Failure of Notched Laminates Under Out-of-Plane Bending, Phase VIII

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Out-of-Plane Shear Mode III Bending

- Principal Investigators & Researchers
  - John Parmigiani (PI); OSU faculty
  - M. Daniels, L. Suryan; 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)
  - Further study of additional delamination interfaces
  - Feasibility of Abaqus/Explicit and XFEM for future work
  - Sensitivity study using Boeing mat'l property values
- Phase V (2011-12)
  - Out-of-plane shear (mode III) experiments
  - Evaluate the Abaqus plug-in Helius for out-of-plane bending
- Phase VI (2012-13)
  - Out-of-plane shear modeling with Abaqus Standard
  - Evaluation of plug-in Helius: MCT for out-of-plane shear
  - Out-of-plane shear modeling with Abaqus Explicit

Project Overview

- Phase VII (2013-14)
  - Evaluation of solid vs. shell elements in modeling
  - Comprehensive report on Phase VI work for Boeing
  - Improvement to Abaqus Explicit models
  - Explore damage softening parameters in Helius: MCT
  - Explore possible inaccuracies in material properties
- Phase VIII (2014-15)
  - Explore significance of damage propagation material properties, i.e. when do energy parameters matter?
  - Begin work on modeling matrix compression damage propagation. Likely topic for future work

Today's

- Review of out-of-plane bending and out-of-plane shear experiments and modeling
- Significance of damage propagation material properties (energies)
- Literature review of modeling matrix compression damage propagation

Today's Topics

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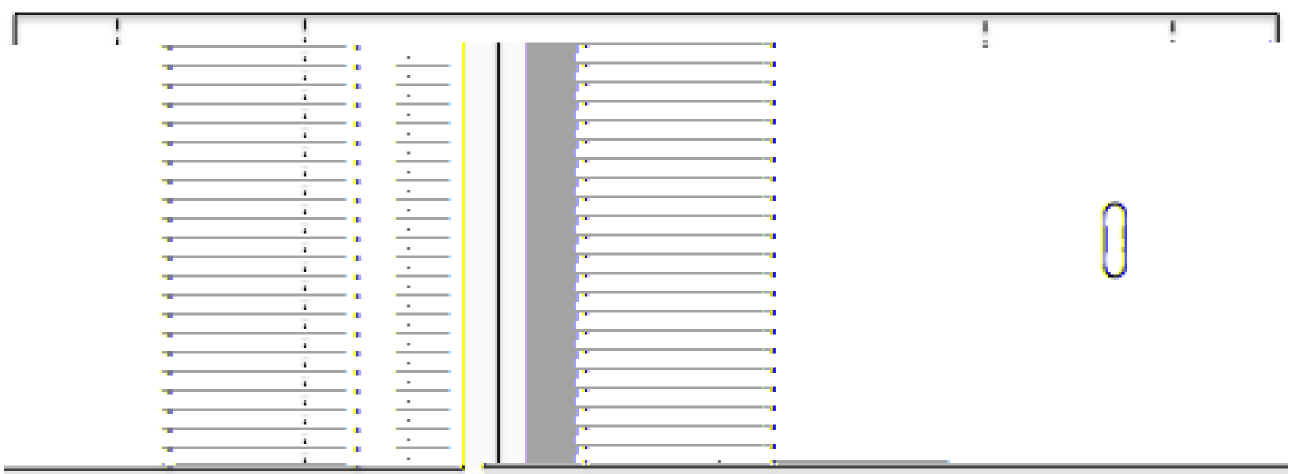
Review: Out-of-Plane Bending

