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# Impact Damage Formation on Composite Aircraft Structures

2012 Technical Review

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# Impact Damage Formation on Composite Aircraft Structures

- **Principal Investigators & Researchers**
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    - » *Prof. J.M. Yang, UCLA – sending subcontract to UCSD*
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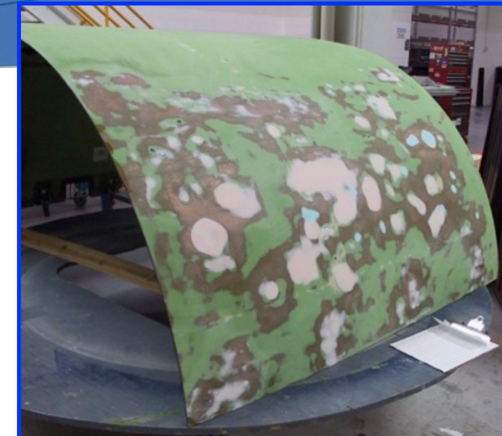
    - » PhD: Gabriela DeFrancisci, Zhi Chen, Jennifer Rhymer
    - » MS: Sho Funai, Mac Delaney, Jacqui Le
  - Undergraduates: Sarah Fung, Jon Hughes, Sean Luong, Isabel Cole
- **FAA Technical Monitor**
  - Lynn Pham
- **Other FAA Personnel Involved**
  - Curt Davies
  - Larry Ilcewicz
- **Industry Participation**
  - Material support by Cytec, San Diego Composites, Boeing
  - Participation by Airbus, Bombardier, UAL, Delta, JC Halpin
  - Collaborations with Sandia Labs, Bishop GMBH (EASA-funded)

# Impact Damage Formation on Composite Aircraft Structures

- **Motivation and Key Issues**
  - impacts are ongoing and major source of (hidden) damage
  - high energy blunt impact damage (**BID**) of key interest
    - involves large contact area, not well understood
    - can exist with ***little or no exterior visibility***
  - **Existing Needs:** (i) establish clear understanding of damage formation from *blunt* sources, (ii) prediction capability
- **Focus: sources of concern are blunt impacts affecting wide area and/or multiple structural elements**



**Hail Ice Impact**

- upward & forward facing surfaces
- low mass, high velocity
- threat: 38-61 mm diam. ice at in-flight speed

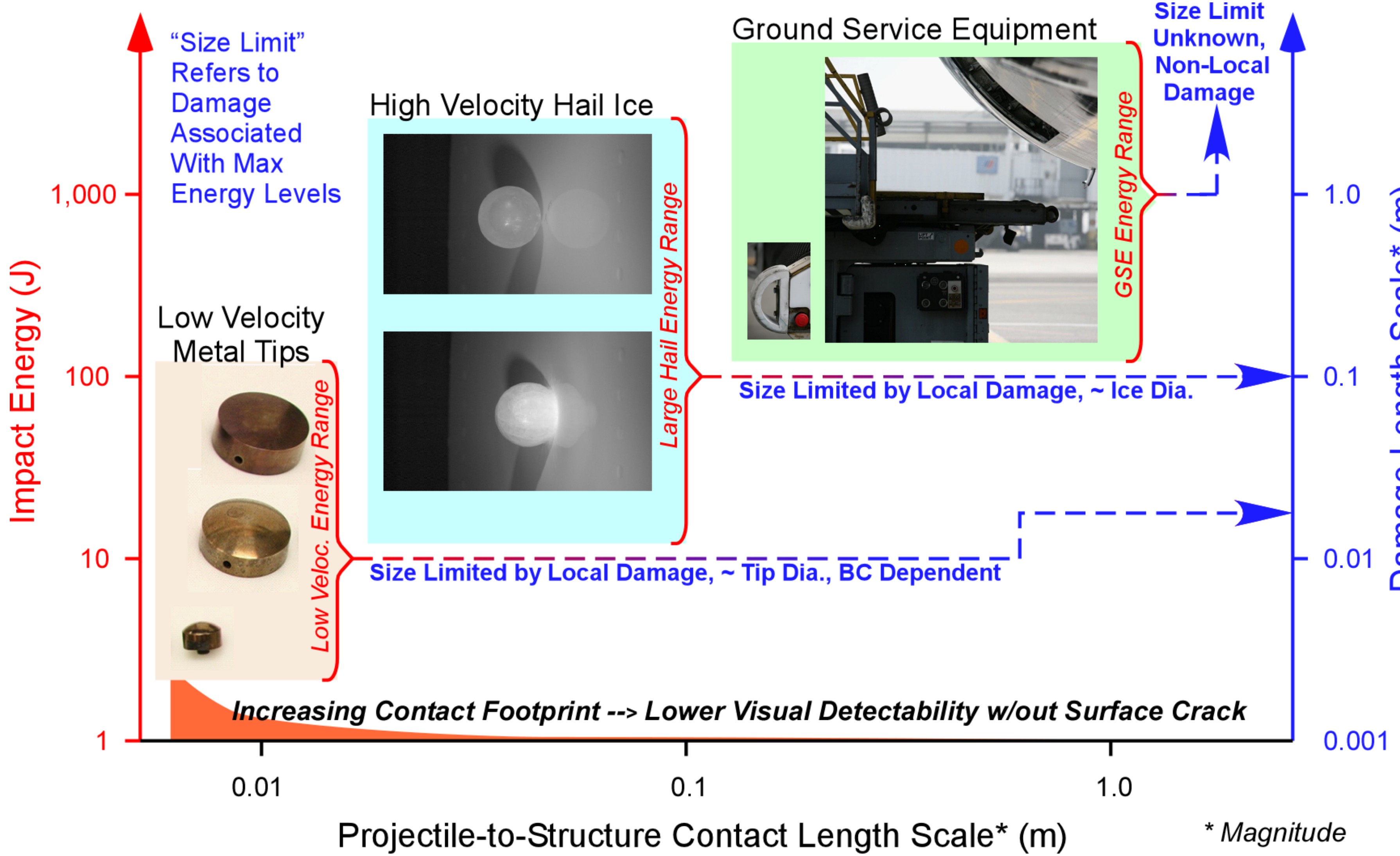
**Ground Vehicles & Service Equipment**

- side & lower facing surfaces
- high mass, low velocity
- wide area contact
- damage at locations away from impact likely
- threats:
  - belt loader ~3,000 kg
  - cargo loader ~15,000 kg

# Impact Damage Formation on Composite Aircraft Structures

- **Objectives**
  - Characterize Blunt Impact threats and the locations where damage can occur
  - Understand BID formation and visual detectability
    - determine key phenomena and parameters
    - how affected by bluntness/contact-area
    - ID & predict failure thresholds (useful for design)
    - what conditions relate to development of significant internal damage with minimal or no *exterior visual detectability?*
  - Develop analysis & testing methodologies, new modeling capabilities validated by tests
- **Approach**
  - Experiments: impact 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, internal stiffeners
    - » low velocity impacts – non-deforming impactor, large radius effects
  - Modeling – nonlinear FEA, analytical
  - Communication of results to industry, collaboration on relevant problems/projects via workshops and meetings (at UCSD, via teleconf)

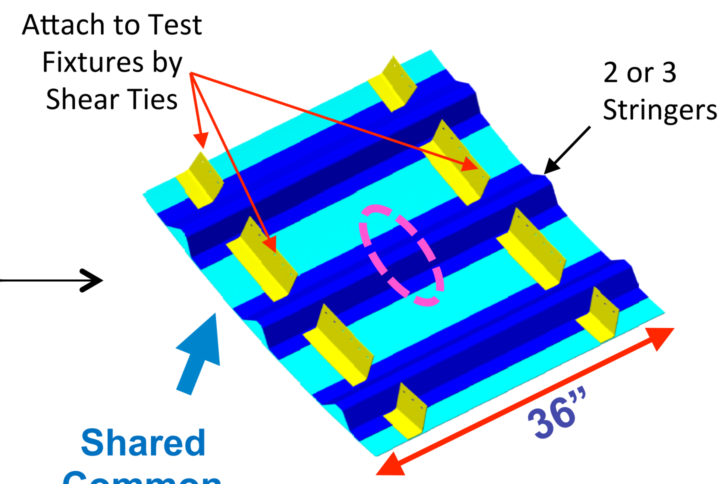
# Blunt Impact Energy-Damage Spectrum



# Ground Service Equipment Blunt Impact

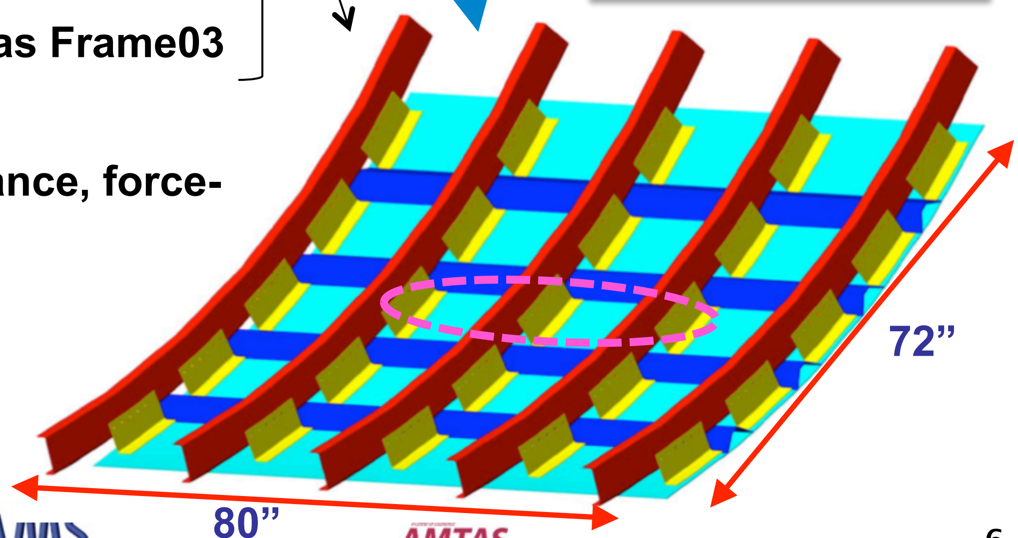
## Summary of NEW Progress

- **Experiments – dynamic loading at 0.5 m/s velocity:**
  - **StringerXX panels**
    - » **Stringer05: 2-stringer panel, D-bumper loading on skin between stringers**
    - » **Stringer06 – 3-stringer panel, loading over center stringer**
  - **FrameXX panels**
    - » **Frame03: 5-frame + 4 stringer panel, long cylindrical-bumper loading across 3 frames on skin between stringers**
    - » **Frame04 – same configuration as Frame03**
- **Model development**
  - **Reduced-order models: energy balance, force-indentation estimation**
  - **Non-linear FEA**
    - » **damage initiation, propagation**




**Shared Common Elements**

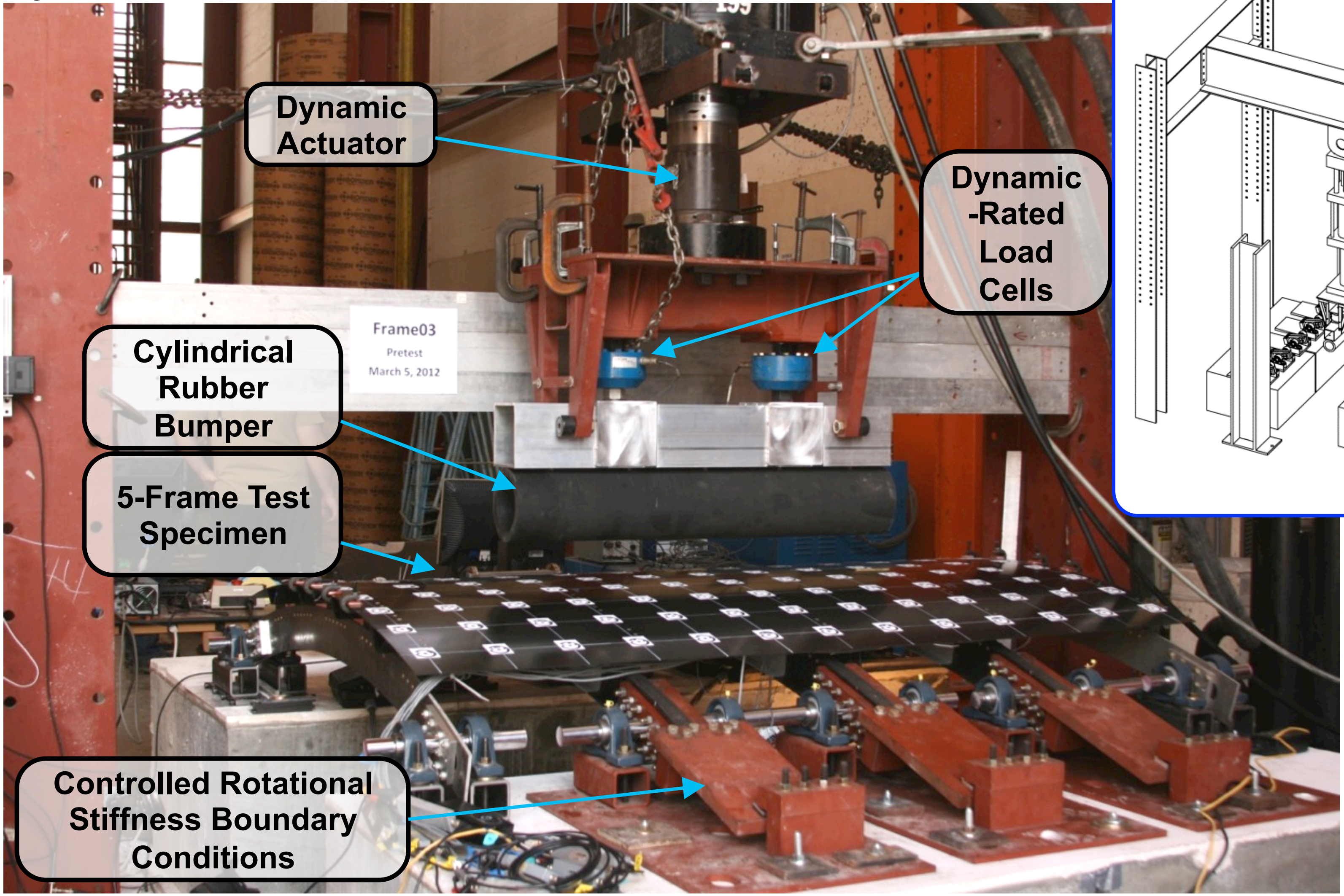
Materials provided by **Cytec**: Z60 / X840

