"Managing Damage Threats for Composite Structures: Unifying Durability and Damage Tolerance Perspective"
John Halpin (JCH Consultants) and Hyonny Kim (UCSD)

• Damage Threat Assessment
  – Technical & Policy AC20-107B
  – Blunt Impact and Hidden Damage

June 4, 2009. FAA/EASA Meeting. JAL Headquarters, Tokyo
AC20-107B(draft):

7. Proof of Structure-Static. and

• “--- When establishing details for the damage tolerance and fatigue attention shall be given to a through damage threat assessment, geometry, inspectability, good design, good design practice, and the types of damage/degradation of the structure under consideration. “ page 11

• a. Damage Tolerance Evaluation. Pages 12 & 13
  (1) A damage threat assessment must be performed
     (a) -- few industrial standards --
     (b) Foreign object damage ---
     (c) Damage classification ----
The Rational for the Use of the B Basis Allowable
(Why can't we design to the mean, vs...... we need an A allowable.)

• Early 1970 concern;
  – Fighter load exceedances above limit load
  – Composite material scatter greater than metallics.
• Today’s definitions of limit load included this aggressive usage
• Typical fighter load spectrum have a Weibull shape parameters $\alpha_p \sim 6$
  – (UL 1000 less likely LL)
  – Probability of exceeding UL of 0.001
• Typical Weibull material shape parameters;
  – $\alpha_R \sim 25$ Aluminum (5% COV)
  – $\alpha_R \sim 20$ Graphite High Strain Fiber composites (6.2% COV)
• Risk of failure (probability of large exceedances occurring with low strength item);
  – $1.5 \times 10^{-3}$ for Graphite composites
  – $1.0 \times 10^{-3}$ for Aluminum structure
• COMPARABLE RISKS

Transport aircraft have load spectra with less variability (fighter maneuver spectrum are sever)
## Status Matrix of Service Induced Impact Damage:

**Composite Structures: 3.2.24**

Should Damage Tolerance Threat Requirements be Defined by a “B or A Level Threat Allowable”?

<table>
<thead>
<tr>
<th>Threat</th>
<th>Test Protocol</th>
<th>Simulation Models</th>
<th>Threat Allowable</th>
<th>Self Evident Event</th>
<th>Impact Location(s); Zones 1 &amp; 2</th>
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<td>Gel-pack</td>
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<td>Hail</td>
<td>Simulated Hail Ice, SHI?</td>
<td>Yes Maturing</td>
<td>“B” Up-date MIL HDBK 310</td>
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<td>Others? Lighting Strike</td>
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Four Different Size Distributions Suggested by Data.
Composite US Hail Threat Data Base for 1955 to 2006 (2829 Reports), Has Been Developed and Is Summarized in the Table
Insert Table Summary for the US Hail Distribution: 1955-2006 Data Base into 12.5.2.3 Ground Hail

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Note: Hailstone Extremes Defined by MBK-310 "GLOBAL CLIMATIC DATA FOR DEVELOPING MILITARY PRODUCTS" as 0.1 percent risk, Gringorten, 1.1. (1972) Hailstone Extremes for Design, AFCRL-TR-72-0081, Air Force Surveys in Geophysics No. 238, AD743831.
Example Problem: Hail impact
In-flight and On-ground - 2.4 inch hail (98% Threat)

Weight ~ 0.24 lbs

\[ V_T \sim 100 \text{ ft/sec.} \]

\[ V_{A/C} \sim 720 \text{ ft/sec.} \]
and 0 ft/sec (ground)

Determine normal velocity vector & Kinetic Energy components.
Example Problem: Hail impact
In-flight: Relative Closing Velocity Vector Approach

\[ V_N = \sqrt{(-100)^2 + (724^2)} = 727 \text{ ft/sec} \]

\[ \cos \beta = -100/720 = 0.1389 \]

\[ \beta = 98 - 90 = 8^0 \]

\[ \sim 8 \text{ degrees below flight path} \]

\[ V_T (\text{Normal}) = 727 \cos 42^0 = 540 \text{ ft/sec} \]

\[ \text{KE(normal)} \sim 12,772 \text{ in-lbs} \]
Comparison: In-Flight and Ground Hail impact

