Impact Damage Formation on Composite Aircraft Structures

2011 Technical Review
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Impact Damage Formation on Composite Aircraft Structures

**Motivation and Key Issues**
- Impact damage to composites remains significant source of concern
  - particularly from high energy blunt sources that are not well understood
  - increasingly more composite primary structure being deployed
- Focus: Blunt Impacts affecting large area and/or multiple structural elements

**Objectives**
- Characterize Blunt Impact threats and the locations where damage can occur
- Understand damage formation from Blunt Impact sources and how this relates to visual detectability
- Develop: analysis & testing methodologies, new modeling capabilities

**Approach**
- Conduct experiments on representative structure/specimens
  - wide area high energy blunt impact – e.g., from ground service equipment
  - high velocity hail ice impacts – in-flight and ground-hail conditions
- Nonlinear finite element modeling – contact, explicit dynamics, material failure
- Workshops and meetings (at UCSD, via teleconf), UCSD Blunt Impact website
- Form collaborations with industry on relevant problems/projects
Impact Damage Formation on Composite Aircraft Structures

- **Principal Investigators & Researchers**
  - PI: Hyonny Kim, Associate Professor, UCSD
    - Prof. JM Yang, UCLA – sending subcontract to UCSD
  - Graduate Students:
    - PhD: Gabriela DeFrancisci, Zhi Chen, Jennifer Rhymer
    - MS: Sho Funai, Jeff Tippmann (graduated Jan. 2011)
  - Undergraduates: Jon Hughes, Sean Luong, Sarah Fung, Mac Delaney

- **FAA Technical Monitor**
  - Lynn Pham

- **Other FAA Personnel Involved**
  - Curt Davies
  - Larry Ilcewicz

- **Industry Participation**
  - Material support by Cytec, San Diego Composites, Boeing
  - Participation by Airbus, Bombardier, UAL, Delta, JC Halpin
  - Collaborations with Bishop GMBH (EASA-funded), Sandia Labs
Project Focus: Blunt Impacts

**Blunt Impacts**
- blunt impact damage (BID) can exist with *little or no exterior visibility*
- sources of interest are those that affect *wide area or multiple structural elements*

**Hail Ice Impact**
- upward & forward facing surfaces
- low mass, high velocity

**Ground Vehicles & Service Equipment**
- side & lower facing surfaces
- high mass, low velocity
- wide area contact
- damage possible at locations away from impact
Part I. Low-Velocity High-Mass Wide-Area Blunt Impact

- ground service equipment (GSE) impact
  - known major source of damage
- determine key phenomena and parameters that are related to damage formation
  - how affected by bluntness
  - ID & predict failure thresholds
- what conditions relate to development of significant internal damage with minimal or no exterior visual detectability?

Part II. High Velocity Hail Ice Impact
Blunt Impact Program Phases

Increasingly Complex Phases of Activity – Gain Fundamental Understanding at Bottom

- **Phase I**
  - **Basic Elements**
    - Excite Key Failure Modes
    - Model Correlation Data
    - Understand Damage Formation & Relationship to Bluntness Parameters
  - **Large Panel**
    - e.g., 5 Bays
    - Damage Excitation
    - Damage Thresholds
    - Model Correlation
  - **OEM Hardware**
    - 1/4 to 1/2 Barrel Size
    - Vehicle Impacts

- **Phase II**
  - Scaling, B.C. Effects
  - Status: Phase I completed. Phase II specimens in preparation.

- **Phase III**
  - Increasing Length Scale, Complexity, and Specificity
  - Modeling Capability Development & Correlation with Test are Key Aspects at Each Level
Blunt Impact Specimen Types
Geometry Reflects Wide Body Composite Fuselage Construction

Phase I – Small Stringer and 3-Frame Specimens

- 2 or 3 Stringers
- Attach to Test Fixtures by Shear Ties
- StringerXX
  - 7 Specimens/ 5 Tested
  - Quasi-Static
  - Dynamic

Phase II – Large 5-Frame Specimens

- 4 or 5 Stringers
- Attach to Test Fixtures by Frames
- FrameXX
  - 2 Specimens Tested
  - Quasi-Static
  - Long Cylindrical Bumper

