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

Fall 2012 Meeting

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

- Motivation and Key Issues

  Develop analysis techniques useful in design of composite aircraft structures under out-of-plane loading (bending and shear)

- Objective

  Determine failure modes and evaluate capabilities of current models to predict failure

- Approach
  - Experiments: Mode 3 fracture
  - Modeling: Progressive damage development and delamination (ABAQUS) under out-of-plane loading

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

- Principal Investigators & Researchers
  - John Parmigiani (PI) & Brian Bay; OSU faculty
  - T. Wright, T. McKenzie, I. Hyder; OSU grad students
- FAA Technical Monitor
  - Curt Davies
  - Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Gerry Mabson, Boeing (technical advisor)
  - Tom Walker, NSE Composites (technical advisor)

Project Overview

Phase I (2007-08)

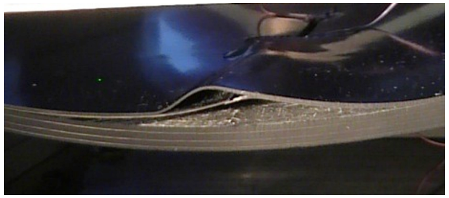
- Out-of-plane bending experiments w/composite plates
- ABAQUS modeling with progressive damage

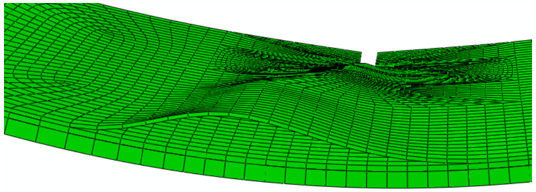
Phase II (2008-09)

- ABAQUS modeling with buckling delamination added
- Sensitivity study of (generic) material property values

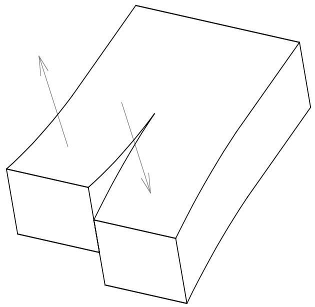
Phase III (2009-10)

- ABAQUS modeling w/ more delamination interfaces





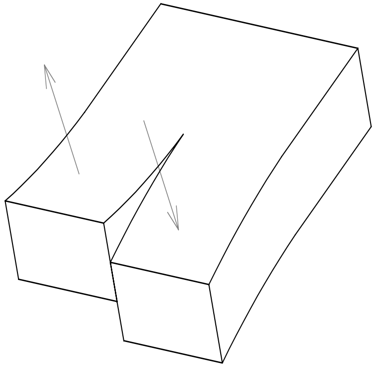
Project Overview



- Phase IV (2010-11)
  - Out-of-plane shear experiments & ABAQUS modeling
  - Further study of additional delamination interfaces for out-of-plane bending
  - Initiating vs. propagating toughness values for out-of-plane bending
  - Feasibility of Abaqus/Explicit and XFEM for future work
  - Sensitivity study using Boeing mat'l property values
  - Special cases: all-ninety and all-zero degree plies for out-of-plane bending

Project Overview

Phase V (2011-12)



- Out-of-plane shear (mode III) experiments & ABAQUS modeling
- Evaluate the ABAQUS plug-in Helius MCT (Firehole Composites) for use in modeling progressive damage in composites and applicability to this project
- Special cases: all-ninety and all-zero degree plies for out-of-plane bending

Today's Topics

- Out-of-plane shear: Experimental results
- Out-of-plane shear: Modeling results
- Helius MCT Evaluation results
- Out-of-plane bending, all-ninety and all-zero ply results

