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

2013 Technical Review

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Failure of Notched Laminates Under Out-of-Plane Bending, all phases

- 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 and model failure

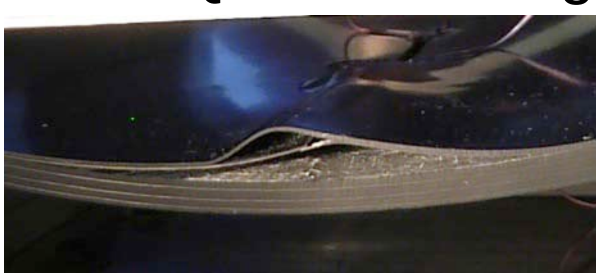
- Approach
  - Modeling of progressive damage development and delamination using ABAQUS
  - Experimentation to validate models and to identify key failure mechanisms

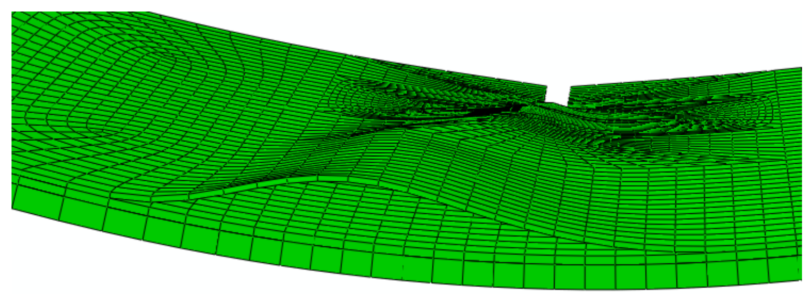
Failure of Notched Laminates Under Out-of-Plane Bending, all phases

- Principal Investigators & Researchers
  - John Parmigiani (PI)
  - Imran Hyder & Nasko Atanasov grad students (2012-13)
- 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 History

- 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





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Project History

- Phase IV (2010-11)
  - Further study of modeling of out-of-plane bending
  - Sensitivity study of (Boeing) material property values
- Phase V (2011-12)
  - Out-of-plane shear (mode III) experiments
  - Evaluate the ABAQUS plug-in Helius MCT

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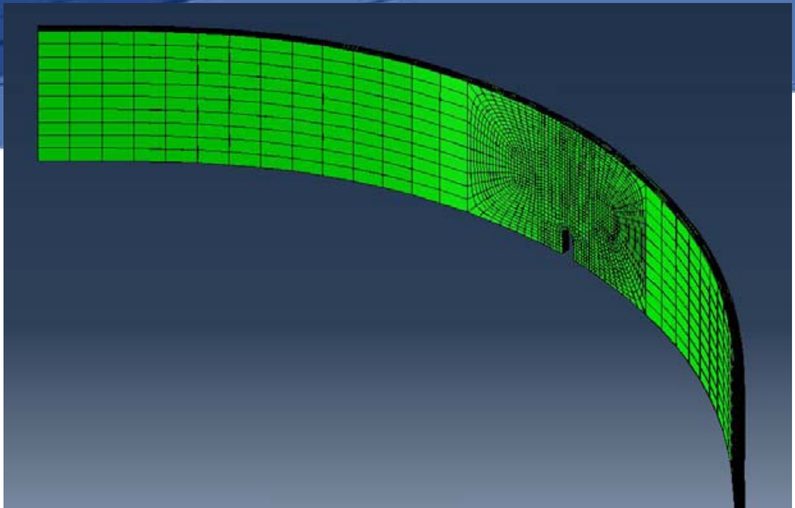
2012-13 Project

- Phase VI
  - Task 1: Investigate non-traditional layups (NTL) for optimization of out-of-plane bending performance
  - Task 2: Determine effective finite element analysis techniques for out-of-plane shear (mode III)

- **Today's Topics**
  - **Update on optimization**
  - **Review and update of out-of-plane shear**

Update on optimization



Half model of out-of-plane bending

- Optimization
  - Maximize failure load
  - Allow plies in15° increments
- To begin, a genetic algorithm approach was used
  - Due to long FEA run times, a simplified 8-ply model without a notch was used. Result was all-zeros (correct)
  - Next a simplified 10-ply model w/ notch was pursued (actual panels are 20 and 40 plies)
  - Even with simplified model, 10 days of runs required to identify a solution of 0/0/-45/-45/-45/90/0/0/0/0
  - This solution is not quite the optimum as all-zeroes gives a failure load 1.5% higher.

