JAMS

Impact Damage Formation on Composite Aircraft Structures

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A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

UCSD

CECAM
center of excellence for composites and advanced materials

FAA Sponsored Project Information

- **Principal Investigators & Researchers**
  - Hyonny Kim, Associate Professor, UCSD PI
  - *Prof. JM Yang, UCLA PI – sending subcontract to UCSD*
  - Graduate Students: Gabriela DeFrancisci (PhD), Zhi Chen (PhD), Jennifer Rhymer (PhD), Jeff Tippmann (MS – completing summer '10), Sho Funai (MS starting summer '10)
  - Undergraduate Students: Jonnathan Hughes, Sean Luong, Sarah Fung
- **FAA Technical Monitor**
  - Curt Davies
- **Other FAA Personnel Involved**
  - Larry Ilcewicz
  - UCSD workshop participants: Scott Fung, Howard Hall, Doug Ostgaard
- **Industry Participation**
  - Airbus, Boeing, Bombardier, Cytec, Delta Airlines, San Diego Composites, United Airlines
  - Govt lab: Sandia National Labs

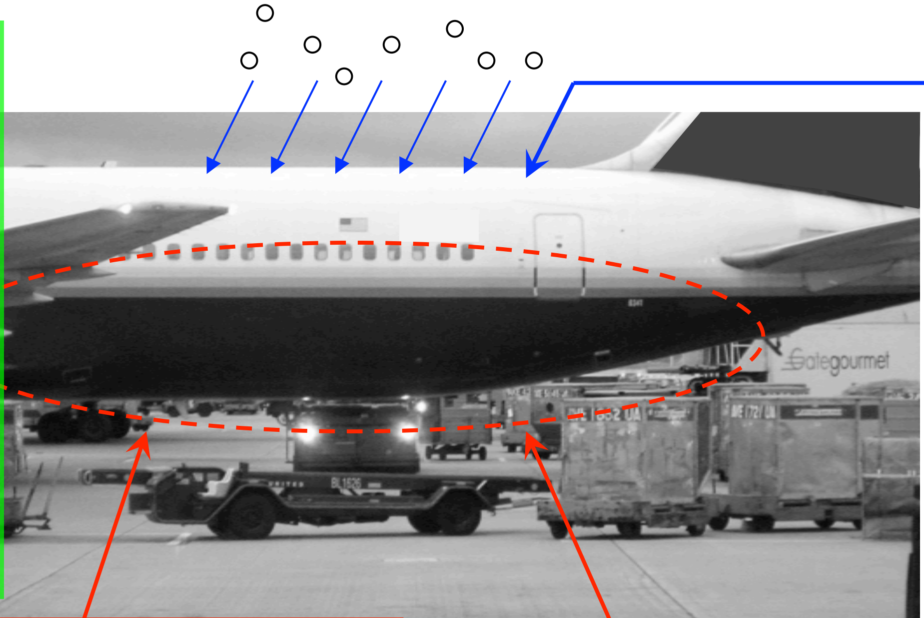
Impact Damage Formation on Composite Aircraft Structures

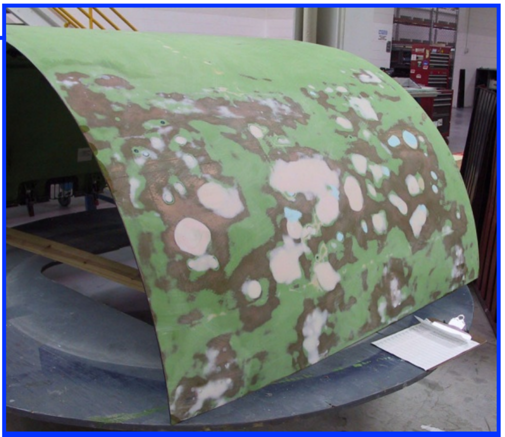
- **Motivation and Key Issues**
  - Impact damage to composites remains significant source of concern
    - » particularly from high energy blunt sources that are not well understood
    - » increasingly more composite primary structure being deployed
  - Focus: Blunt Impacts affecting large area and/or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