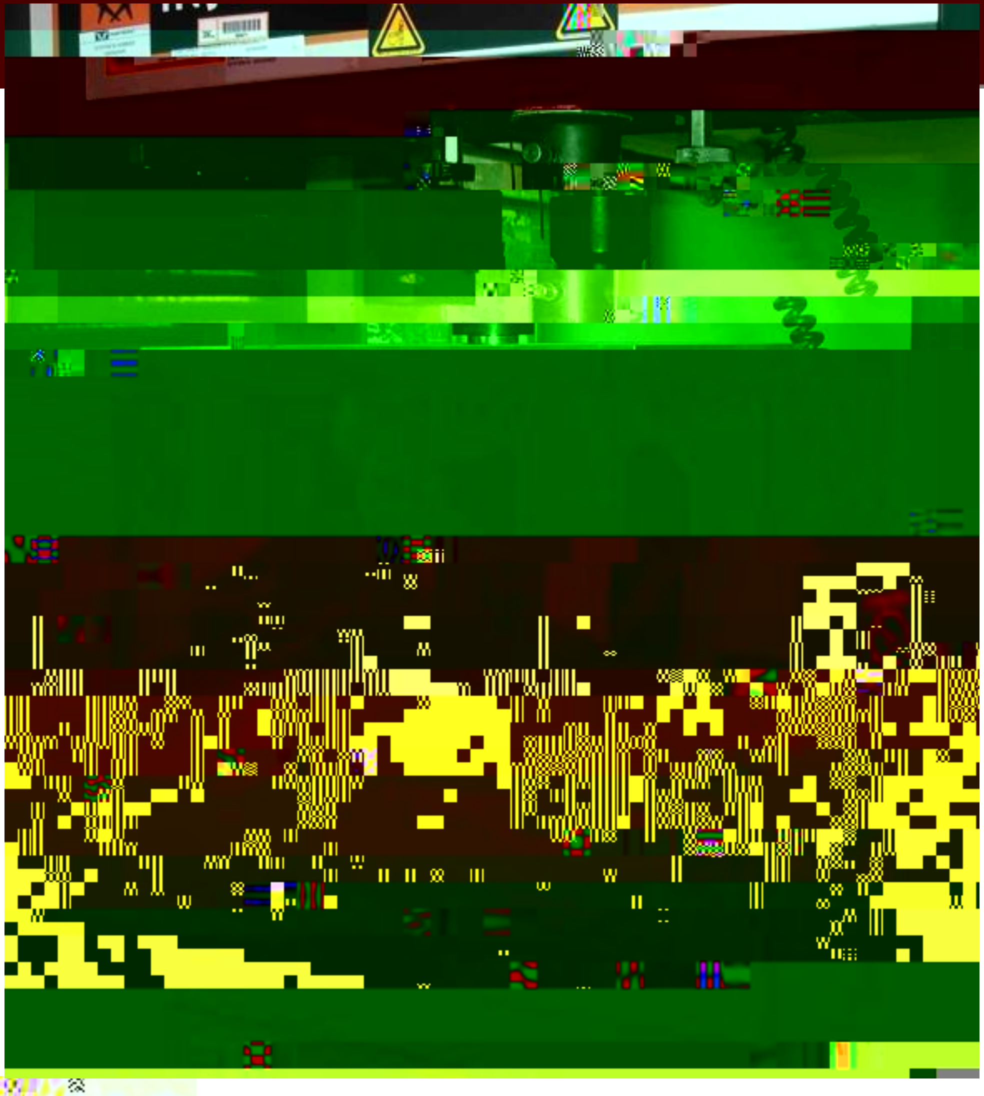
- Due to a need to understand its effects and a lack of useful information in the literature, out-of-plane bending loading was investigated
- Specimens: Center-notched carbon fiber panels having 20 ply and 40 ply layups with 10%, 30%, and 50% zero-degree plies



