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

Spring 2015

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Motivation, Objective, and Approach

- 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: Bending and Mode III fracture

  Modeling: Progressive damage development and delamination (Abaqus)

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 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

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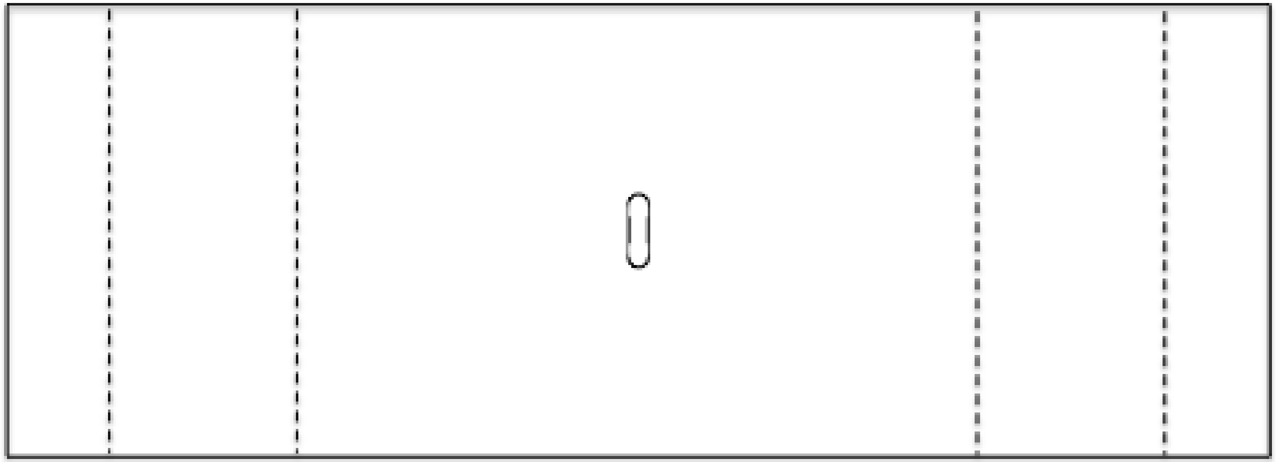
Review: Out-of-Plane Bending

- 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



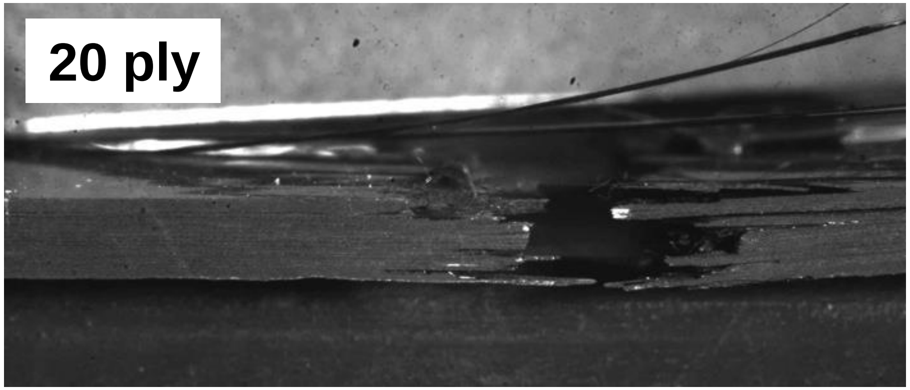
Dashed lines are load lines for 4-point bending