Update on optimization

- Given long run time and failure to find true optimum, genetic algorithms were not pursued further
- Next idea pursued was to use a Design-of-Experiments approach to identify significant factors
  - Explore perturbations in ply angle about zero-degrees i.e. -15/0/15
  - Use a fractional factorial design
  - For no-notch case, all-zeros is obvious optimum and the method correctly gives this result
  - For notched-case, it is not obvious that all-zeros will be optimum

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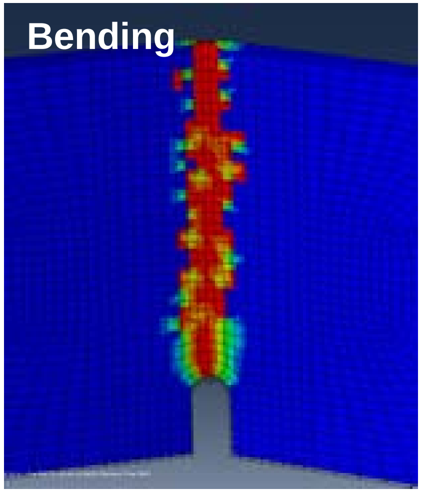
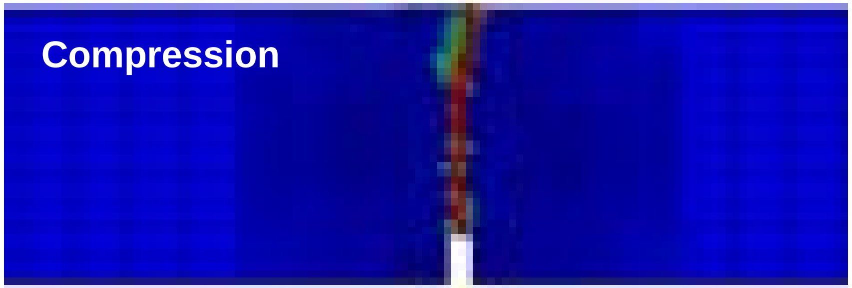
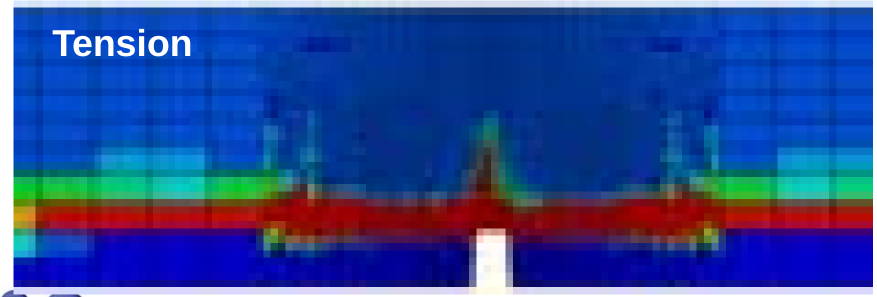
Update on optimization

- Using DoE approach for notched panel, all-zeros was found to be optimal (i.e. gave maximum failure load)
- Fracture path was found to be self-similar.
- Self-similar result was somewhat surprising so comparisons were made to all-zeros in tension and compression
- All zeros tension case gave the expected splitting failure mode







