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

2012 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) & Brian Bay, faculty
  - Thomas Wright & Tyler Froemming, 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)

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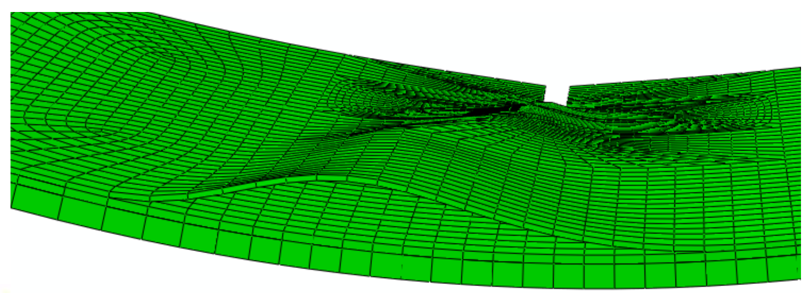
Project Overview

- 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



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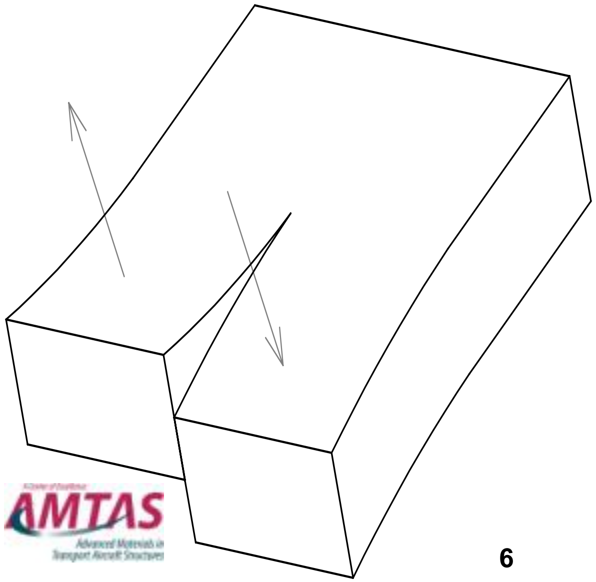
Project Overview

- Phase IV (2010-11)
  - 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 for future work
  - Feasibility of ABAQUS XFEM for future work
  - Sensitivity study of Hashin damage parameters using Boeing mat’l property values

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



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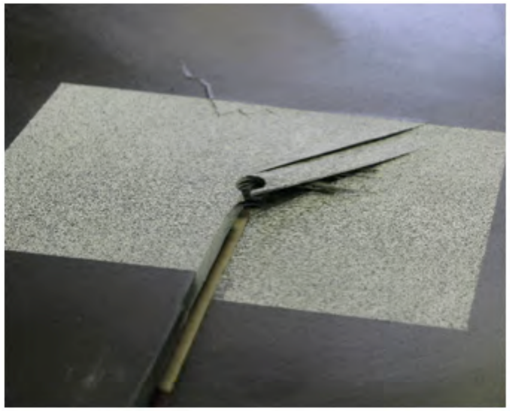
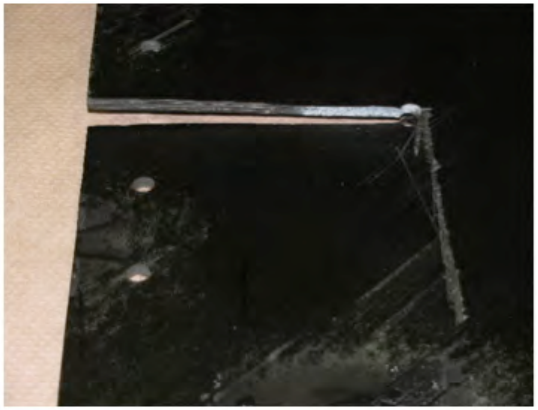
AMTAS Advanced Materials in Transport Aircraft Structures

Today’s Topics

- Today’s Topics
  - Out-of-plane shear
    - Background
    - New Results
  - Update on Helius MCT
  - Update on applicability of ABAQUS Explicit
    - Background
    - Conclusions

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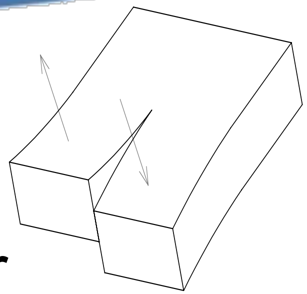
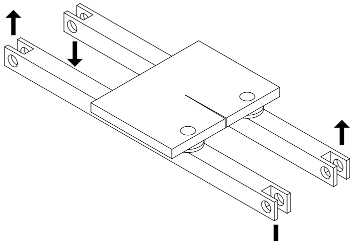
Out-of-Plane Shear: Background



- Goals
  - Create an experimental set-up to load notched laminate plates to failure via out-of-plane shear
  - Measure load-displacement and surface strains
  - Model in ABAQUS



- Literature Review (selected)
  - Jones & Subramonian [1983] (plexiglass, Al, wood)

  - Sutton et al [2007] , Yan et al [2007] (Al, steel)
  - Sutton et al [2001] (Al)

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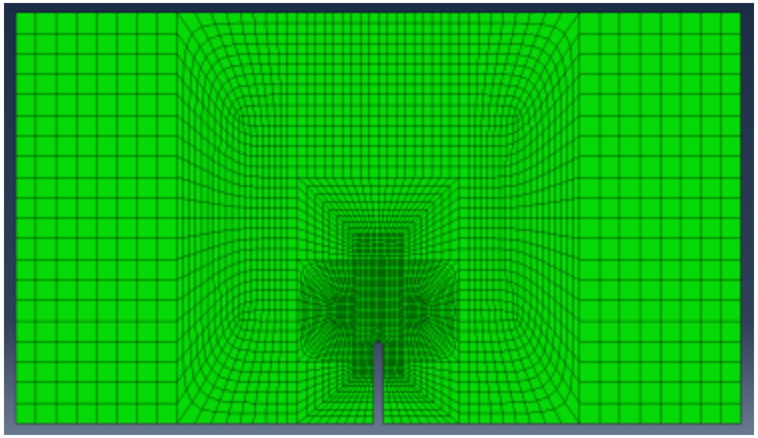
Out-of-Plane Shear: Background

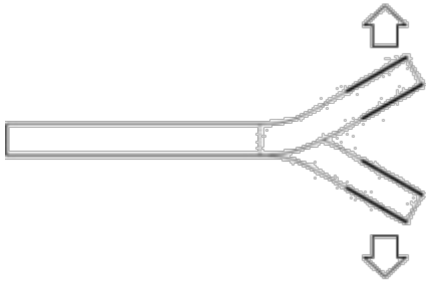
- Approach
  - Use specimens of size comparable to out-of-plane bending study (18” x 10” w/ 2” notch)

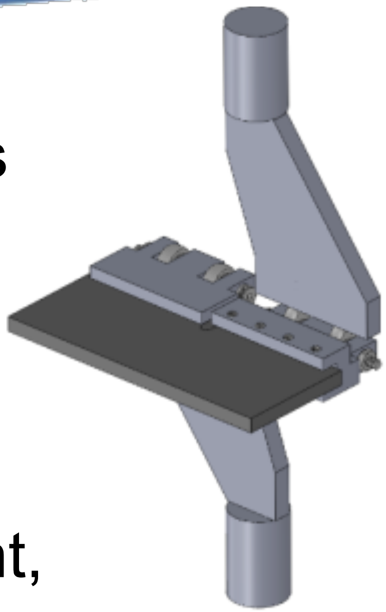


  - Measure surface strains using Digital Image Correlation (DIC)
  - Measure load vs displacement, identify maximum load