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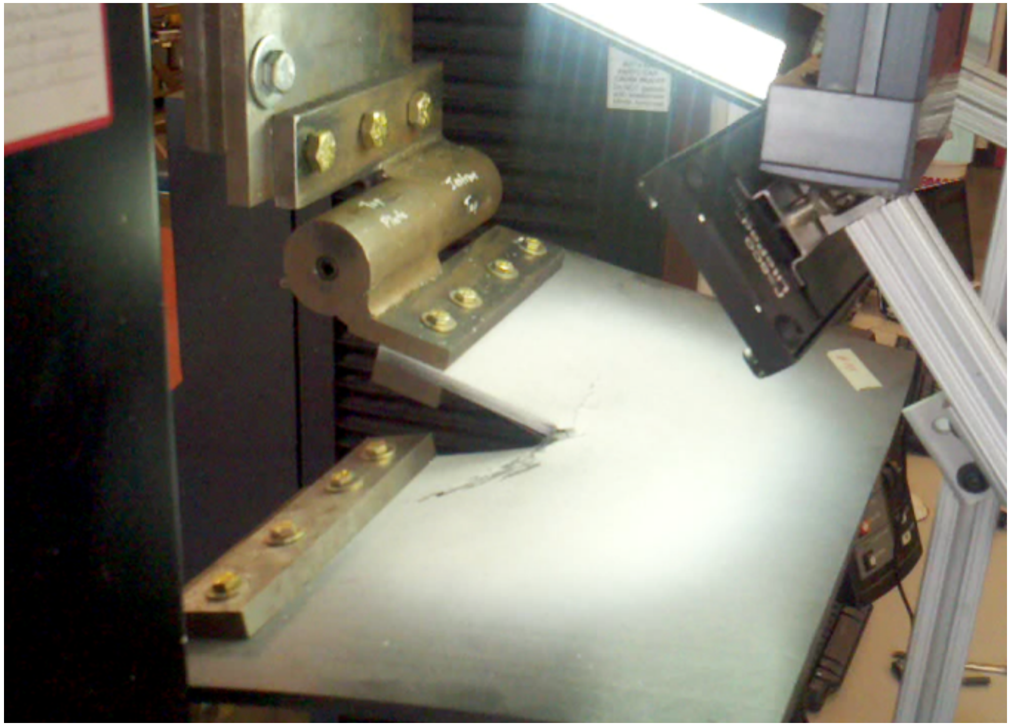
Out-of-plane shear: Experimental results

- Experimental Set-up & Plan
  - Edge-notched CF panels displaced to maximum load
  - Mode III fracture
  - Metrics
    - Applied displacement
    - Applied load
    - Notch-tip strain field (via DIC, digital image correlation)
  - Six ply layups
  - Six specimens / layup
    - Three “up”
    - Three “down”



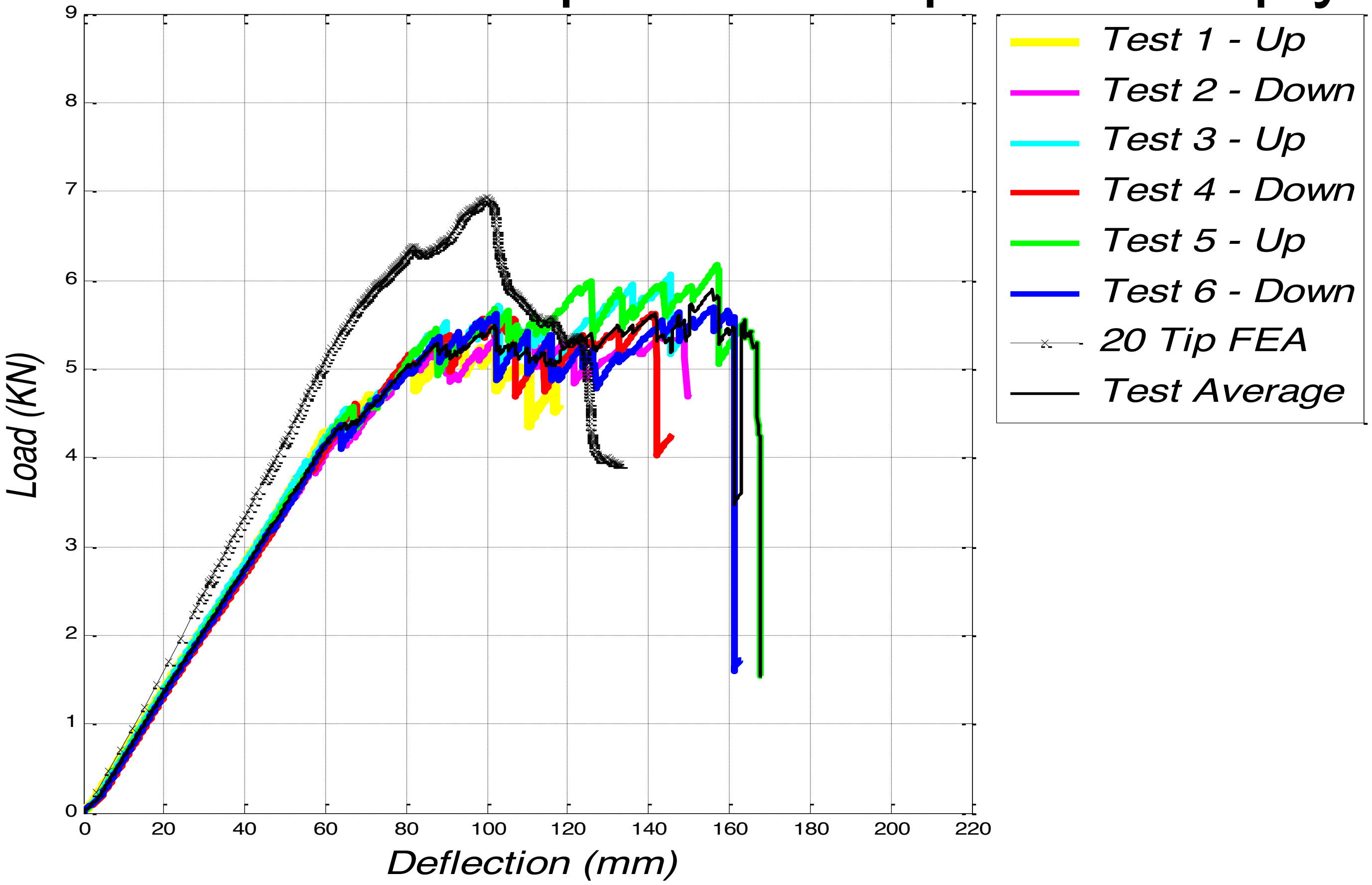
Out-of-plane shear: Experimental results