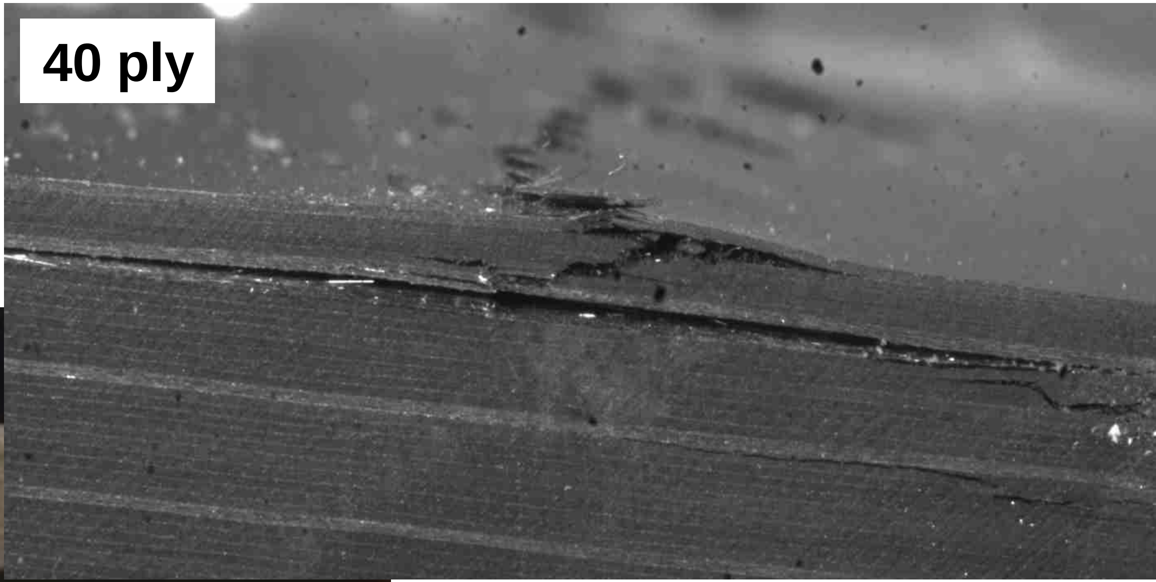
Review: Out-of-Plane Bending

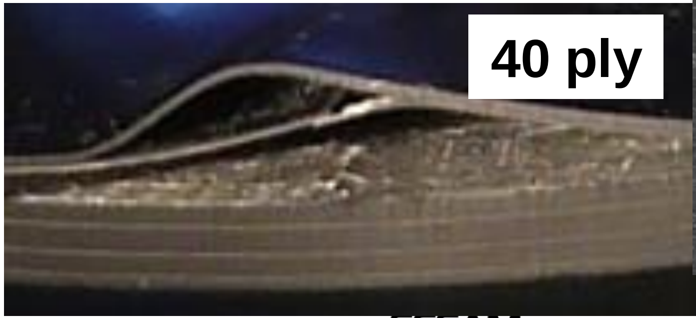
- Panels were fabricated by Boeing and tested at OSU
- Applied load versus crosshead displacement data was collected
- Results showed that
  - Initially load increased with displacement
  - As panels became damaged rate of increase decreased
  - Eventually, accumulated damage caused load to decrease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