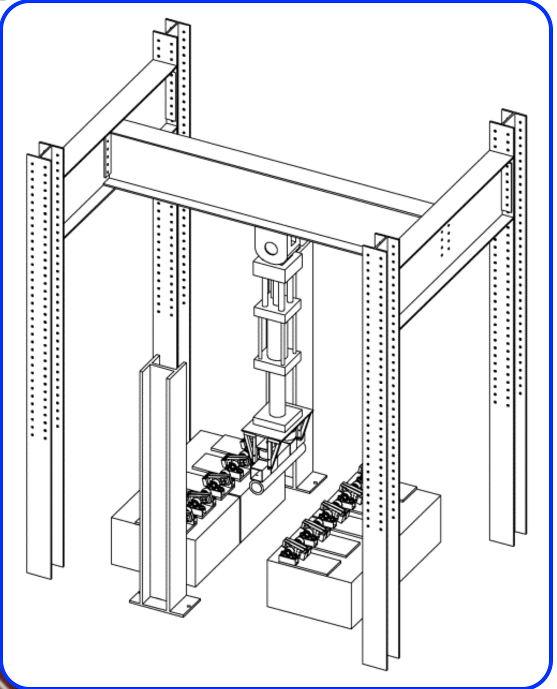



**(Only red color font items summarized in presentation)**

# Large Specimen Frame03 Test Setup

Dynamic Test at 0.5 m/s

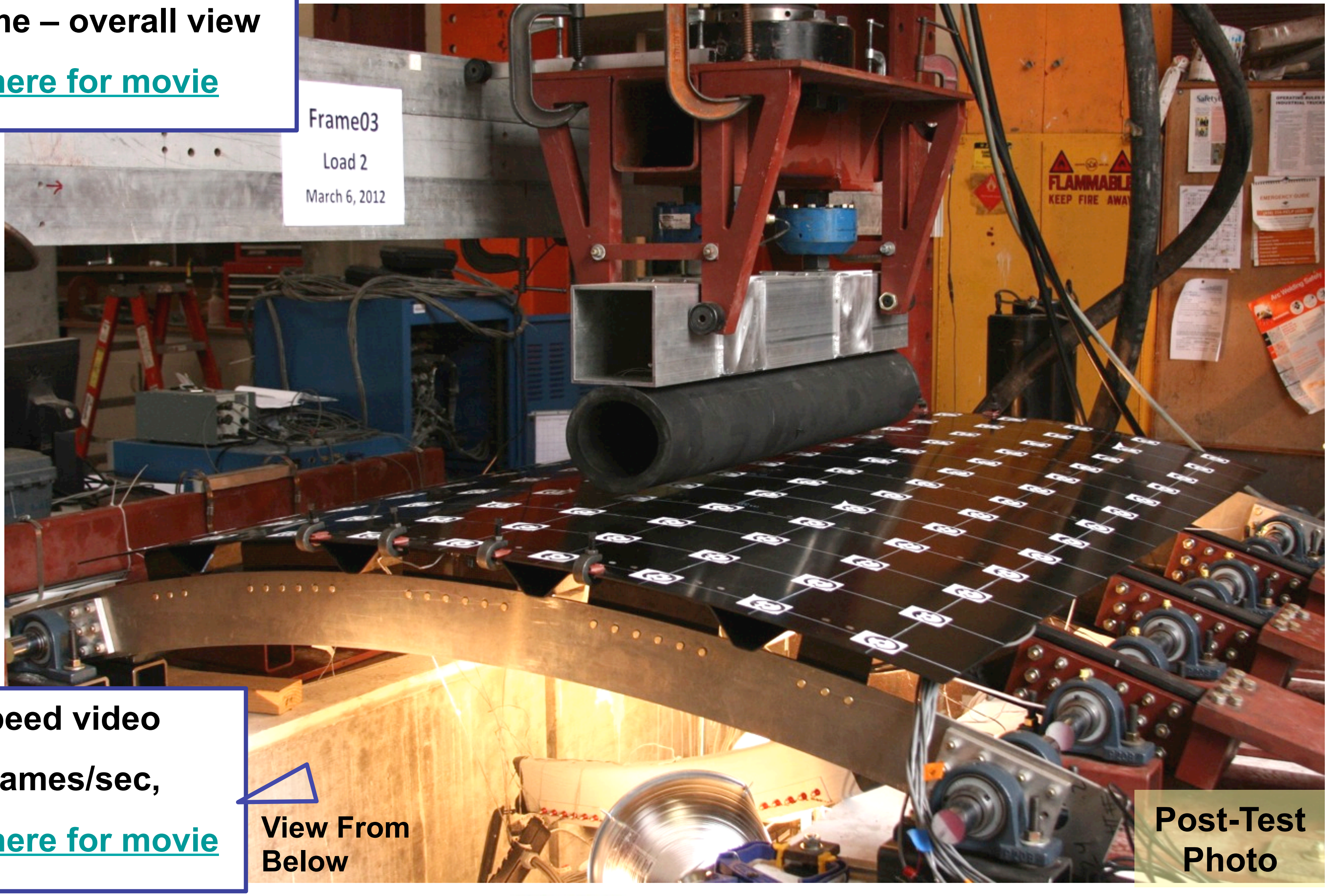


# Frame03 Test Videos

Real time – overall view

- click here for movie




High speed video

6,006 frames/sec,

- click here for movie

View From Below

Post-Test Photo

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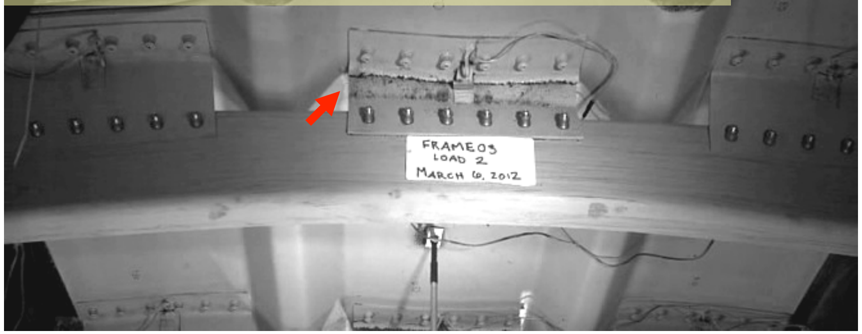
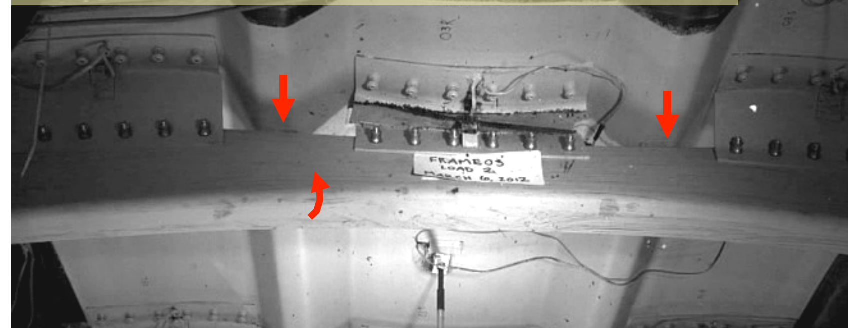
# Sequence Leading to Frame Failure

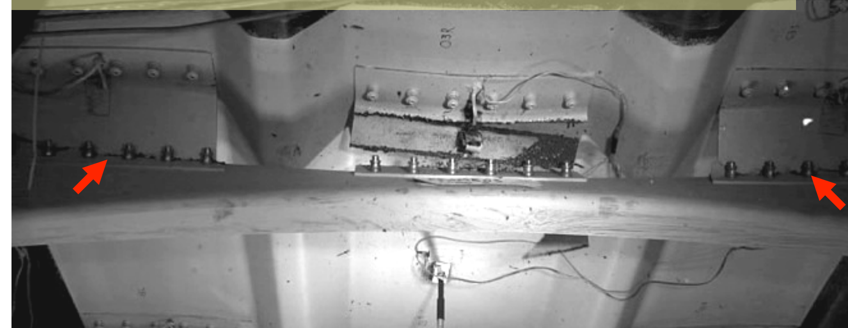
1. Center Shear Ties Fail/Crush (3 Locations)




2. Frames Rotate (Twist) + Contact Stringers



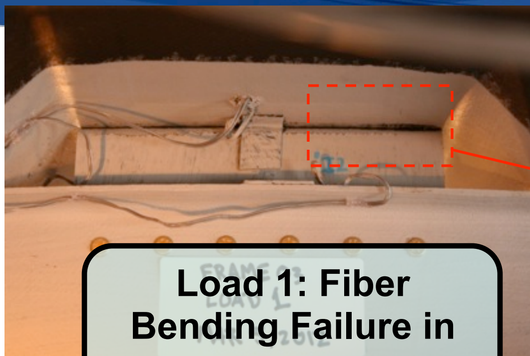
3. Outer Shear Ties Fail in Bending (6 Locations)

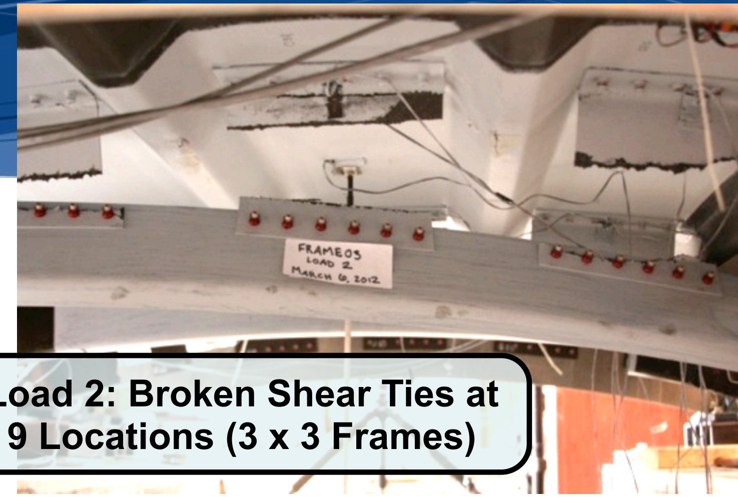


4. Frame Failure - 4 Pt Bending + Torsion (6 Locations)

Ph.D. students Gabriela DeFrancisci and Zhi Chen holding liberated frame fragment which dropped during impact test.