Dashed lines are load lines for 4-point bending

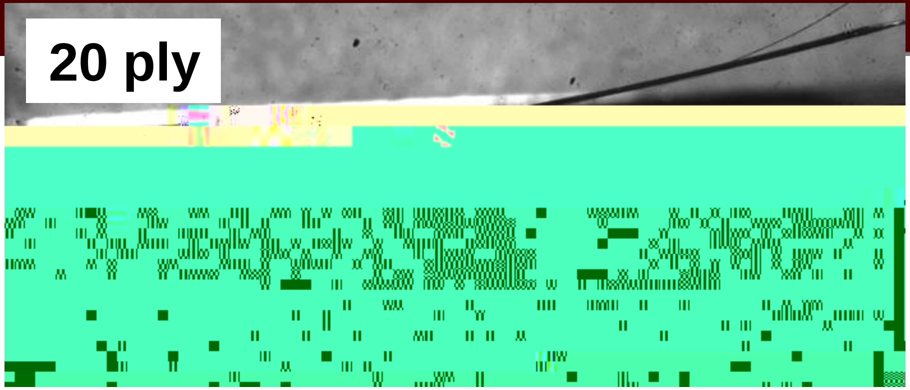
Review: Out-of-Plane Bending

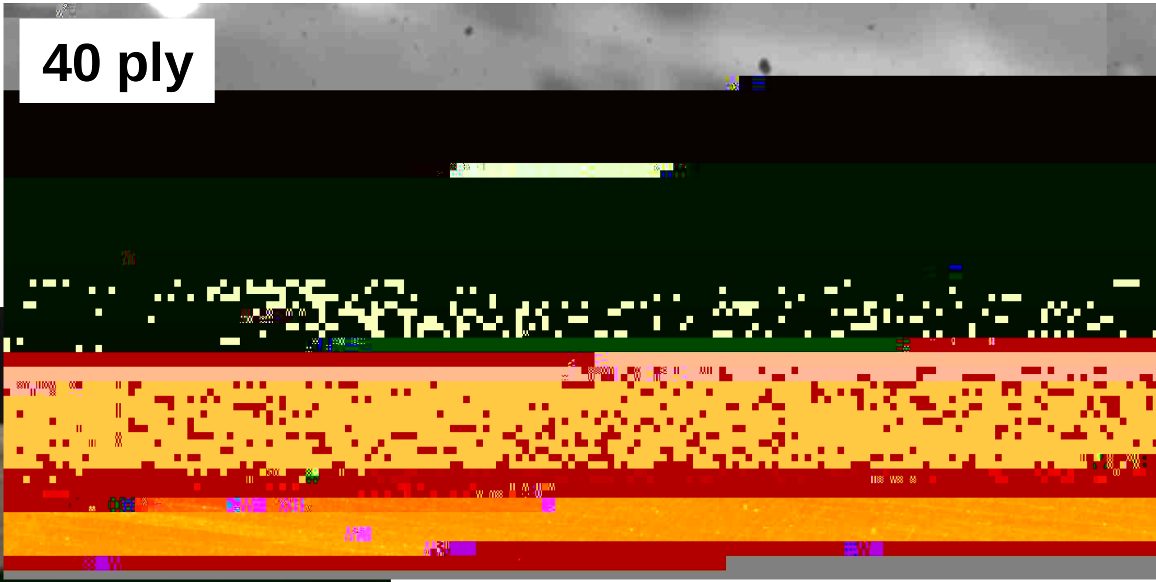
- Panels were fabricated by Boeing and tested at OSU
- Applied load versus crosshead displacement data was collected
- Results showed that
  - Initially load increased with displacement
  - As panels became damaged rate of increase decreased
  - Eventually, accumulated damage caused load to decrease with displacement
- Key parameter was the maximum load the panel was able to support



Review: Out-of-Plane Bending

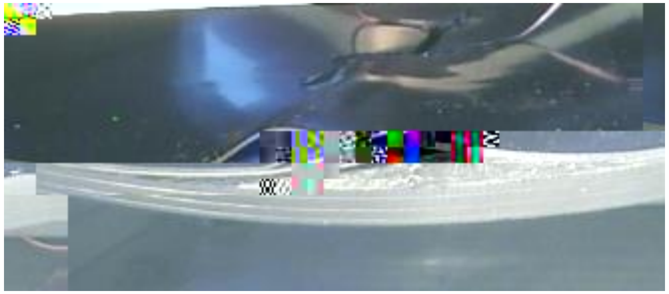
- Observations of tested specimens showed that
  - 20-ply panels failed by local damage
  - 40-ply panels failed by local damage and also by ply delamination
- Finite element models were created to predict damage