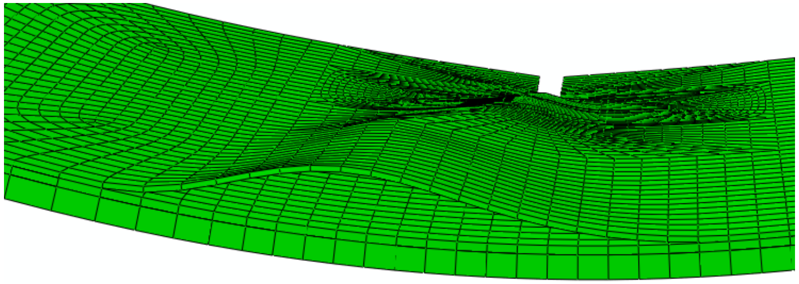






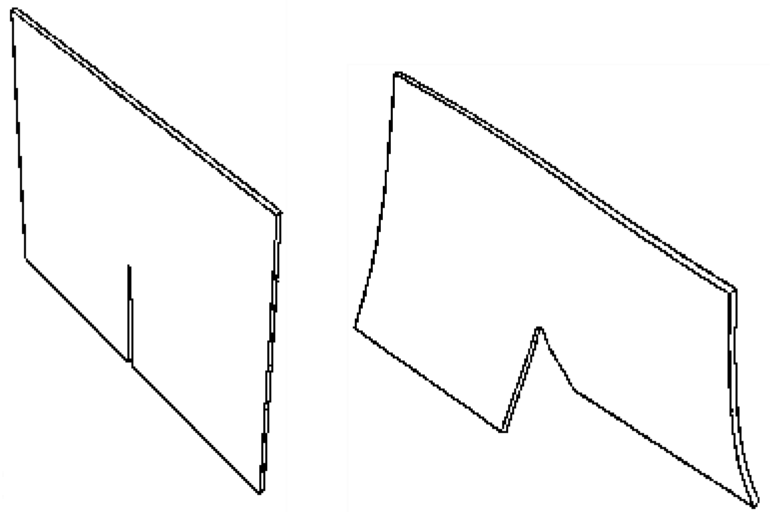
Review: Out-of-Plane Bending

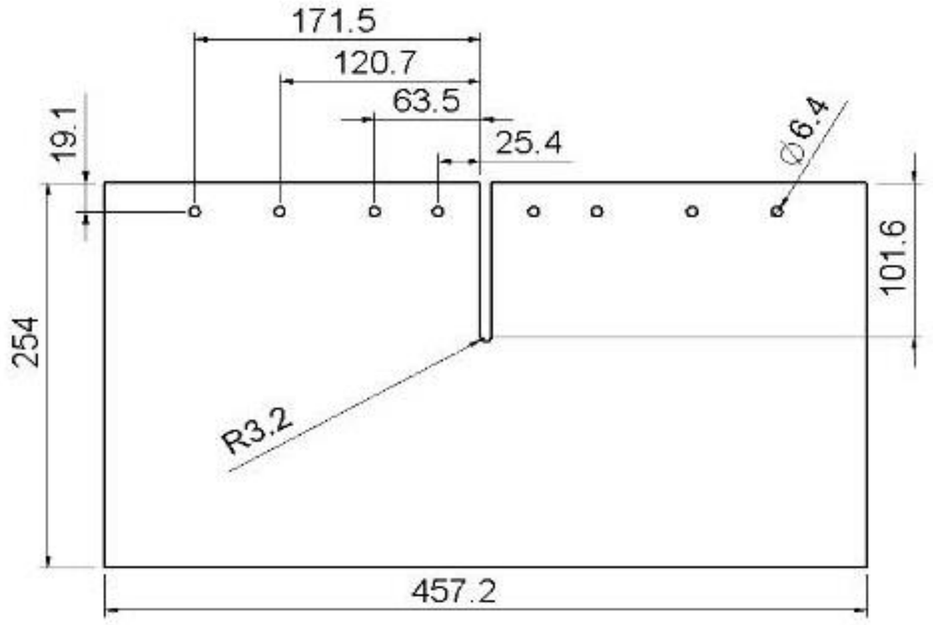
- Finite element models for out-of-plane bending
  - Used Abaqus/Standard with Hashin progressive damage model
  - The need to model multiple plies, to use Hashin in Abaqus, and to include delamination interfaces (VCCT) resulted in the use of continuum shell elements
  - Finite element results were compared 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