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Update on optimization

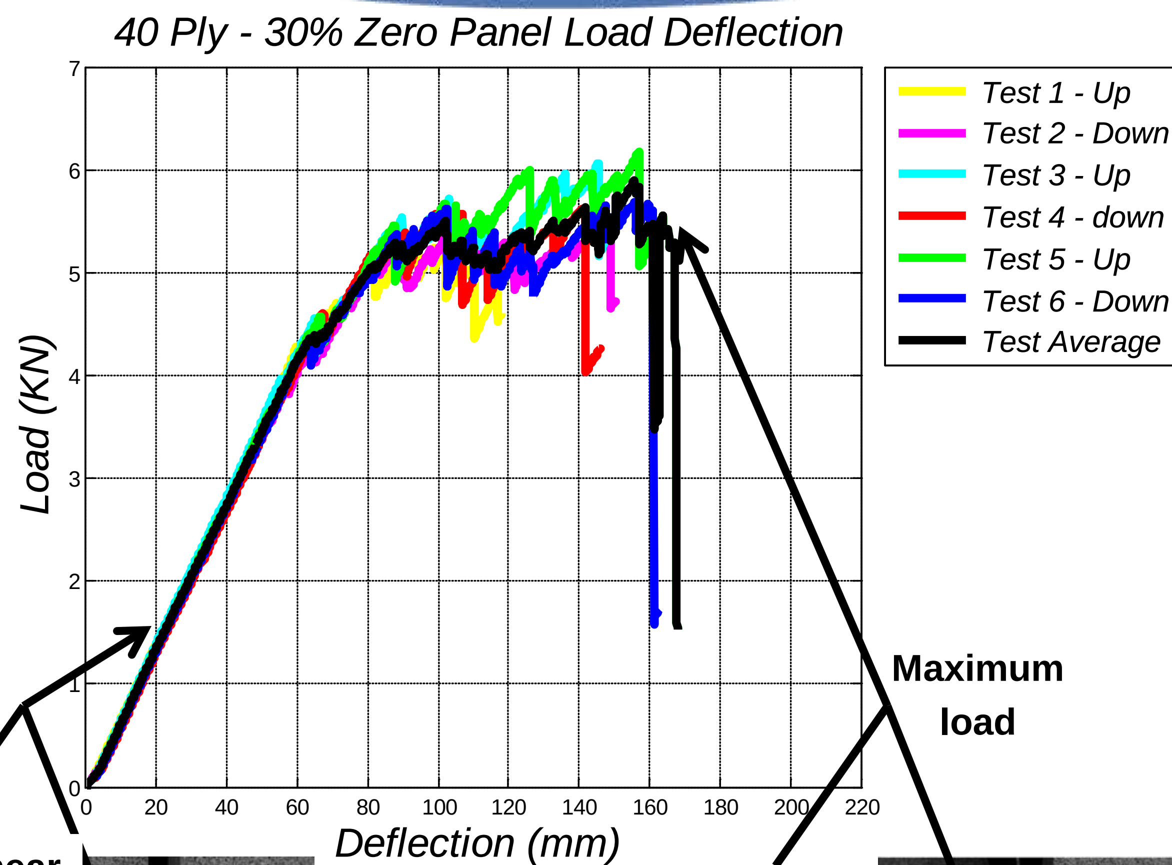
- Current Status
  - For the notched-panel geometry of this study, an all-zero-degree plies lay-up gives the maximum failure load for pure out-of-plane bending
  - Exploration of “more interesting” cases of multiple loads and general far-field boundary conditions requires more sophisticated computational equipment and validation of current mode III work and is deferred to a later project.

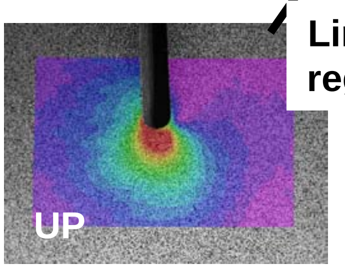
Review and update of out-of-plane shear

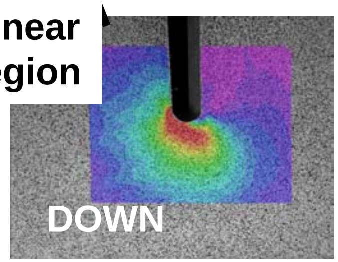
- Experimental Set-up & Plan
  - Edge-notched CF panels displaced to maximum load
  - Mode III fracture
  - Metrics
    - Applied displacement
    - Applied load
    - Notch-tip strain field (via DIC, digital image correlation)
  - Six ply layups
  - Six specimens / layup
    - Three “up”
    - Three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