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

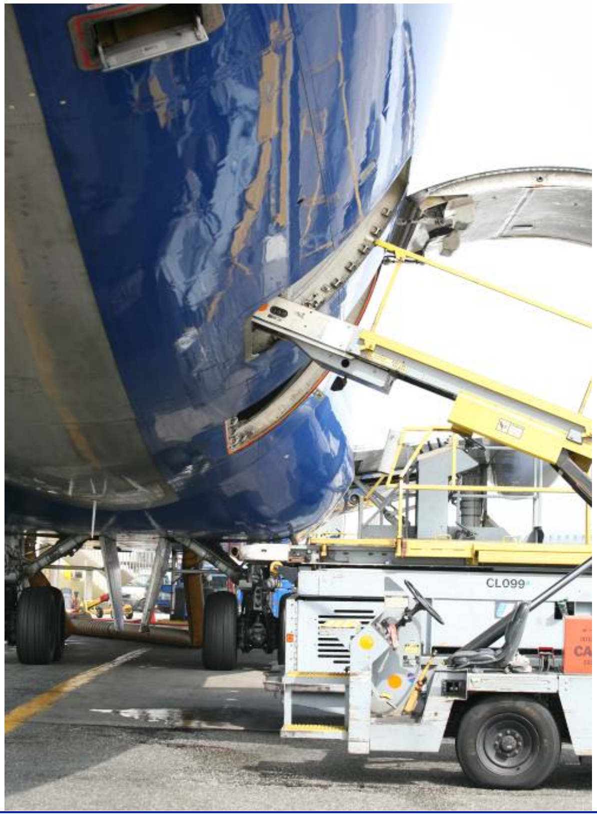
- upward & forward facing surfaces
- low mass, high velocity

Ground Vehicles & Service Equipment

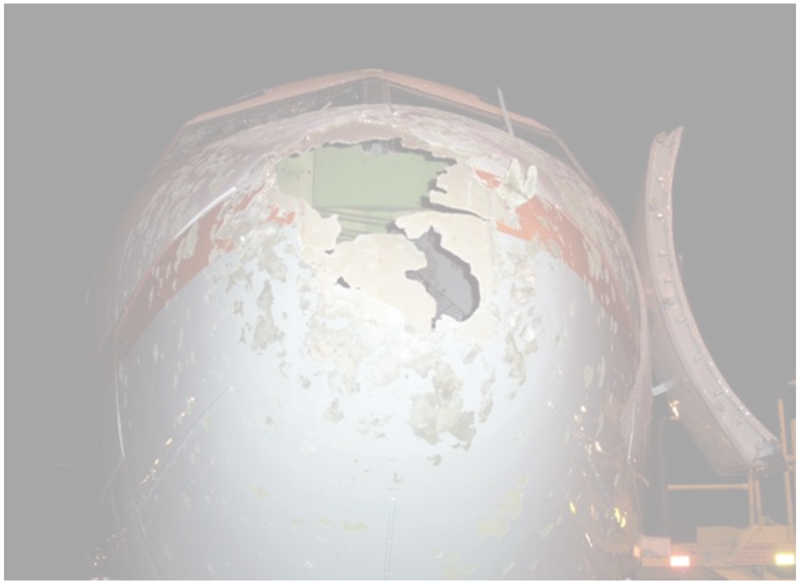
- side & lower facing surfaces
- high mass, low velocity
- wide area contact
- damage possible at locations away from impact

Low-Velocity High-Mass Wide-Area Blunt Impact

- ground service equipment (GSE) impact
- 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 widespread damage with minimal or no *exterior visual detectability?*