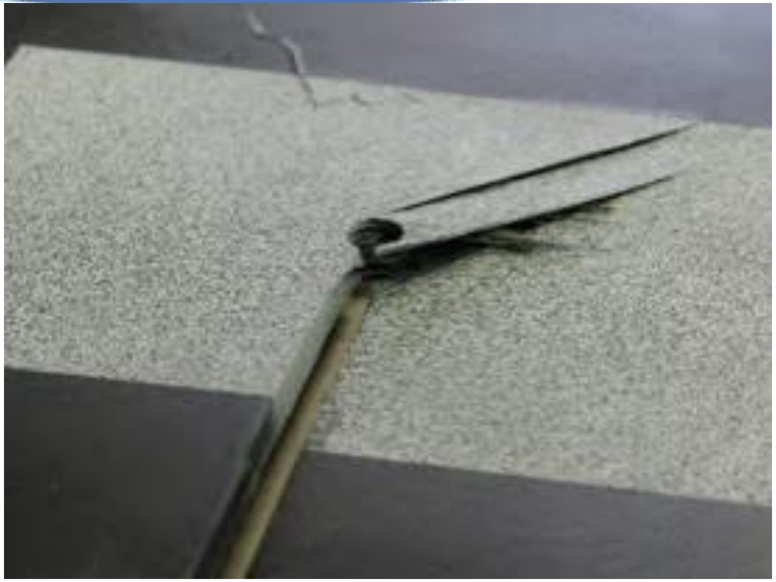


Review: Out-of-Plane Shear

- 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



Review: Out-of-Plane Shear

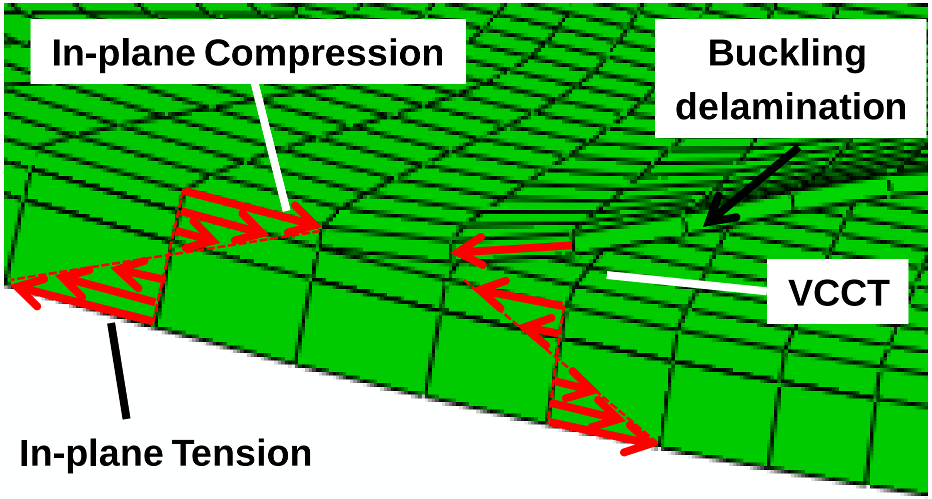
- Finite element models for out-of-plane shear
  - Used same approach as with out-of-plane bending
    - Abaqus/Explicit with Hashin progressive damage model
    - Continuum shell elements
    - Delamination interfaces (VCCT)
  - Results
    - Maximum load: Model calculations agreeing with experimental measurements to **within 25% for all layups**
    - Notch-tip strain fields (E1,E2) agree **within +/- 40%** before any visible damage. Error gets **much larger** when damage occurs.

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?

Review: Out-of-Plane Bending & Shear

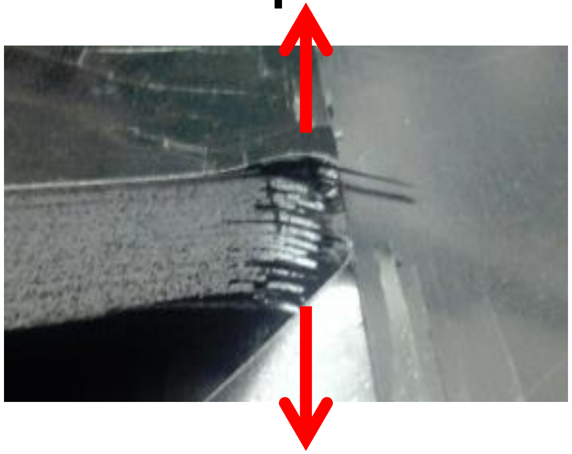
- Out-of-plane shear is a more complicated than out-of-plane bending
- Under out-of-plane bending, the panel experiences out-of-plane applied loading, **but internal loading is primarily planar** (in the plane of the panel)



- Buckling occurs but is due to in-plane compression. Resulting crack propagation is modeled well with VCCT
- Abaqus continuum shell elements work well since they include planar response and allow for interfaces to model delamination

Review: Out-of-Plane Bending & Shear

- 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**



- This is not in-plane compressive buckling, but is caused by out-of-plane normal strain.
- Abaqus continuum shell elements do not work well since they **do not include out-of-plane normal strain response**
- Given the need to model multiple plies and use the Hashin progressive damage model, it is not feasible to use other element types