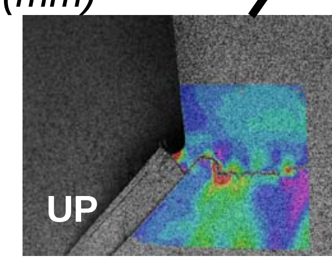
Review and update of out-of-plane shear

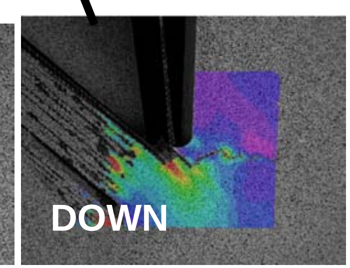
Layup (#plies / % zero degree)	MEAN Max Force [kN]
40/50%	5.473
40/30%	5.708
40/10%	4.101
20/50%	1.795
20/30%	1.531
20/10%	1.259









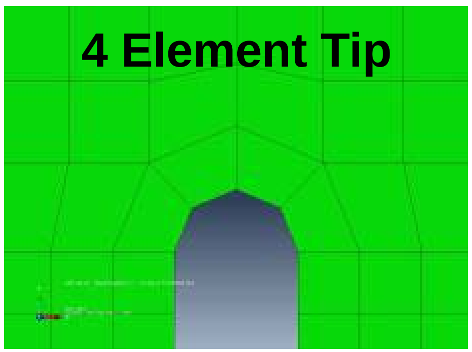


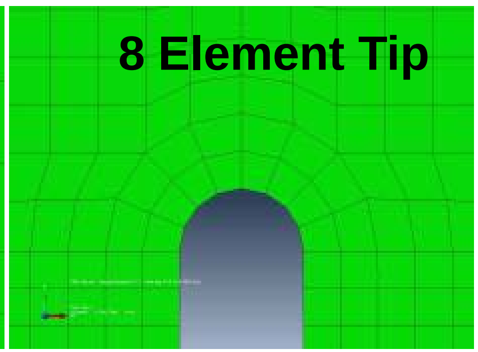
Review and update of out-of-plane shear

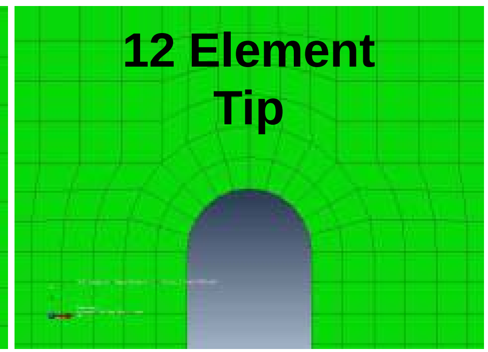
- FEA modeling
  - Use progressive damage to reduce material stiffness and strength as fracture occurs.
  - Stiffness and strength reductions cause strain softening and mesh dependence (results depend on mesh density and do not converge to a unique solution)
  - Mesh selection method used is to choose the coarsest mesh giving a converged elastic solution
    - Successfully used out-of-plane bending study
    - Does not depend on experimental data (is not a curve fit)