Materials provided by Cytec: Z60 / X840
Cure and manuf. assistance from San Diego Composites

- 2 Specimens to be Constructed
- Coordination with EASA Blunt Impact Program
- Dynamic Loading
- Fabrication in 2011
Specimen Testing Details

FrameXX Setup:
- Loading by 1D table, specimens on strong wall
- Indentor head moves into specimen – simulates GSE contact
- Velocity up to 1 m/s

Frame Specimen ~6 x 4 ft.
Indentor Assembly on Rigid Frame
Controlled Rotational Stiffness BC

GSE Cylindrical Rubber Bumper
StringerXX Setup – Uniaxial Machine – D-Bumper
### Test Matrix and Results Summary

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Panel Config</th>
<th>Loading Details (Q.Static Unless Noted)</th>
<th>Intermediate Failure Modes</th>
<th>Final Failure Mode</th>
<th>Visible</th>
<th>Max Load (kN)</th>
<th>Max Displ (mm)</th>
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</thead>
<tbody>
<tr>
<td>Stringer00</td>
<td>3 Stringers</td>
<td>R3&quot; Alum. at Stringer</td>
<td>Skin Delamination</td>
<td>Local Skin Penetration</td>
<td>Y</td>
<td>30.7</td>
<td>25.3</td>
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<tr>
<td>Stringer01</td>
<td>2 Stringers</td>
<td>R3&quot; Alum. on Skin Between Stringers</td>
<td>Skin Delamination</td>
<td>Local Skin Penetration</td>
<td>Y</td>
<td>26.7</td>
<td>21.8</td>
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<td>Stringer02</td>
<td>2 Stringers</td>
<td>D-Bumper on Skin Between Stringers</td>
<td>Skin-Stringer Delamination of Each Adjacent Stringer</td>
<td>Extensive Stringer-Skin Delamination</td>
<td>N</td>
<td>61.7</td>
<td>39.5</td>
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<td>Stringer03</td>
<td>3 Stringers</td>
<td>D-Bumper at Stringer</td>
<td>Stringer Radius Cracks Under Indentor</td>
<td>Extensive Stringer-Skin Delamination</td>
<td>Y</td>
<td>61.6</td>
<td>48.5</td>
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<td>Stringer04</td>
<td>3 Stringers</td>
<td>D-Bumper on Stringer Flange</td>
<td>Stringer Radius Cracks Under Indentor</td>
<td>Extensive Stringer-Skin Delamination</td>
<td>Y</td>
<td>78.2</td>
<td>44.2</td>
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<td>Stringer05</td>
<td>2 Stringers</td>
<td>D-Bumper on Skin Between Stringers, Dynamic</td>
<td>-- test not run yet -- expected June 2011</td>
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<td>Stringer06</td>
<td>3 Stringers</td>
<td>D-Bumper at Stringer, Dynamic</td>
<td>-- test not run yet -- expected June 2011</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Frame01</td>
<td>4 Stringers, 3 Frames</td>
<td>Long Cyl. Bumper Between Stringers</td>
<td>Shear Ties Crush, Stringer Sever &amp; Flange Delam</td>
<td>Frame Crack</td>
<td>N</td>
<td>57.4</td>
<td>75.5</td>
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<tr>
<td>Frame02</td>
<td>5 Stringers, 3 Frames</td>
<td>Long Cyl. Bumper at Stringer</td>
<td>Shear Ties Crush, Stringer Sever &amp; Flange Delam, Skin Crack</td>
<td>Frame Crack</td>
<td>Y</td>
<td>71.0</td>
<td>55.9</td>
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</table>

Frame03 and Frame04: four stringers + five-frame panels – specimen fab. Summer 2011, test Jan 2012
StringerXX Summary

Annotations
1. Skin Delamination
2. Skin Penetration
3. Shear Tie Radius Crushing
4. Shear Tie Radial Delamination
5. Stringer-to-Skin Delamination
6. Skin Matrix Cracks
7. Skin Fiber Cracks
8. Stringer Radius Bending Failure
Stringer02 Delamination

Panel Surface after the 4\textsuperscript{th} Loading
- blue hatching shows delamination after the 3\textsuperscript{rd} loading
- red outline shows additional delamination after 4\textsuperscript{th} loading