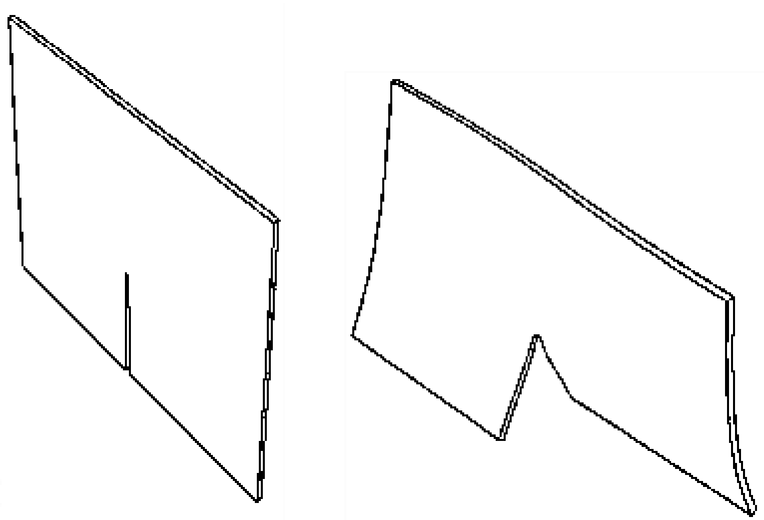
Review: Out-of-Plane Bending

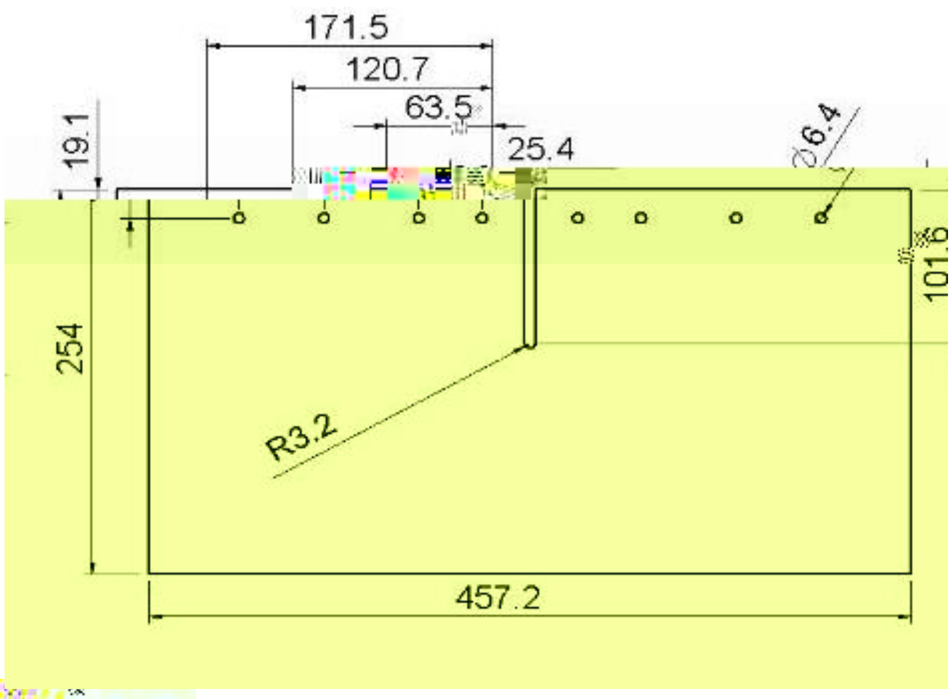
- Finite element models for out-of-plane bending
  - Used Abaqus/Standard with Hashin progressive damage model
  - The need to model multiple plies, to use Hashin in Abaqus, and to include delamination interfaces (VCCT) resulted in the use of continuum shell elements
  - Finite element results were compared to experiments using maximum load
  - Excellent results were obtained with model calculations agreeing with experimental measurements to **within 10% for all layups**