Out-of-Plane Shear: Background

- Experimental Set-up
  - Displace specimen edge using hinged grips

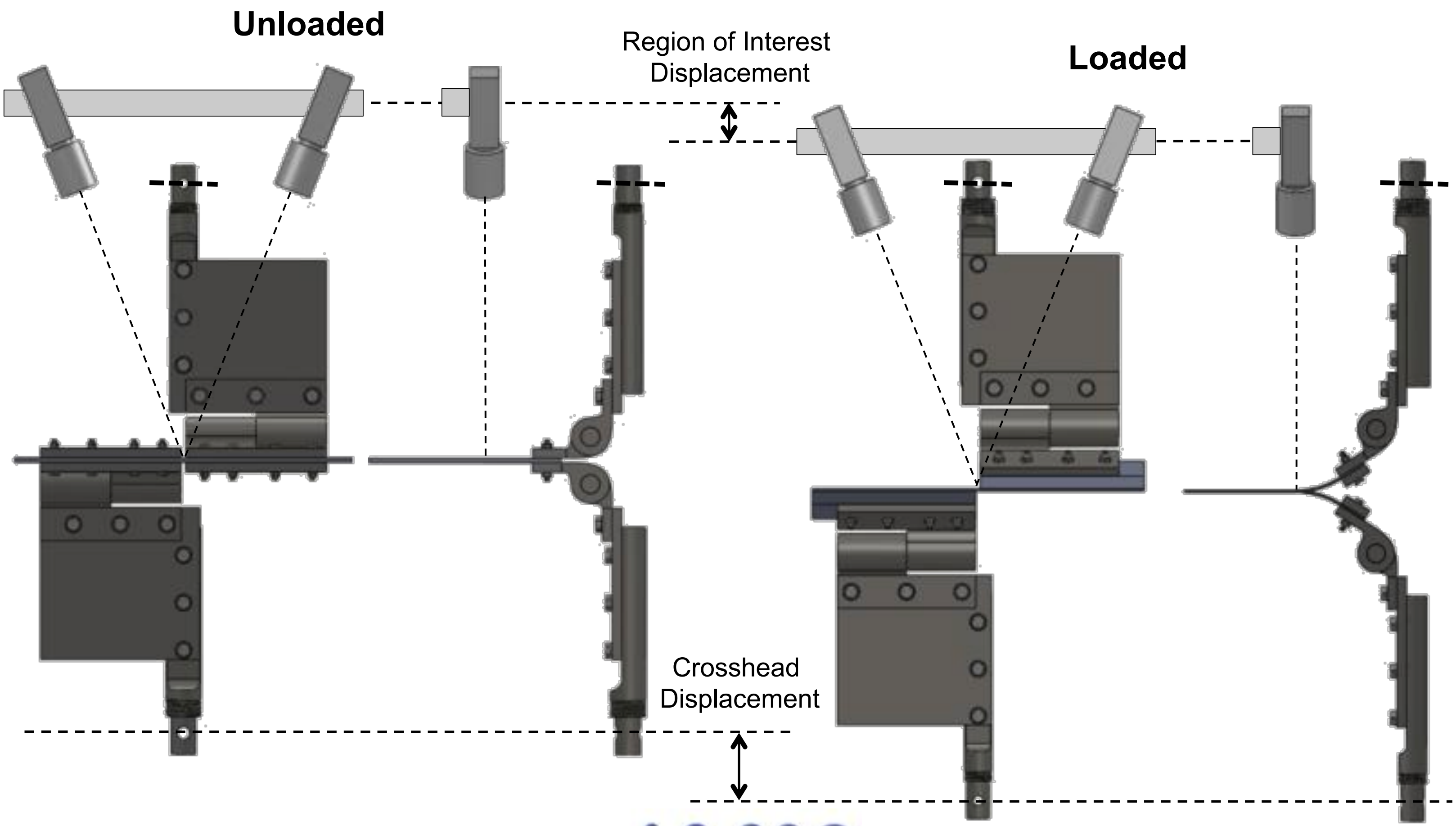




  - Continuously Measure load vs displacement, identify maximum load
  - Continuously measure surface strains using Digital Image Correlation (DIC)

Out-of-Plane Shear: Background

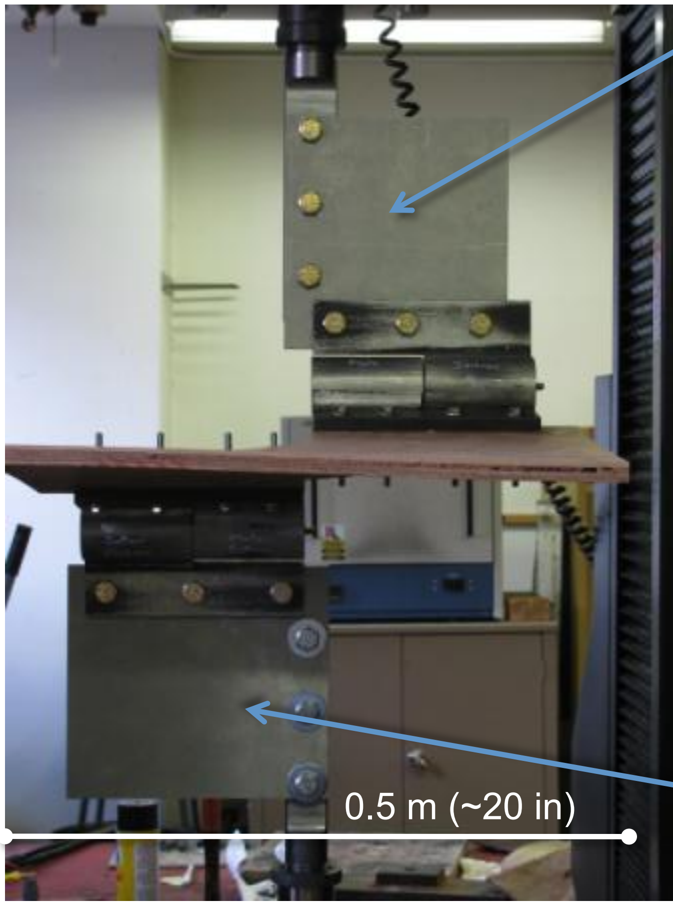
- Cameras maintain constant distance to the sample surface for accurate DIC measurements