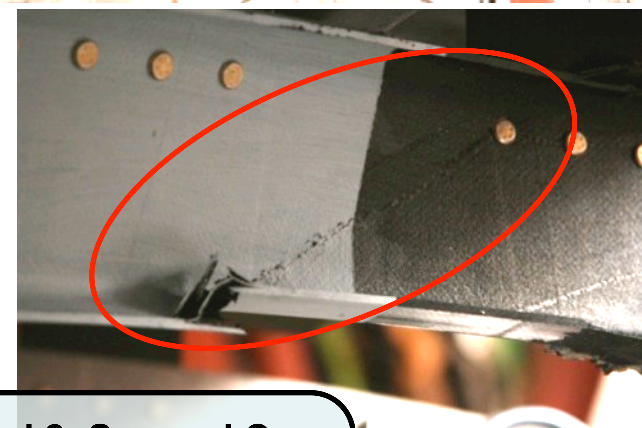
# Frame03 Damage Views

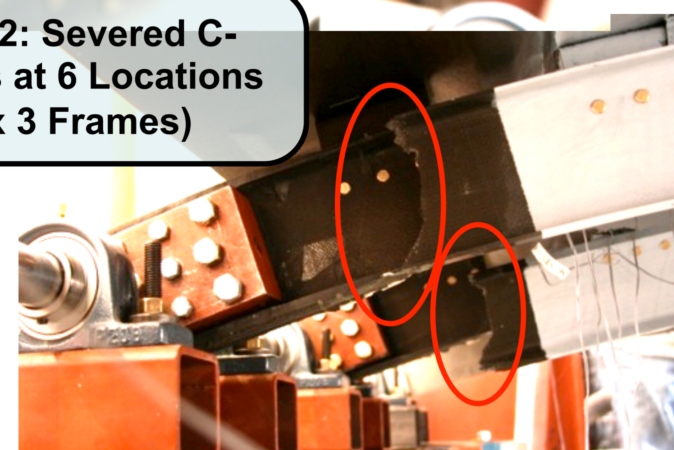


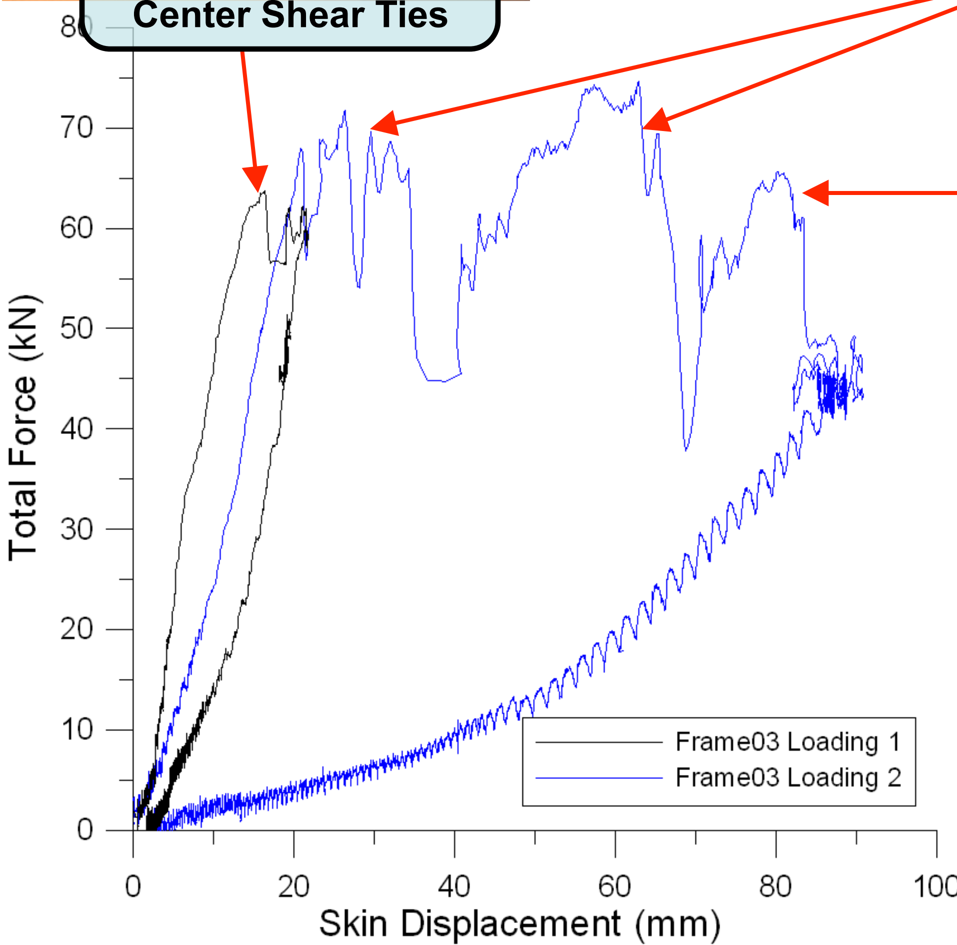

**Load 1: Fiber Bending Failure in Center Shear Ties**

**Load 2: Broken Shear Ties at 9 Locations (3 x 3 Frames)**

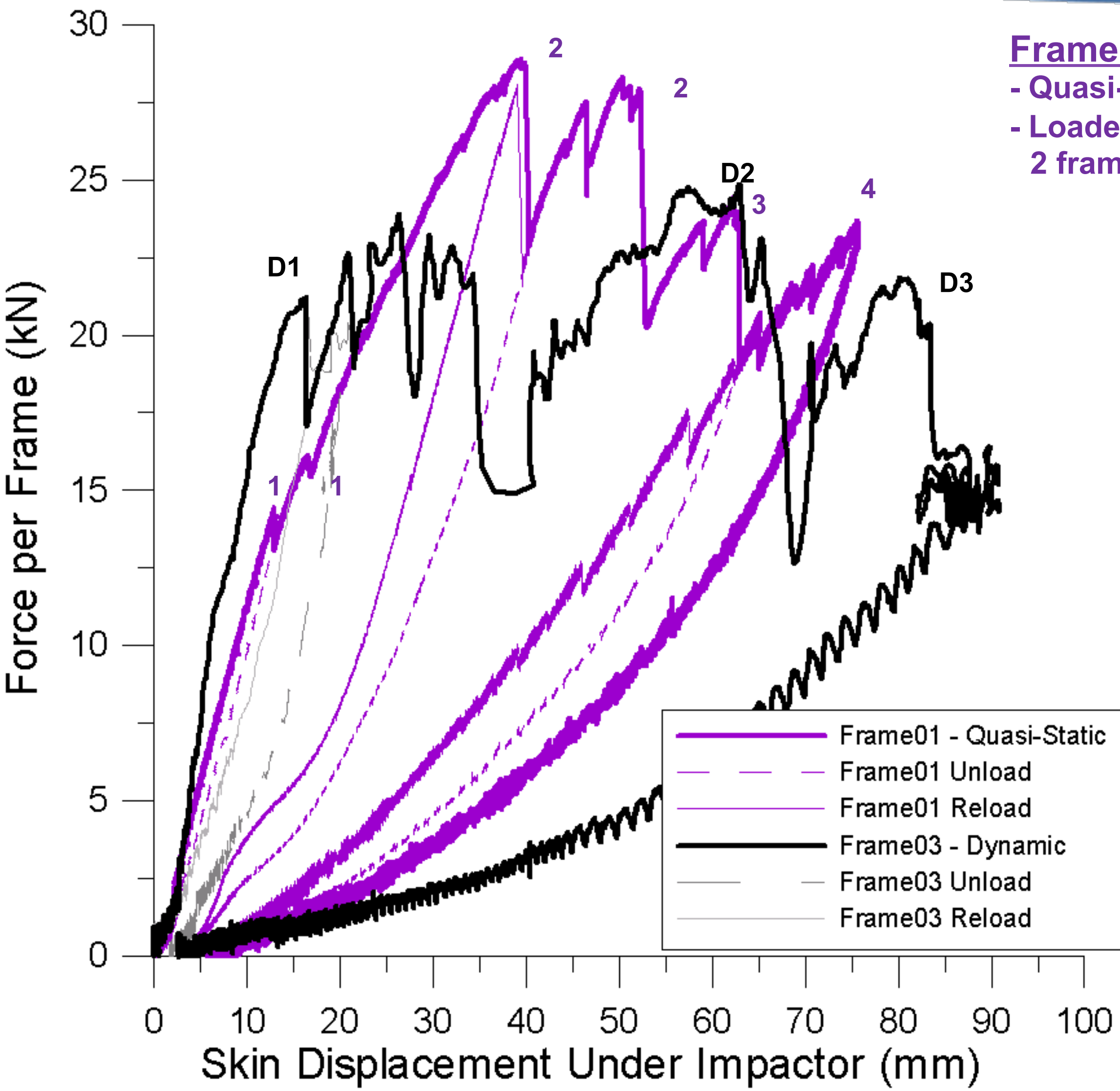




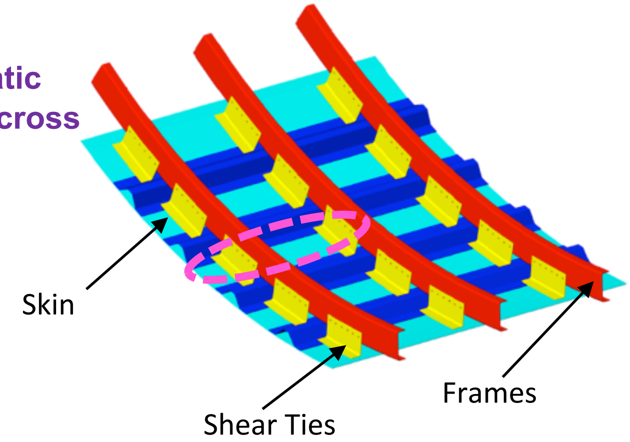
**Load 2: Severed C-Frames at 6 Locations (2 x 3 Frames)**



# Frame03 Dynamic Response vs. Quasi-Static




**Frame01**
**- Quasi-Static**
**- Loaded across 2 frames**



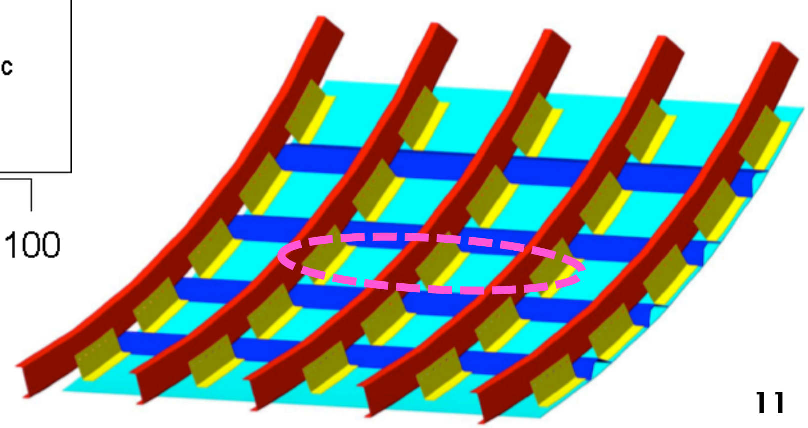

**Frame01 Annotations**

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

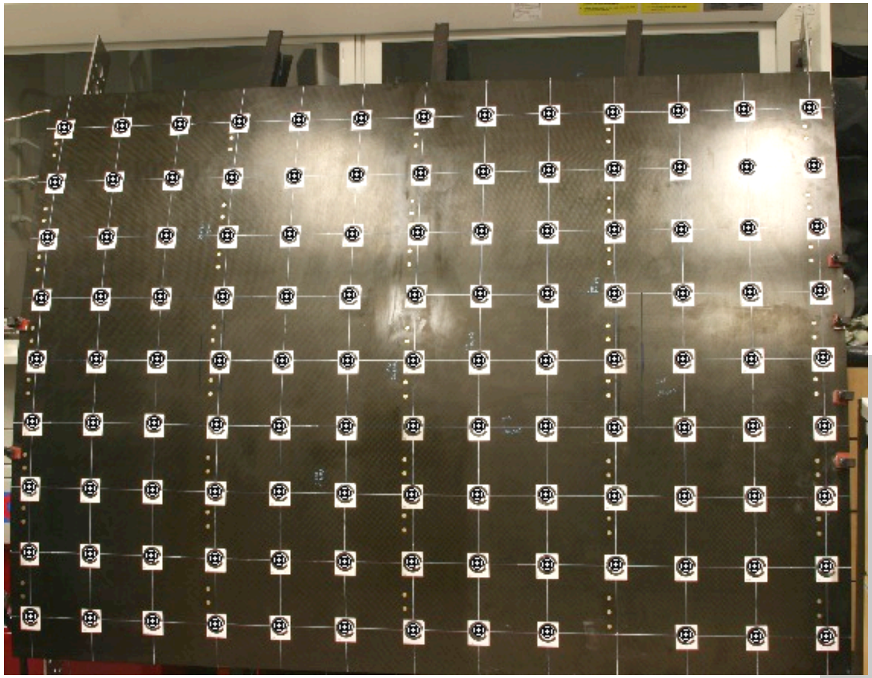
**Frame03 Annotations**

- **D1.** **Ctr. Shear Ties Crush/Bend**
- **D2.** **Outer Shear Ties Bend Fail**
- **D3.** **Frames Severed, Multi-Loc.**