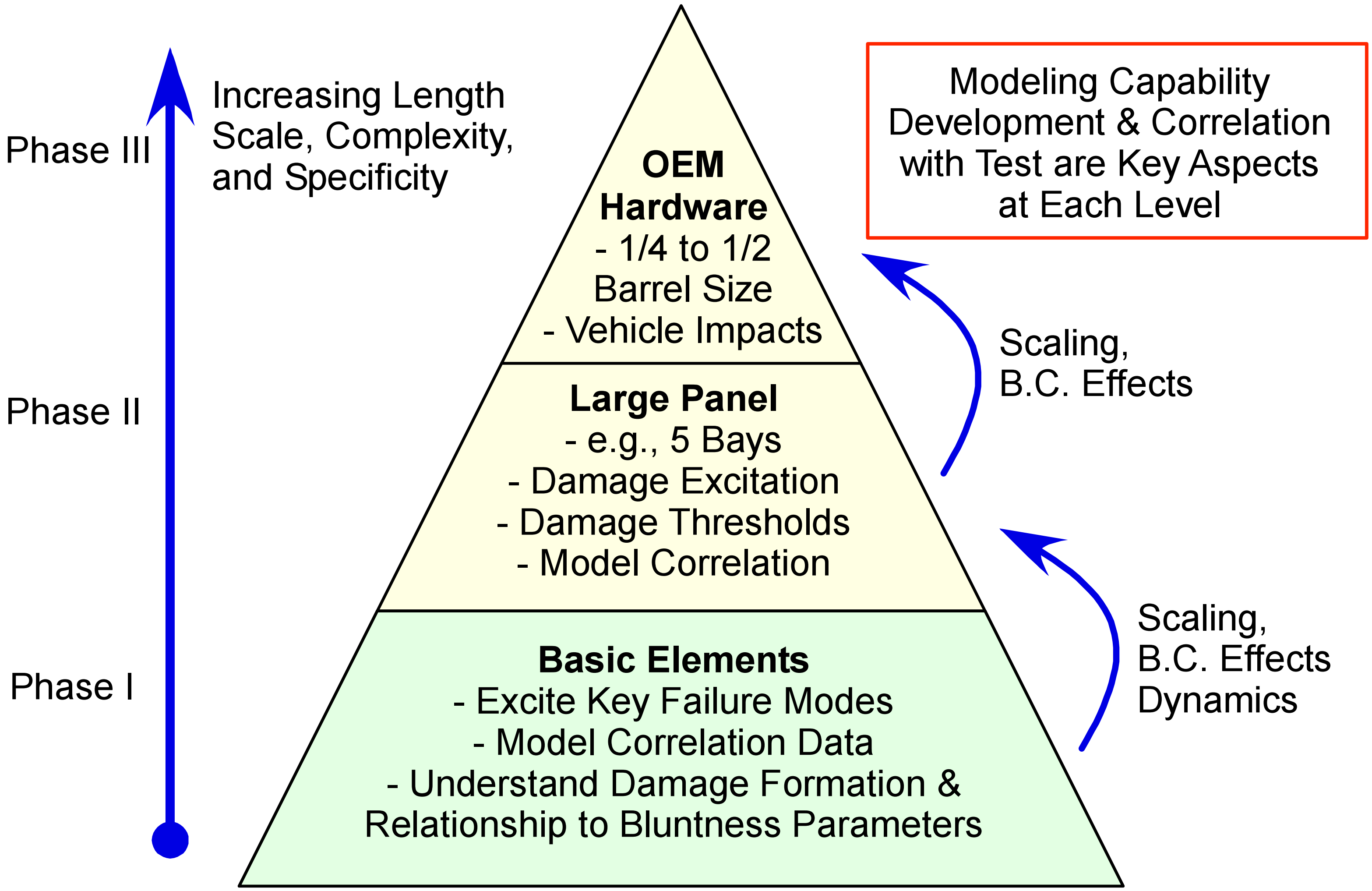
More info at UCSD Blunt Impact website:
http://csrl.ucsd.edu/UCSDbluntimpact/



High Velocity Hail Ice Impact:

Blunt Impact Program Phases

Understanding of Blunt Impact Damage by Increasingly Complex Phases of Activity



Phase III

Phase II

Phase I

Increasing Length Scale, Complexity, and Specificity

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

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

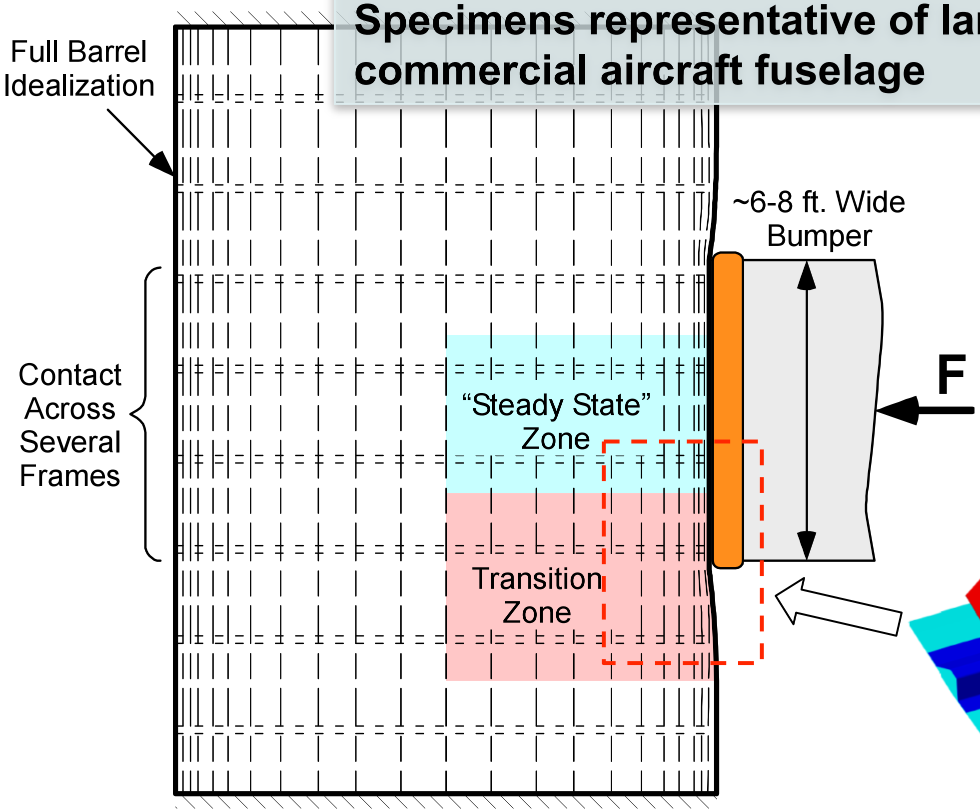
Scaling,
B.C. Effects

Scaling,
B.C. Effects
Dynamics

Two Test Specimen Types

Defined During Workshops at UCSD (1/23/09 & 7/1/09)

Specimens representative of large commercial aircraft fuselage

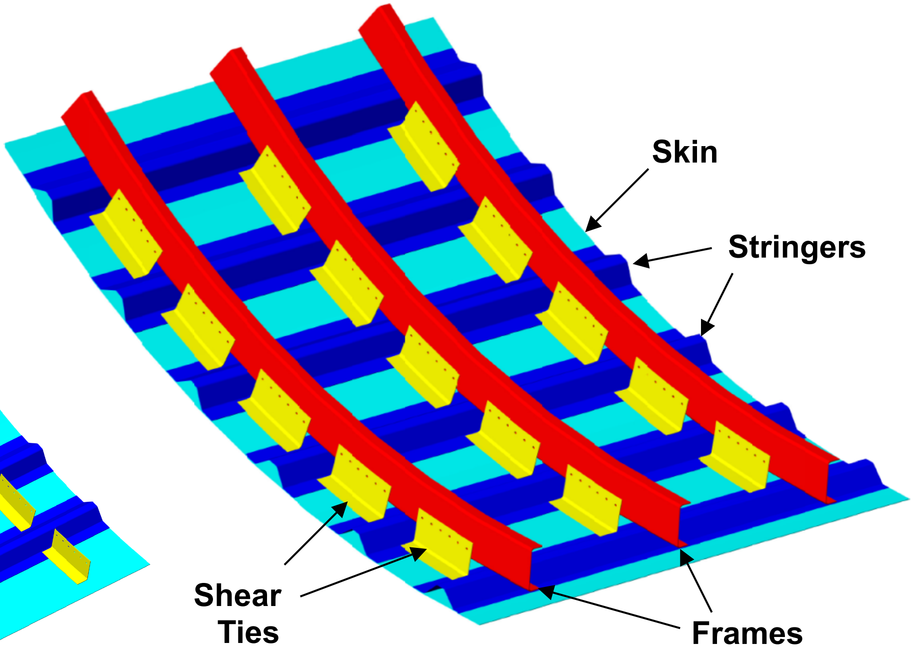


Transition Zone

- includes end of bumper
- phenomena not present in "steady state" zone
  - » biaxial bending in skin
  - » shear in stringer-skin interface