Out-of-Plane Shear: Background

- Fracture of plywood test specimens

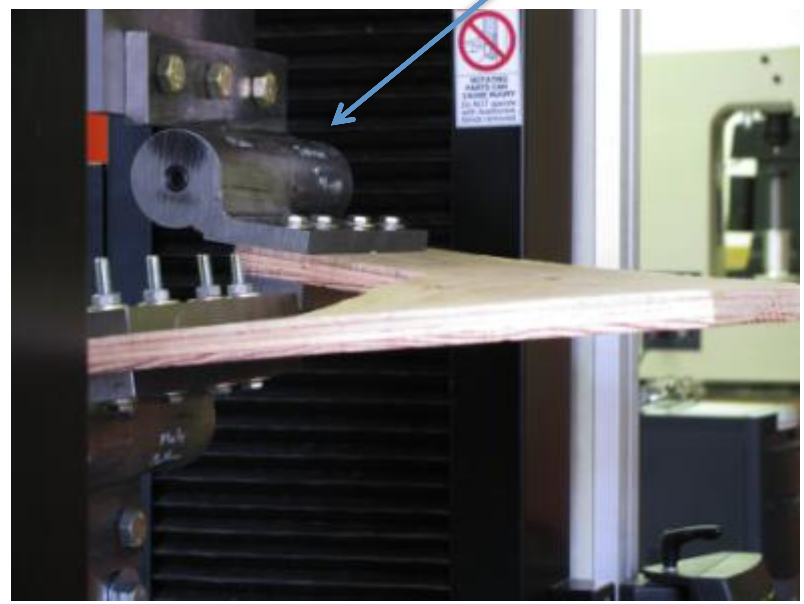
100 kN Capacity Instron Load Frame



Fixed Platen Attached to Load Cell

Moving Platen Attached to Crosshead

High-Load Precision Hinge Interfaces Between Platens and Sample



Out-of-Plane Shear: Background

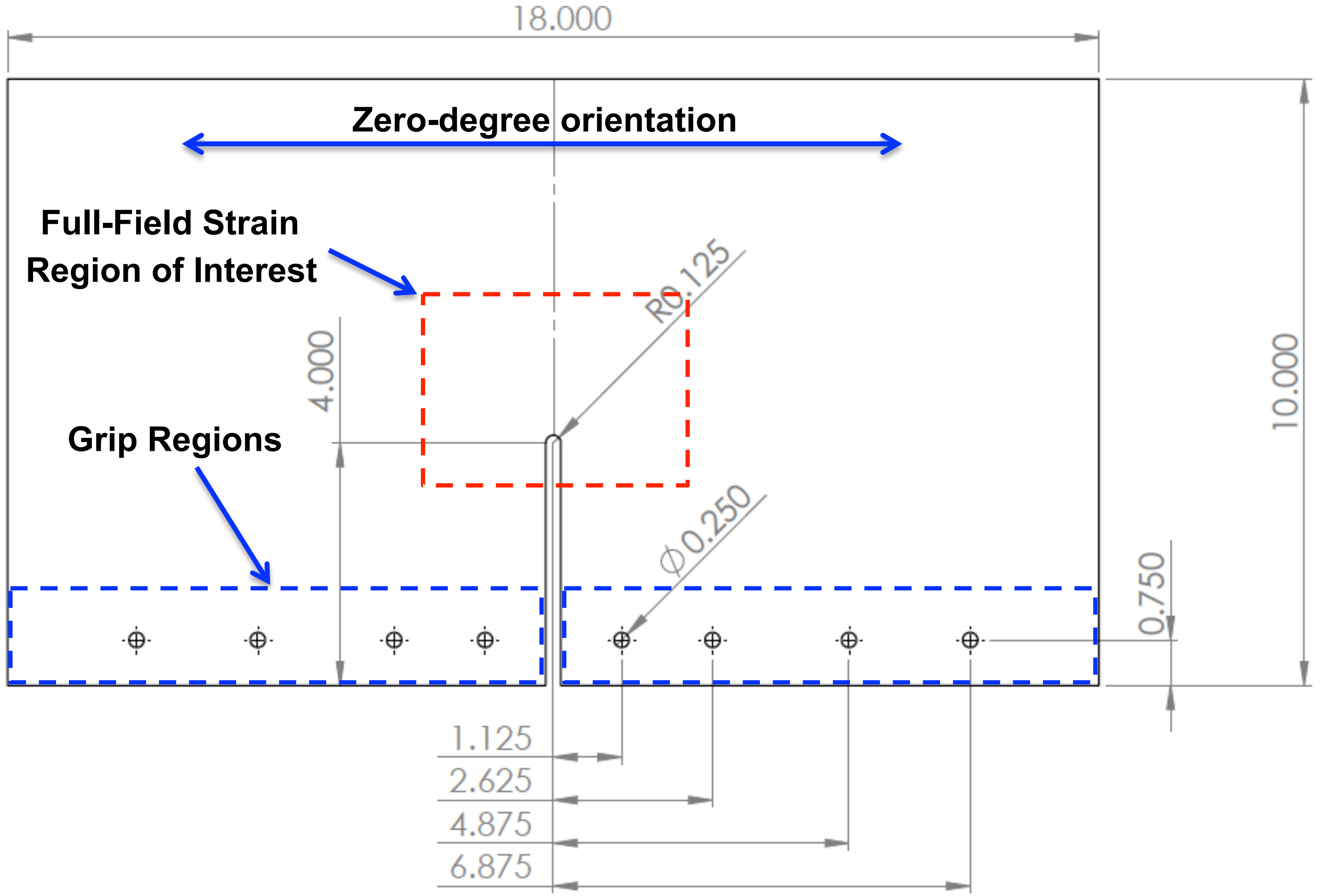
- Digital Image Correlation
  - Quasi-static loading
    - Rate of 25 mm/min crosshead displacement
    - Test stopped at dramatic or persistent load drop
  - Two-camera surface Digital Image Correlation
    - Vic-3D software (Correlated Solutions Inc., Columbia, SC, USA)
    - ~ 70 x 80 mm region of interest surrounding the notch tip
  - Large deflection considerations
    - ROI moves vertically several centimeters during a test
    - Limited depth of field makes ROI focus difficult to maintain
    - Cameras on vertically oriented translational stage
    - Pulley-linked to achieve ½ crosshead motion rate

Out-of-Plane Shear: Background

- Previous results
  - Extensive preliminary testing was conducted with plywood panels and salvaged panels from the out-of-plane bending study (Phase I) to gain experience with experimental set-up. Results of this work were presented at fall 2011 AMTAS meeting
  - Also, additional preliminary testing was conducted in late 2011 and early 2012 to train a new graduate student on the experimental techniques
  - All preliminary testing and training has been completed and testing of the out-of-plane shear specimens is underway

Out-of-Plane Shear: Background

- Test Sample Geometry



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Out-of-Plane Shear: New Results