Ground

- 90° impact
  - KE_T = 438 in-lbs
- 40° impact
  - KE_T = 335 in-lbs

In-Flight

- KE(40°)~12,772 in-lbs

Ground hail impact condition

KE_T = 438 in-lbs as ball of 0.235lbs collides with surface at 90°

\[ KE_N(TV) = KE_T \cos 40° \]

= 335 in-lbs

\[ V_T = 100 \text{ ft/sec.} \]

\[ V_A/C = 0 \text{ ft/sec} \]

\[ \alpha = 40° \]
Probabilistic Parameters for an In-flight Hail Requirement; Primary Structure Elements

<table>
<thead>
<tr>
<th>Cumulative Probability of Occurrence, %</th>
<th>Air vehicle Velocity, KTAS</th>
<th>Hail Diameter, inches</th>
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<td>90</td>
<td>375</td>
<td>1.76</td>
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<td>95</td>
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<td>99</td>
<td>455</td>
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NOTE: Kinetic Energy requirements would use these values and the relative velocity calculation for the individual subassemblies.
High velocity Simulated Hail Ice Ball Impacting a Toughened Graphite-Epoxy Panel (data by H. Kim)

Oblique View from Impact-Side

Oblique View from Back-Side (white stripe painted on panel)

Test Details:
42.7 mm ice sphere at 106 m/s impacting 1.22 mm thick carbon/epoxy panel
Hail Impact Damage Size is Dependent on Kinetic Energy
Demonstration Failure Threshold Energy
0.072 in. thick panel Woven Carbon/Epoxy Panels impacted by 1.68 in. Dia. Simulated Hail Ice, (data by H Kim)
Parametric Correlation For SHI Impact Data by H. Kim

\[ FTE = \alpha \cdot \left( \frac{V_{HS}}{G_{HS}} \right) = \alpha \cdot \frac{\pi D^3}{6} \cdot \left( \frac{\tau_{ILS}}{G_{ILS}} \right) \]

- \( D \) = Hail diameter, meters
- \( H \) = thickness
- \( G_{ILS} \) = Transverse shear Modulus, \( \sim 517 \) GPa
- \( \tau \) = Interlaminar shear strength \( \sim 100 \) MPa
- \( \alpha \) = “Normalized FTE”

- \( FTE \)
- \( Poly. (FTE) \)
Withstanding Thickness Estimates for Ground Hail Exposure Impacting at 90 degrees to Surface

Ground hail impact occurs at Terminal Velocities, TV, and Kinetic Energies, J,

\[ KE \ (TV, \ J) \rightarrow FTE = \alpha \ (506382) \ D^3 \]

Rearranging the equation:

\[ \alpha = KE \ (TV, \ J) /\{506382 \ D^3\} \]

Using the previous table & graph the H/D ratio is defined by \( \alpha \)

<table>
<thead>
<tr>
<th>Cumulative Probability (%)</th>
<th>Hail Diameter, inches</th>
<th>Impacting Velocity, ft/Sec</th>
<th>Impacting Kinetic Energy, Joules</th>
<th>“Normalized“ Impacting Kinetic Energy, ( \alpha )</th>
<th>H/D</th>
<th>Damage Withstanding Thickness, inches</th>
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Current dual aisle fuselage skins ~ ECONOMIC LIMIT ~ 0.070 to 0.090 inches thick
What Metric Should the Designer Use? Is BVID a Design Parameter? What Makes Physical Sense, Damage Threshold or the Bottom of the CAI Curve?

Which Approach Recognizes the Benefits of Toughness and Provides the Basis for Continuing Airworthiness?
Self Evident Rogue Events
Impact Damage Tolerance-Management: Example of Random Discrete Threat Events
Damage Tolerance Awareness Criteria?

(Durability and Continuing Airworthiness)

- **Self Evident Damage?**
  - Cracking and corrosion
  - Fail-safety; Readily detectable means that a local failure or partial failure would be apparent from in-flight or post-flight visual observations, or they would be obvious during a scheduled visual inspection conducted within the predicted safe period of unrepaired usage.