**Frame03**
**- Dynamic Impact**
**- Loaded across 3 frames**



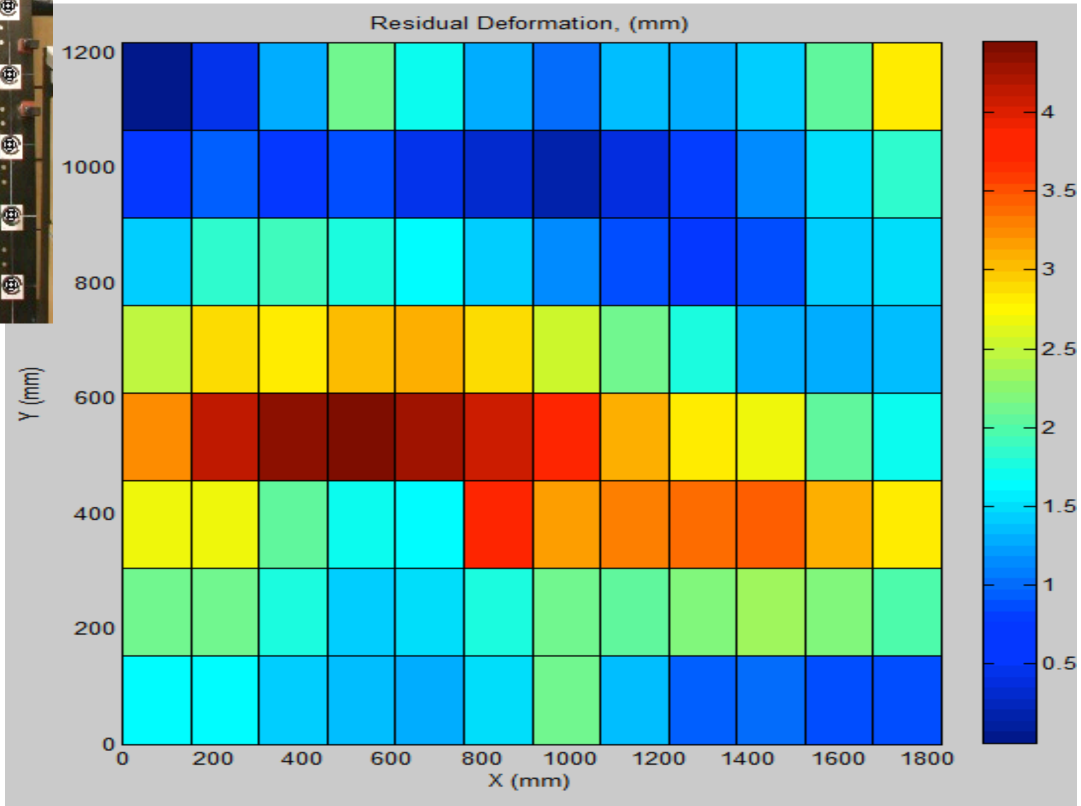
# Frame03 Residual Deformation



Photogrammetry with coded targets

- compare pre- and post-test photos
- creates 3-D surface map

Residual Deformation (Change in Surface Profile)




## Results

- 4.5 mm deformation
  - difficult to visually detect over large ~1 m span
- measurement made several days post-test → permanent deformation

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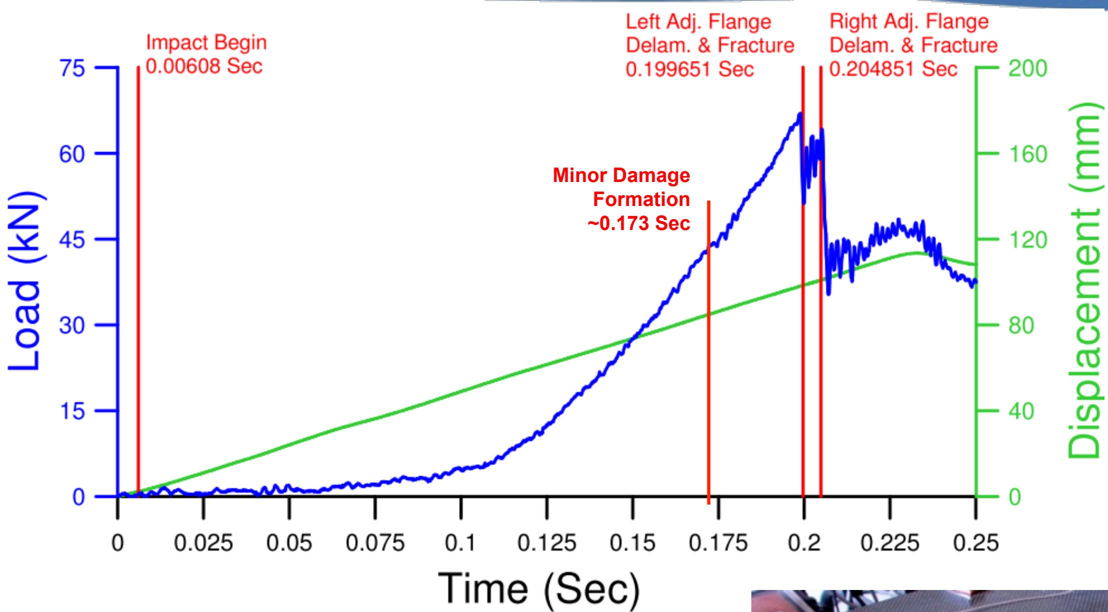
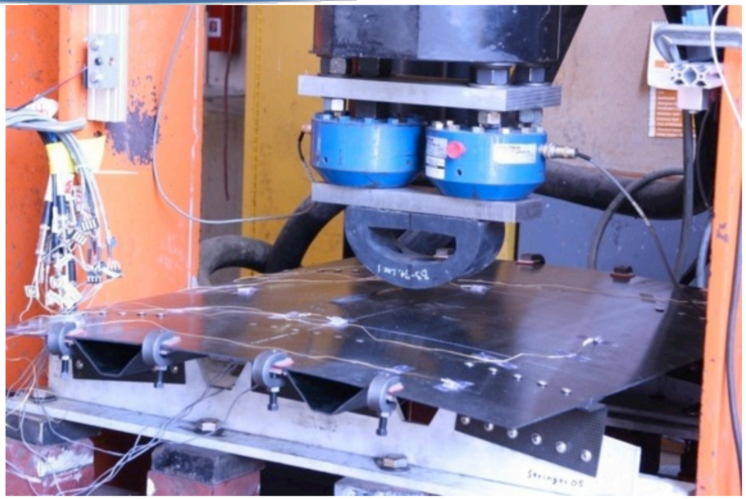
# FrameXX Specimens Results Summary

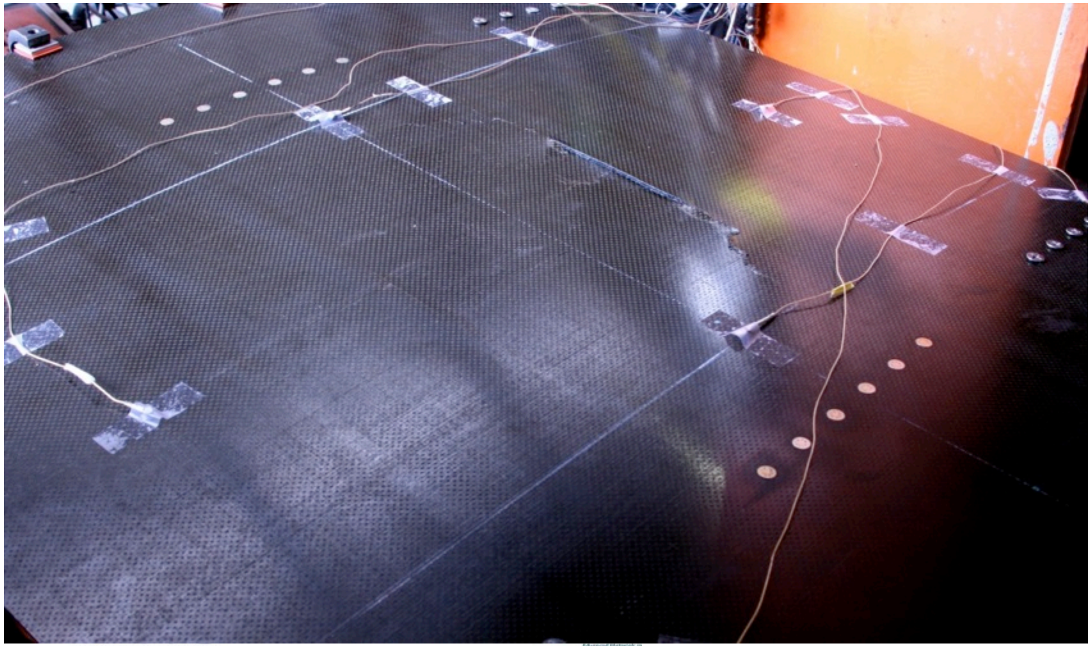
| Specimen ID | Panel Config | Loading Details | Intermediate Failure Modes | Final Failure Mode | Vis-ible? | Max Load (kN) | Max Indent (mm) |
|---|---|---|---|---|---|---|---|
| Frame01 | 4 Stringers, 3 Frames | Long Cyl. Bumper Spans 2 Frames, Between Stringers, Q-Static | Shear Ties Crush, Stringer Sever & Flange Delam | Frame Crack | **N** | 57.4 (28.7/ Frame) | 75.5 |
| Frame02 | 5 Stringers, 3 Frames | Long Cyl. Bumper Spans 2 Frames, at Stringer, Q-Static | Shear Ties Crush, Stringer Sever & Flange Delam, Skin Crack | Frame Crack | Y | 71.0 (35.5/ Frame) | 55.9 |
| Frame03 | 4 Stringers, 5 Frames | Long Cyl. Bumper Spans 3 Frames, Between Stringers, *Dynamic* | Shear Ties Crush (Qnty 3) & Bending Failure (Qnty 6) | 3 Frames Severed, Each @ 2 Locations | **N** | 74.1 (24.7/ Frame) | 90.9 |
| Frame04 | 4 Stringers, 5 Frames | Long Cyl. Bumper Spans 3 Frames, Between Stringers, *Dynamic* | *Specimen assembly & instrumentation near complete.* | *Test planned for April 2012.* | | | |

# Small Panel - Stringer05 Test Summary

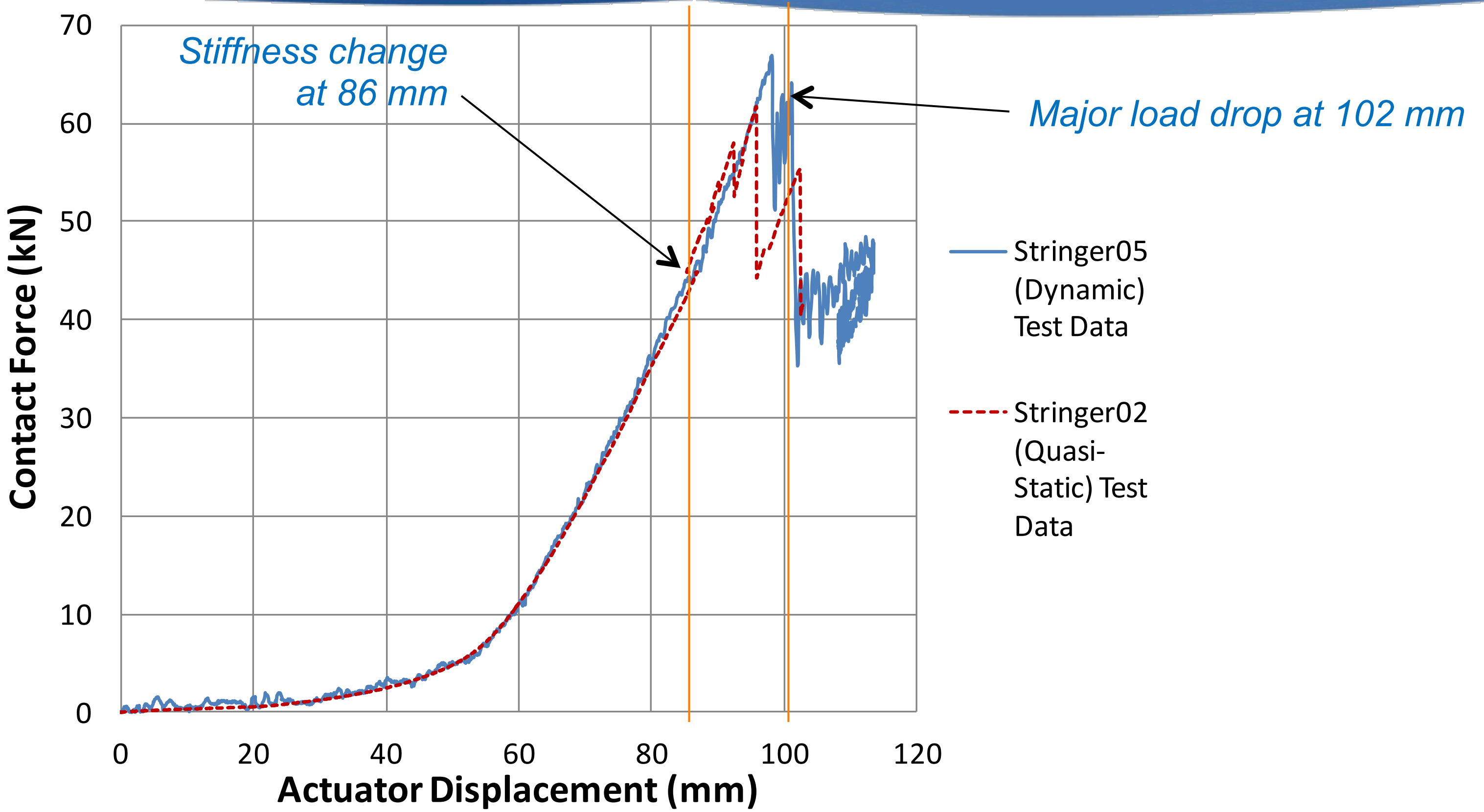


- **Dynamic loading at 0.5 m/s**
- **Damage:**
  - **local penetration of skin**
  - **highly visible surface cracks**
  - **widespread stringer separation from skin**



