Critical Progressive Damage Analysis Model Features for Low-Velocity Impact on Thermoset and Thermoplastic Panels

Frank Leone\textsuperscript{1}, Wade Jackson\textsuperscript{1}, Cheryl Rose\textsuperscript{1}, Banavara Seshadri\textsuperscript{2}

\textsuperscript{1}Durability, Damage Tolerance, and Reliability Branch, NASA Langley Research Center, Hampton, Virginia
\textsuperscript{2}Analytical Mechanics Associates, Hampton, Virginia

American Society for Composites 38\textsuperscript{th} Technical Conference
Greater Boston, Massachusetts, September 18–20, 2023
Background

• Progressive damage analysis (PDA) tools for fiber-reinforced composite materials have a wide range of damage modes, nonlinearities, and other complex features

• All PDA model features have assumptions and limitations that require verification and validation (V&V) in isolation and in combination

• A previous V&V campaign found that PDA tools could predict the onset, mode, morphology, and general size of damage in post-buckled stiffened structures composed of thermoset materials

• The NASA Hi-Rate Composite Aircraft Manufacturing (HiCAM) project is investigating the performance of state-of-the-art PDA tools and modeling best practices when applied to thermoplastic panels subjected to low-velocity impact (LVI)
Outline

• Specimen and material
• LVI experimental setup
• Damage characterization
• PDA finite element (FE) modelling approach
• Effect of model features on test/analysis correlation
LVI Specimens

Thermoset panels
• Material: Hexcel™ IM7/8552
• Stacking sequence: \([-45_2/0_2/+45_2/90_2]\)\(_S\)
• Nominal panel thickness: 0.076 inch
• 14-inch-by-14-inch panel geometry

Thermoplastic panels
• Material: Solvay™ AS4D/PEKK-FC
• Stacking sequence: \([-45/0/+45/90]\)\(_3S\)
• Nominal panel thickness: 0.135 inch
• 8-inch-by-8-inch panel geometry

\(^{†}\) Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the material studied. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified material is the best available.
LVI Experimental Test Setup

8-inch-Square Specimen

- Eight through-bolts to minimize edge movements
- 5-in-square unsupported region

Impact Fixture

- Optical gage for velocity measurement

Impact Drop Tower

- Slotted tube
- Load cell
- Release hook
- Interchangeable mass
- Teflon ring with velocity flag

Impactor

- 1-inch-diameter tip (interchangeable)

Data collected during impact:

- Force history (impact load cell)
- Impactor velocity (optical sensor with flag)
- Back-surface center displacement (fiber-optic probe)
Ultrasonic Testing (UT) Scan

- 2-inch-by-2-inch scan area
- Spatial resolution of 0.005 inch
- Impact and back surface scans
- B-scan and time-of-flight data used to approximate depth

X-Ray Computed Tomography (CT) Scan

- 1.9-inch by 1.4-inch scan area
- $6.57 \times 10^{-4}$-inch (16.7-micron) voxel size
- X-ray source: 70 kV and 140 mA

See Wade Jackson’s presentation “Characterization of Low-Velocity Impact Damage in Thermoplastic Laminated Composites” for more information on the experimental methods and results.
Interpretation of UT and X-Ray CT Data

8-inch-by-8-inch thermoplastic panel, 10 ft-lb\textsubscript{f} impact energy
PDA FE Model Setup

**FE model**
- Boundary conditions included through-thickness picture frame constraints and through-bolts
- Conventional shell elements used in far-field, transitioning to discrete solid elements in center
- Explicit dynamic analysis step
- Minimal mass-scaling, no time-scaling

**Damage modeling approach**
- Ply-by-ply, solid-element, fiber-aligned ply meshes
- **Cohesive elements** used to predict delaminations
- Plies and interfaces connected via tie constraints
- **Matrix crack spacing** enforced to better represent crack tip stress fields
- NASA CompDam material model used for intralaminar and interlaminar damage predictions
  
  https://github.com/nasa/CompDam_DGD/
Thermoset Panel Impact Response

14-inch-by-14-inch panel, 3.5 ft-lb\textsubscript{f} impact energy
Thermoset Panel Damage Maps

14-inch-by-14-inch panel, 3.5 ft-lbf impact energy

UT

Analysis

Impacted side

Back side

0°

Matrix cracks

Impacted side

0.5 inch

Back side

Delaminations
Thermoplastic Panel Impact Response

8-inch-by-8-inch panel, 10 ft-lbf impact energy
Thermoplastic Panel Damage Maps

8-inch-by-8-inch panel, 10 ft-lb_{f} impact energy

UT

Analysis

Impacted side

Back side

Matrix cracks

0.5 inch

Impacted side

Back side

Delaminations
Model Features of Interest

• Delamination representation
• Residual thermal stresses
• Pre-peak nonlinearity
• Tensile fiber damage
• Compressive fiber damage
• Through-thickness matrix crack orientation
Conventional Shell Impact Response