- Maximum applied load (failure load)

	Max Force per Test [kN]						
Layup (#plies / % zero degree)	1	2	3	4	5	6	**MEAN**
40/50%	5.552	5.345	5.122	6.103	5.395	5.321	**5.473**
40/30%	5.342	5.363	6.061	5.616	6.176	5.690	**5.708**
40/10%	3.891	4.161	4.112	4.016	4.277	4.148	**4.101**
20/50%	1.751	1.859	1.929	1.691	1.740	1.801	**1.795**
20/30%	1.484	1.541	1.541	1.456	1.527	1.638	**1.531**
20/10%	1.290	1.215	1.258	1.254	1.198	1.336	**1.259**

Out-of-plane shear: Experimental results

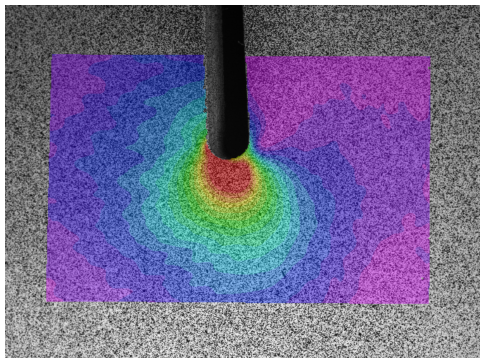
- Applied Load vs. Displacement plot for 40ply/30%



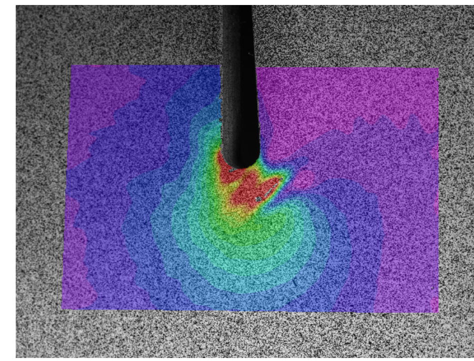
Out-of-plane shear: Experimental results

- Notch-tip strain fields for 40ply/30%, UP orientation

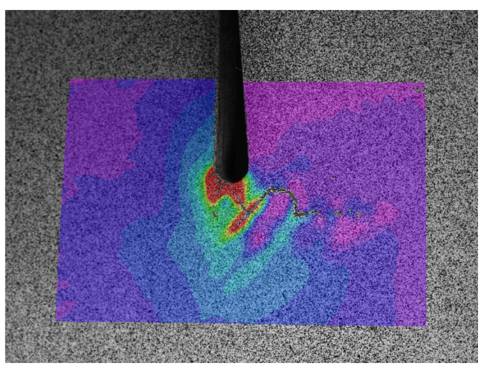
1.
Linear Region
Before 1st
Visible Fracture