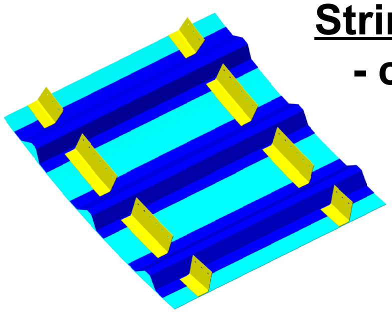
Frame Specimens

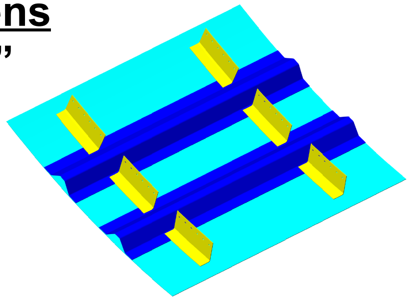
- half-width "line" loading



Stringer Specimens

- central "point" loading





Fabricated Test Specimens

Stringer Specimen ~ 3 x 3 ft.

Materials provided by Cytec: Z60 / X840

Cure cycles courtesy of San Diego Composites

Frame Specimen (skin + stringers) ~ 6 x 4 ft.

Group Photo with Test Specimens

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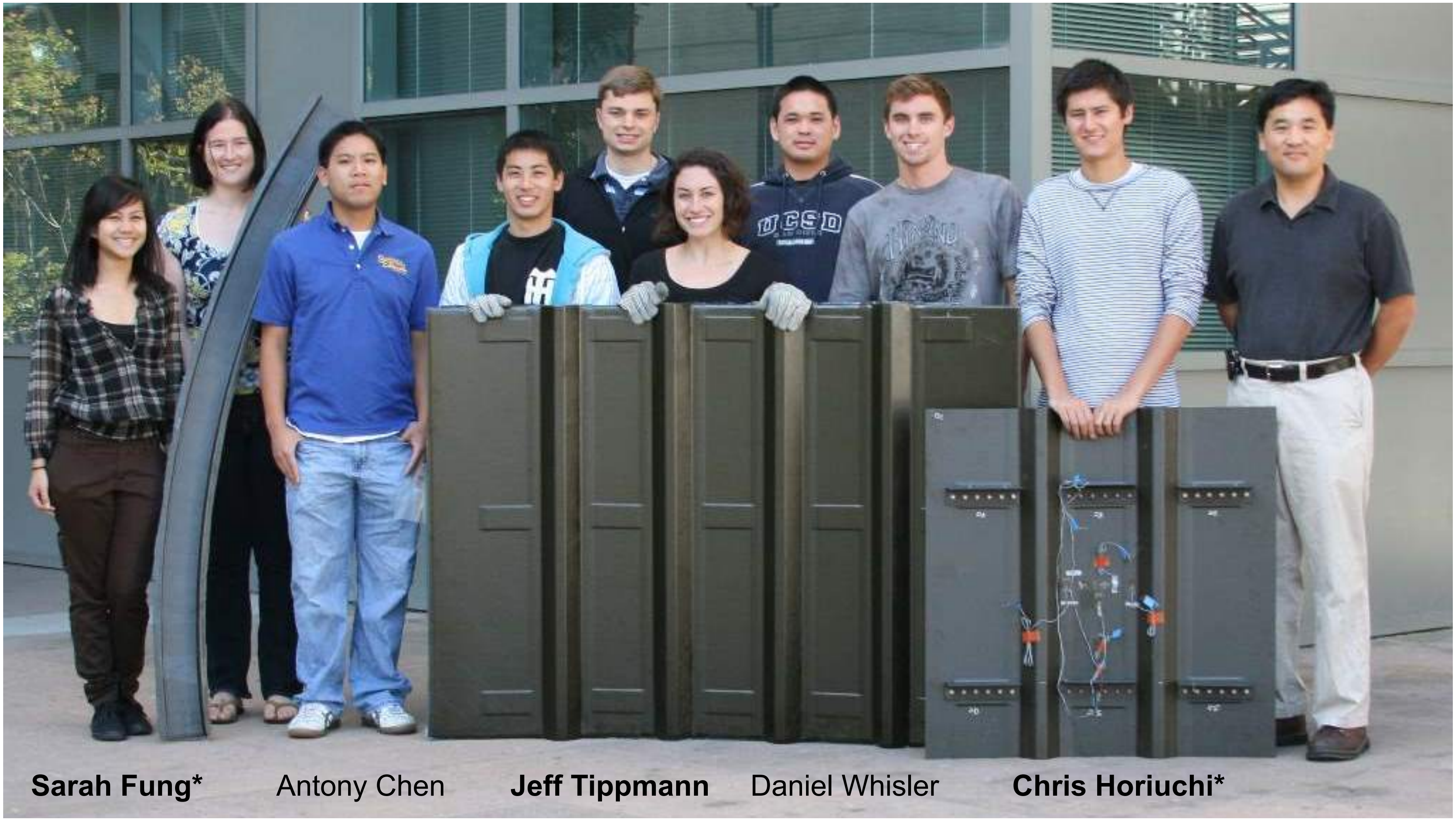