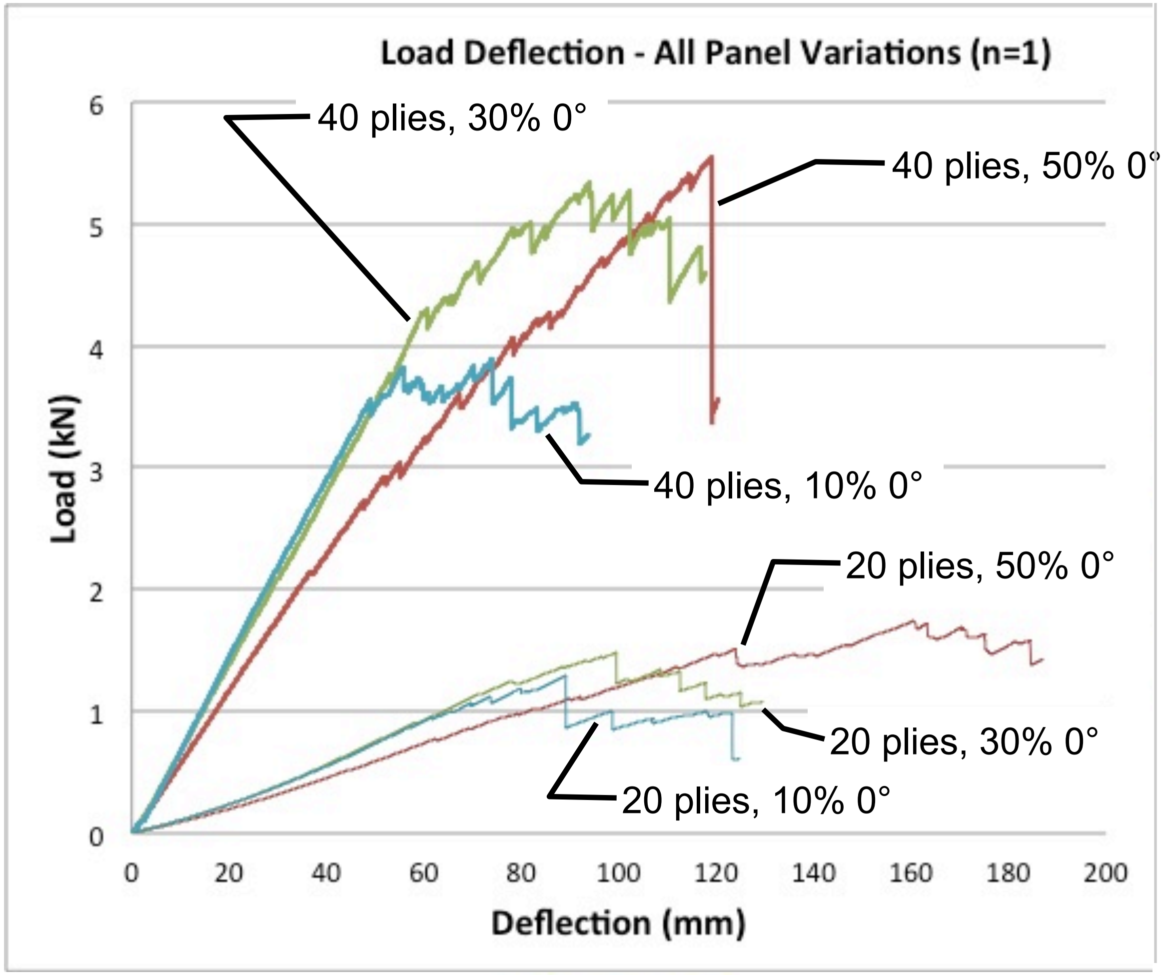
- Testing Matrix

Layup	# of Plies	% 0 deg	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
1	40	50	up , n1	dn , n1	up , n2	dn , n2	up , n3	dn , n3
2	40	30	up , n1	dn , n1	up , n2	dn , n2	up , n3	dn , n3
3	40	10	up , n1	dn , n1	up , n2	dn , n2	up , n3	dn , n3
4	20	50	up , n1	dn , n1	up , n2	dn , n2	up , n3	dn , n3
5	20	30	up , n1	dn , n1	up , n2	dn , n2	up , n3	dn , n3
6	20	10	up , n1	dn , n1	up , n2	dn , n2	up , n3	dn , n3

- Six panel variations organized into six test groups (N = 36 total).
- Up and Dn (down) reflect panel orientation within text fixture (asymmetric).
- n1, n2, n3 indicate repeated tests of the same panel variation and orientation.
- Series 1 complete at time of presentation submission (26 Mar 2012).

