Impact Damage Formation on Composite Aircraft Structures

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Impact Damage Formation on Composite Aircraft Structures

• Principal Investigators & Researchers
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    ▪ MS: none

• FAA Technical Monitor
  – Lynn Pham

• Other FAA Personnel Involved
  – Larry Ilcewicz, Ahmet Oztekin

• Industry Participation
  – Boeing, Bombardier, UAL, Delta, DuPont, JC Halpin Consulting
Impact Damage Formation on Composite Aircraft Structures

• Motivation and Key Issues
  • impacts are ongoing and major source of damage
  • high energy **blunt** impact damage (**BID**) of main interest
    • involves large contact area
    • damage created can exist with **little/no exterior visibility**

• Sources of Interest: those acting over wide area and/or across multiple structural elements
  • ground service equipment (GSE) with rubber bumpers
  • railings, blunt/round corners, FOD of unknown geometry
  • hail ice, bird

Sandwich Blunt Impact
• core crush with low/non-visible dent
• low velocity: GSE, tools
• high velocity: ice, bird

Ground Vehicles & Service Equipment
• side & lower facing surfaces
• high mass, low velocity
Program Objectives

• Understand blunt impact damage formation and visual detectability
  • determine key phenomena and parameters controlling both internal and external/visual damage formation
    • internal vs. external damage formation vs. bluntness/contact-area size
  • identify and predict failure thresholds (useful for design)

• Develop analysis and testing methodologies, including:
  • full structure vs. sub-structure testing for HEWABI investigations
  • accurate modeling capabilities and tools validation
  • establish damage visibility criteria – surface crack, residual dent
Outline

• Ground Service Equipment (GSE) High Energy Blunt Impact
• Impact Damage to Sandwich Panels & Core Crush Mechanics
• Summary, Benefits to Aviation, and Future Work
Next-Generation Specimen Blunt Impact Tests
Focus: Failure Near Floor Joint

Key Features:
• revised skin & stringer geom
• frame-floor stiffness interaction
• continuous shear ties

Representative Stiffness

Continuous Shear Tie Assembled to Frame

Frame-to-Floor Stiffness Interaction

Region of Interest

Loading:
Loc 3
Loc 4
# New Specimen Design & Test Matrix

<table>
<thead>
<tr>
<th>Part</th>
<th>Layup</th>
<th>THK (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>[0w/0/45/90/-45/0/90]s</td>
<td>2.79</td>
</tr>
<tr>
<td>Stringer</td>
<td>[0w/0/45/90/-45/0/90]s</td>
<td>2.79</td>
</tr>
<tr>
<td>C-Frame</td>
<td>[45/0/-45/45/0/-45]s (web)</td>
<td>2.64</td>
</tr>
<tr>
<td></td>
<td>[45/0/0/-45/45/0/0/-45]s (flange)</td>
<td>3.53</td>
</tr>
<tr>
<td>Shear tie</td>
<td>[45/0/-45/0/45/0/-45/0]s</td>
<td>3.53</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Skin</th>
<th>THK (mm)</th>
<th>Shear Tie</th>
<th>THK (mm)</th>
<th>Load Loc</th>
<th>Load Speed</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>14 plies</td>
<td>2.79</td>
<td>16 plies</td>
<td>3.53</td>
<td>3</td>
<td>Quasi-Static</td>
</tr>
<tr>
<td>2</td>
<td>14 plies</td>
<td>2.79</td>
<td>16 plies</td>
<td>3.53</td>
<td>3</td>
<td>0.25 m/s</td>
</tr>
<tr>
<td>3</td>
<td>14 plies</td>
<td>2.79</td>
<td>16 plies</td>
<td>3.53</td>
<td>4</td>
<td>Quasi-Static</td>
</tr>
<tr>
<td>4</td>
<td>14 plies</td>
<td>2.79</td>
<td>16 plies</td>
<td>3.53</td>
<td>4</td>
<td>0.25 m/s</td>
</tr>
</tbody>
</table>

Load Speed “Quasi-Static” = slow speed until just past initial failure; stop & inspect; reload, stop etc.