Review: Out-of-Plane Shear

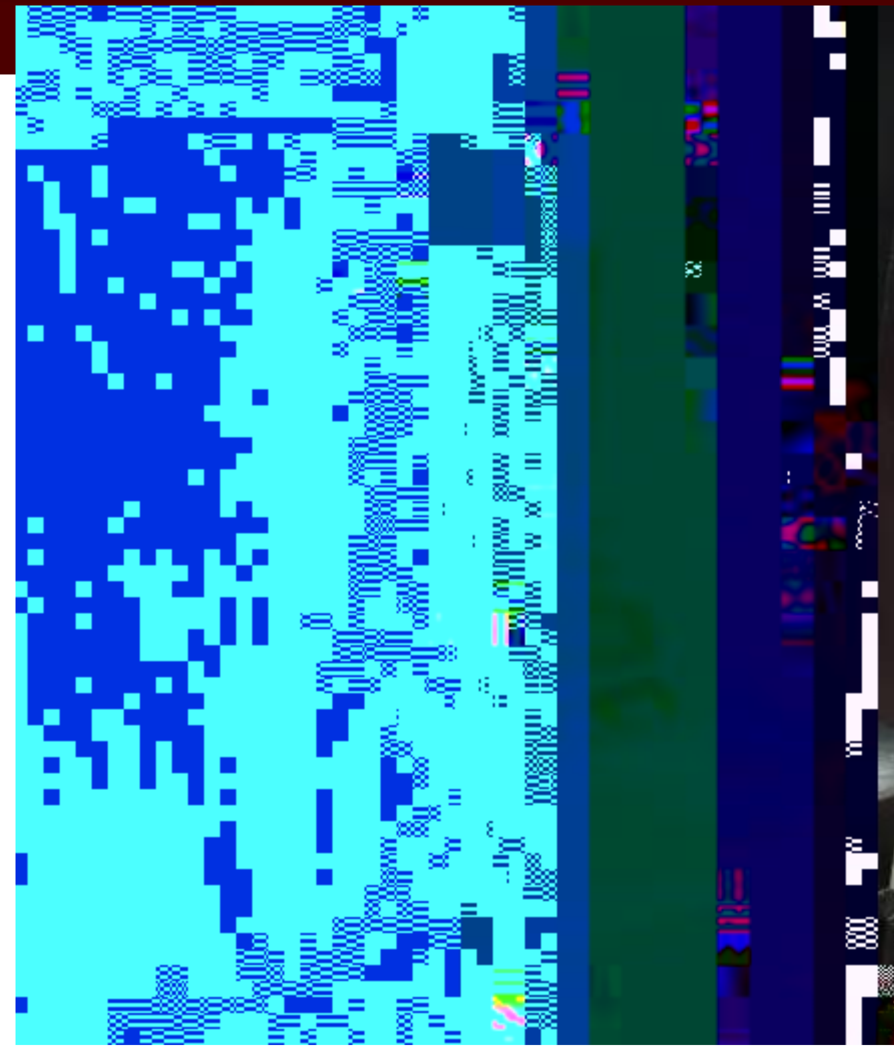
- Based on the success of the out-of-plane bending study, attention was shifted to out-of-plane shear.
- Specimens: Edge-notched carbon fiber panels having 20 ply and 40 ply layups with 10%, 30%, and 50% zero-degree plies