- **Self Evident Damaging Events**
  - Bird strike, tire rupture, hail, --
  - Damage Threats EXTERNAL TO AIRFRAME
    - Threat Characterization?
    - B-Allowable and/or enveloping?
    - Performance based criteria (FAA Tire rupture example)
    - Typically impact threats
  - Maintenance for Cause option?

- **Ground Operations Concerns**
  - Blunt Impact with GSE & Buildings
  - Hot GSE engine exhaust impinging airframe surface
    - exceeding composite in-service $T_G$
The FAA Has Proposes 5 Damage Detection Categories.

**Historical (FAR & JSSG) Implied Risk for Quantified Damage Threats**

- **Category 1**: They are damages that may go undetected by field inspection methods (or allowable defects). Ultimate loads capability must be retained anytime (birdstrike, MIL ground-hail, tool drop & FOD). A fatigue substantiation allowing for these damages is a sort of flaw tolerant safe life demonstration including completion of ultimate loads capability.

  *Category 1 90% KE Level (Damage Threshold?)*

- **Category 2**: Damage detected by field inspection at specified intervals. They are the so-called Visible Impact Damage (VID). A reliable inspection interval must be demonstrated and Limit Load capability retained.

  *Category 2 90% or 95% KE Level (Self Evident Event?)
  (Minimum Period of Unrepaired Service Usage?)*

- **Category 3**: Obvious damage detectable within a few flights. They are damages obvious to operations in a "Walk Around" inspection or due to a loss of form/fit/function. Quick detection must be demonstrated and Limit Loads capability retained.

  *Category 3 95% KE Level (Self Evident Event?)*

- **Category 4**: Discrete source damage known by pilot to limit flight maneuvers. They are damage in flight from events that are obvious to pilot (rotor burst, birdstrike, lightning, in-flight hail). "Get home" capability must be retained as defined for discrete source events.

  *Category 4 99% KE Level (Self Evident Event?)*

- **Category 5**: Severe damage created by anomalous ground or flight events. They are damages due to RARE SERVICE EVENTS or to an extent beyond what is considered in design. Collision with a vehicle on ground, or severe ground hail exposure, are typical of such events. Immediate reporting is required with new substantiation.
Lightning Damage?

• Rogue Event
• Inspection and maintenance for cause?
  – Structural integrity; Damage Tolerance
    • Damage threshold?
    • Punch through criteria?
  – Electo-magnetic integrity
  – Equivalent to local thermal spike or local impact?
Overlapping AIR WORTHINESS MANAGEMENT:

• Preventive design

• Maintenance for Cause (discrete source damage, JSSG) when possible:
  – Bird strike, FOD, Hail Ice (in-flight & on-ground), Tire rupture (on-ground, in-flight), Lightning, & --- (Threats characterized, structures zoned, cause and effect --)
  – Individual aircraft focus
    ▪ Self evident damaging event
    ▪ Visually self evident damage?
    ▪ Inspections & maintenance (What, When, Where, How?) provides a focused and timely process

• Operations Focused Inspection, management of other damage classes:
  – Other Potential Failure modes:
    ▪ Load induced delamination (maybe heavy landings, --)
    ▪ Thermal induced delamination (GSE exhaust, --)
    ▪ Corrosion & Other
  – Anomalous events (Blunt Impacts, --- )
  – Individual aircraft focus
  – Damage Categories

• General inspection at heavy maintenance (all aircraft)
  – Defined usage or age interval (maybe 10 years)
  – Protection from hidden damage, unknown events, ---
  – Provides data for updating individual aircraft air worthiness management.

• Balancing Risk
Typical A/C plan form:
Different Exposed Areas and Impact Threats
Blunt Impact

- Low velocity, high mass large contact area event, i.e., “Blunt impact” (e.g., ground vehicle impact, GSE) where significant damage may not be clearly visible:
  - representing 30-40% plus of aircraft damage
  - IATA statistics suggest 767 class aircraft experiencing about 1.5 ground impact events per aircraft per year.
  - ground impact frequency is an OPERATIONAL ISSUE independent of airframe construction
  - typical GSE impact could involve a vehicle of about 6,000 lbs traveling at 3 to 5 miles per hour (4.8 to 8 kilometers per hour) distributed across an area of 1 to 4 square feet (0.1 to 0.37) square meters.
Logic for Low Velocity High-mass Large Area, "Blunt," Impact

In-service Experience

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?