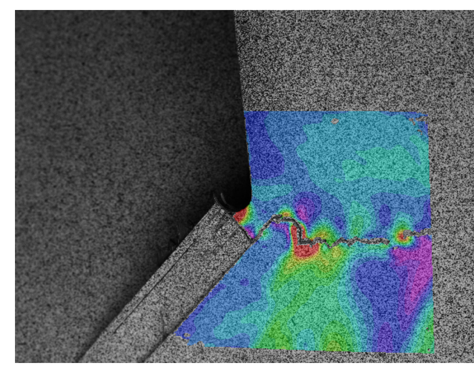
2.
Linear Region
At 1st
Visible Fracture



3.
End of
Linear Region



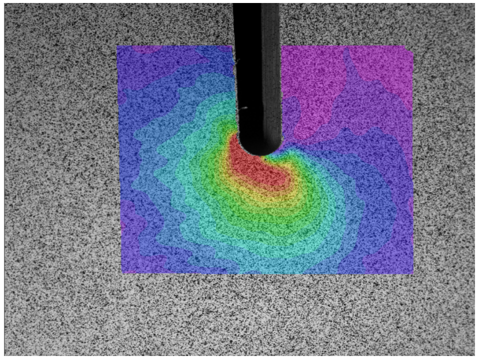
4.
Point of Max
Load



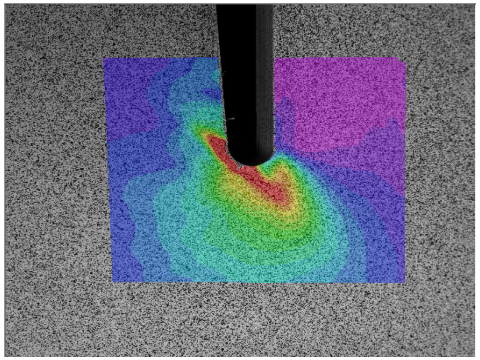
Out-of-plane shear: Experimental results

- Notch-tip strain fields for 40ply/30%, DOWN

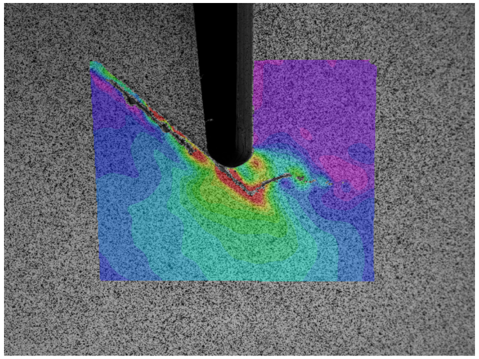
1.
Linear Region
Before 1st
Visible Fracture



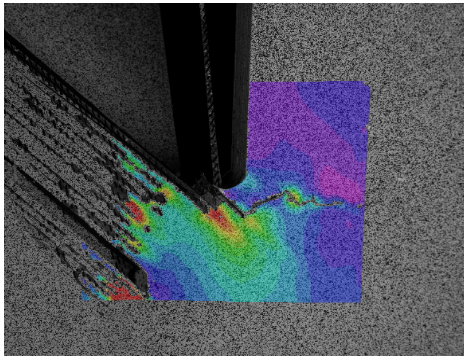
2.
Linear Region
At 1st
Visible Fracture



3.
End of
Linear Region



4.
Point of Max
Load



Out-of-plane shear: Experimental results

- Conclusions / Future work
  - Experimental set-up works well… good data
  - Time to write – up final results
  - Graduate student!

Today's Topics

- Out-of-plane shear: Experimental results
- Out-of-plane shear: Modeling results
- Helius MCT Evaluation results
- Out-of-plane bending, all-ninety and all-zero ply results

Out-of-plane shear: Modeling results

- Notch-tip mesh selection
  - Damage causes strength and stiffness degradation leading to strain softening behavior
  - Strain softening causes a mesh-dependent solution
  - Mesh selection method not obvious
  - Approach used in out-of-plane bending study used here
  - Select coarsest mesh giving a converged **elastic** solution (damage turned off)

