A Composite Damage Tolerance Simulation Technique to Augment the Building Block Approach

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MOTIVATION

Building Block Approach

<table>
<thead>
<tr>
<th># of tests</th>
<th>Test article scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Full scale</td>
</tr>
<tr>
<td></td>
<td>Element</td>
</tr>
<tr>
<td></td>
<td>Sub-element</td>
</tr>
<tr>
<td></td>
<td>Coupon</td>
</tr>
</tbody>
</table>

Goal: Determine reduced strength when damage is present

FRACTURE CONTROL REQUIREMENTS FOR SPACEFLIGHT HARDWARE
(damage tolerance is required for human spacecraft structures)
MOTIVATION

Design and certification process for composite aerospace structures

- Heavily reliant on tests
- Expensive
- Damage simulation tools may reduce the need for some testing
  - manufacturing flaw
  - compression after impact
  - worst case credible damage

[Diagram showing the design and certification process with stages: Preliminary Design, Detail Design, Certification, Testing, Simulation – desired]
Example 1: X-ray CT scan of impact damage in a CFRP plate

Example 2: Ultrasonic scan of multiple impact sites on stiffened panel

Example 3: X-ray CT scan of impact damage in a CFRP plate
COMPOSITES IN ORION

- NASA crew module
- Deep space human exploration
- First test flight: 2014
- First crewed flight: 2023

Composite considered in this study
- Solid laminate
- IM7/977-3 Woven Carbon Fiber Reinforced Polymer
- Layup
  - $[+45^\circ/0^\circ/-45^\circ/90^\circ]_{2s}$
  - Adhesive at mid-plane
Compression after impact test are at “coupon scale”

Impact energy = 15 ft-lbs

X-ray CT scan at impact site

Flash IR: impacted side

damage radius = 0.44 in

Flash IR: back side

damage radius = 0.66 in

ASTM Impact Test Fixture
COMPRESSION AFTER IMPACT

Test set-up

Test fixture

Test coupon (with strain gauges installed)

Crosshead platen

Test specimen (failed)

INSERT TEST COUPON PIC
How should preexisting impact damage be represented?
MODEL DEVELOPMENT

• Is Flash IR NDE fidelity sufficient for CAI model definition?
• Goal: Determine model configuration that…
  ✓ Predicts critical force accurately
  ✓ Is insensitive to slight variations in model definition
  ✓ Can be defined and solved in a “timely manner”

Projected damage area only in Flash IR

Parametric study
• Depth of damage
• Spread of two cracks
• Eccentricity of cracks
• Number of cracks

<table>
<thead>
<tr>
<th>Number of Cracks</th>
<th>0 Cracks</th>
<th>1 Crack</th>
<th>2 Cracks</th>
<th>3 Cracks</th>
<th>4 Cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ply 16</td>
<td></td>
<td>ply 16</td>
<td>ply 7</td>
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<td>Ply 25</td>
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<td>Ply 25</td>
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<td>ply 25</td>
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</tbody>
</table>

depth of damage
spread of two cracks
eccentricity of two cracks

0.11375"
LINEAR ELASTIC RESPONSE

1. Elastic response is well captured by model
2. Test specimen is positioned in fixture to ensure uniform strain
1. Global response is highly sensitive to contact algorithm
2. Global response constrained if VCCT activated
3. Case 1 and 4 to be used henceforth

<table>
<thead>
<tr>
<th>Case</th>
<th>VCCT Status</th>
<th>Contact Property option</th>
<th>Pressure Overclosure</th>
<th>Constraint reinforcement method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>On</td>
<td>VCCT Fracture Criterion</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Off</td>
<td>Normal Behavior</td>
<td>&quot;Hard Contact&quot;</td>
<td>Penalty</td>
</tr>
<tr>
<td>3</td>
<td>Off</td>
<td>Normal Behavior</td>
<td>&quot;Hard Contact&quot;</td>
<td>Direct</td>
</tr>
<tr>
<td>4</td>
<td>Off</td>
<td>Normal Behavior</td>
<td>&quot;Hard Contact&quot;</td>
<td>Default</td>
</tr>
</tbody>
</table>
1. Generally, model over predicts test data
2. Predictions are insensitive if crack is placed at least 3 plies away from the impacted laminate surface
1. Generally, model over predicts test data
2. Predictions are insensitive if cracks are spread at less than 0.11375”
3. VCCT causes non-convergence or near zero critical force prediction
ECCENTRICITY OF TWO DELAMINATIONS

1. Prediction accuracy is a function of proximity to the laminate surface
2. Good correlation is seen when the delaminations are defined near the laminate surface
3. VCCT predictions are more sensitive than first ply failure
4. VCCT often causes non-convergence

![Graph showing eccentricity of two cracks with Tsai-Hill, Tsai-Wu, Azzi-Tsai-Hill, VCCT-Min, Hashin-Min, and Target lines. The eccentricity of two cracks is indicated at 0.11375”]
1. Predictions are not sensitive to the number of cracks
2. If VCCT is activated, predictions change significantly
3. VCCT under-predicts strength
4. VCCT causes convergence problems
How should preexisting impact damage be represented?

- Two preexisting delaminations
- Spaced less than or equal to 0.11375” apart
- Located near the impacted surface of the coupon (3 plies)
- Sizes of the two preexisting delaminations correspond to projected damage area from Flash IR NDE of each side of the coupon
GRAPHICAL USER INTERFACE

- Abaqus plug-in
- CAI simulation of solid laminate
- User enters model definition parameters
- Automatic model definition and execution
CLOSING REMARKS

• Current status
  • Completed sensitivity study on model definition parameters
  • Validated model prediction accuracy
    • One impact energy
    • One layup
    • One material system

• Future work
  • Attempt model test correlation of additional impact energies
  • Attempt test correlation of additional layups
  • Generate recommendation for use in future BBA

• Application: if used to replace otherwise planned CAI test…
  • Same material system
  • Similar layup
  • Similar environment
  • No expected differences in failure mode
QUESTIONS

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