Load Speed “0.25 m/s” = single load step until well past initial failure.
Test Setup

1D Table Movement

Dynamic Load Cells

Floor Beam to Frame Connection Stiffness
Truncated vs. Full ¼ Barrel Equivalency?
Assess via Finite Element Analysis
Loading Location 3 Response

Shear Tie Failure Initiation: 20.0 kN

Shear Tie – Stringer Contact

Stringer Failure Initiation: 53.4 kN

No Skin Failure Predicted
Loading Location 4 Response

Shear Tie Failure
Initiation: 22.7 kN

Stringer Failure Initiation: 50.3 kN

Shear Tie – Stringer Contact

C-Frame Failure Initiation: 50.3 kN

No Skin Failure Predicted
Panel Edge BC Consideration

Consider the edge BC on panel long side
- In FEA, $U_3 = 0$ for symmetry condition
- $U_3 = 0$ difficult to replicate in the laboratory environment

Account for friction between rubber bumper and skin
- Friction coefficient range: 0.3 to 0.6

Max $U_3$ displ.: 0.087”
Panel Edge BC Comparison: U3 = 0 or Free Loading Loc. 4, Friction Coefficient 0.3

Force-Displacement Comparison - Loc.4

Shear tie corner radius element deletion initiation

Shear tie web to stringer hat contact deletion initiation

Stringer hat radius element deletion initiation by contact

Shear tie web element deletion initiation by contact

Stringer Failure Initiation

Frame Failure Initiation

Conclusion:
U3 = 0 Not Required at Edge for Experiments

MT: Matrix tension
MC: Matrix compression
FC: Fiber compression
FT: Fiber tension
Element-Level C-Frame Experiments

- C-frame test specimen
  - short section w/ extension arm
- Fixed end boundary condition
- Loaded end:
  - 2 point connection → bending
  - 1 point → bending + torsion
FE Modeling: Element-Level Validation

- Materials:
  - Cytec X840/Z60 6k woven carbon/epoxy with Hill failure Criterion
    - Failure criterion for woven composites
    - Examination of transverse shear effect
  - Aluminum 6061-T6 (box beam)

- Element type
  - C-frame: Solid (C3D8R) – layer by layer modeling
  - Aluminum: Solid (C3D8R)

- Abaqus/Explicit solver

Frame section information (Unit: mm)

Web layup: [45,0,-45,90,45,0]s

Flange layup:
[45,0,0,-45,90,45,0]s
Bending A2 Model: Hill Failure Criterion
Load – Displacement Curve

<table>
<thead>
<tr>
<th>Fail Load (N)</th>
<th>Test A1</th>
<th>Test A2</th>
<th>Model A2</th>
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<tbody>
<tr>
<td></td>
<td>7011</td>
<td>6856</td>
<td>11164</td>
</tr>
</tbody>
</table>

Load vs. Displacement

Displacement at Pot2 (mm)

Bending Test A1
Bending Test A2
FE Solid A2
Hand-Calc.
• Buckling mode from the measured strain curve on the compression flange.
• FE-predicted strain curve qualitatively agrees with the test result.
**Bending A2 Model – 3D Hill Failure Criterion**

**FE Model Failure mode:**
- Compression flange fractures at midspan
- Doesn’t match with experiment location – slip and clamping effects need to be accounted for

Failure location in test
Including slip in FE analysis

- Need model refinement to account for fixture to specimen interaction (slip was observed in real tests).
- Friction contact formulation is applied in detached adhesive zone between aluminum tab and c-frame.
- Clamping effect is considered with 3D Hill criterion.

1\textsuperscript{st} trial:
Hypothetical wedge pressure and friction coefficient applied
Outline

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• Conclusions, Benefits to Aviation, and Future Work
Introduction

• Complex Nomex® core mesostructure (ρ = 64 kg/m³) affects core crush response

Goals:
  o Determination of core damage extent under impact loads
  o Focus on cellular core fracture mechanisms
  o Employ image processing techniques to quantify core geometry imperfections
  o Simulation of flatwise compression tests to include key features and manufacturing defects
Example: Hail Impact on Low Glancing Angle Panels

- 10° glancing angle, 80 - 160 m/s velocity; 275 - 590 J kinetic energy, 4-ply PW

\[ t = 1.332 \text{ ms from trigger} \]

\[ t = 1.665 \text{ ms from trigger} \]