# Stringer05 Dynamic vs. Quasi-Static Comparison




- **Dynamic up-loading response matches almost exactly with quasi-static case**
- **Stringer05 peaked at 67 kN – an 8.6% increase for dynamic (failure onset delay)**
- **Different failure modes**
  - **Quasi-static: wide spread skin-stringer delamination – starting at shear ties**
  - **Dynamic: localized skin-stringer delam. + skin penetration, stringer radius bending failures**

# StringerXX Specimens Results Summary

| Specimen ID | Panel Config | Loading Details | Intermediate Failure Modes | Final Failure Mode | Vis-ible? | Max Load (kN) | Max Indent (mm) |
|---|---|---|---|---|---|---|---|
| Stringer00 | 3 Stringers | R3" Alum. Over Stringer, Q-Static | Skin Delamination | Local Skin Penetration | Y | 30.7 | 25.3 |
| Stringer01 | 2 Stringers | R3" Alum. on Skin Between Stringers, Q-Static | Skin Delamination | Local Skin Penetration | Y | 26.7 | 21.8 |
| Stringer02 | 2 Stringers | D-Bumper on Skin Between Stringers, Q-Static | Skin-Stringer Delamination of Each Adjacent Stringer | Extensive Stringer-Skin Delamination | **N** | 61.7 | 39.5 |
| Stringer03 | 3 Stringers | D-Bumper Over Stringer, Q-Static | Stringer Radius Cracks Under Indentor | Extensive Stringer-Skin Delamination | Y | 61.6 | ~48.5 |
| Stringer04 | 3 Stringers | D-Bumper on Stringer Flange, Q-Static | Stringer Radius Cracks Under Indentor | Extensive Stringer-Skin Delamination | Y | 78.2 | ~44.2 |
| Stringer05 | 2 Stringers | D-Bumper on Skin Between Stringers, *Dynamic* | Stringer-Skin Delamination (Just Before Final Failure) | Stringer Flange & Rad. Failure & Fracture, Delamination | **Y** | 67.0 | n/a |
| Stringer06 | 3 Stringers | D-Bumper Over Stringer, *Dynamic* | Stringer-Skin Delamination (Just Before Final Failure) | Stringer Radius Failure & Fracture, Delamination | Y | 57.4 | n/a |

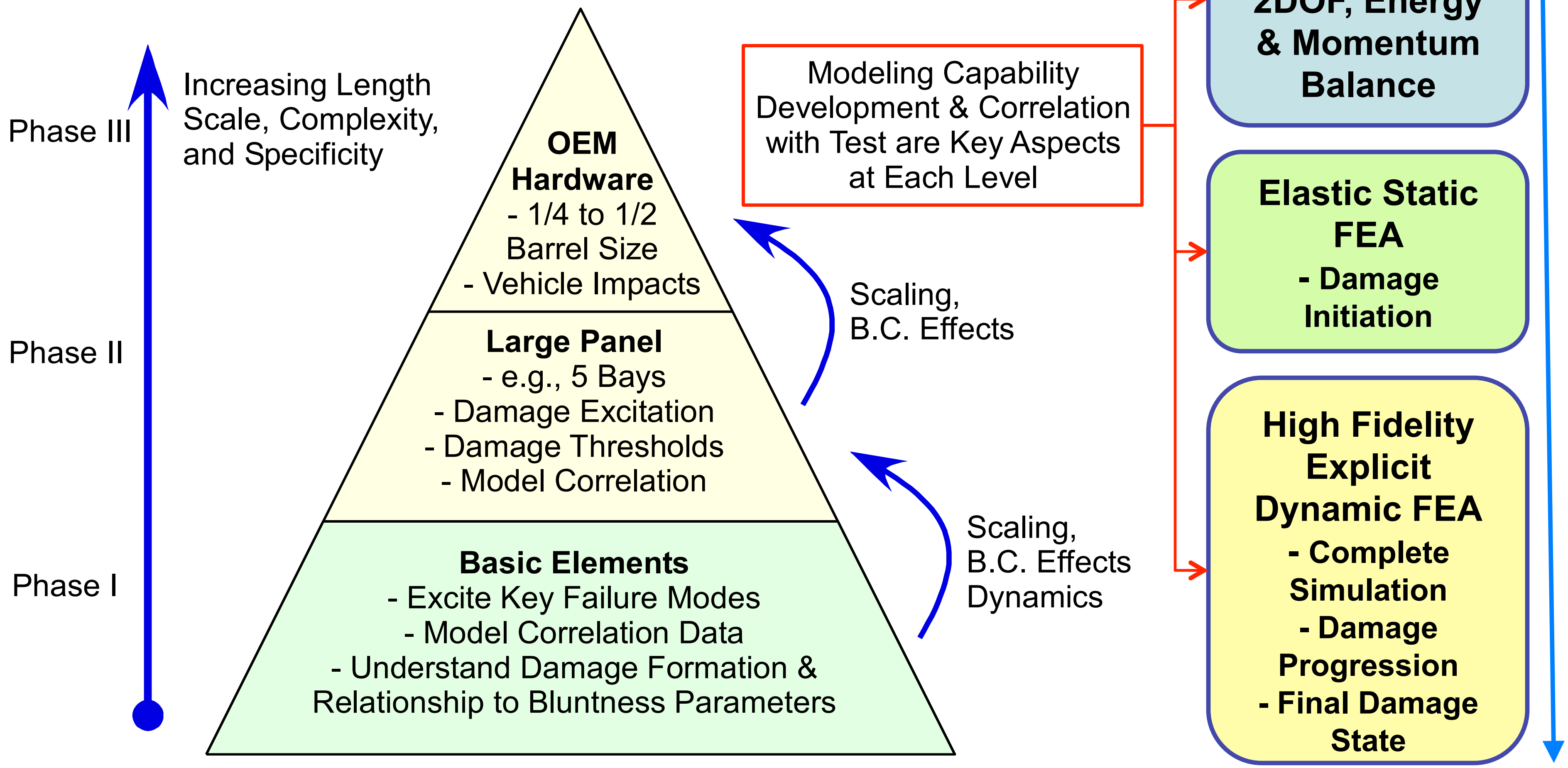
# Blunt Impact Program Phases & Modeling Capability Development

*UCSD Developing Methodologies at All Levels*

**Increasingly Complex Phases of Activity**

**- gain fundamental understanding at bottom**

**- use modeling to generalize**

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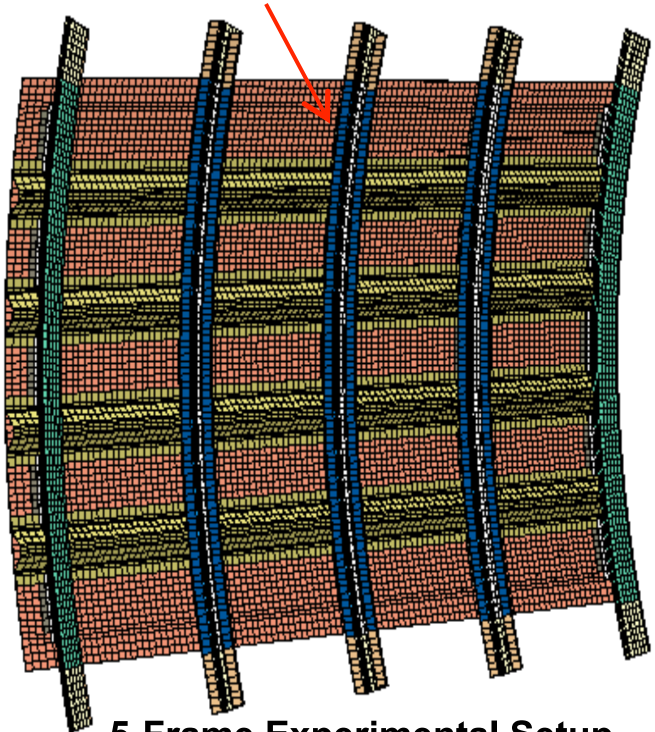
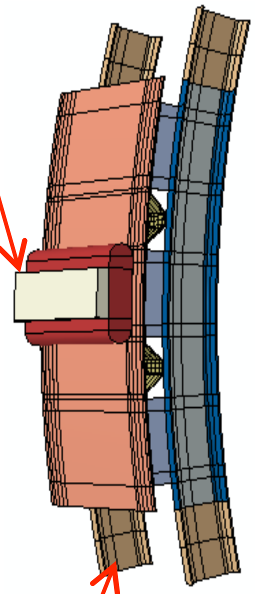
# Script-Based Model Build - Preliminary Design Tool

**Specimen:**
**SC8R elements**
**(8 node continuum shell) with Hashin-Rotem Failure**

**Bumper:**
**C3D8I elements**
**(8 node solid)**





**Boundary Region**

**5-Frame Experimental Setup**

**Allows efficient & consistent construction of many models to explore effects of parametric variation.**

**Input Parameters in Program:**

- Component geometry and layup
- Frame/stringer spacing and number
- Impactor initial velocity and mass
- Impactor geometry (# frames impacted)
- Impact location (e.g., centered on stringer, on skin between stringers, at foot of stringer)

**Python Script Output:**

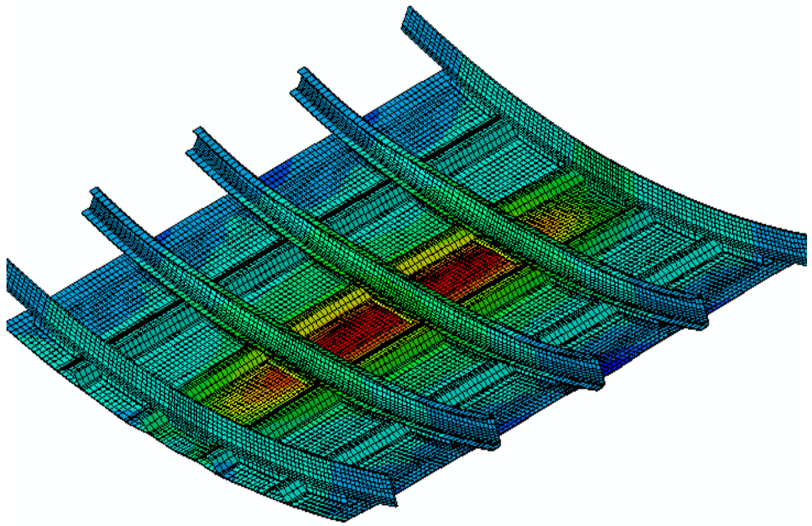
- ABAQUS .cae model file. Use to ensure script creates boundary conditions, loads, geometries correctly.
- ABAQUS .inp input file to submit job