NDI Details: pulse/echo c-scan using manual x-y scanner; 5 MHz, 0.1x0.1 in.
FrameXX Summary

**Frame01 Annotations**
1. Shear Tie Damage (Delam)
2. Shear Tie Crush/Bend Failure
3. Stringer Penetration + Delam
4. Frame #2 Cracking

**Frame02 Annotations**
1. Skin Cracking
2. Shear Tie Crush/Bend Failure
3. Stringer Penetration
4. Frame #1 Cracking

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**Specimen Frame01**
- 4 Stringers + 3 Frames
- Loaded Area

**Specimen Frame02**
- 5 Stringers + 3 Frames
- Loaded Area

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Contact Load (kN) vs. Indentation (mm)

- Frame01
- Frame01 Unload
- Frame01 Reload
- Frame02
- Frame02 Unload
- Frame02 Reload
Shear Tie Crushing and Bending Failure

Specimen Frame02

- Contact & Scraping Along Stringer as Frame #1 Rotates
- Local Crushing at Shear Tie Corners
- Shear Tie Corner Crushing and Delam
- Frame #1
- Stringer
- Shear Tie Bending Failure at Bolt Line Like Hinge – Allows More Frame Rotation
Severed Stringer

Delaminated Flange

Runs Toward Frame #3

Upper Stringer

Fractured Shear Tie (Liberated Fragment Not Shown)

Frame #2

Stringer Penetration

Frame01 – Post L3. Closeup Interior View
Frame Cracking Closeup View

Specimen Frame01

Fractured Shear Tie

Specimen Frame02

Through-Thickness Crack in Frame Web
- Precipitated by Contact with Stringer
- Crack Length ~ 1.5 in.
Specimen Frame01
Post-loading 3 exterior view.
Extensive internal damage.

Specimen Frame02 (not shown) developed skin crack originating from free edge.
Damage Progression Process

1. **Initial Contact**
2. **Open Bumper Collapses**
3. **Shear Tie Delamination & Crushing**
4. **Stringers and Frames Contact at Multiple Points**
   - **Focus Load Path to**
   - **At Each Contact Point**
   - **Which is Desirable Path?**
5. **Penetrate/Sever Stringer**
6. **Extensive Stringer Delam.**
7. **Crack Frame**
8. **Large Stiffness Loss / Major Damage**
9. **Shear Tie Bending Failure**
10. **More Frame Rotation**

**Note:**
Rotation of c-shaped frame promotes bending failure of shear ties and presents “sharp” corner contact onto stringer.

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**Graph:**
- **Absorbed Energy**
- **Indentation Displacement**
- **Contact Force**

**Diagrams:**
- **Rotated Frame**
- **High Contact Stress**
- **Stringer**

**Images:**
- **CECAM**
- **JAMS**
- **AMTAS**
GSE Blunt Impact Test Conclusions

- High forces and indentation displacements
  - Significant damage develops at ~70 kN (15,700 lbf) and 76 mm
    » this is a major event – entire aircraft will move
    » modest contact (bumper just touches) likely causes no damage
  - Damage at locations away from impact site possible
    » along load path, at joints/transitions
    » secondary impacts from aircraft subsequently bumping other surrounding GSE

- Progressive failure process documented
  - Load drops associated with intermediate failures
  - Contact of frames and stringers plays major role – penetration of either frame or stringer
    » affected by rotation of frame
  - Insight into improved blunt impact damage resistance
    » e.g., change frame cross-section to reduce rotation, modify shear ties to resist crushing/bending failure, prevent frame-stringer contact

- Exterior visibility (cracks)
  - depends on loading location relative to stringers
  - no visible cracks: bumper on skin between stringers
  - visible: bumper on stringer or at stringer flange
Prediction Methodologies Overview

- **Reduced Order 2DOF**
  - Estimate Contact Force & Indentation Displacement
  - Damage Thresholds

- **Energy & Momentum Balance**
  - Estimate Failure Modes

- **Elastic Static FEA**
  - Damage Initiation
  - Estimate Final Damage Onset

- **High Fidelity Explicit Dynamic FEA**
  - Complete Simulation
  - Damage Progression
  - Final Damage State