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

Inspection For Cause?

When
What
Where
How
Other
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

Design Criteria
  - Decision Criteria for Inspection & Repair

When
  - What
  - Where
  - Other

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

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

Inspection for Cause?
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
LAX Observation

- Focus on Ground Service Equipment (GSE)
  - major source of damage
  - damage anticipated near doors and access panels
  - also observed further away in unreinforced areas

- Other events possible, such as:
  - maintenance equipment or unattended GSE blown into the aircraft
  - aircraft settling onto equipment during the fueling and passenger loading
  - luggage cart can impact a belt loader, forcing contact between the belt loader and aircraft

- Different aircraft size/geometry influences impact sources
  - small aircraft
    » at risk of contact with lower GSE
    » more crowded at gate
  - larger aircraft have difficult docking angles (e.g., at aft door); risk for scraping body fairing
Additional Observations

- Patches observed significant distance away from door.
- Almost touching, low incidence angle.
- Movement direction.
- Potential low angle contact w/out bumper.
- Contact with aircraft.
Video Analysis: Catering Truck Approach

Catering Vehicle Weight: 5000 lb (2270 kg)
Velocity of \(~0.25\) m/s within 10 cm of stopping

Kinetic Energy:
- 284 J at 0.5 m/s (209 ft-lbf at 1.12 mph)
- 71 J at 0.25 m/s (52 ft-lbf at 0.56 mph)
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)
Department of Structural Engineering

**Roadmap for Low Velocity High-Mass Wide-Area “Blunt” Impact Project**

- **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

- **Inspection for Cause?**
  - When
  - Where
  - How
  - Other

- Understanding what is already covered by Design Requirements, Criteria, ---, Ops. Awareness
Blunt Impact Damage Experiments

Full-Scale Test Specimens

- Two different specimen types defined during Jan09 Workshop at UCSD
  - Frame Specimen
  - Stringer Specimen

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

Full-Scale Blunt Impact Test Phases

- 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

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

Phase III (Year 3)
Phase II (Year 2)
Phase I (Year 1)
Frame Specimens

- Specimens primarily focused on damage development to circumferential frame members and their connection to the skins
- Quasi-isotropic layups
- Frame bolted to shear ties which are bonded to panel skin

Simply-supported + rotational stiffness

Free

Simply-supported + rotational stiffness
Stringer Specimens

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

- Rigid 3.5” radius impactor
- Rigid 12” radius impactor
- Soft Bumper (actual product)
- Rigid 12” radius line loading impactor
- Rigid 3.25” radius line loading impactor
- Bumper line loading impactor

Planned Contact Locations

“point” load

“line” load
Roadmap for Low Velocity High-Mass Wide-Area “Blunt” Impact Project

Department of Structural Engineering

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- Characterization
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Design Criteria
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When
- What
- Where

How
- Other

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

Inspection for Cause?
FEA of Frame Specimens

- 12” radius rigid line loading at 0.5” indentation depth
- Stresses plotted at the midplane
- Peak bending stress in frame (S11)
- Large tensile stresses (S22) exists in shear ties located away from impact location – pull-off loading
- Warpage/rotation of frames (open section)
Summary of Activities

- Blunt Impact Workshop at UCSD in La Jolla, CA – held on Jan. 23, 2009
  - 40 participants from OEM, airlines, agency, industry, academia
  - Summary document posted to website: [http://csrl.ucsd.edu/UCSDbluntimpact/](http://csrl.ucsd.edu/UCSDbluntimpact/)
    - Major source of damage (30-40%) is from ground service equipment, during pushback
    - Frequency of occurrence for composite a/c expected to be same as for metal
    - Need exists for basic experiments and modeling methods

- LAX observation – March 19, 2009
  - Direct observation of ground operations at UAL ramps
    - Quantitative information extracted from photos, video documentation
  - Much thanks to Eric Chesmar and United Airlines for hosting activity