Review: Out-of-Plane Bending & Shear

- 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

- The Hashin progressive damage model, as implemented in Abaqus, is used for all finite element modeling
- It consists of
  - 6 parameters (strengths) which control damage initiation
    - XT & XC: tensile & compressive strengths parallel to the fibers
    - YT & YC: tensile & compressive strengths normal to the fibers
    - SL & ST: Longitudinal & transverse shear strengths
  - 4 parameters (energies) which control damage propagation (areas under stress-displacement curves, nominally fracture energies)
    - Gft & Gfc: Fiber tension and compression fracture energies
    - Gmt & Gmc: matrix tension and compression fracture energies
- A number of sensitivity studies conducted in prior phases have very seldom indicated the energies to be significant in affecting maximum load

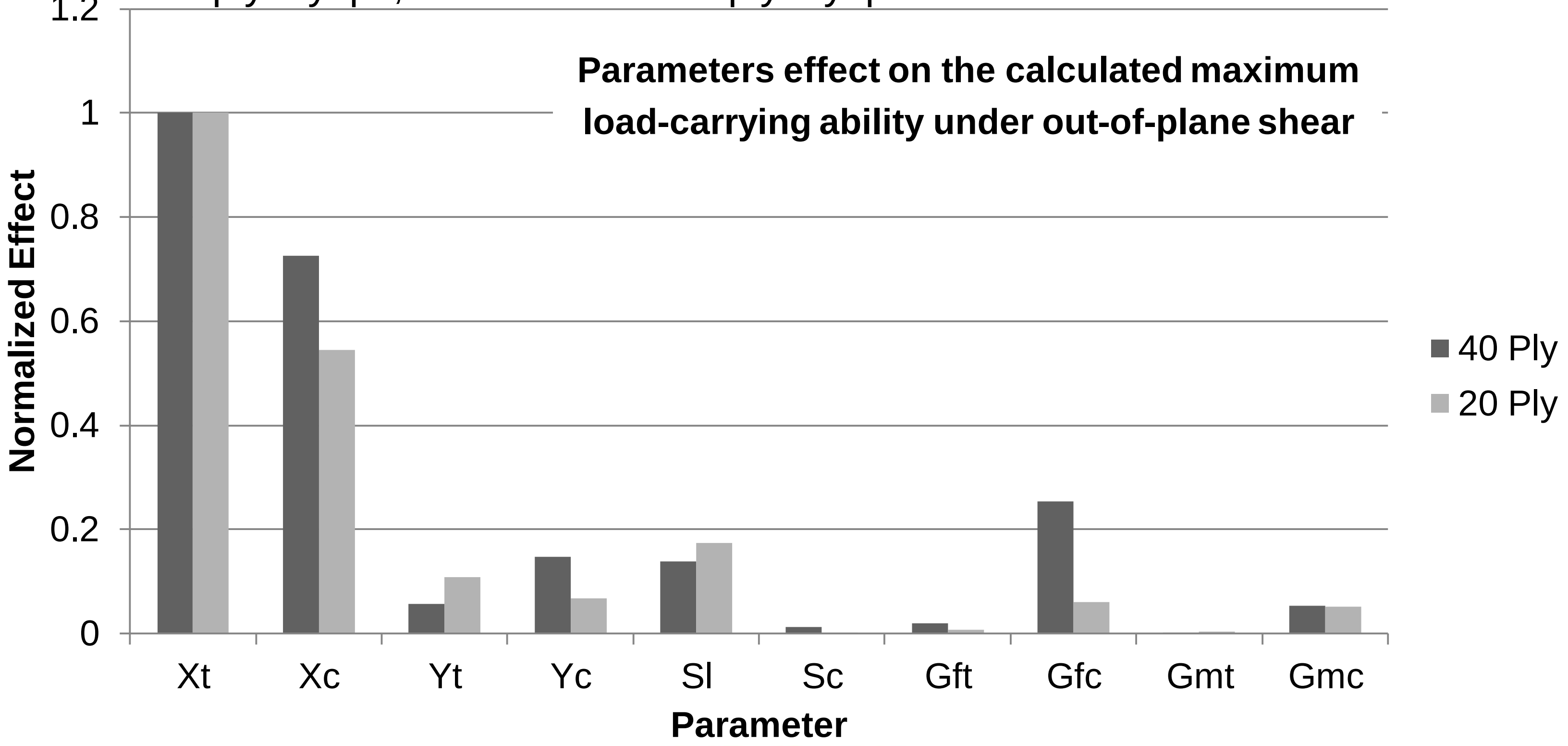
*** Areas under the associated stress-displacement curves, nominally fracture energies**

