Impact Damage Formation on Composite Aircraft Structures

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FAA Sponsored Project Information

- **Principal Investigators & Researchers**
  - Hyonny Kim, Associate Professor, UCSD PI
  - *Prof. Tom Hahn, UCLA PI – sending subcontract to UCSD*
  - Gabriella DeFrancisci, Graduate Student, UCSD
  - Daniel Whisler, Graduate Student, UCSD (completing Aug 09)
  - Jennifer Rhymer, Graduate Student, UCSD
  - Zhi Chen, Graduate Student, UCSD

- **FAA Technical Monitor**
  - Curt Davies

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

- **Industry Participation**
  - Airbus, Boeing, Bombardier, Cytec, Northwest Airlines, San Diego Composites, United Airlines
  - Govt lab: Sandia National 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
Parallel Project Activities

Low-Velocity High-Mass Wide-Area Blunt Impact
- ground vehicles and ground service equipment (GSE) impacts

High Velocity Hail Ice Impact
Low-Velocity High-Mass Wide-Area Blunt Impact Project Overview

- **Project Partners**
  - Team Members: Bombardier, Cytec, San Diego Composites,
  - Consultants: JC Halpin (aircraft), Jack Bish (automobile crash)
  - Other Participants: Airbus, Boeing, United Airlines

- **Overarching Objectives of Blunt Impact Project (Multi-Year Effort)**
  - Identify which blunt impact scenarios are:
    - commonly occurring
    - of major concern to airlines, OEM
  - Develop Methodology for Blunt Impact Threat Characterization and Prediction
    - establishing relationship between full-barrel vs. “small” panel BC’s
    - identification of key phenomena and parameters that are related to damage formation
      - how affected by bluntness?
      - failure initiation thresholds
    - focus: what conditions relate to **development of massive damage** occurring **with minimal or no exterior visual detectability**?
      - can this be tied to a **self evident** event? (self reported or system-based)
  - Damage tolerance assessment of blunt impact damaged structures
    - loss of limit load capability?
    - ID structural configurations and details more prone to this loss of capability
Logic Diagram for Low Velocity High-Mass Wide-Area “Blunt” Impacts

Characterizing Threat Sources & Locations
• Runway Ops.
• Others

Understanding Damage
• Large Area Damage Formation
• Experimental Verification

Modeling Large Area Damage
• High-mass
• Low velocity
• Simulation tools

Structural Assessment
• Characterization
• What level required to compromise Residual strength?

Design Criteria
• Decision Criteria for Inspection & Repair

What
When
How
Where
Other

Inspection for Cause?

UCSD’s Role
- ongoing activity in all three areas
Understanding Damage

Achieved by Conducting Tests:

- Two different specimen types defined during two Workshops at UCSD (1/23/09 & 7/1/09)
  - Frame Specimen
  - Stringer Specimen

- Specimens intended to be representative of large commercial aircraft fuselage
  - geometry
  - failure modes produced

Blunt Impact Test Phases

- **OEM Hardware**
  - 1/4 to 1/2 Barrel Size
  - Vehicle Impacts

- **Large Panel**
  - e.g., 5 Bays
  - Damage Excitation
  - Damage Thresholds
  - Model Correlation

- **Basic Elements**
  - Excite Key Failure Modes
  - Model Correlation Data
  - Understand Damage Formation & Relationship to Bluntness Parameters

Increasing Length Scale, Complexity, and Specificity

Modeling Capability Development & Correlation with Test are Key Aspects at Each Level

Scaling, B.C. Effects

Scaling, B.C. Effects Dynamics

Current phase of activity: Test specimens are starting to be built.
Test Specimen Types

Transition Zone – focus defined in 7/1/09 UCSD Workshop by industry participants
- includes end of bumper
- phenomena not present in “steady state” zone
  » biaxial bending in skin (affects visual detection?)
  » shear in stringer-skin interface

Frame Specimens
- half-width line loading

Stringer Specimens
- centrally “point” loaded

Full Barrel Idealization

Contact Across Several Frames

“Steady State” Zone

Transition Zone

~6-8 ft. Wide Bumper
Frame Specimen Loading

“Half” Line Loaded, Panel Supported 4 Sides

Tests to be conducted at UCSD’s Large-Scale Powell Structural Research Labs
Frame Specimen Details