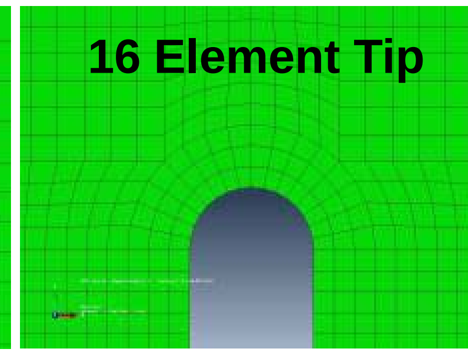
Review and update of out-of-plane shear

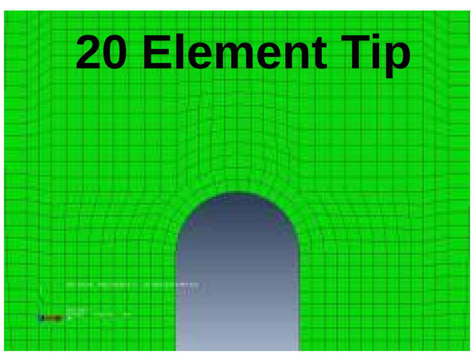
- Seven notch-tip meshes were analyzed
- 20 element tip was selected based on elastic convergence (not experimental data)

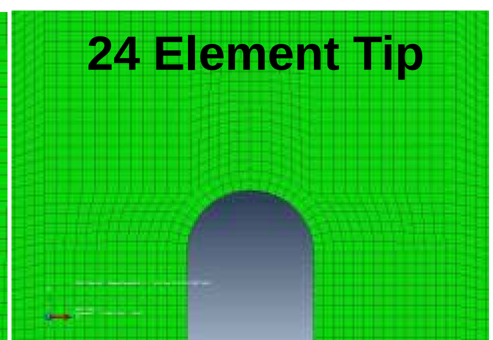


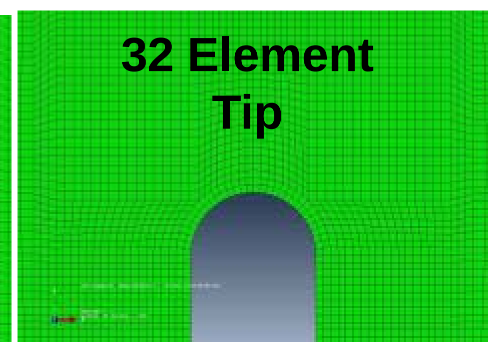












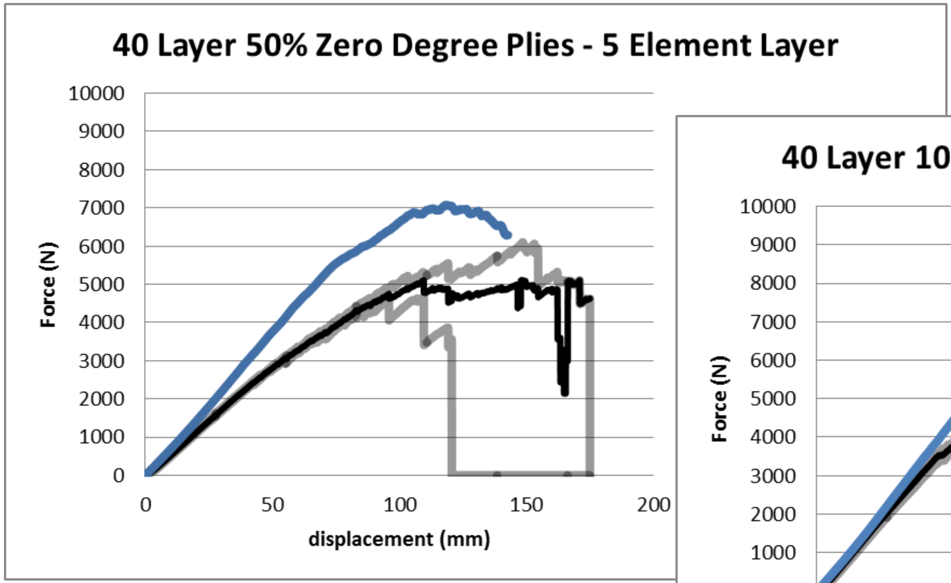
Review and update of out-of-plane shear

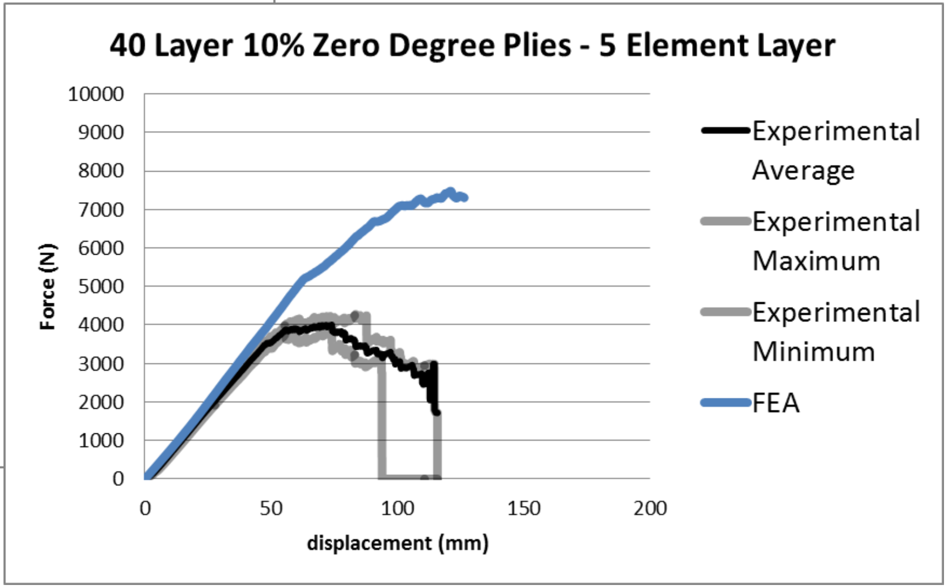
- Using this mesh, six approaches are being pursued
  - Abaqus w/ Hashin progressive damage model
    - 1 element layer, no ply-to-ply delamination (no VCCT*)
    - 5 element layers, no ply-to-ply delamination (no VCCT*)
