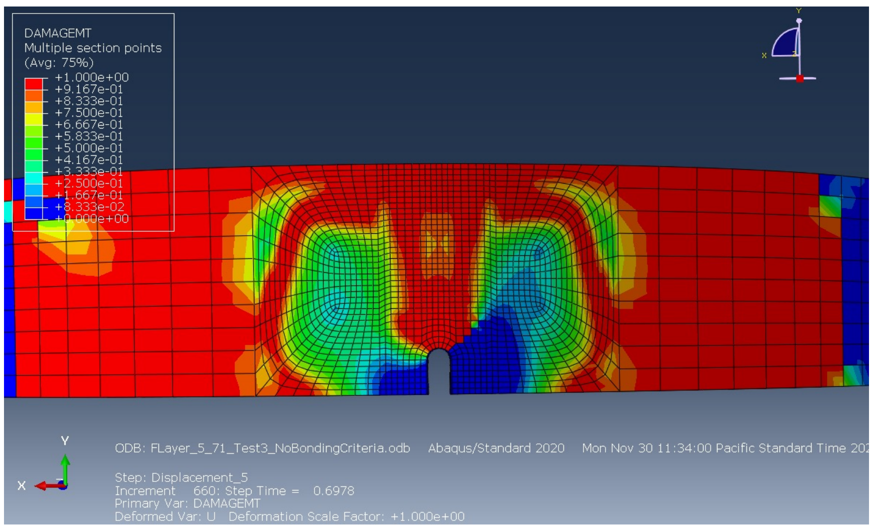
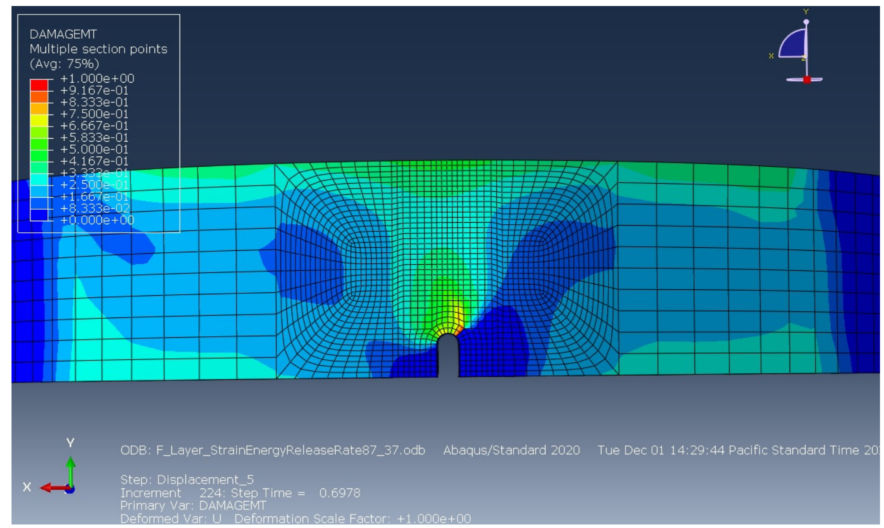


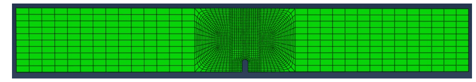
G^{MC} currently used

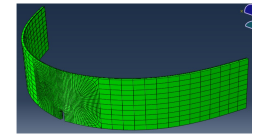


G^{MC} from this project

- Use of the current G^{MC} value significantly overestimates the extent of matrix tension damage.

Finite Element Results, Out-of-Plane Bending: Shear Damage





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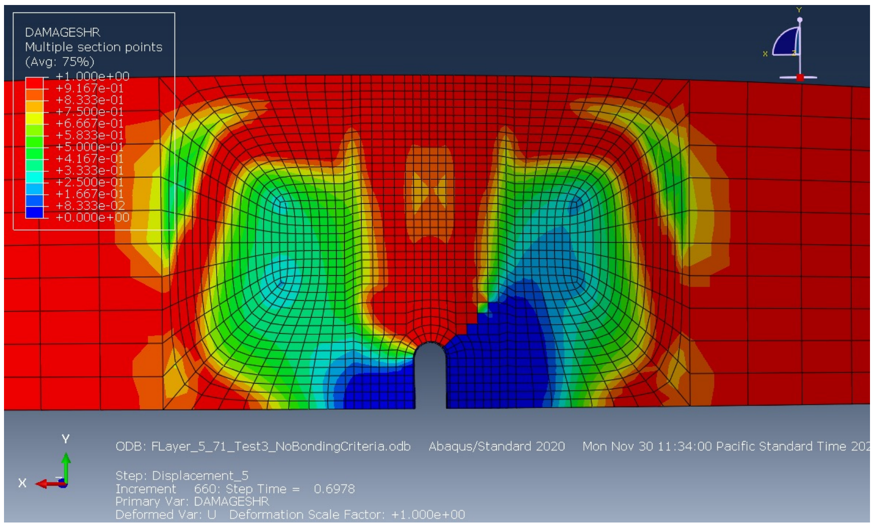
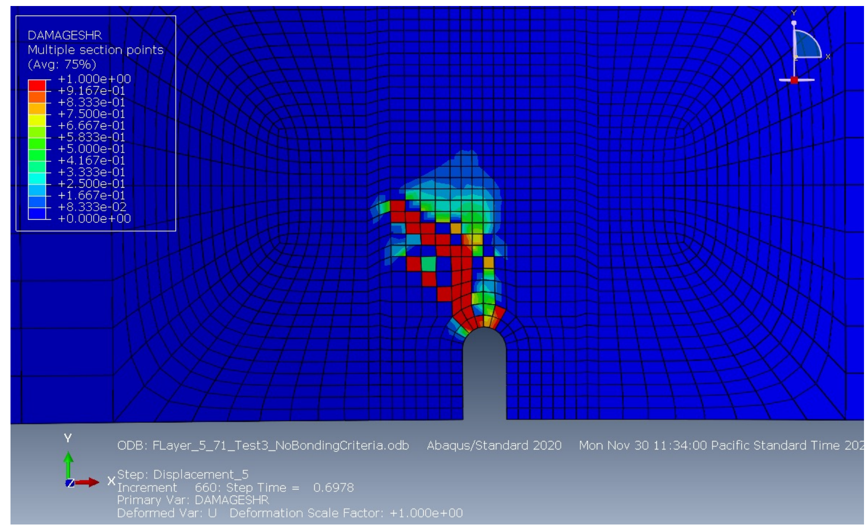


G^{MC} currently used



G^{MC} from this project

- Use of the current G^{MC} value significantly overestimates the extent of shear damage.

Conclusions

- Through this project for matrix compression
  - – Effective test specimens were developed for both Boeing-proprietary and commercially-available carbon fiber laminates
  - – Testing was conducted to determine an physically-realistic material model for matrix compression
  - – The magnitude of crack-tip toughness was found to be significantly greater than the currently-used value
  - –The magnitude of the crack-wake toughness was found to be insignificant.
  - – Use of this “new” toughness value was shown to significantly effect finite element predictions for several common loading scenarios.