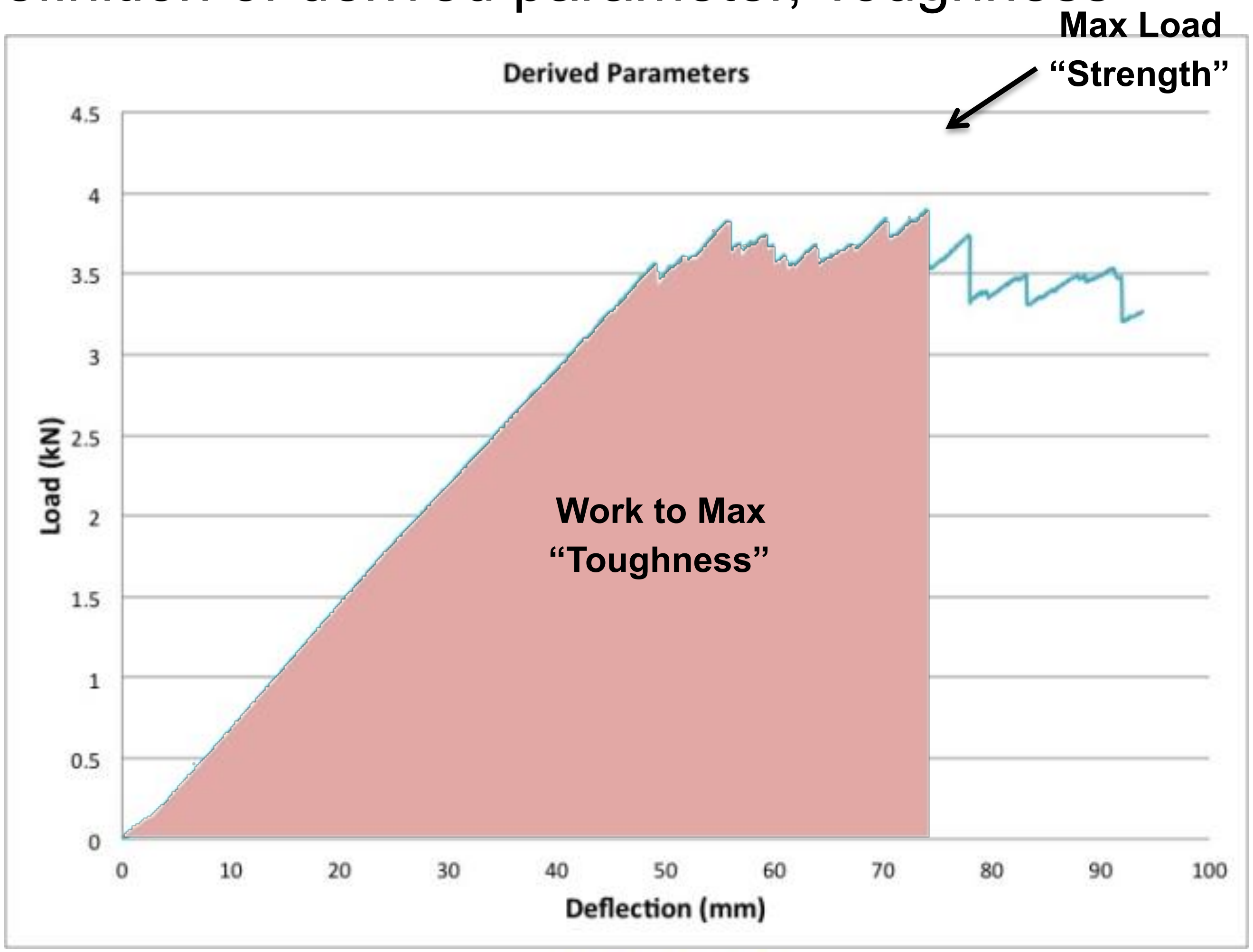
Out-of-Plane Shear: New Results

- Initial Results



Out-of-Plane Shear: New Results

- Definition of derived parameter, Toughness



Out-of-Plane Shear: New Results

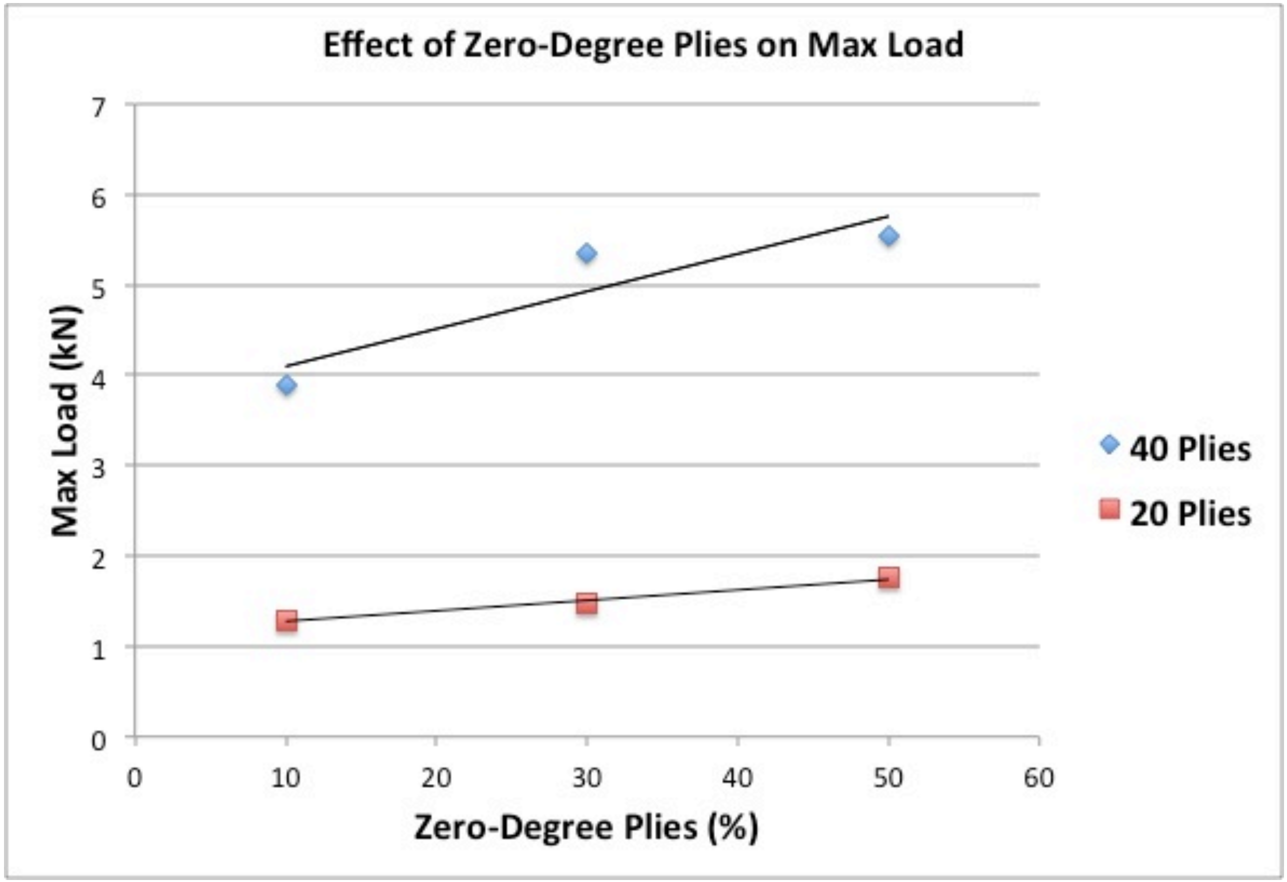
- Max load and Toughness

Layup	# of Plies	% 0 deg	Max Load (kN)	Work to Max (J)
1	40	50	5.55	362.0
2	40	30	5.34	287.8
3	40	10	3.89	177.9
4	20	50	1.75	147.8
5	20	30	1.48	73.8
6	20	10	1.29	56.7

- Max Load is highest force level recorded during test.
- Work to Max is the integrated load-deflection trace up to the max load point.
- No variability available yet, just one sample of three repeats tested to submission date.

Out-of-Plane Shear: New Results

- Correlation between zero-degree plies and strength



- For both panel types additional zero-degree plies increase the maximum load achieved.
  (The curves overlap with 20-ply max load values multiplied by ~ 3)

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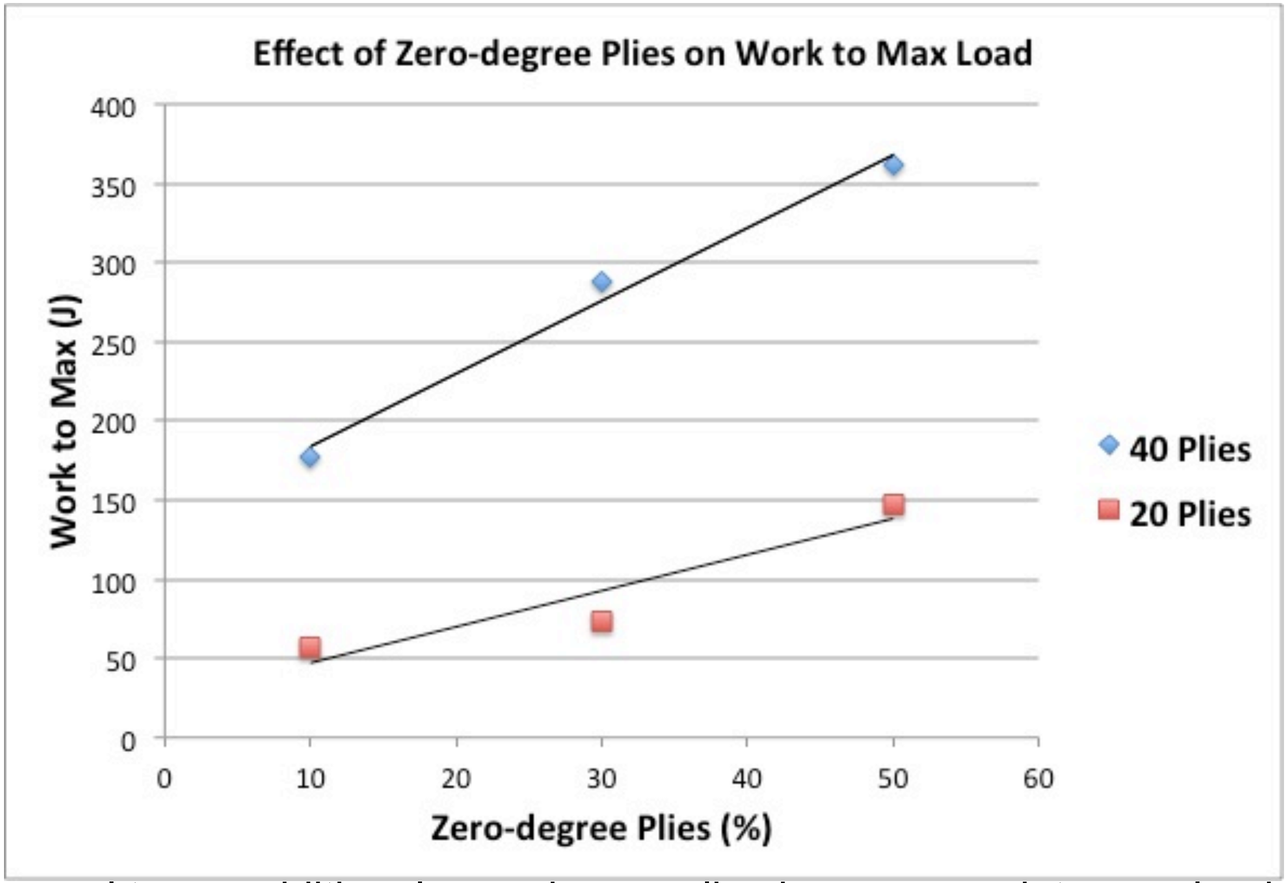
Out-of-Plane Shear: New Results

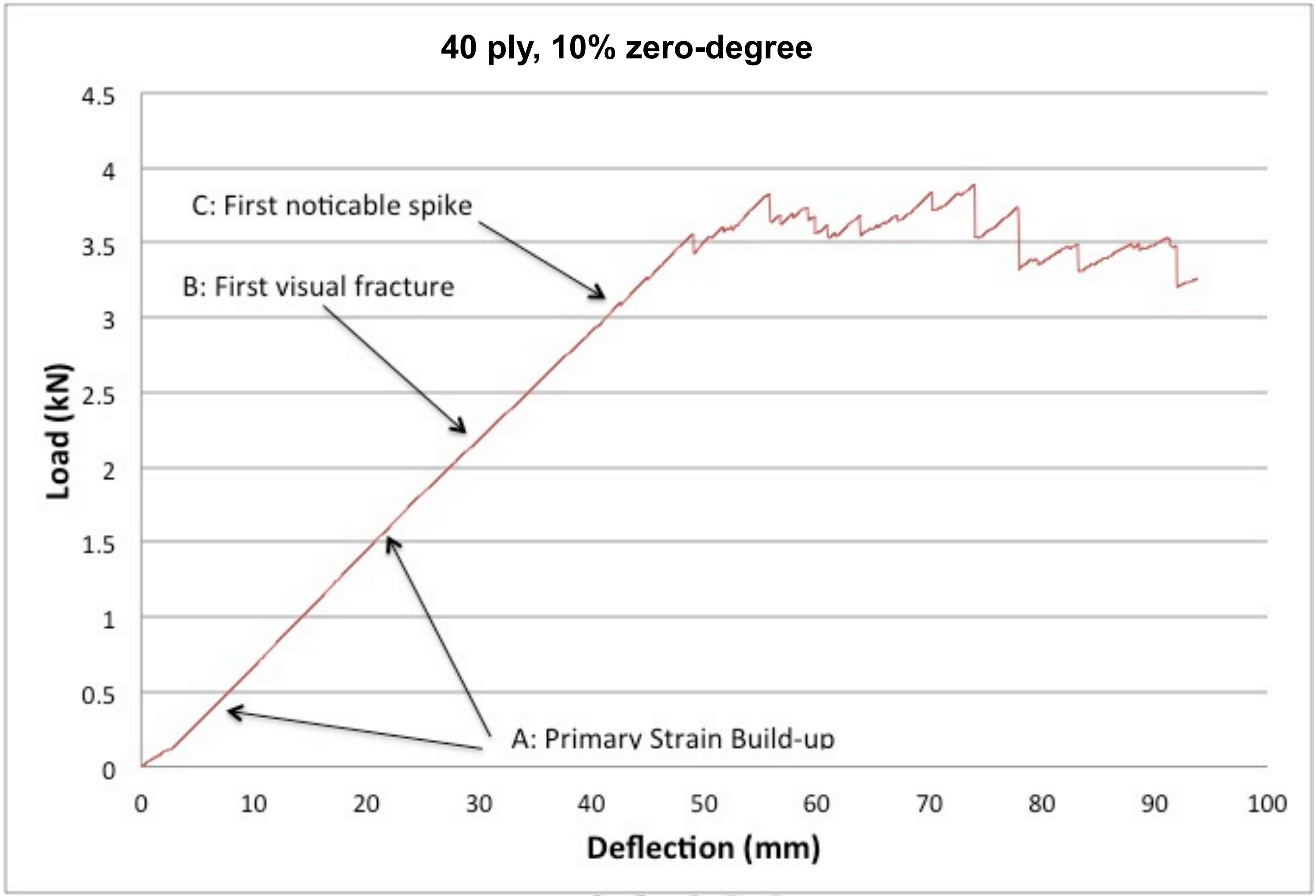
- Correlation between no. zero-degree plies and toughness