- Specimen design and test definition
  - Test plan (1st ver) issued April 23, 2009 – posted on blunt impact website
  - Working Meeting planned for June 29-July 1, 2009 at UCSD

- Lab scale impact experiments
  - Basic investigation of effects of impactor radius on localized damage development
Roadmap for Low Velocity High-Mass Wide-Area “Blunt” Impact Project

Characterizing Threat Sources & Locations
- Runway Ops.
- Others

Understanding Damage
- Large Area Damage Formation
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- High-mass
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Structural Assessment
- Characterization
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Design Criteria
Decision Criteria for Inspection & Repair

What
Where
Other

When
How

Inspection for Cause?
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:**

<table>
<thead>
<tr>
<th>Glass/Epoxy Panel Thk (mm)</th>
<th>Number of panels tested for tip radius</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12.7mm</td>
</tr>
<tr>
<td>3.18</td>
<td>9</td>
</tr>
<tr>
<td>6.35</td>
<td>9</td>
</tr>
</tbody>
</table>
Peak Contact Force

Contact force not function of tip radius.

6.35 mm panel

3.18 mm panel

Contact Force vs Time
FTE1 for T 3.18mm

- 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+
Contact Area & Pressure

Contact area strong function of tip radius.

**Contact Pressure**

- 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)

Average Pressure (MPa)

Area Raw Data
## Lab Scale Impact Tests
### Summary

#### Damage Initiation (Delam.) Threshold

<table>
<thead>
<tr>
<th>FTE1 for each panel thickness T, impactor tip radius R</th>
<th>R 12.7mm</th>
<th>R 50.8mm</th>
<th>R 152.4mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 3.18mm</td>
<td>2.44J</td>
<td>4.44J</td>
<td>10.3J</td>
</tr>
<tr>
<td>T 6.35mm</td>
<td>6.47J</td>
<td>7.45J</td>
<td>10.8J</td>
</tr>
</tbody>
</table>

#### Cracking/Fiber Rupture Threshold

<table>
<thead>
<tr>
<th>FTE2 for each panel thickness T, impactor tip radius R</th>
<th>R 12.7mm</th>
<th>R 50.8mm</th>
<th>R 152.4mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 3.18mm</td>
<td>7.04J</td>
<td>10.3J</td>
<td>N/A</td>
</tr>
<tr>
<td>T 6.35mm</td>
<td>17.0J</td>
<td>25.5J</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Damage Initiation (Delam.) Threshold:
- For T 3.18mm, the values are 2.44J, 4.44J, and 10.3J.
- For T 6.35mm, the values are 6.47J, 7.45J, and 10.8J.

Cracking/Fiber Rupture Threshold:
- For T 3.18mm, the values are 7.04J, 10.3J, and N/A.
- For T 6.35mm, the values are 17.0J, 25.5J, and N/A.

For T 6.35mm, the values for T 50.8mm and T 152.4mm are 25.5J and N/A, respectively.
Overall Conclusions

- Blunter impactor requires significantly higher energy impact to initiate damage – must 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?

- FEA of blunt impact test specimens shows
  - large internal stress develops for small indentation (0.25 to 0.5 in.)
  - high stresses in frame, shear ties
    » pull-off loading in shear ties away from impact location
Project funding from FAA with cost-share from team members
- part of JAMS COE – technical monitor is Curt Davies
- teaming: JC Halpin, Bombardier, Cytec, San Diego Composites, Sandia, Jack Bish
- ice and other high velocity impacts are also part of this program

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
  - 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 visual detectability?
- 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
Project Timeline (Year 1)

- January 23, 2009 – Blunt Impact Workshop
- February to May – design test specimen (including stress predictions)
- June 29 to July 1, 2009 Working Meeting
  - review UCSD test specimen design
  - detailed test plan development
  - feedback from industry & agencies on direction of project
  - more info at: http://csrl.ucsd.edu/UCSDbluntimpact/
- June & July – test fixtures and manuf. tooling design, material acquisition
  - Cytec will provide prepreg and adhesive
- July & August – fabrication
- late August – conduct stringer panel tests
- September & October – conduct frame panel tests

For more information, contact Hyonny Kim at hyonny@ucsd.edu