    - 5 element layers, ply-to-ply delamination (VCCT*)
  - Abaqus w/ Helius:MCT plug-in
    - 1 element layer, no ply-to-ply delamination (no CZ**)
    - 5 element layers, no ply-to-ply delamination (no CZ**)
    - 5 element layers, ply-to-ply delamination (CZ**)

*** VCCT: Virtual Crack Closure Technique** **** CZ: Cohesive Zone**

Review and update of out-of-plane shear

- Results for Abaqus w/ Hashin & w/o delamination capability have been completed and, in general, model predictions are too high.





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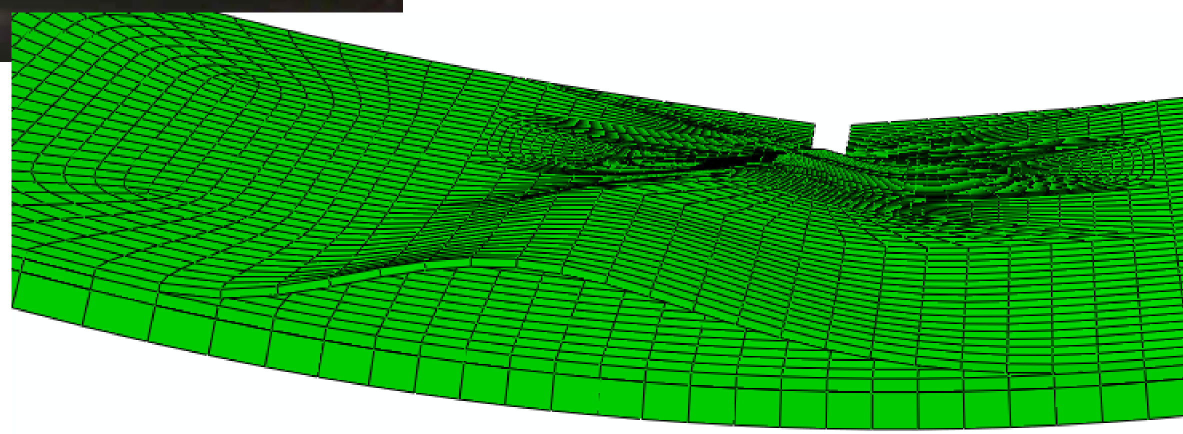
Review and update of out-of-plane shear