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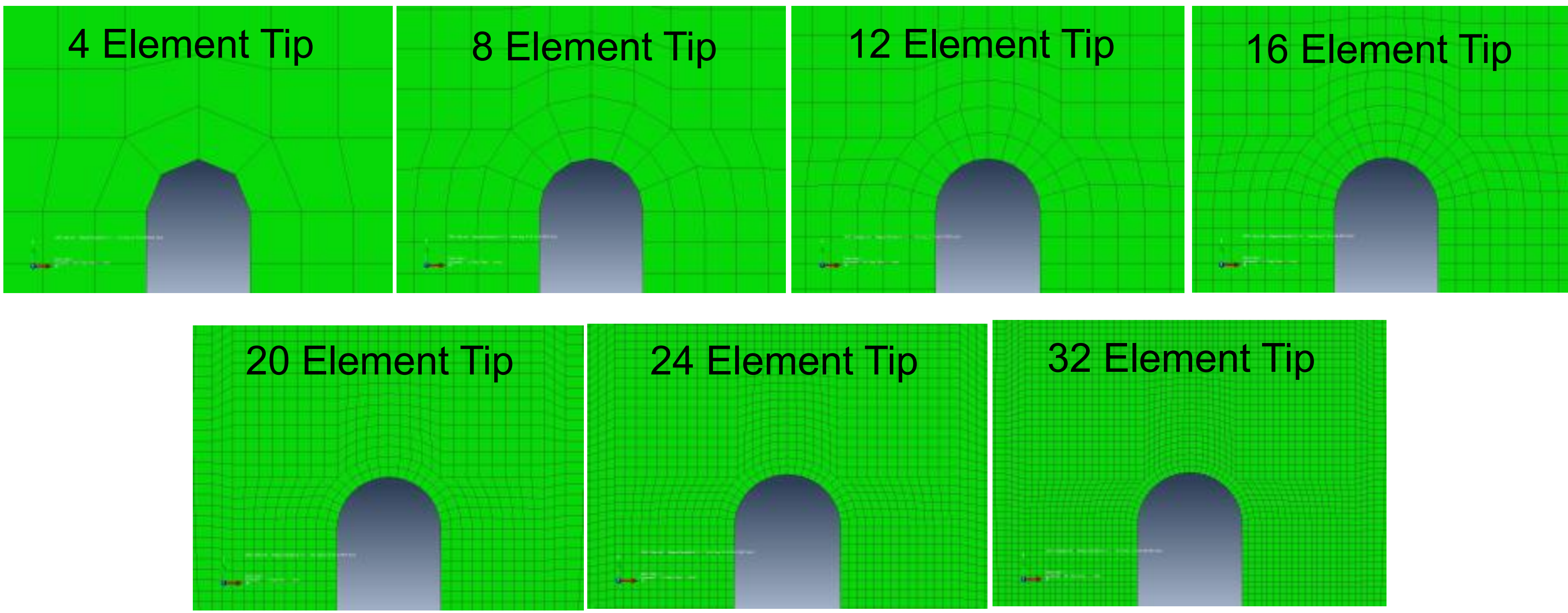
Out-of-plane shear: Modeling results