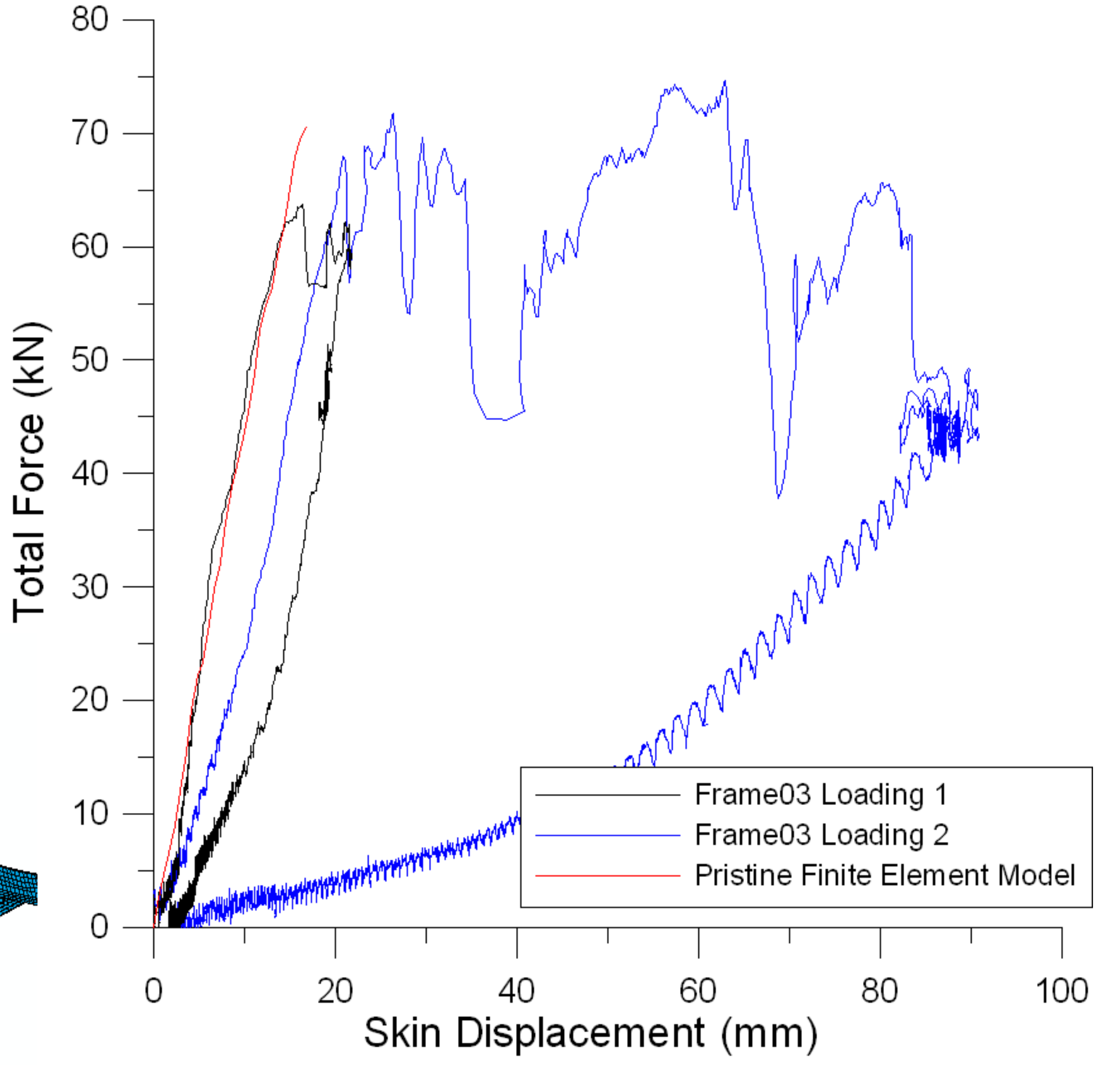
**Create database of different impact scenarios. Compare parameters, determine sensitivity of parameters to blunt impact events.**

**Verify model accuracy by comparison with experimental results.**

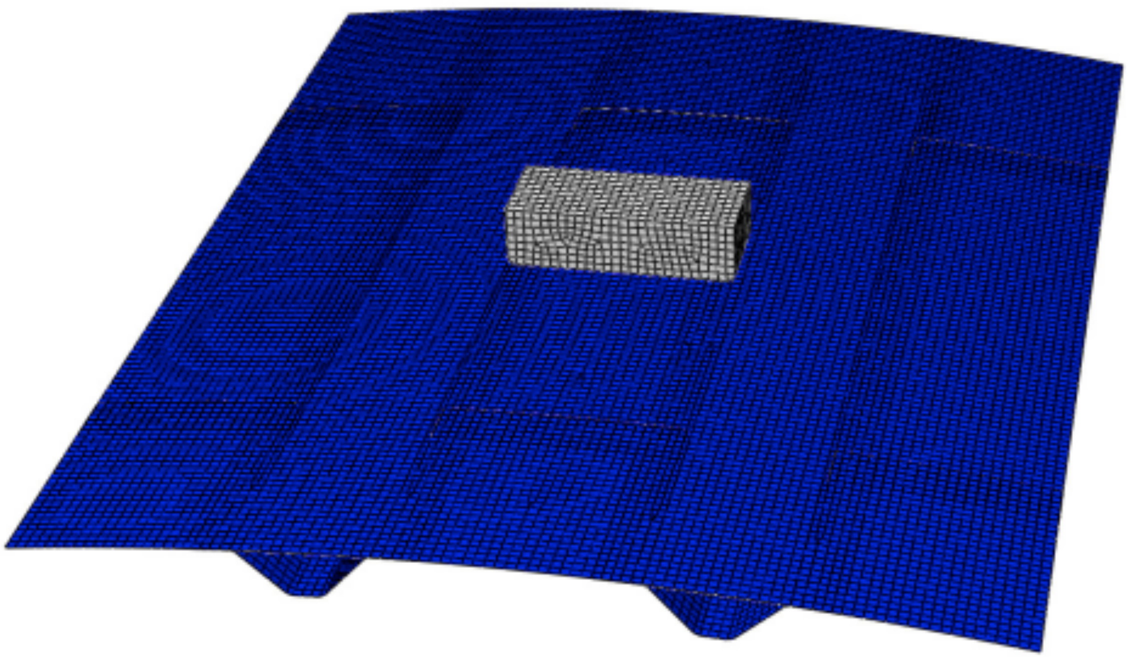
# Frame03 Modeling – Initial Response

- **Loading 1 caused crushing damage of center shear ties**
- **Initial path predicted well by "Pristine Model" (i.e., no failure, softening)**
- ***WORK IN PROGRESS:***
  **Delamination + fiber failure will be incorporated to predict failure initiation + propagation**





# Stringer05 Finite Element Model



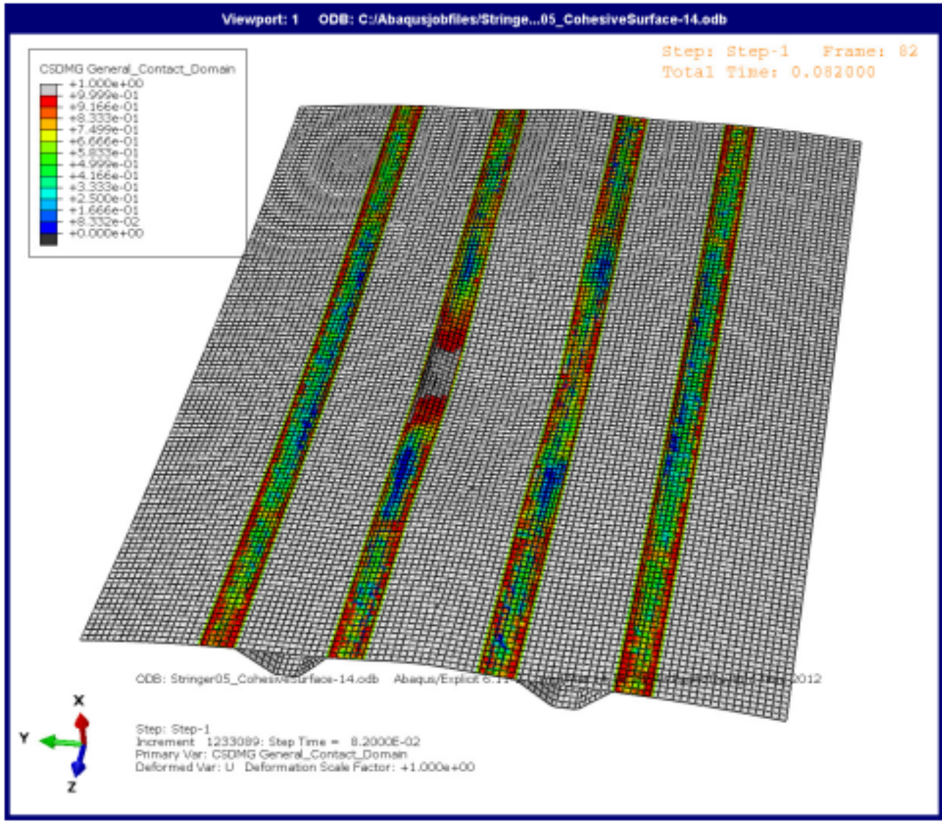
**Model Details**

- ABAQUS/Explicit dynamic simulation
- Shell elements (SR4)
- Flattened rubber bumper (solid)
  - used in place of D-shaped bumper to reduce computational costs
- Hashin-Rotem failure criteria
  - in-plane fiber and matrix failure
- Cohesive Surfaces to model delamination
  - implemented between skin and stringer flanges
- Tied constraints represent mechanical fastener connections

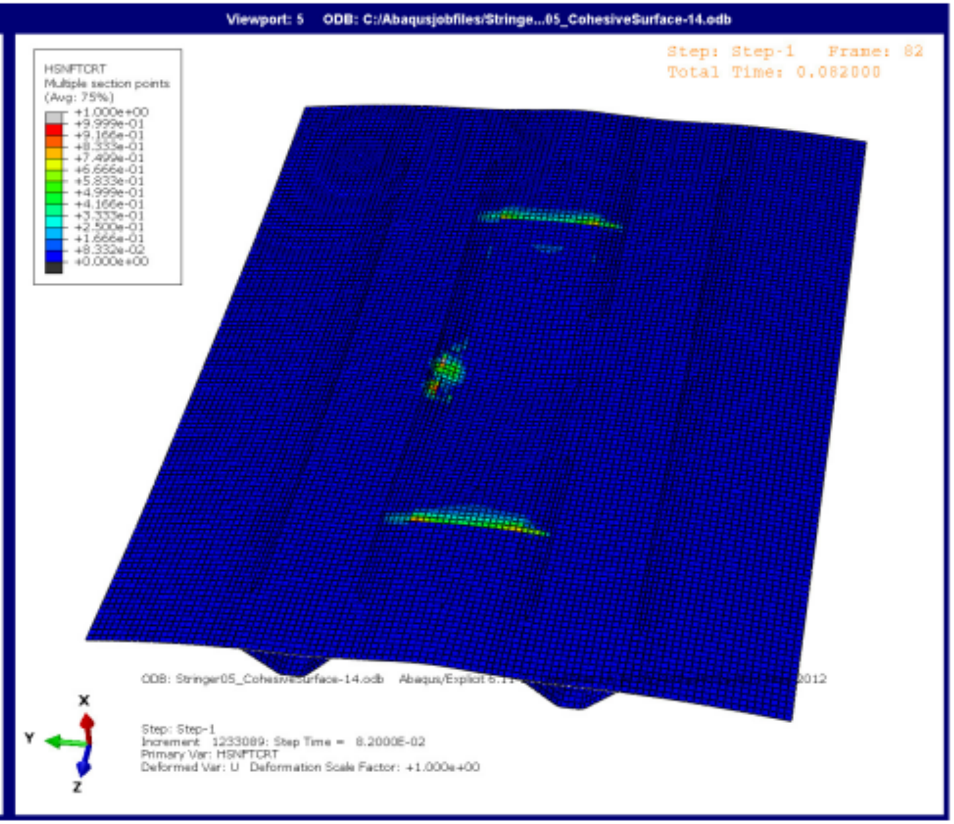
**Notes:**

1. Composite and cohesive properties obtained for similar materials – values found in open literature.
2. No "tuning" of any properties or failure parameters done to achieve better correlation.

# Stringer05 Finite Element Model Failure Predictions




Cohesive surface damage (CSDMG)
- stringer separation from skin

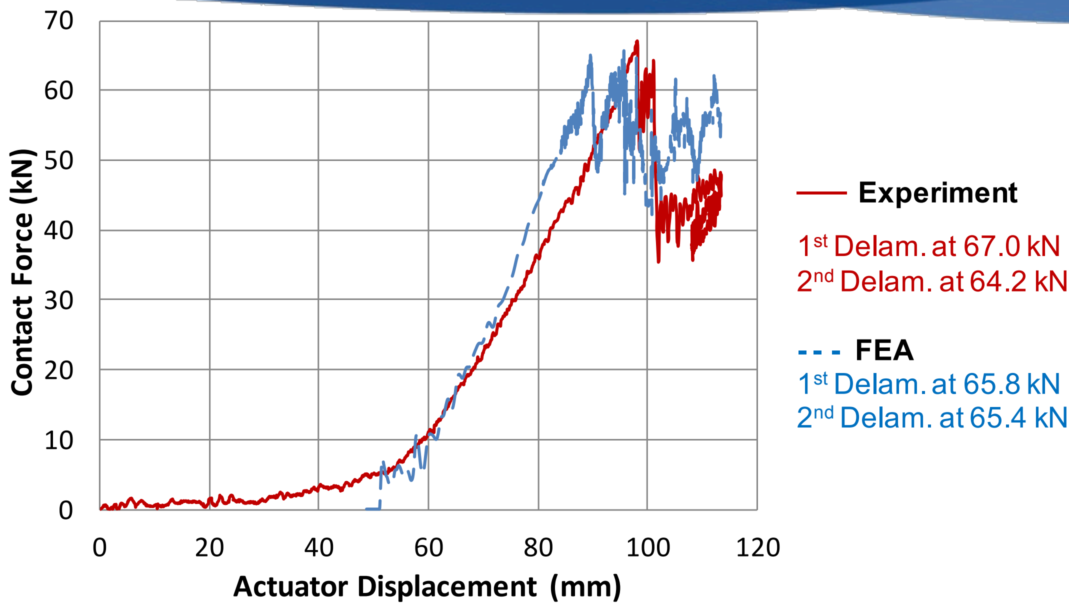



Hashin-Rotem tensile failure criterion (HSNFTCRT)
- skin and stringer flange cracks due to fiber tension (visible damage)

Both damage types initiate at the same time.