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

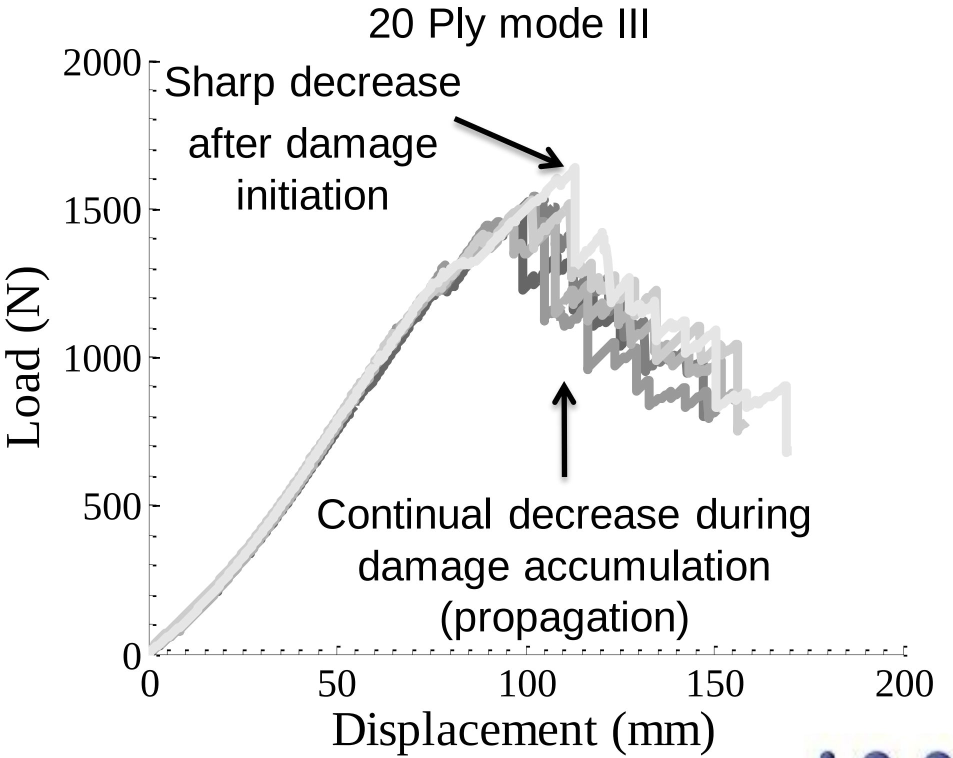


Interpretation of Results

- Examination of these results and the associated load displacement plots provides the answer.
- The **effect on maximum load** is being determined by the sensitivity studies
- The energies control the **propagation of damage**
- For out-of-plane bending, the maximum load is predominantly a function of when damage **initiates** (i.e. the maximum load carrying ability is reached when a critical amount of damage has initiated)
- Damage initiation is controlled by the strengths, thus they consistently appear as significant in the sensitivity studies
- Energies are significant in determining load-displacement behavior for all loading cases **after** maximum load is reached