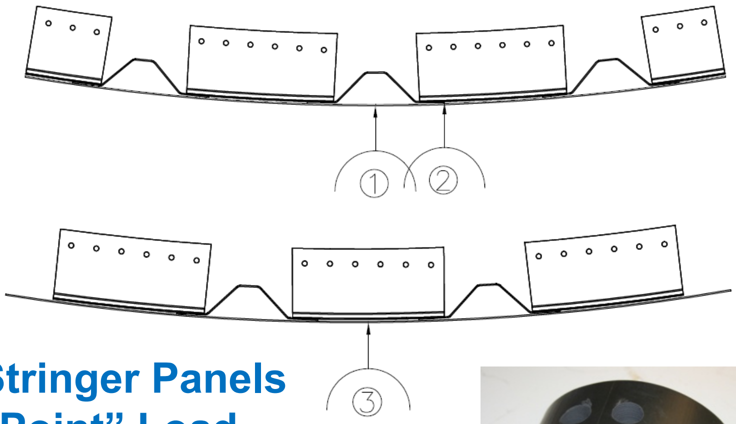
Sarah Fung* Antony Chen **Jeff Tippmann** Daniel Whisler **Chris Horiuchi***

Jennifer Rhymer **Sho Funai** **Gabriela DeFrancisci** **Jon Hughes*** **Prof. Hyonny Kim**