- Ply-to-ply delamination was found to be critical in modeling out-of-plane bending, however it causes a considerable increase in run times (e.g. hours to days)



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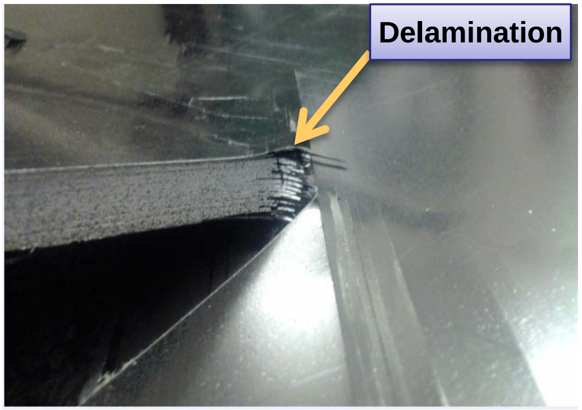
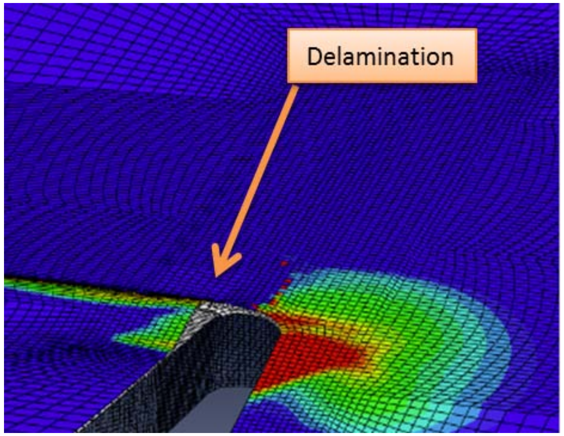
Review and update of out-of-plane shear

- Current efforts are focused on adding ply-to-ply delamination to models
  - Location of interfaces appears to be important

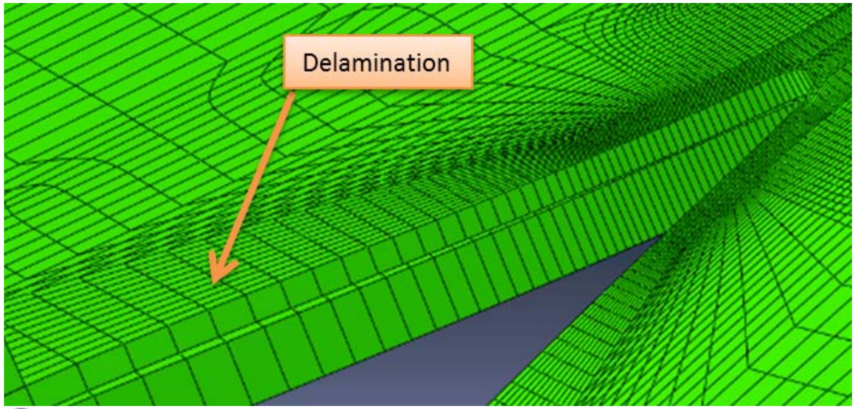
Experiment



Model w/ interface @ top 90-degree ply



Model w/ interface @ second 90-degree ply



  - Out-of-plane bending models appear to be more tolerant of "misplaced" interfaces

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Looking Forward

- Benefit to Aviation
  - Provide experimentally-validated FEA analysis methods for composite materials
  - Explore new analysis techniques
  - Identify, via experiment and analysis, failure modes of composites under relevant loading conditions
  - Educate graduate students in relevant topics
- Future needs
  - Continue to refine and define appropriate design and analysis tools for aircraft design and analysis of composite materials
  - Experimentally validate conclusions

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End of Presentation.

Thank you.

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