Easier to Use + Lower Cost = Able to Rapidly Explore Wide Range of Parameters

- FEA will also validate and confirm assumptions of simple models

UCSD Developing Methodologies at All Levels

Model Complexity and Computational Cost
Complete failure of Shear Tie F01C, 12,500 lbf
Penetration of Frame#2 into stringer, immediately followed by stringer-skin delamination

Failure of Shear Tie F01H, 12,950 lbf
FEA: two Shear ties removed

Frame#2 crack

FEA: pristine specimen
Estimation of Absorbed Energy for Contact Across Two Frames

Absorbed Energy
1150 J to Sever Stringers
1990 J to Crack Frame

Failure of Shear Tie F01H, 12,950 lbf
Penetration of Frame#2 into stringer, immediately followed by stringer-skin delamination
Complete failure of Shear Tie F01C, 12,500 lbf
Frame#2 crack

FEA: pristine specimen
FEA: two Shear ties removed

Total Load (kips)

Pot04, Skin Under Impactor Displacement (in.)
Comparison to Field Observations

TUG Belt Loader Approaching B757

TUG vehicle weight: 3,030 kg (6,680 lb)

Velocities as high as 1 m/s (2.2 mph) are realistic within close proximity of the aircraft

- Realistic velocity range: 0.25 to 1 m/s (0.6 to 2.2 mph)

ex. kinetic energy = 1,515 J at 1 m/s (1,117 ft-lbf)
Reduced Order Models

Full Aircraft Impacted by GSE with Initial Velocity $v_o$

2DOF Model Parameters:
- $M_{\text{GSE}} = \text{mass of GSE}$
- $k_c = \text{contact stiffness}$

Rigid Body Representation

2DOF Model Representation

$M_{\text{eff}}$ defined via inertial equivalence about aircraft c.g.
- total mass $M_{\text{AC}}$
- rotational inertia $I_{\text{AC}}$

$v_o = \text{GSE velocity at impact}$

$M_{\text{eff}} = \text{effective mass}$

$k_{\text{eff}} = \text{effective stiffness}$
Damage Occurrence Prediction
Did Event Cause Damage? Yes or No

- Explore key parameters: $M_{\text{GSE}}$, $v_o$, $k_c$
- GSE threat ($M_{\text{GSE}}$ and $v_o$) externally-defined, mostly independent of aircraft
- Contact stiffness $k_c$ (most complex term)
  - determine via models and experiments
  - establish as zones for various aircraft locations
- Design-oriented curves to assess threat vs. prospect for creating damage
  - based on critical force or indentation **failure thresholds** known from experiments on panel specimens

Velocity contours for 48.95 kN threshold force

Contact Stiffness
Zone 1
Zone 2
Zone 3
Zone 4
...

Failure Thresholds Established Within Each Zone Based on
- Impactor Geom.
- Internal Structure
...

$M_{\text{GSE}} = 1000 \text{ kg}$
$3000 \text{ kg}$
$10,000 \text{ kg}$
$20,000 \text{ kg}$
Part I. Low-Velocity High-Mass Wide-Area Blunt Impact

- ground service equipment (GSE) impact – known major source of damage

Part II. High Velocity Hail Ice Impact

- Investigate damage formation to composites
  - monolithic, skin+stringer, sandwich
- Establish methodology for damage initiation prediction and failure threshold force scaling
- Develop models predicting impact damage extent
Ice Impact Activity Overview

- Experimental:
  - damage resistance of Toray T800/3900-2 unidirectional tape
    » 1.59 to 4.66 mm thick quasi-isotropic panels
  - high velocity ice sphere impact
    » 38.1, 50.8, and 61 mm diameter
  - established failure threshold energy (FTE) and failure threshold velocity (FTV)

- normal and glancing (20 to 40°) impact on monolithic
  » stringer-stiffened panels to be investigated in summer/fall 2011
- Sandia Lab collaboration – advanced NDI to detect and image damage state

- Modeling – seeking to establish prediction capability for:
  - onset of delamination – cohesive zone elements in explicit/dynamic FEA
  - extent of damage (delamination + fiber failure)
  - skin-stringer interaction and damage under ice impact – normal, glancing
## FEA Results – Normal Impact