- Seven notch-tip meshes were analyzed
- 20 element tip was selected



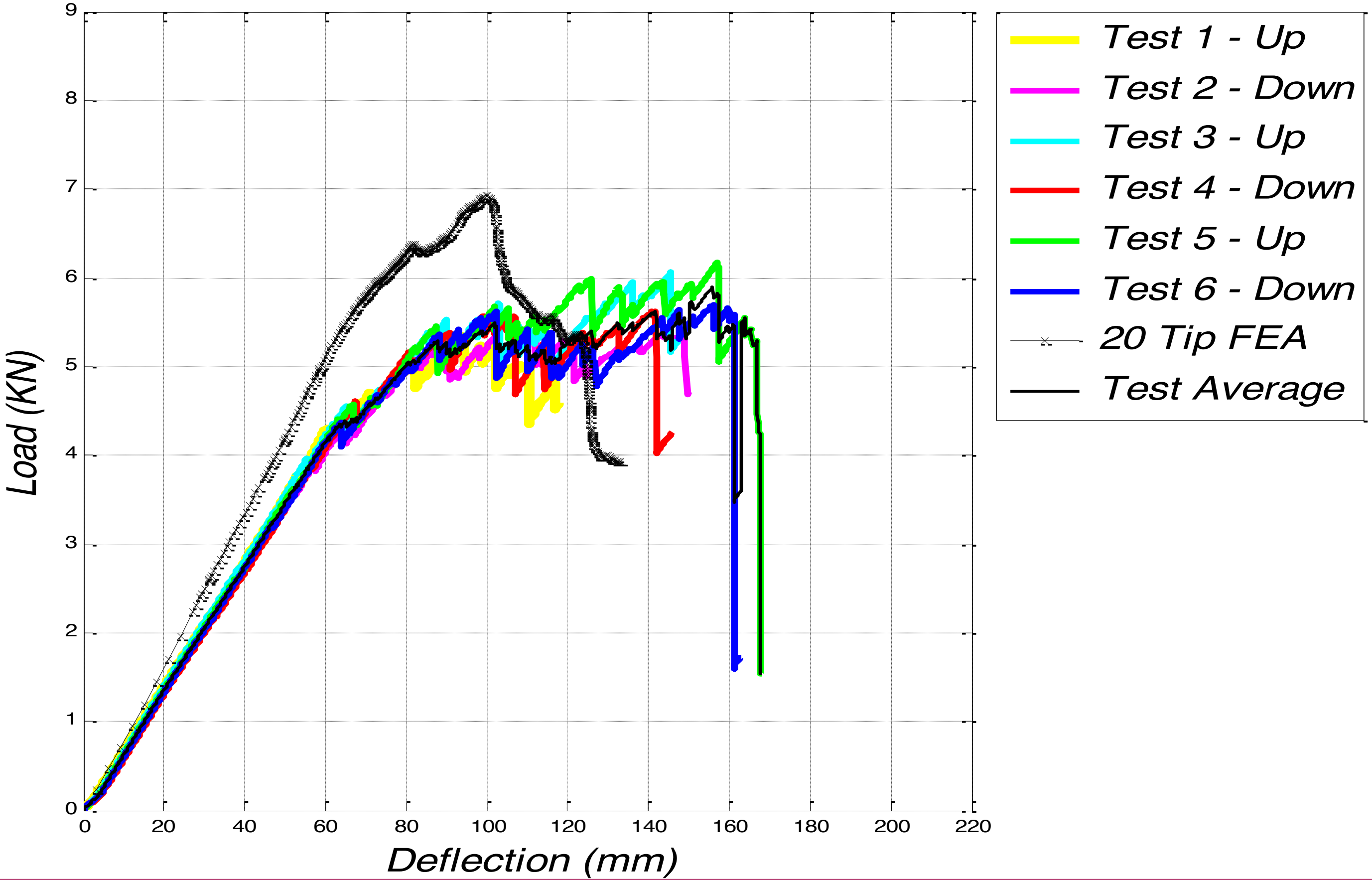
Out-of-plane shear: Modeling results

- Notch-tip mesh: Comparison to experiments

Layup (#plies / zero degree)	**Experiment**	**8-Element Mesh, Error**	**20-Element Mesh, Error**	**32-Element Mesh, Error**
40/50%	5.473	14.53%	**9.96%**	47.52%
40/30%	5.708	33.50%	**21.34%**	30.06%
40/10%	4.101	74.87%	**40.14%**	38.19%
20/50%	1.795	-10.04%	**-0.68%**	25.45%
20/30%	1.531	28.33%	**34.54%**	82.93%
20/10%	1.259	33.17%	**16.57%**	64.00%