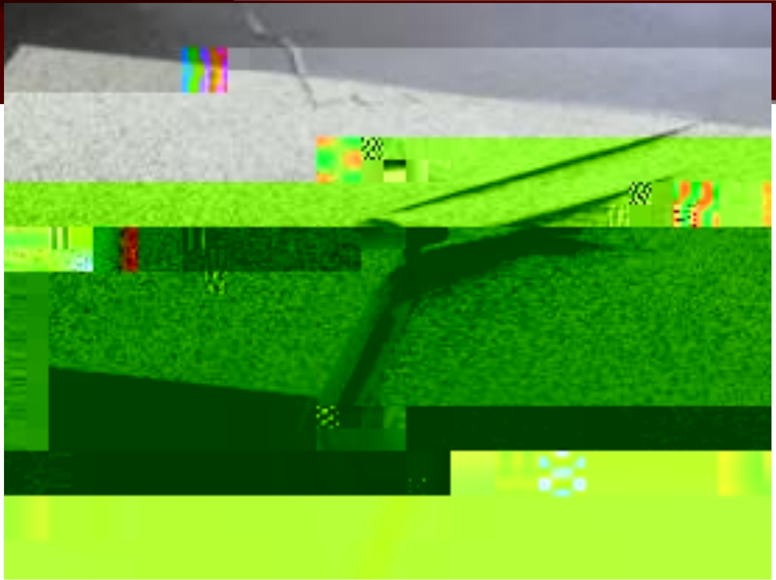
Review: Out-of-Plane Shear

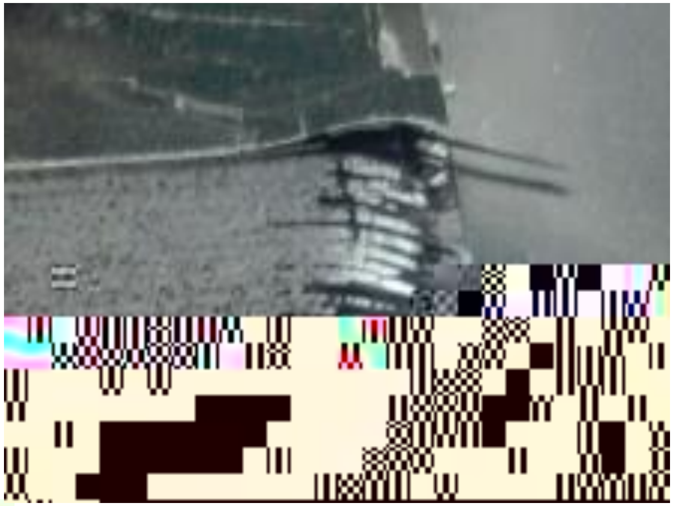
- Panels were fabricated by Boeing and tested at OSU
- Collected data
  - Load vs. Displacement
  - DIC-measured strain fields
- Key parameters
  - Maximum load
  - Notch-tip strain



Review: Out-of-Plane Shear

- Observations of tested specimens showed that damage concentrated at the notch tip
- Finite element models were created to predict damage
  - Match maximum load
  - Match notch-tip strain fields





- Finite element models for out-of-plane shear
  - Used same approach as with out-of-plane bending

Review: Out-of-Plane Bending & Shear

- Modeling approach worked better for out-of-plane bending than for out-of-plane shear
- Agreement between experimentally-measured and FEA-calculated maximum loads
  - Within 10% for bending
  - Within 25% for shear
- Also large differences between experimentally-measured and FEA-calculated notch-tip strain fields
- Why?

- Out-of-plane shear i

- Out-of-plane shear is a more complicated than out-of-plane bending
- Under out-of-plane shear, the panel experiences out-of-plane applied loading, **and significant out-of-plane internal loading at the notch tip**
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- The goal of the out-of-plane loading study has been to develop effective finite element models, validated by experiments, to predict response using **the built-in features of Abaqus.** The development of custom methods has not been part of the statement of work.
- In the case of out-of-plane bending, this appears to work quite well
- In the case of out-of-plane shear, the inability to capture out-of-plane normal effects appears to be a limiting factor
- Over the recent phases, we have made a **very thorough** evaluation of the built-in capabilities of Abaqus/Standard, Explicit, and the Abaqus plug-in, Helius:MCT
- It is our conclusion that the results we are obtaining for out-of-plane shear are the **best that can be obtained** using the built-in features of Abaqus.