- Features incrementally removed from the PDA to identify the cause of the vibrations
- Removing the cohesive elements between solid-element plies improved the test/analysis force-time response correlation
Finite-thickness Cohesive Elements

• Cohesive elements in explicit FE analyses require a density, which in turn affects the minimum stable time increment and analysis run time
• Zero-thickness cohesive elements with non-zero density add mass to models
• Explicit dynamic LVI simulations are significantly more sensitive to added mass than prior quasi-static analyses of post-buckled structures

• The finite-thickness cohesive element formulation of Sarrado and Leone (2016) was implemented in NASA CompDam material model version 2.6.0
  • Allows for physical moduli to be used instead of numerical penalty stiffnesses
  • Allows physical density to be used, based on the initial volume of the cohesive element

Thick Cohesive Elements on Impact Response

Thermoplastic panel, 10 ft-lb:
- Zero-thickness cohesives
- Conventional shell model
- Finite-thickness cohesives

Thermoset panel, 3.5 ft-lb:
- Zero-thickness cohesives
- Conventional shell model
- Finite-thickness cohesives

- Much improved test/analysis correlation in terms of force-time histories

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Thick Cohesive Elements on Damage Maps

Thermoplastic panel, 10 ft-lbf impact energy

**UT**

**Analysis**

**Impacted side**

**Back side**

No significant improvement in predicted delaminated area or damage morphology
Feature of Interest: Residual Thermal Stress

Motivation

• Earlier matrix crack initiation could affect the predicted delamination morphology, yielding predictions of wedge-shaped delaminations
• Additional matrix cracks could also allow for delaminations to grow larger

Approach

• PDAs of a thermoplastic panel subjected to 6 ft-lb\textsubscript{f} impacts with and without residual thermal stresses and with multiple stress-free temperature differences (\(\Delta T\))
  • \(\Delta T = 200^\circ F, 300^\circ F,\) and \(400^\circ F\)
• Use finite-thickness cohesive elements
• Fiber damage not predicted in these analyses
Residual Stress on Impact Response

Thermoplastic panel, 6 ft-lb of impact energy

- Experiment
- PDA with $\Delta T = 0^\circ F$
- PDA with $\Delta T = 200^\circ F$
- PDA with $\Delta T = 300^\circ F$
- PDA with $\Delta T = 400^\circ F$
Residual Stress on Damage Maps

Thermoplastic panel, 6 ft-lbf impact energy

- No residual thermal stress
- $\Delta T = 200^\circ F$
- $\Delta T = 300^\circ F$
- $\Delta T = 400^\circ F$

- No residual thermal stress
- $\Delta T = 200^\circ F$
- $\Delta T = 300^\circ F$
- $\Delta T = 400^\circ F$

- No substantial change observed for fracture energy dissipated into delaminations or to overall projected delaminated area
Feature of Interest: Fiber Damage

Motivation

• Characterize the effects of tensile fiber damage on predicted force-time responses and damage maps for LVI specimens

Approach

• Use a continuum damage mechanics approach to tensile fiber damage
  • Damage initiation: Maximum strain failure criterion
  • Damage evolution: Two-part piecewise linear stress-strain softening law
• Perform analyses of an 8-inch thermoplastic panel subjected to a 10 ft-lb impact
• Use finite-thickness cohesive elements
• Consider residual thermal stresses and assume ΔT = 200°F
Fiber Damage on Impact Response

Thermoplastic panel, 10 ft-lb impact energy

Fully-developed fiber damage prediction

Possible fiber failure in experiments

- Experiments
- PDA without fiber damage
- PDA with fiber damage
Fiber Damage on Damage Maps

Thermoplastic panel, 10 ft-lbf impact energy

Impacted side

Back side

UT  PDA without fiber damage  PDA with fiber damage

Matrix cracks

Impacted side

0.5 inch

Back side

Delaminations

Impacted side

0°
Closing Remarks

• The sensitivity of LVI PDA results to changes in interface representation, residual thermal stresses, and fiber damage was studied

• Force-time histories and predicted damage size are not closely coupled
  • Force-time response varied significantly with changes to the interface representation, but the predicted damage size remained relatively constant
  • The coarse features of LVI responses (e.g., peak load, impact duration) were not affected by any of the studied features
  • Including residual thermal stresses caused a large increase in matrix crack predictions but had little effect on force-time and delamination size predictions
• The test/analysis correlation gap is larger for the thermoplastic specimens than for the thermoset specimens

• None of the model features had a significant effect on the apparent interfacial fracture toughness of the impacted thermoplastic panels

• Given the remaining gap between the experiments and analyses, additional assumptions and the use of other material property inputs should be considered