Out-of-plane shear: Modeling results

- Comparison to experiments, 40-ply, **30%** zero



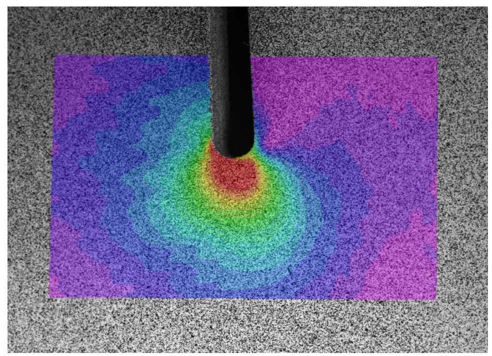
Principle Strain, e1

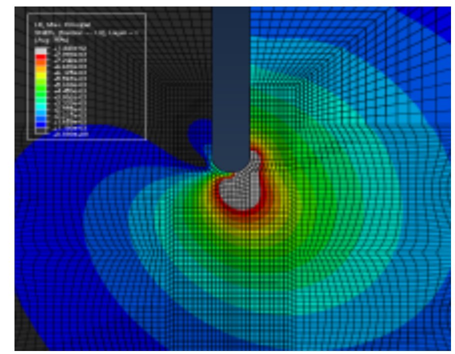
Out-of-plane shear: Modeling results

- Comparison to experiments, 40-ply, **10%** zero, UP

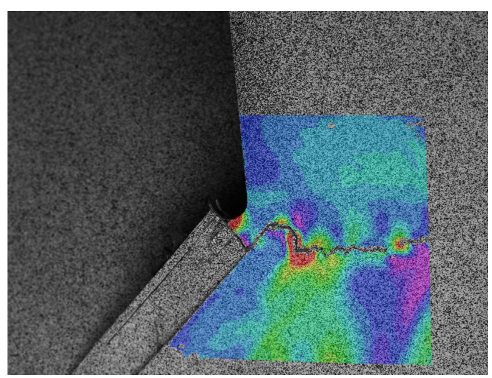
Experiment | Model

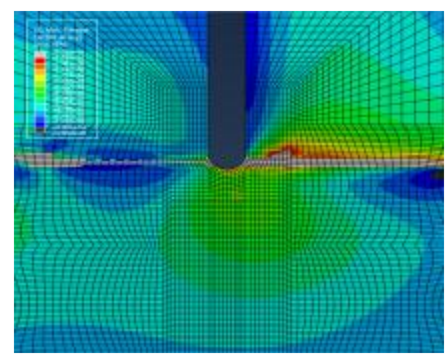
1.
Linear Region





2.
Point of Max Load





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Principle Strain, e1
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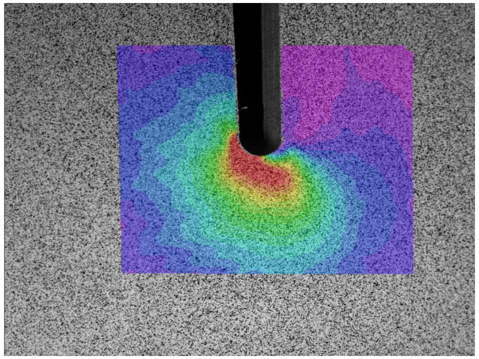
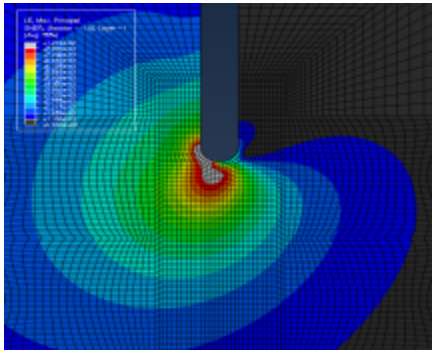
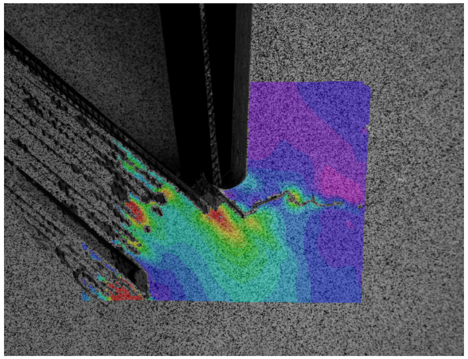
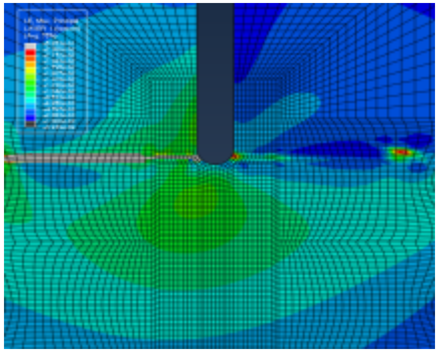
Out-of-plane shear: Modeling results

- Comparison to experiments, 40-ply, **10%** zero, DOWN

	Experiment	Model
1. Linear Region		
2. Point of Max Load		

Out-of-plane shear: Modeling results

Principle Strain, e1

- Conclusions / Future Work
  - Approach of using coarsest mesh to give converged elastic solution appears reasonable
  - Model predictions vs. Experiments
    - Model linear region stiffness equal or greater
    - Model failure load near-equal or greater
    - Model failure displacement less
    - Strain-fields appear to capture some major features
  - Part of 2012-13 project is to improve model predictions

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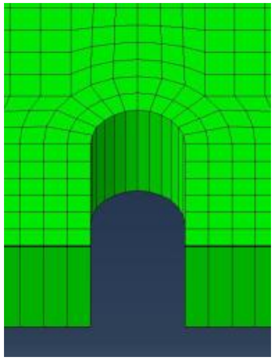
- Out-of-plane shear: Experimental results
- Out-of-plane shear: Modeling results
- Helius MCT Evaluation results
- Out-of-plane bending, all-ninety and all-zero ply results