- Specimens primarily focused on damage development to circumferential frame members and their connection to the skins
- Quasi-isotropic layups, thickness ~ 0.12 in.
- Frame bolted to shear ties which are bolted to panel skin

BC stiffness on ALL FOUR sides to be determined via full barrel FE models (ongoing activity)
Frame Specimen Details
Stringer Specimens

- Specimens focused on damage formation to stringers and their connection to the skins
- Quasi-isotropic layups
- Co-cured stringers

Shear Ties Directly Mount Here

2 and 3 Stringer Versions

Stringer Versions

12" 36"

Department of Structural Engineering
Logic Diagram for Low Velocity High-Mass Wide-Area “Blunt” Impacts

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Structural Assessment-
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- What level required to compromise Residual strength?

Design Criteria
Decision Criteria for Inspection & Repair
- What
- Where
- Other

When
How

Inspection for Cause?
Blunt Impact Threat Characterization

- Surveys to industry – conducted in 2008
- Blunt Impact Workshop held at UCSD campus January 23, 2009
  - presentations from airlines identified ground service vehicles as key source
- LAX observation – March 19, 2009
  - direct observation of ground operations at United Airlines ramps
    - quantitative information extracted from photos, video documentation
    - discussion with personnel
  - much thanks to Eric Chesmar and United Airlines for hosting activity

GSE bumpers and walkway bumper

Belt loader
LAX Video Analysis: TUG Belt Loader Approach

TUG Belt Loader Approaching B757

TUG Vehicle Weight: 6680 lb (3030 kg)

Velocities as high as 2 mph are realistic within close proximity of the aircraft

Kinetic Energy:

- 1515 J at 1 m/s (1117 ft-lbf at 2.24 mph)
- 379 J at 0.5 m/s (280 ft-lbf at 1.12 mph)
Impactor Geometries to be Tested

- Rigid 12” radius impactor
- Rigid 3” radius impactor
- Soft Bumper (actual product)
- Rigid 12” radius line loading impactor
- Rigid 3” radius line loading impactor
- Bumper line loading impactor

Stringer Panels: "point" load

Frame Panels: "line" load

Planned Contact Locations
Logic Diagram for Low Velocity High-Mass Wide-Area “Blunt” Impacts

**Characterizing Threat Sources & Locations**
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**Structural Assessment**
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**Design Criteria**
- Decision Criteria for Inspection & Repair

**UCSD’s Role**
- ongoing activity in all three areas

**Inspection for Cause?**

- When
- What
- Where
- How
- Other

- Understanding what is already covered by Design Requirements, Criteria, ---, Ops. Awareness

- Awareness
Simulation Tools

- Use of detailed FE modeling is critical for understanding
  - relationship between “small” panel vs. full barrel behavior
    » how to interpret results from “small” panel test to full barrel
    » how to scale up
  - whether failure modes are relevant and what are each test’s weaknesses
  - how to establish correct boundary conditions so that realistic stress state in “small” panel is achieved
Prospective Failure Modes

- Impactor location between stringers – similar response with R3” and R12” impactors
- Buckling and rolling of frame causes severe bending of shear tie
  - shear tie pull-off / fastener pullout from both skin and frame
  - interlaminar tension in shear tie radius due to opening moments
- Bulging of skin under stringers – mode I debonding

![Diagram showing stress distributions and failure modes](image)
Full Barrel Models

- Full Barrel Model: 19 ft. dia, 20 ft. length
- 7 ft. length blunt impactor
- Deformation localized to quadrants adjacent to impact location
- Plot of normal stress (bending-induced) in frames shows “steady state” and “transition” zones