- For both panel types additional zero-degree plies increase work to max load.
 (The curves overlap with 20-ply work to max values multiplied by ~ 3)

Out-of-Plane Shear: New Results

- Load deflection curve and observed phenomena



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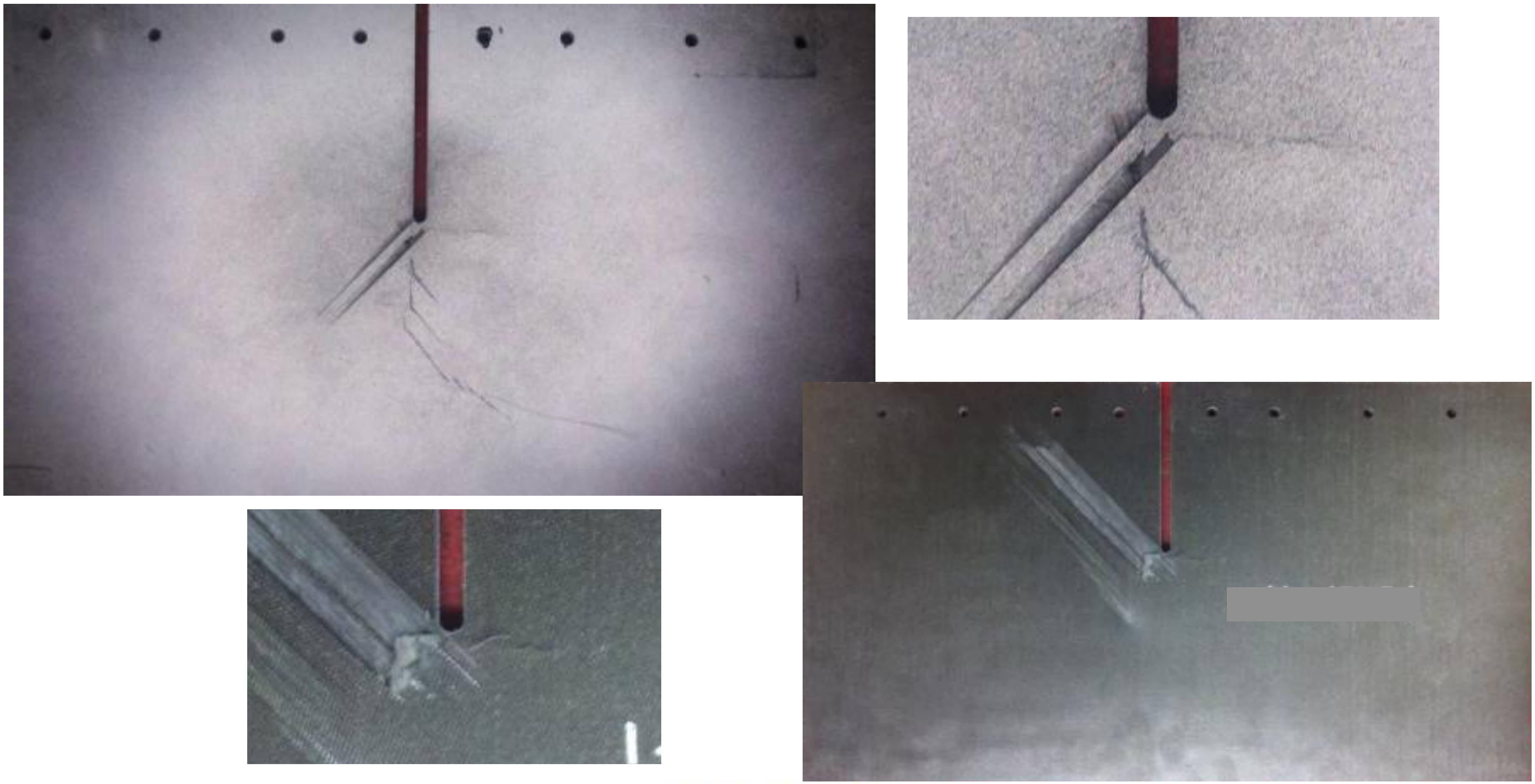
Out-of-Plane Shear: New Results

- Visual Inspection

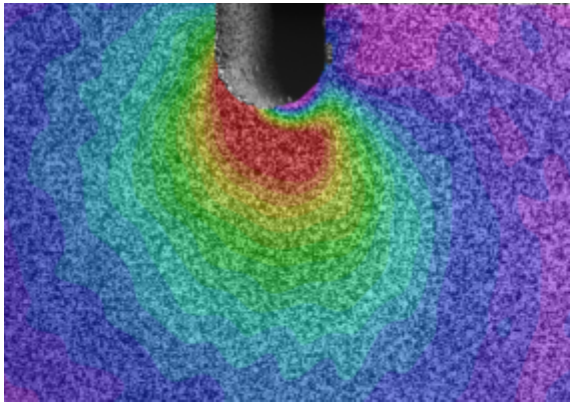


Out-of-Plane Shear: New Results

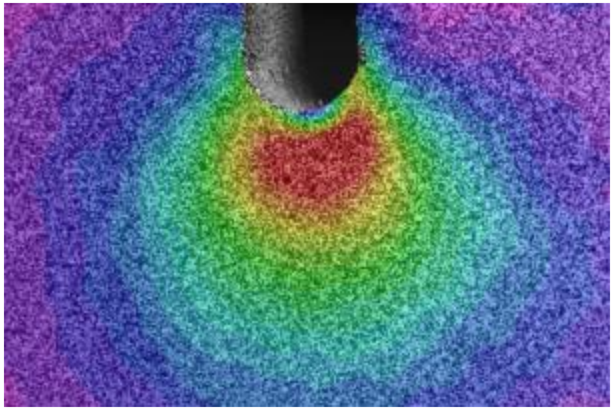
- A: Primary strain build up: 8mm – 25mm

Principle | **Von Mises**

8 mm Disp.