### Failure Threshold Experiments and Modeling Results Summary:

<table>
<thead>
<tr>
<th>Panel Type (Thickness)</th>
<th>SHI Diameter</th>
<th>FTV Experimental Value (10% Threshold) [m/s]</th>
<th>FTV FEA Value (average) [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 ply (1.59 mm)</td>
<td>38.1 mm</td>
<td>115</td>
<td>107</td>
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<tr>
<td></td>
<td>50.8 mm</td>
<td>91</td>
<td>92</td>
</tr>
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<td></td>
<td>61.0 mm</td>
<td>65</td>
<td>87</td>
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<tr>
<td>16 ply (3.11 mm)</td>
<td>38.1 mm</td>
<td>154</td>
<td>165</td>
</tr>
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<td></td>
<td>50.8 mm</td>
<td>121</td>
<td>137</td>
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<tr>
<td></td>
<td>61.0 mm</td>
<td>96</td>
<td>125</td>
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<tr>
<td>24 ply (4.66 mm)</td>
<td>38.1 mm</td>
<td>178</td>
<td>205</td>
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<tr>
<td></td>
<td>50.8 mm</td>
<td>154</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>61.0 mm</td>
<td>127</td>
<td>152</td>
</tr>
</tbody>
</table>

### Model Details:

- **Ice Model**
  - UCSD-developed ice projectile model (UCSD MS Thesis – Tippmann 2011)
  - strain rate sensitive strength

- **Composite Target Panel**
  - solid elements – ply-by-ply layers
  - cohesive zone elements between layers
  - all model properties from literature – no “tweaking” or parameter adjustments

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**Tentative Values - Being Refined**
Glancing vs Normal Impact
8 and 16 Ply Panels – Impact at 20° and 40° by 38.1, 50.8, & 61 mm Ice

Damage comparison: 16 ply panels (3.15 mm) impacted with 50.8mm SHI
- Glancing impact (40° w.r.t. normal)
  - Velocity: 178 m/s
    - Energy: 982 J
  - Damage area: 4,000 mm²
- Perpendicular impact
  - Velocity: 127 m/s
    - Energy: 488 J
  - Damage area: 4,101 mm²

Define Scaling Relationship

Delamination shape at onset similar. Damage extent at higher velocity under investigation.
Benefit to Aviation

Wide Area Blunt Impact
- Understanding of damage produced from GSE impact events
  - provides critical information on mode and extent of seeded damage, particularly non-visible impact damage (NVID) from blunt impact threats
  - what inspection technique should be used? where?
- Establish analytical capability to predict blunt impact damage – relate to field operations
- Identify how to detect/monitor occurrence of damaging events
  - e.g., video cameras and sensors that can help to determine impact energy

Large Hail Ice Impact
- Damage resistance established by experimental database – allows for skin sizing
  - understanding of what ice impact threat conditions causes damage on an aircraft – ice size, velocity, impact location on aircraft, etc.
  - effects of internal structural components (e.g., stringers)
- Models predicting damage onset (i.e., FTE)
  - reduce amount of testing required and allow many configurations to be explored
  - accurate ice projectile model is critical for accurate target response
Looking Forward – Ongoing/Future Plans

- Conduct *dynamic* blunt impact experiments
  - completion of Phase I “StringerXX” panels loaded by D-bumper
  - Phase II large frame specimens 4 bays/5 frames loaded with cylindrical rubber bumper
  - relation between quasi-static indentation vs dynamic impact

- Developing high fidelity FEA modeling capability
  - predict damage initiation, progressive failure process, damage extent, energy absorption
    - correlation to large panel test results and supporting small coupon data
  - effective representation of delamination – implementation into shell-based models

- Developing reduced order models
  - estimate damage onset for wide parameter range: GSE mass, velocity, impact location
    - based on critical force and energy threshold
  - relate test results to GSE field operations

- Investigate glancing impacts effects
  - define scaling relationships via momentum and angle
  - moving contact area – e.g., pushing across multiple stringers

- Consideration other primary structure types – e.g., wing, tail

- Hail ice-specific: investigate damage resistance and damage morphology of sandwich construction and stiffened skin

- Education/Training: dissemination of results, workshops
End of Presentation.

Thank you.