Using Abaqus to Model Delamination in Fiber-Reinforced Composite Materials

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Outline

- Background
- Methodology
- Finite Element Simulations
- Summary
Simulating the Manufacture of Composite Parts

- Increasing use of composite materials (automotive, aerospace, wind energy, marine, military, infrastructure, etc.):
  - High specific stiffness,
  - Corrosion and fire-resistance,
  - Tailored energy absorption
- Uncertainties in material behavior and manufacturing processes require simulations to predict part quality

**Thermostamping process**
Abaqus Manufacturing Process Simulations

Benchmark Exercise:
Double-dome

USCAR Project:
Rear Tub

USCAR Project:
Floorpan

Wind Turbine Blade
Linking the Manufacturing Process to In-Service Performance

- Forming simulations predict part quality as a result of the manufacturing process
- What will the resulting in-service structural performance be?
  - Stiffness
  - State of stress
  - Mode of failure

Amplification of strain in a wind turbine blade due to a defect
Fabric Material Model

- Consider a unit cell of a balanced plain-weave fabric.
  - A 2-D conventional shell element (S4R) shares its nodes with four 1-D beam elements (B31)
  - Beam elements carry tensile and bending loads
  - Shell element defines the shear stiffness of the fabric
- Mechanical behavior of the fabric is captured via shear frame, tensile, bending, friction, and bias-extension tests.
- Nonlinear constitutive equations are associated with beam and shell elements via user-defined material subroutine in Abaqus/Explicit (VUMAT).
Fabric Material Model

- Dry fabric model captures the reorientation of the fabric yarns as they conform to a geometry
- A method has been developed to capture the structural stiffness of the cured part:
  - Beam elements represent the infused yarns
  - Shell elements represent the resin
- Tie constraints are currently used to bond multiple layers of fabric together
  - Assume a perfect bond/no failure criteria
  - Cannot predict in-service performance and reliability of manufactured parts without the ability to predict potential delamination modes of failure
Cohesive Behavior

- Defined between contacting shell surfaces
- Considers the initial bond strength between adjacent layers
- Predicts possible failure of bond due to various loading conditions

Two-layer specimen loaded in compression

Cohesion not defined: Layers act independently

Cohesion defined: Layers buckle together
Brittle Fracture in Isotropic Materials

- Involves at least two stages:
  - Crack initiation
  - Crack propagation
- Crack propagation occurs as a function of 1) loading conditions and 2) material properties
- Three pure modes of crack propagation:
  - Opening
  - In-plane shear
  - Out-of-plane shear
Fracture in Composite Materials

- Fracture properties are relatively complex due to anisotropic behavior.
- Test methods are different from those used for isotropic materials.
- Consider a Mode I (opening mode) failure:
  - Test setup (ASTM D5528) involves a Double Cantilever Beam (DCB)
  - Two layers of unidirectional fabric (rectangular, uniform thickness)
  - Non-adhesive insert is placed in the midplane to serve as a delamination initiator.
  - Non-adhesive insert is a polymer or aluminum foil film with \( t < 13 \text{ mm} \).
Mode I Failure

- Specimens are attached to the grips of a load-sensing device such that slipping will not occur.
- A load is applied to record load-displacement data.
- Delamination length measured using an optical method.
- Failure should occur at the midplane of the plies without slipping or debonding of the attachment methods.

<table>
<thead>
<tr>
<th>Specimen Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (Length)</td>
<td>125 mm (5.0 in)</td>
</tr>
<tr>
<td>b (Width)</td>
<td>20 to 25 mm (0.8 to 1.0 in)</td>
</tr>
<tr>
<td>a (Effective Insert Length)</td>
<td>50 mm (2.0 in)</td>
</tr>
<tr>
<td>h (Thickness)</td>
<td>3 to 5 mm (0.12 to 0.2 in)</td>
</tr>
</tbody>
</table>

Zwick, 2011
Mode I Interlaminar Fracture Toughness

- Strain energy release rate, $G_I$, calculated by:

$$G_I = \frac{3P\delta}{2ba}$$

where:
- $P$ = load
- $\delta$ = load point displacement
- $b$ = specimen width
- $a$ = delamination length

- Assumes a built-in condition
- Actual testing allows for rotation at the delamination front:

where $\Delta$ can be obtained experimentally:

\[ C^{1/3} \] vs. $a$
Finite Element Simulations

- Predict crack initiation and propagation in composite structures upon loading.
- Define the bond strength properties between adjacent plies using contact through cohesive surfaces.
- In lieu of mechanical test data in the current research, fracture properties from an Abaqus documentation example are used to demonstrate the proposed methodology.
- Parametric study to determine if results are element-type dependent:

![Continuum Shells](image1)
![Conventional Shells](image2)
Material Orientations

• Unlike 2-D conventional shell elements, material orientation of 3-D continuum elements must be explicitly assigned:

• Global Coordinate System: Orientation does not rotate with model curvature.

Displacement is 2.4 times less than that predicted using a global system.
Modeling Composite Failure in Abaqus

- Maximum stress and Tsai-Wu failure criteria
  - Compute damage initiation due to given stress/strain limits
  - No degradation in material properties as a function of the magnitude of the effective stress or Tsai-Wu parameter
  - Only useful for indicating whether or not a structure is damaged and the potential extent of the damage throughout the part

- Cohesive elements, VCCT (Virtual Crack Closure Technique), & cohesive surfaces
  - Take into account transverse shear stresses
  - Cohesive surfaces chosen for this research because of ease of implementation into current forming simulation models
  - Cohesive elements would require layers of elements to be generated in between plies
  - VCCT captures only crack propagation → a crack must be initially defined
DCB Simulations

- Vectorply® biaxial non-crimp fabric (NCF) used as an example

Red = damaged bond

- Difference in stiffness degradation may be attributed to element type
- Future work will explore importance of mesh density
Summary

- Failure criteria and damage properties were investigated to model delaminations in composite parts.
- Delaminations due to Mode I failure were modeled using Abaqus/Standard.
- Models show promise as a method for capturing the delamination phenomenon of laminated composites using both conventional and continuum shell elements.
- Other modes of failure must be investigated and model results must be validated with experimental results.
- Importance of mesh density must be studied.
- Eventual goal is to incorporate cohesive behavior to model potential delamination modes of failure in composite structures such as wind turbine blades.
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