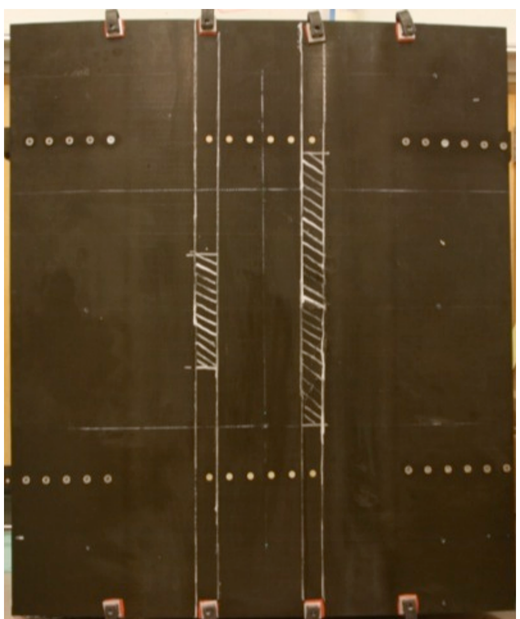
Click here for movie.

# Stringer05 Finite Element Model Comparison

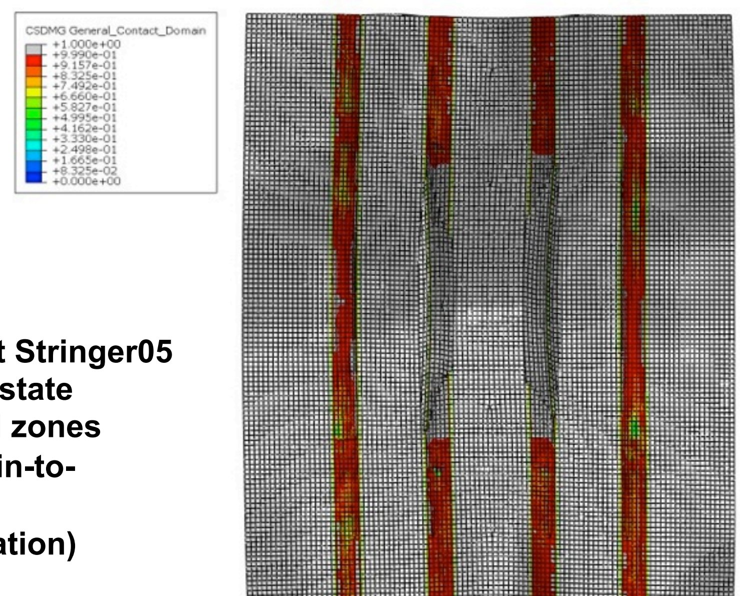



## Test and Model Comparison

- Stringer-skin delamination confined between shear ties and grows from loading location outwards
  - significant load drops
- FEA Model successfully matches :
  - initial loading response
  - failure initiation loads
  - failure modes
  - final damage state



Post-test Stringer05 damage state (hatched zones show skin-to-stringer delamination)

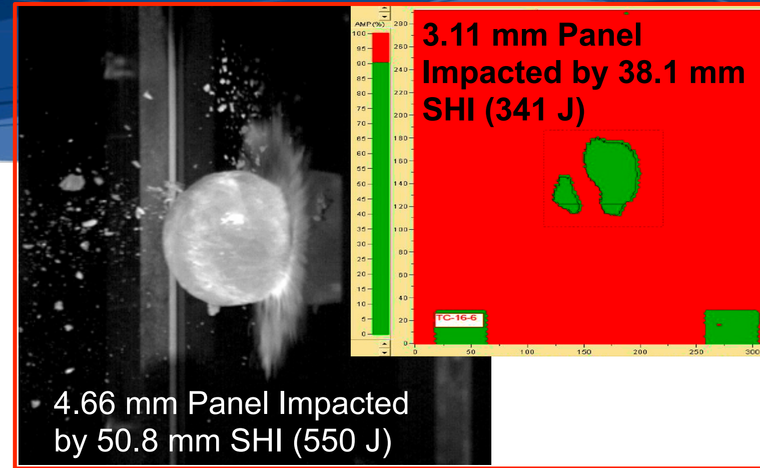



FEA model predicted damage state after full actuator displacement (red zone shows where stringer flanges are intact)

# GSE Blunt Impact Conclusions

- **Experiments**
  - Impacts onto FrameXX configuration can be treated on per-frame basis
  - Significant damage requires high forces – e.g., ~70 kN (15,700 lbf) on 3 frame impact
    - » major event – loud noise, entire aircraft will move
    - » modest contact (bumper just touches) likely causes no damage, or shear tie damage only
    - » force thresholds can be identified
  - Dynamic effects (vs. quasi-static):
    - » localization of response – can lead to penetration of skin at impact point
      - – failure mode change – particularly when non-local response occurred for quasi-static
    - » non-local response possible if load path to internal frames is close to impact point
      - – failure anywhere along load path, especially at joints/transitions
      - – secondary impacts from aircraft bumping other surrounding GSE
  - Contact of frames and stringers plays major role
    - » promotes rotation of frame
    - » penetration of frame or stringer, or failure in frame at locations further away
  - No exterior visibility (cracks) for long bumper on skin between stringers across frames
- **Model Development**
  - Methodology being established – "how to" analyze
  - Capability to predict damage initiation and final failure state
    - » demonstrated in smaller StringerXX specimens – will extend to larger FrameXX

# High Velocity Ice Impact



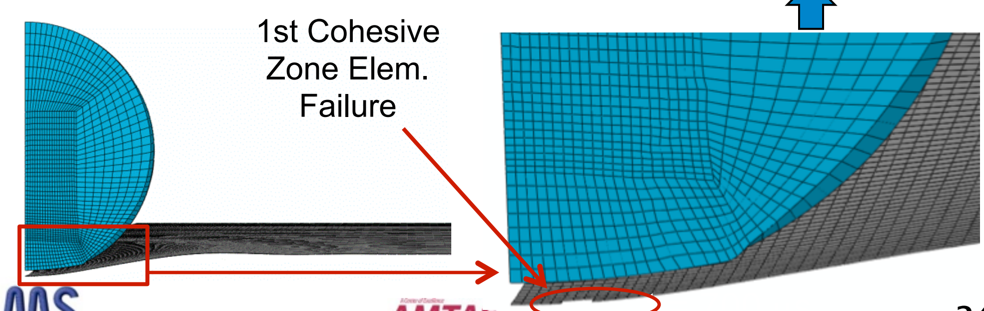

## Experiments Summary

- Established failure threshold energy (FTE) and failure threshold velocity (FTV) 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 dia.

| Panel Type (Thickness) | SHI Diameter | Experimental FTE (J) | Experimental FTV (m/s) | FEA-Predicted FTV (m/s) |
|---|---|---|---|---|
| 8 ply (1.59 mm) | 38.1 mm | 172 | 115 | 98 |
| | 50.8 mm | 258 | 91 | 68 |
| | 61.0 mm | 223 | 65 | 48 |
| 16 ply (3.11 mm) | 38.1 mm | 311 | 154 | 148 |
| | 50.8 mm | 456 | 121 | 108 |
| | 61.0 mm | 489 | 96 | 83 |
| 24 ply (4.66 mm) | 38.1 mm | 413 | 178 | 178 |
| | 50.8 mm | 733 | 154 | 153 |
| | 61.0 mm | 865 | 127 | 118 |

## FEA Model Details

- Ice material model developed by UCSD (MS Thesis – Jeff Tippmann 2011)
  - strain rate sensitive strength
- Composite Panel
  - solid element ply-by-ply modeling
  - cohesive zone elements between plies
  - all properties from literature – no "tuning" to match test data

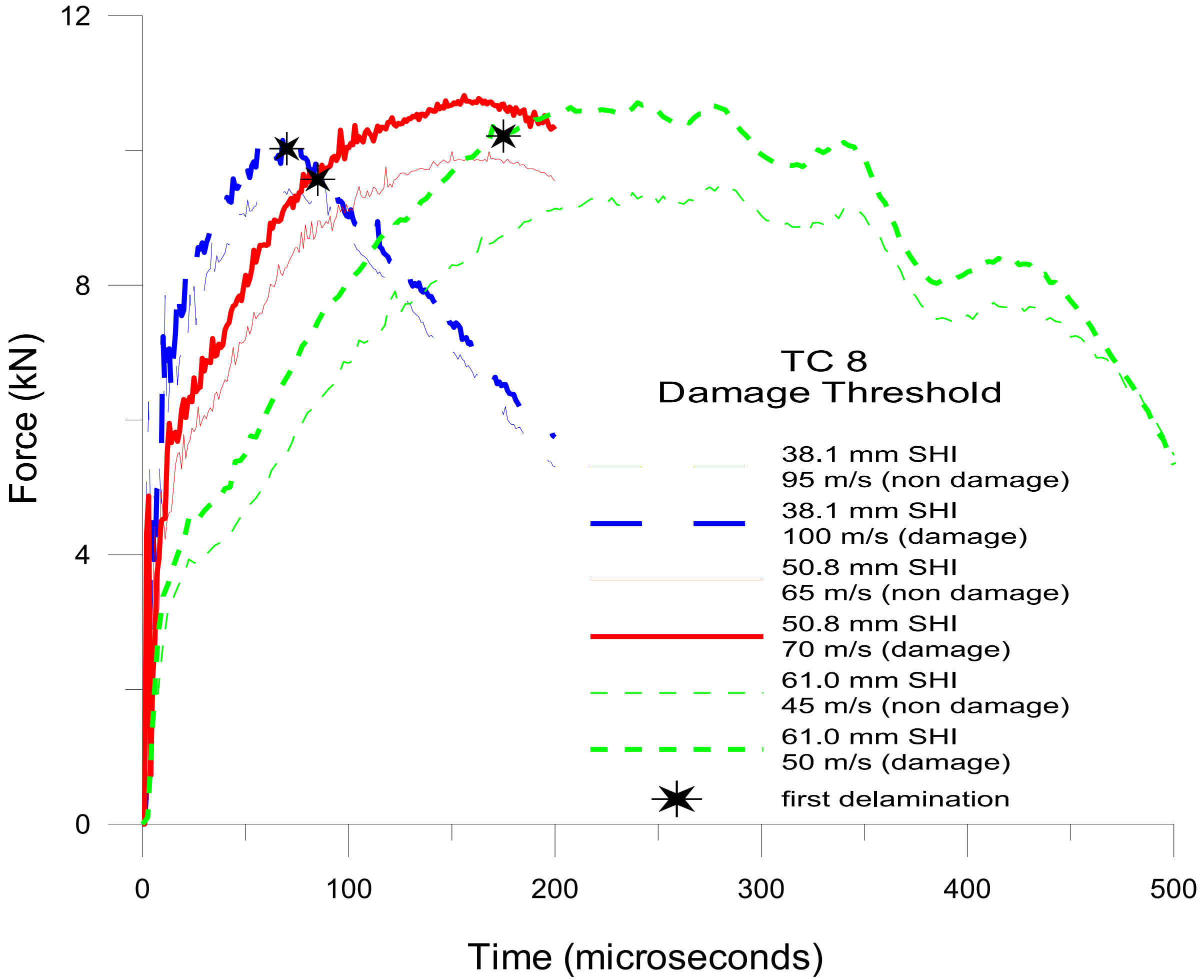


# Ice Impact Critical Threshold Force

**Critical Threshold Force**

- Contact force at initiation of delamination damage
  - high interlaminar shear triggers cohesive failure → delamination
- Each panel thickness has unique critical force found to be <u>independent of SHI diameter</u>

Example: 8-ply panels (1.59 mm thick)