High speed video from 590J impact (velocity: 360 mph)
Damage on Nomex® Cores (Flatwise Compression)

Unloading at peak stress (point #1):
- Onset of resin fillet disbonding from cell wall
- Strength is recoverable upon re-loading

Unloading at unstable region (point #2):
- Fractured fillet leading to local cell collapse
- Strength and stiffness not recoverable

Sequence of failure events

(A): Onset of post-buckling
(B): Onset of resin fracture
(C): Core crushing plateau
Computed Tomography Scans for Initial Damage Level in Flatwise Compression Coupons

- Collaboration with University of Utah: CT-scans provided by Prof. M. Czabaj
- Through thickness scans provide clear description of damage
- Fillet fracture and detachment from paper walls are the prevailing modes (right figure)
Automated procedure utilized in Matlab

1) Image processing of each slice to obtain pixels representative of the shape of the cellular structure
   - Pixels at triangular fillets
   - Pixels at cell walls

2) Repeat steps 1 at different through-thickness CT-slices

3) B-spline surfaces fitted through data pixels obtained in steps 1) and 2)
   - Characterize imperfection metrics of pre-buckled walls
   - Perform collapse/post-buckling computational analysis on actual geometry honeycomb structure
Extract cell interpolated pixels from CT-scan slices

1) Get corner pixels of triangular-shaped fillets using threshold color segmentation

2) Get pixels of cell wall structure using matrix color segmentation

Shared nodes between fillet zones and intersecting boundaries
Application of B-spline curves (one CT-slice)

3) Use B-spline curve fit to extract planar honeycomb geometry

- Obtain the spline of each paper ribbon (as in expansion process)
- B-splines at double wall region match perfectly between adjacent layers

Finite fillet angles
Only C0 continuity at intersecting boundaries
3D Core Reconstruction & Imperfection Metrics

Extend into many slices and reconstruct 3D geometry based B-spline surfaces

Cross-section A-A (Single wall section)
- Distorted
- Cell Wall Geom
- Pre-Buckled

Exact 3D Actual Geom FE Model
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Summary

Ground Service Equipment (GSE) High Energy Blunt Impact

- Next Generation HEWABI specimen design completed and parts fabricated
  - focus on blunt impact tests near floor beam locations
- Simulations of blunt impacts near floor beam completed
  - predict sequence of failure modes; no skin failure
  - truncated specimen geometry shows equivalence to full quarter barrel
- Element-level C-frame FE models developed for bending and torsion
  - to be incorporated into large panel blunt impact models

Impact Damage to Sandwich Panels

- Core damage has been experimentally documented via ice sphere impact gas gun tests at low angles of attack; no dent visible with core crush/fracture.
- For Nomex® paper based cores, phenolic resin pre-impregnated paper cells exhibit mesoscale structural complexity
  - Phenolic resin accumulation zones around wall intersection boundaries significantly improve stability of system during flatwise compression tests
  - CT-scans on post-tested compression coupons revealed partial detachment of fillet columns due to cell wall post-buckling
- CT-scans on untested configuration provides insight on actual in-situ geometric imperfection state of Nomex® core in sandwich
Benefits to Aviation

- Understanding the damage resulting from HEWABI through element level and structural level studies – particularly for impacts near floor beams
  - key phenomena awareness and possible internal damage modes can be predicted
  - guides inspection strategies and location definition
  - permits more accurate model representation, could influence design
- Improved FE modeling methodology and validation for blunt impact damage.
- Demonstrate techniques for effective boundary conditions definition for smaller sub-structure specimens to represent larger full structure.
- Establish relationship between core features vs crushing and fracture
  - resin fillet columns
  - resin thickness coating cell walls
  - geometric imperfection of walls
  - more accurate modeling representation of core
- Understand effects of manufacturing defects/variability on core mechanics – FE model generation by CT-scan permits accurate actual geometry definition
Looking Forward

- Complete HEWABI specimen machining, drilling, assembly
- Test HEWABI specimens
- Continued development of high fidelity FEA modeling capability – validated at element level.
- In large-scale FE models, define effective representation of fasteners and its influence in damage initiation and progression.
- Simulation of core crush response with actual geometry defined by CT scans.