Normal Stress (S11) Plot
## Status of Ongoing Activities

<table>
<thead>
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<th>Activity</th>
<th>Status:</th>
<th>Ongoing: % Complete</th>
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<th>Notes</th>
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<tr>
<td>Blunt Impact Threats</td>
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<td>Definition</td>
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<td>Lab-Scale Impact Tests</td>
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<td>Basic studies w/ 1, 4, 12 in. dia. impactors (+rubber pad) onto glass/epoxy plates.</td>
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<td>Studies w/ generic geometry. Models of lab-scale impact test specimens.</td>
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<td>Modeling - FEA of Specimens</td>
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<td>Linear matl behavior. Determine high stress &amp; deformation regions. Definition of BCs.</td>
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<td>Barrel/BCs</td>
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<td>Lower-Order Models</td>
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<td>3 to 4 dof spring &amp; mass models for estimation of forces, displ.</td>
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<td>Specimen Design</td>
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<td>Phase I frame and stringer panels.</td>
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<td>Curved panel tool, frame mold.</td>
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<td>Test Fixtures Design</td>
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<td>Quasi-static indentation tests for Phase I.</td>
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Basic Study: Lab Scale Blunt Impact Experiments

- Objectives:
  - Investigate impact damage formation as function of tip radius (i.e., bluntness)
  - Establish database for model development

- Low Velocity Pendulum Impact System
  - instrumented tip, 5.5 kg mass, 150 J capacity

Test Matrix:

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<tr>
<th>Glass/Epoxy Panel Thk (mm)</th>
<th>Number of panels tested for tip radius</th>
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<td>12.7mm</td>
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<tr>
<td>3.18</td>
<td>9</td>
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<tr>
<td>6.35</td>
<td>9</td>
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</tbody>
</table>
Contact force not function of tip radius.

6.35 mm panel

3.18 mm panel
Contact Area & Pressure

Contact area strong function of tip radius.

- R 12.7mm No Dam
- R 12.7mm FTE1+
- R 50.8mm No Dam
- R 50.8mm FTE1+
- R 152.4mm No Dam
- R 152.4mm FTE1+

Energy (J)

Contact Pressure

Average Pressure (MPa)

Area Raw Data

Energy (J)
Lab Scale Impact Tests Summary

Damage Initiation (Delam.) Threshold

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<tr>
<th>T</th>
<th>R 12.7mm</th>
<th>R 50.8mm</th>
<th>R 152.4mm</th>
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<tr>
<td>3.18mm</td>
<td>2.44J</td>
<td>4.44J</td>
<td>10.3J</td>
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<td>6.35mm</td>
<td>6.47J</td>
<td>7.45J</td>
<td>10.8J</td>
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Cracking/Fiber Rupture Threshold

<table>
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<th>R 12.7mm</th>
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<th>R 152.4mm</th>
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<tbody>
<tr>
<td>3.18mm</td>
<td>7.04J</td>
<td>10.3J</td>
<td>N/A</td>
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<tr>
<td>6.35mm</td>
<td>17.0J</td>
<td>25.5J</td>
<td>N/A</td>
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</table>

- Blunter impactor requires significantly higher energy impact to initiate damage – must hit hit harder
  - higher total force (despite lower contact pressure)
    » more internal deflection with higher energy
    » possible to produce more internal damage?
  - LOWER contact pressure developed – less propensity for surface marking?

> 50J
Hail Ice Impact

High Velocity Hail Ice Impact:
- Investigate impact damage initiation and formation to composite panels, including those of skin-stiffened and sandwich construction.
- Develop unified treatment methodology for predicting damage initiation by variety of high speed impactor projectile types – e.g., bird, hail, tire fragment, runway debris, lost access panel, etc.

Project partner: Dennis Roach, Sandia Natl. Labs

<table>
<thead>
<tr>
<th>Panel Thickness</th>
<th>Quasi-Isotropic Layup</th>
<th>Number of Panels Needed for Each Condition *</th>
<th>Material: T800/3900-2</th>
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<tr>
<td></td>
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<td>Hail Dia 1 12x12</td>
<td>Hail Dia 2 12x12</td>
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<tr>
<td>8 plies</td>
<td>[0/45/90/-45]_s</td>
<td>9</td>
<td>9</td>
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<tr>
<td>16 plies</td>
<td>[0/45/90/-45]_2s</td>
<td>10</td>
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<tr>
<td>24 plies</td>
<td>[0/45/90/-45]_3s</td>
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* Matrix set-up: 3 specimens for structural/NDI testing; 3 specimens for trial impact calibration tests; 3 specimens retained for NDI use