Interpretation of Results

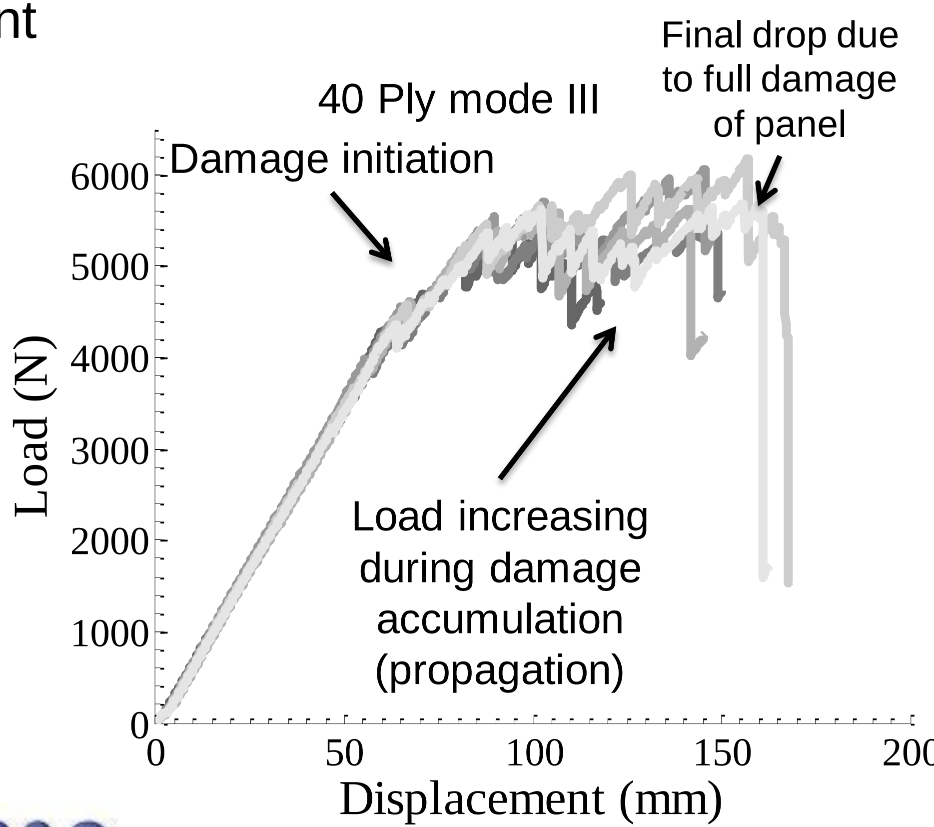
- Out-of-plane shear loading (mode III) clearly shows this behavior
- 20-ply panels reach maximum load with little damage propagation, thus energies are not significant
- 40-ply panels reach maximum load after considerable damage propagation, thus energy is significant



20 Ply mode III

Sharp decrease after damage initiation

Continual decrease during damage accumulation (propagation)



40 Ply mode III

Damage initiation

Final drop due to full damage of panel

Load increasing during damage accumulation (propagation)

Other comments on energy significance

- The energy parameters will also tend to become (more) significant for materials in which the strengths are lower.
  - When strengths are high, initiation occurs with a relatively large amount of accompanying damage. Extensive damage can exist before energies play a role (before propagation)
  - When strengths are low, initiation occurs with a relatively small amount of accompanying damage. Extensive damage exists only after energies play a role (after propagation)
- Notch Size may have a significant effect
  - Results are presented for a single notch size for out-of-plane bending and a single notch size for out-of-plane shear
  - Significantly different notch sizes may give significantly different results

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Literature review of modeling matrix compression-damage propagation

- Damage propagation behavior of the matrix under compressive loading is a possible topic for future research
- A first step is to review current literature
- Relevant literature can be classified into five categories
  - Fiber compression damage propagation
  - Determination of matrix compressive energy-release rate
  - Matrix tension damage propagation
  - Fracture of unreinforced polymers
  - Composite damage initiation criteria

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

Literature review of modeling matrix compression-damage propagation

- Matrix tension damage propagation
  - Provides plastic damage models for matrix under tension
  - Models may be relevant for matrix under compression
- Fracture of unreinforced polymers
  - Matrix materials are typically polymers
  - Study of polymers is likely relevant
- Composite damage initiation criteria
  - Provides models for damage initiation in composites and specifically the matrix
  - Initiation criteria may be relevant for propagation also

Overall, no literature was found which discusses in detail damage propagation behavior of the matrix under compression