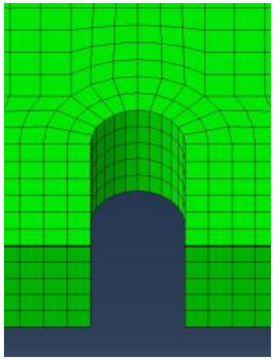
Helius:MCT Evaluation Results

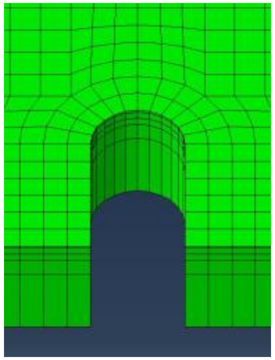
- Evaluate Helius:MCT as an alternative to Abaqus built-in composite damage capabilities
- Helius:MCT
  - Uses a material-model subroutine (UMAT) and deals well with material non-linearity.
  - No special features to deal with geometric non-linearity
  - For best results, one layer of solid elements per ply (element damage corresponds to ply damage)
  - However, one layer / ply led to convergence problems
  - Solution was to use continuum shell elements with multiple plies / element

Helius:MCT Evaluation Results

- Comparison
  - Abaqus Built-in (Hashin)
    - One continuum element through thickness
    - Five equally spaced continuum elements thick
    - Five continuum elements w/ VCCT to model delamination
  - Abaqus w/ Helius:MCT
    - One continuum element through thickness
    - Five equally spaced continuum elements thick
    - Five continuum elements w/ CZ to model delamination







Helius:MCT Evaluation Results

- Comparison results

Run Description	Maximum Moment [in-lbs/in]	Error (%)	Run Time [hrs]
Experimental	740	-	-
Abaqus, 1 el, no delamination	839.9	13.5	1:20
Abaqus, 5 el, no delamination	1027.4	38.8	8:49
Abaqus, 5 el, VCCT	770.8	4.2	74:17
Helius, 1 el, no delamination	725.5	-2.0	0:38
Helius, 5 el, no delamination	719.7	-2.7	2:32
Helius, 5 el, CZ	788.9	6.6	12:32

Helius:MCT Evaluation Results

- Conclusions / Future Work
  - Comparison results: Promising!
  - Study will continue with this year’s specimens.

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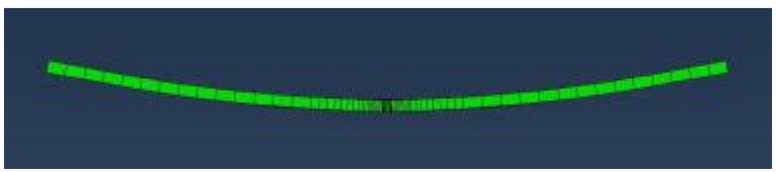
- Out-of-plane shear: Experimental results
- Out-of-plane shear: Modeling results
- Helius MCT Evaluation results
- Out-of-plane bending, all-ninety and all-zero ply results

Out-of-plane bending, all-ninety and all-zero ply results

- Analyze the special cases of all-ninety-degree plies and all-zero-degree plies in out-of-plane bending
- Plan
  - 40 all-zero-degree ply layup
  - 40 all-ninety-degree ply layup
  - Compare to 40 / 30% zero-degree ply layup
  - Use Helius:MCT

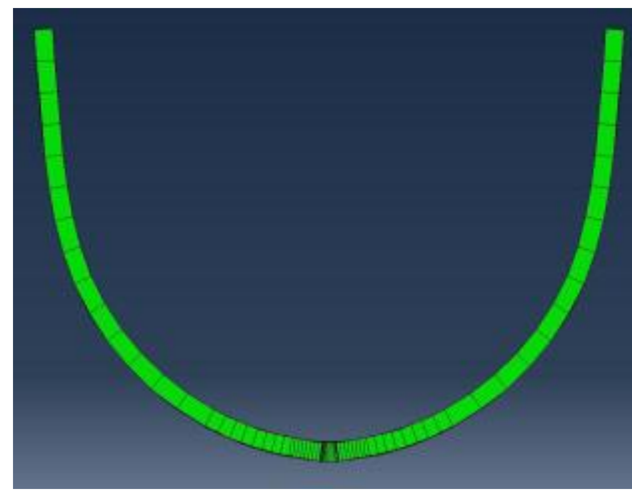
Out-of-plane bending, all-ninety and all-zero ply results

- Results (max. moment at corresponding deflection)
  - All zero: 1114.5 in-lbs/in @ 1.26 inches
  - 40 / 30% zero-degree 839.9 in-lbs @ 2.18 inches
  - All ninety: None @ 4.1 inches



All Zero

40 / 30% zero



All Ninety

Out-of-plane bending, all-ninety and all-zero ply results

- Conclusions / Future Work
  - Lack of failure load for all-90 case limits usefulness
  - May repeat with out-of-plane shear case

Questions