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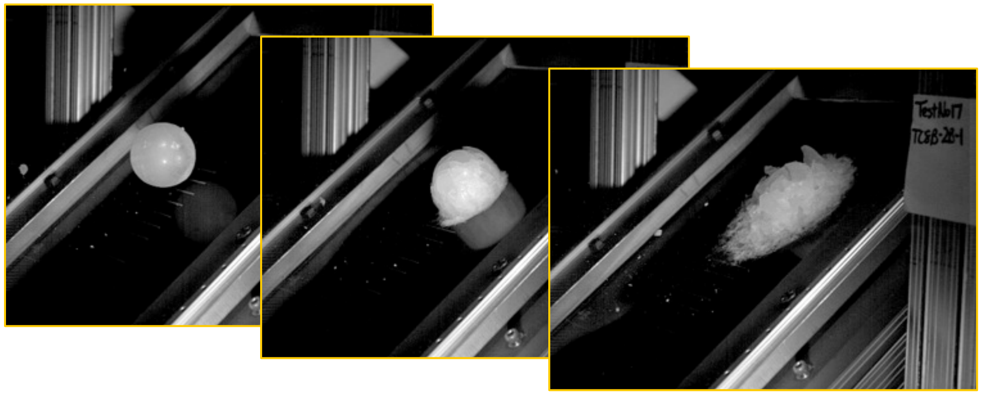
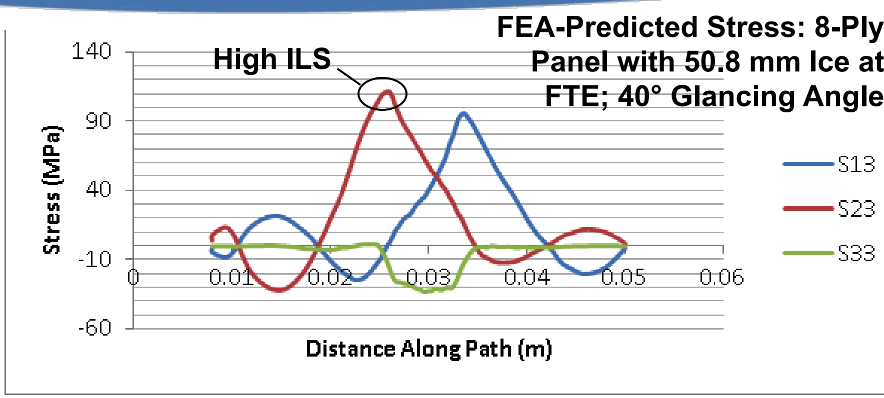
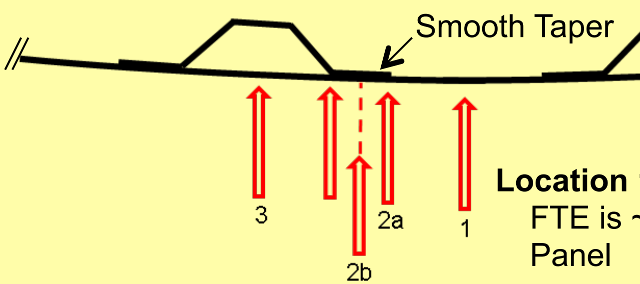
# Glancing and Stiffened Panel Ice Impact

**8 Ply Panel Impacted by 50.8 mm Ice at 108 m/s**






**T800 Stringer-Stiffened Panel (16 Ply Skin) Impacted by 61 mm Ice – Delamination Created**

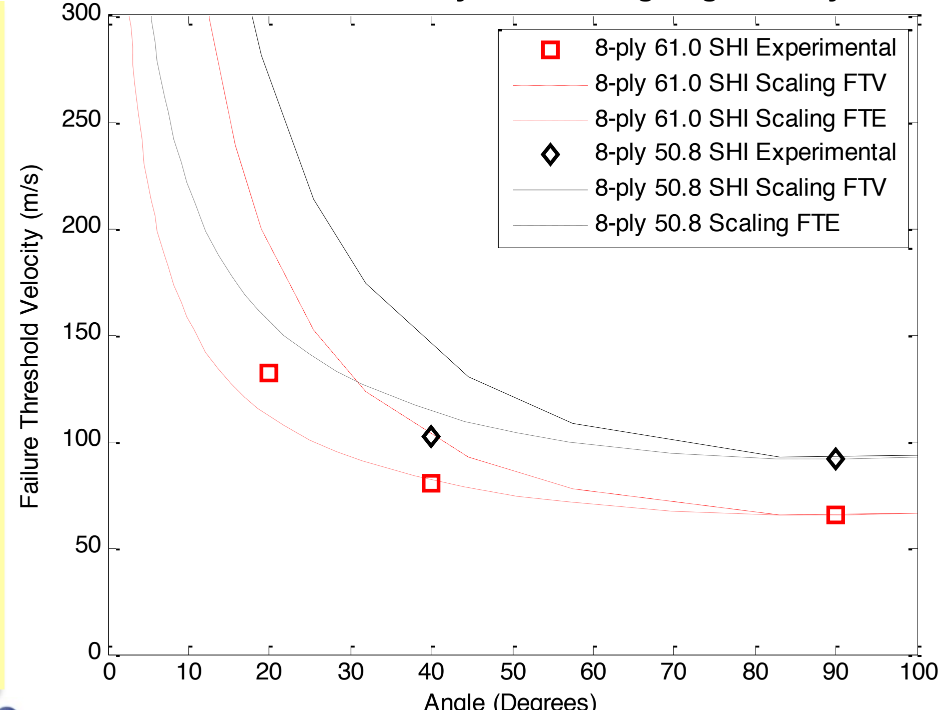



**Location 1.** Mid-Bay: FTE is ~Same as Flat Panel

**Location 2b.** Stringer Flange: FTE is ~50% of Flat Panel

**Roughly 50% Knockdown for Impact on Stringer**

**Failure Threshold Velocity vs. Glancing Angle – 8 Ply**



# Low Velocity Blunt Drop-Weight Impacts

**Objectives**

- Determine damage thresholds for composite laminates
  - how affected by radius of impact tip?
  - damage modes for different energy levels and tip radii
- Monitor dent formation and relaxation vs. radius

**Test Setup**

- Specimens are T800/3900-2 Carbon/Epoxy, quasi isotropic laminates of 8, 16, and 24 plies
  - aerospace paint layer on impact surface
- Drop-weight pendulum impactor up to 100 J
- Impact tips radii: 12.7, 25.4, and 50.8 mm

**Failure Thresholds – Metal Tips**

| | FTE (J) for Impactor Radius | |
|---|---|---|
| Panel Type | 12.7 mm | 50. 8 mm |
| 8 Plies | 10 | 20 |
| 16 Plies | 16 | 40 |
| 24 Plies | 20 | 43 |

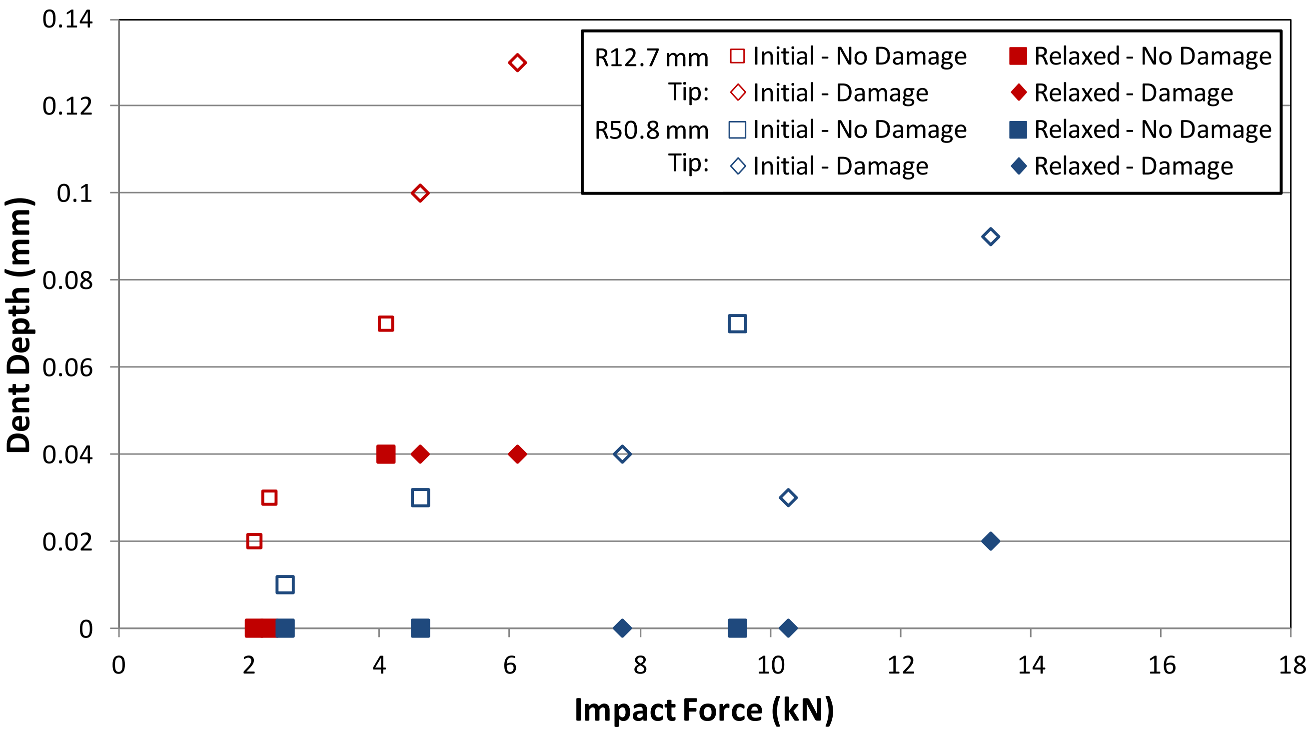
**Damage to 16-ply panel by 12.7 mm radius tip.**

# Blunt Drop-Weight Impact Results

- Damage modes: delamination and surface dents + backside fiber breakage for higher energy
- External visibility strongly depends on impactor radius
  - 12.7 mm radius tip: usually leaves visible dent – even without internal damage
  - blunt tips: possible to create no visible dent – even with internal damage
- Surface dent relaxation
  - less visible than immediately after impact
  - blunt tips: initially measurable dent can relax to immeasurable level

## Initial vs. Relaxed Dent Depths

- relaxation after 24+ hrs
- no change measured for beyond 24 hrs



# Benefit to Aviation – Part 1 of 2

**Wide Area Blunt Impact**

- Understanding of damage produced from wide-area GSE impact events
  - awareness of phenomena and possible internal failure modes
  - provides key information on mode and extent of seeded damage, particularly non-visible impact damage (NVID) from blunt impact threats
  - threat conditions causing significant damage – range of energy level needed
- Establish experimental methods – full vs. substructure, dynamic effects
- Establish analytical capability to predict blunt impact damage
  - simple models – energy balance
    - failure threshold force to estimate damage onset
    - relate to ground operations – vehicle mass and speed
  - nonlinear FEA – high fidelity damage simulation
    - initiation to final state
  - script-based FEA model build for preliminary design/analysis tool
    - evaluate various configurations and wide-ranging parametric dependencies
- Identify how to detect/monitor occurrence of damaging events
  - what inspection technique should be used? where?
  - e.g., video cameras and sensors that can help to determine impact energy

# Benefit to Aviation – Part 2 of 2

**Large Hail Ice Impact**

- Damage resistance database established – allows for skin sizing
  - understanding ice impact threat conditions causing damage – ice size, velocity
  - effects of internal structural components (e.g., stringers)
- Models predicting damage onset (i.e., FTE)
  - reduce amount of testing required – explore many configurations
  - accurate ice projectile model defined – critical for accurate target response
- Glancing impact studies provide scaling relationship to use normal impact data
- Stringer hit adjacency provides information on % knockdown relative to skin-only impact

**Low Velocity Blunt Drop-Weight Impacts**

- Understanding of damage produced from blunt metal tip impacts
  - correlation between damage onset and impactor radius
  - establish relationship between visible and internal damage
  - dent relaxation dependency on impactor radius
- Material-level test results are widely applicable
  - threshold force measurements facilitate applicability to other structural components

# Looking Forward – Ongoing/Future Plans

- Complete ***dynamic*** blunt impact test on Phase II large 5-frame specimen (Frame04)
  - dynamic impact vs quasi-static indentation – rate, scaling, and BC effects
- Continued developments to establish high fidelity FEA modeling capability
  - damage initiation, progressive failure process, damage extent, energy absorption
    - » correlation to large panel test results – use direct material properties (no “tuning”)
    - » define visibility metrics compatible with FEA
  - cohesive surfaces implementation into shell-based models to represent delamination
- Develop and refine reduced order models
  - estimate damage onset for wide parameter range:  GSE mass, velocity, impact location
  - relate test results to GSE field operations
- New investigations needed (experimental + analytical):
  - glancing impacts effects
    - » define scaling relationships via momentum and angle
    - » moving contact area – e.g., pushing across multiple stringers
  - BC and dynamic localization effects on larger sized specimen – ¼ or ½ barrel w/ floors
  - metal fuselage for metal baseline compare – particularly visibility aspects
  - other primary structure types – e.g., wing, tail
- Hail ice damage resistance and morphology for sandwich construction, multi-hit, stiffened skin (stiffened skin impact has started)
- Education/Training: dissemination of results, workshops

End of Presentation.

Thank you.

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