Today's Topics

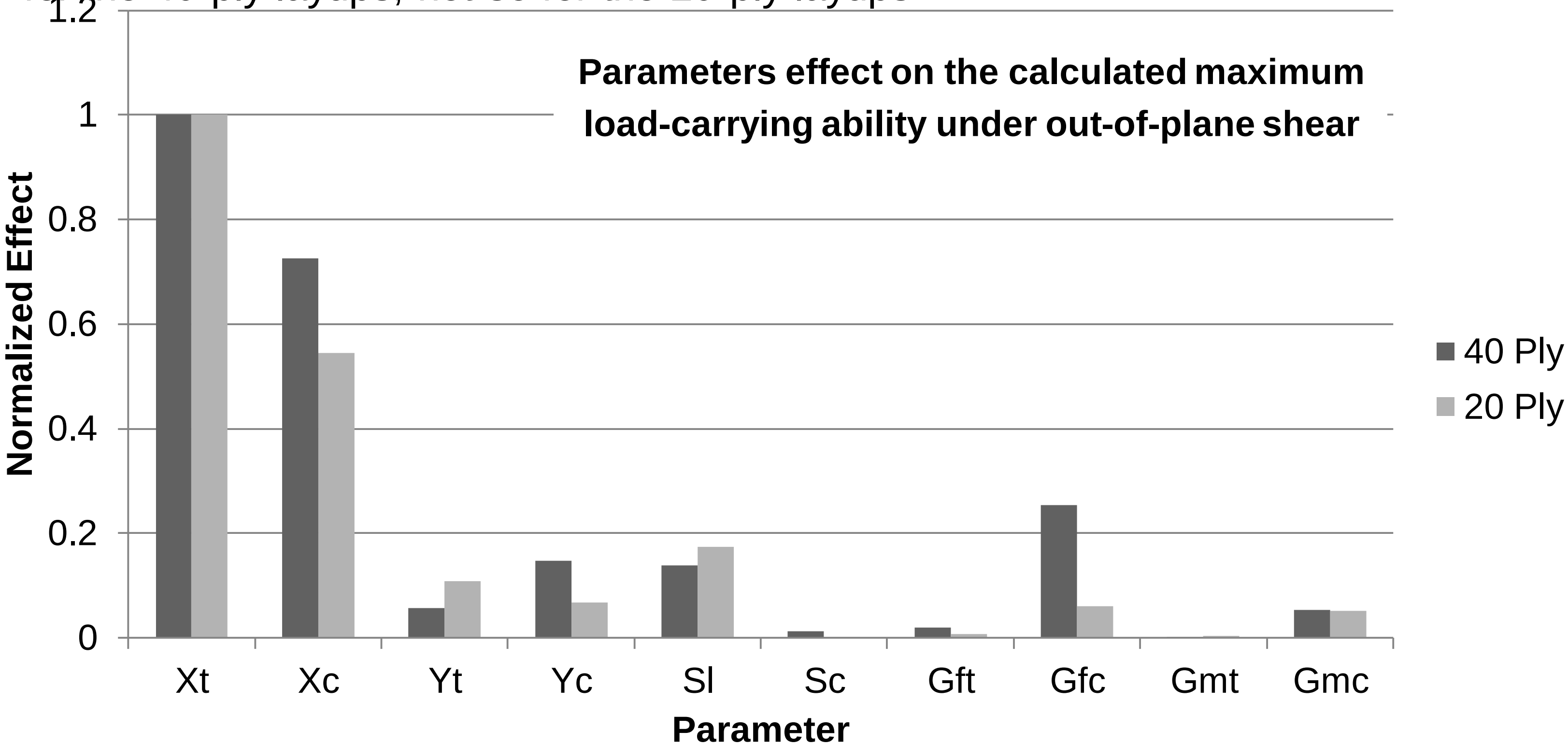
- Review of out-of-plane bending and out-of-plane shear experiments and modeling
- Significance of damage propagation material properties (energies)
- Literature review of modeling matrix compression damage propagation

Energy Sensitivity Study Goals and Motivations

- Intuitively, one would expect fracture energy parameters to be significant in determining maximum load since extensive damage occurs during panel loading
- The goal of the work presented here is to determine when/how damage progression energies are significant
- This will improve the understanding of the effect of damage progression parameters in models
- Also, if one understands when energies are significant, one can devise effective methods for their measurement (It is currently difficult to accurately experimentally measure the energy parameters)

Energy Sensitivity Studies: Results

- Sensitivity studies were conducted for out-of-plane bending and out-of-plane shear
- Out-of-plane bending showed only the case of all-90 ° plies to have significant energy parameters, Gmt and Gmc, other layups did not show energies to be significant.
- Results for out-of-plane shear, shown below normalized, indicated Gfc was significant for the 40-ply layups, not so for the 20-ply layups



Interpretation of Results

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Literature review of modeling matrix compression-damage propagation

- Fiber compression damage propagation
  - Fiber micro-buckling is a common failure mode
  - Matrix properties and mechanical response contribute to the occurrence of micro-buckling
  - Papers in this area are a source of models for matrix behavior

    Matrix plasticity response under compression

    Matrix response under shear
- Determination of matrix compressive energy-release rate
  - Model the propagation of compressive damage in the matrix as a mode II crack in the 90 ° layers
  - Calculate energy release rates

- Matrix tension damage propagation
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