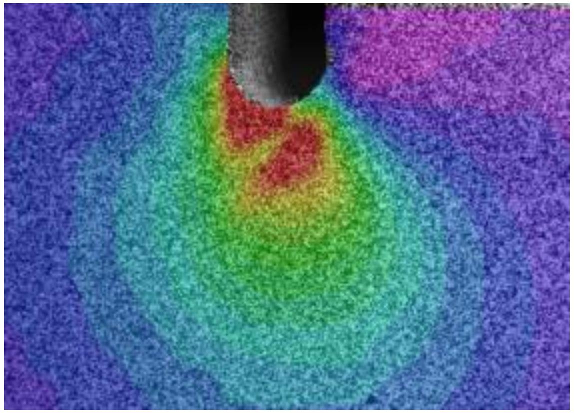


Range: .0007 - .0038

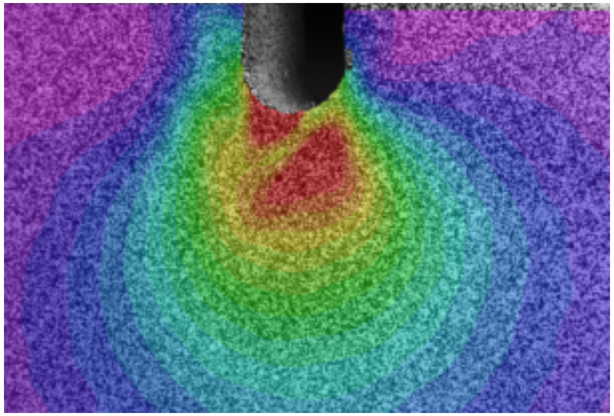


Range: .0007 - .0028

25 mm Disp.



Range: .0016 - .0206



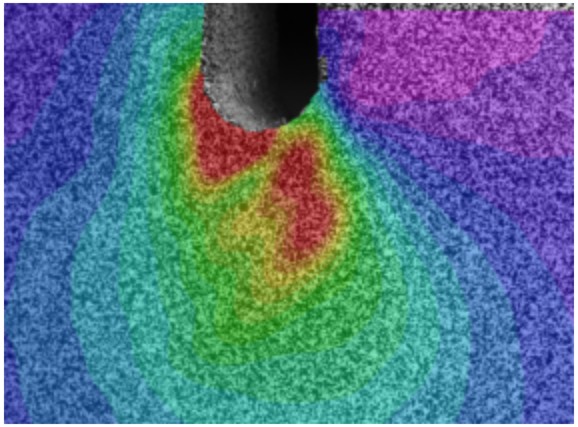
Range: .0024 - .0115

Out-of-Plane Shear: New Results

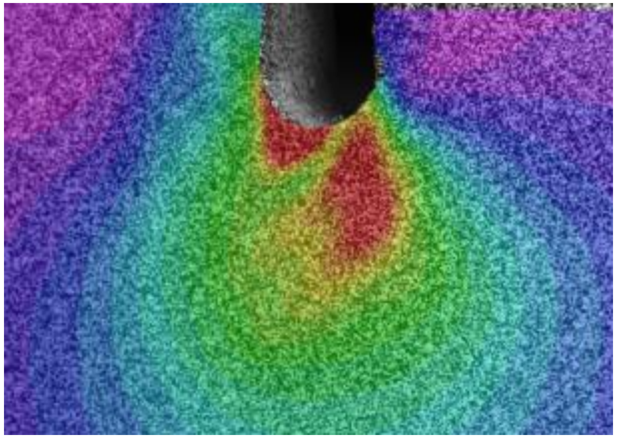
- B: First visual fracture: 30mm – 31mm

Principle Strain | **Von Mises**

30 mm Disp.

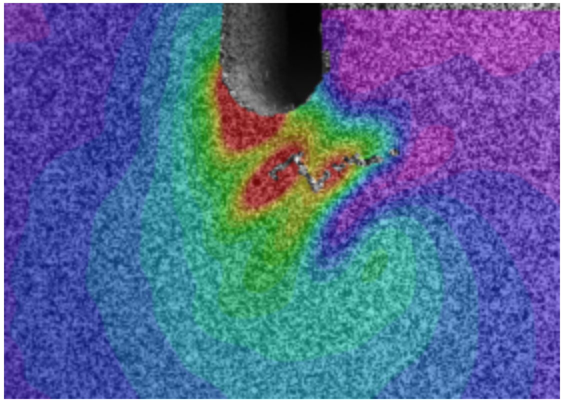


Range: .0016 - .0206

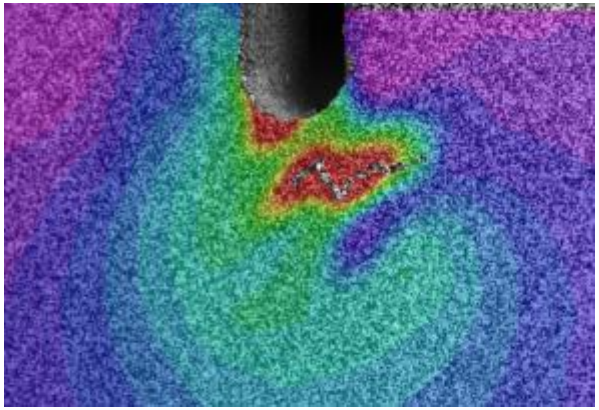


Range: .0024 - .0140

31 mm Disp.



Range: .0017 - .0240



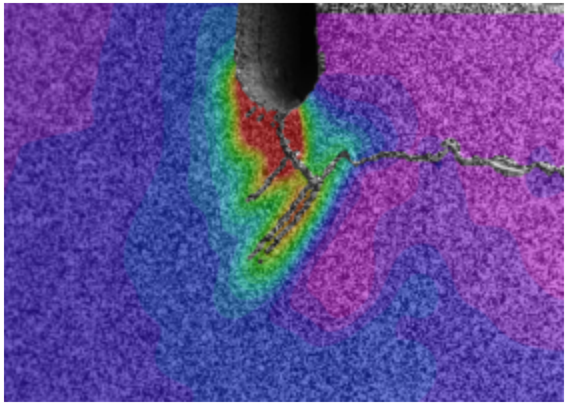
Range: .0024 - .0180

Out-of-Plane Shear: New Results

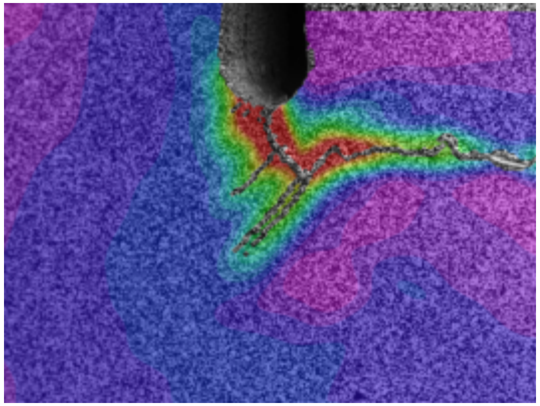
- C: First Noticeable Spike: 42mm – 43mm

Principle Strain | **Von Mises**

42 mm Disp.

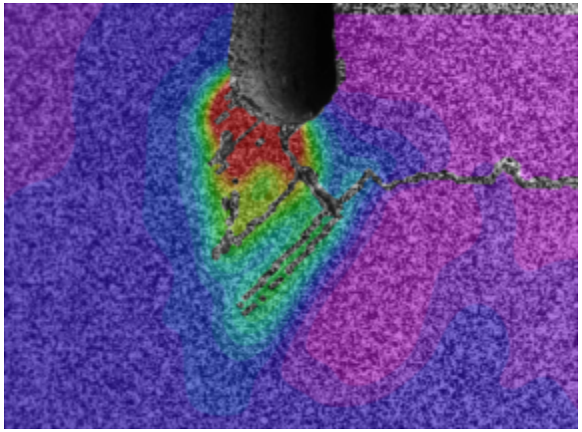


Range: .0005 - .0505

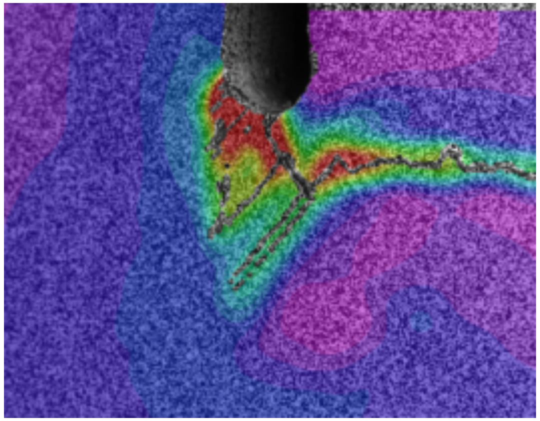


Range: .0014 - .0386

43 mm Disp.



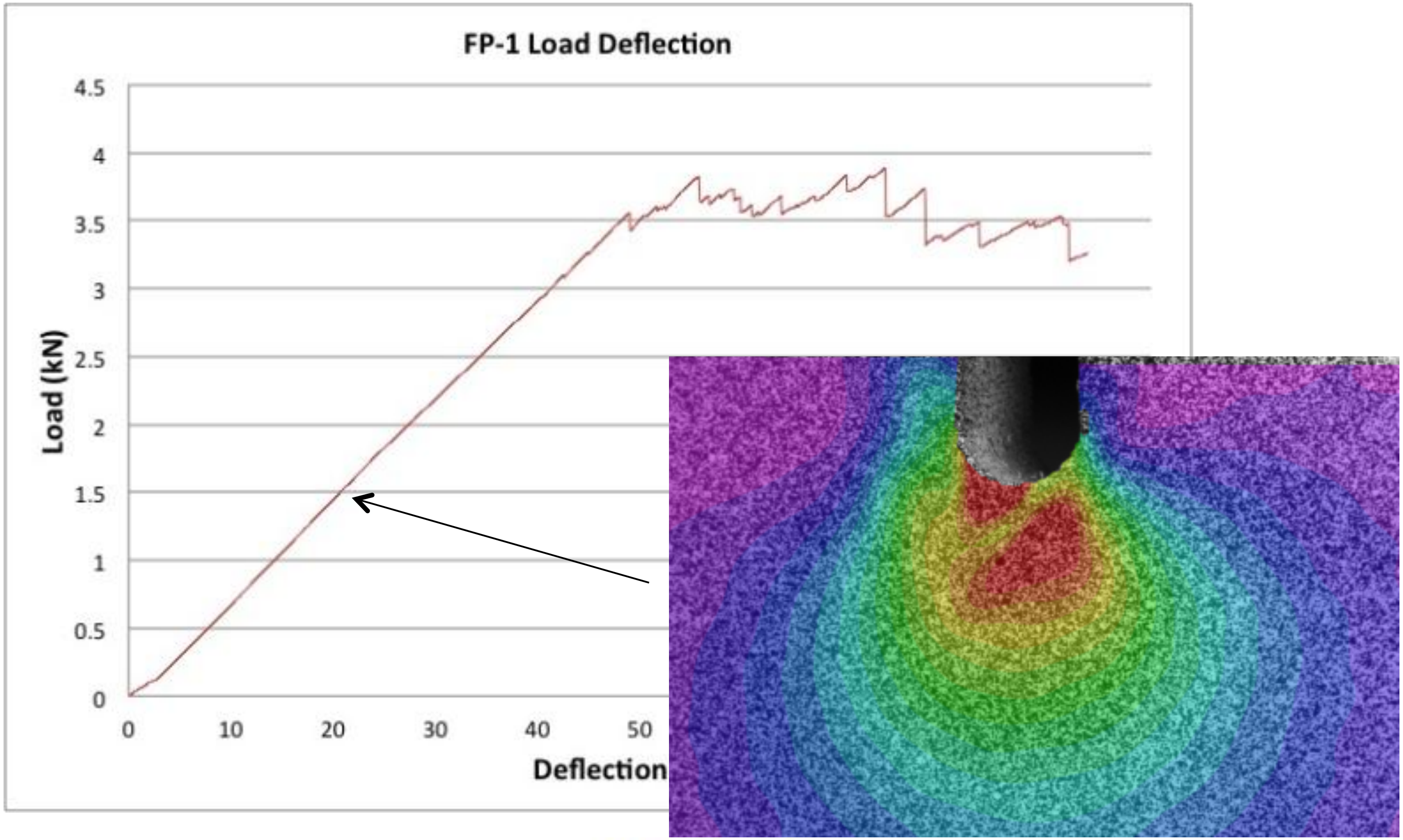
Range: .0005 - .0670



Range: .0010 - .0402

Out-of-Plane Shear: New Results

- Possible very early sub-surface fracture in linear region



Out-of-Plane Shear: New Results

- Observations: Initial 40-ply, 10%-0° panel
  - Localized strain builds at notch-tip as expected for a geometric stress concentration
  - Evidence of a fracture appears in the full-field measurement very early in the load sequence
    - Before any indication on the load-deflection curve
    - Before any fracture is visible at the surface
  - The first visible surface fracture appears before any obvious load-deflection drop

Out-of-Plane Shear: New Results

- Thoughts for further work on out-of-plane shear…
  - ABAQUS modeling to attempt to match load-displacement and strain field from experiments (this phase and beyond?)
  - Use X-ray tomography to map damage region and compare with ABAQUS predictions (future phase?)
    - Damage initiation
    - Damage propagation
  - Fatigue implications of damage in linear region (future phase?)

Update on Helius MCT

- Helius is ABAQUS plug-in from Firehole Comp.
- Marketed as superior to ABAQUS built-in capabilities for progressive damage in composites
- Evaluation plan
  - Use Helius and repeat out-of-plane bending analysis from earlier phases. Compare to ABAQUS built-in.
  - May use for out-of-plane shear & all-90° / all-0° studies
- Status
  - Some delays at OSU getting set-up , fully functional now
  - Emmitt Nelson (Principal Engineer & Chief Technology Officer @ Firehole) visited OSU on 3/12/12 for consult

Update on ABAQUS Explicit: Background

- Exploration of the feasibility of ABAQUS Explicit as an alternative to ABAQUS Standard (i.e. Implicit) was a task in Phase IV (2010-11)
- Hope was Explicit would be faster
- Results were presented at AMTAS Fall meeting
- Questions and comments following the presentation raised some compelling points, so follow-up work was conducted in late 2011 and early 2012
- Today's presentation will include a brief recap of the task and the results of the additional work

Follow-up on ABAQUS Explicit: Background

- Explicit Methods
  - Explicit methods include dynamic effects
  - If the total time-of-the-simulated-event is sufficiently long (deformation and motion sufficiently slow), kinetic energy is small and quasi-static events can be modeled
  - Advantage of explicit method is that it is unconditionally stable, convergence issues of ABAQUS Standard (implicit method) are gone
  - Disadvantage of Explicit is that the required time increment can be very small and run times very long…
  - Explicit = headache, Implicit = upset stomach ???

Follow-up on ABAQUS Explicit: Conclusions

- Conclusions from all work on Explicit vs. Implicit
  - For the material properties of the specimens, if the actual conditions of the physical experiments were modeled using Explicit, run times would be several months (implicit is 1-3 days)
  - Methods Considered to shorten Explicit run times
    - Shorten model time so it is << actual physical experiment time
      - Can be acceptable if quasi-static conditions are maintained
      - Quantified by internal vs. kinetic energy
    - Mass scaling: Mass in model >> actual physical mass
      - Since quasi-static, might be okay (intent is no dynamic effects)
      - Very large changes in density are required to achieve the needed run-time reductions, need to be sure this isn't affecting results

Follow-up on ABAQUS Explicit: Conclusions

- Methods to shorten Explicit run times (Con't)
  - Sub-modeling: Run part of model in Explicit, part in Implicit
    - Offers best of both worlds…
    - May be problematic when changes in model material stiffness occur between Explicit and Implicit regions (progressive damage will cause this to happen)
- Methods pursued to shorten Explicit run times
  - Shorten model time: Time reduced to a few seconds (KE limit)
  - Mass scaling: Mass increased 52000%
- Effect: run times **approaching** Implicit with comparable accuracy (one layup examined) but differences between model and experiment are a concern
- Bottom line: Explicit does not appear to be an attractive alternative, but additional research necessary to be sure

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

End of Presentation.

Thank you.

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