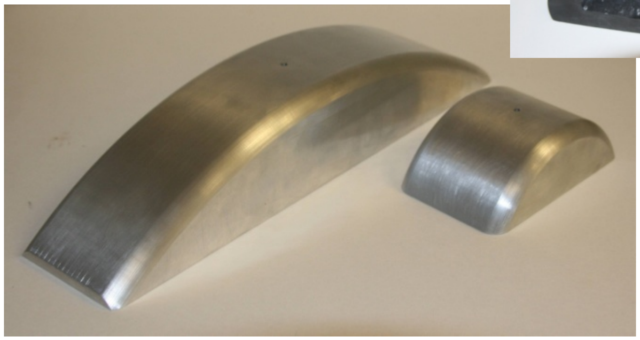
Not present: **Zhi Chen, Sean Luong***

* undergraduate assistants

Phase I Test Matrix

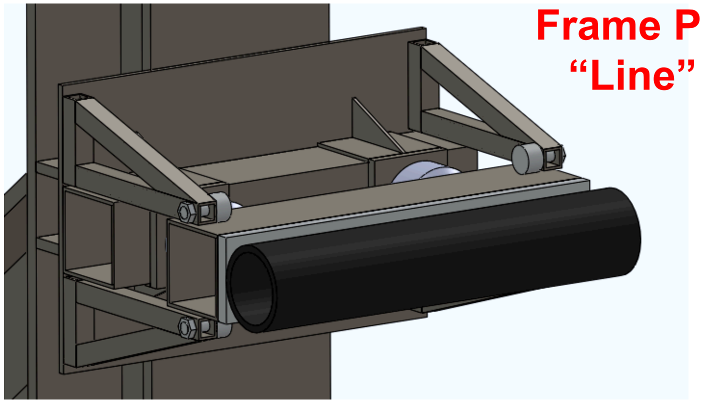


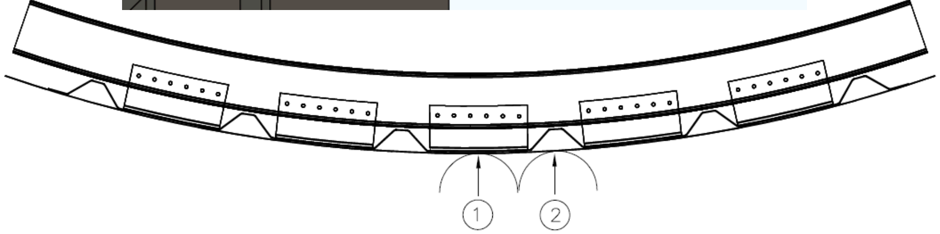
Stringer Panels “Point” Load



Stringer Specimen ID	Indentor		
	Rigid 12"R	Rigid 3"R	Bumper
Stringer00		L1-F	
Stringer01		L3-F	
Stringer02			L3-F
Stringer03	L3-F		
Stringer04	L1-F		
Stringer05			L1-F
Stringer06	L2	L2	

Frame Panels “Line” Load



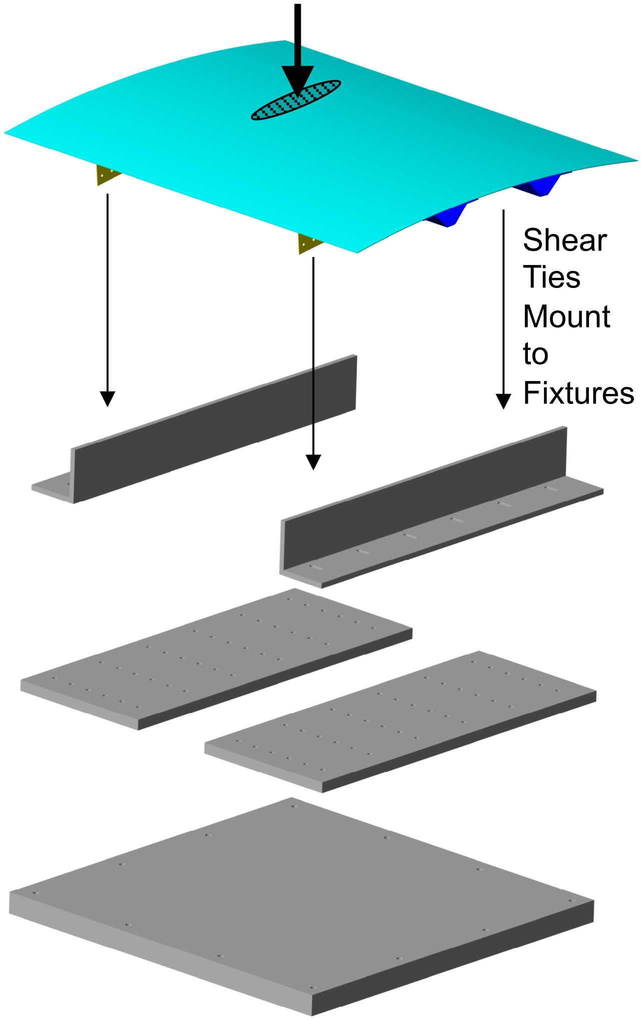


Frame Specimen ID	Indentor	
	Rigid 3"R	Bumper
Frame01	L1	L1-F
Frame02	L2	L2-F

Stringer Specimen Tests

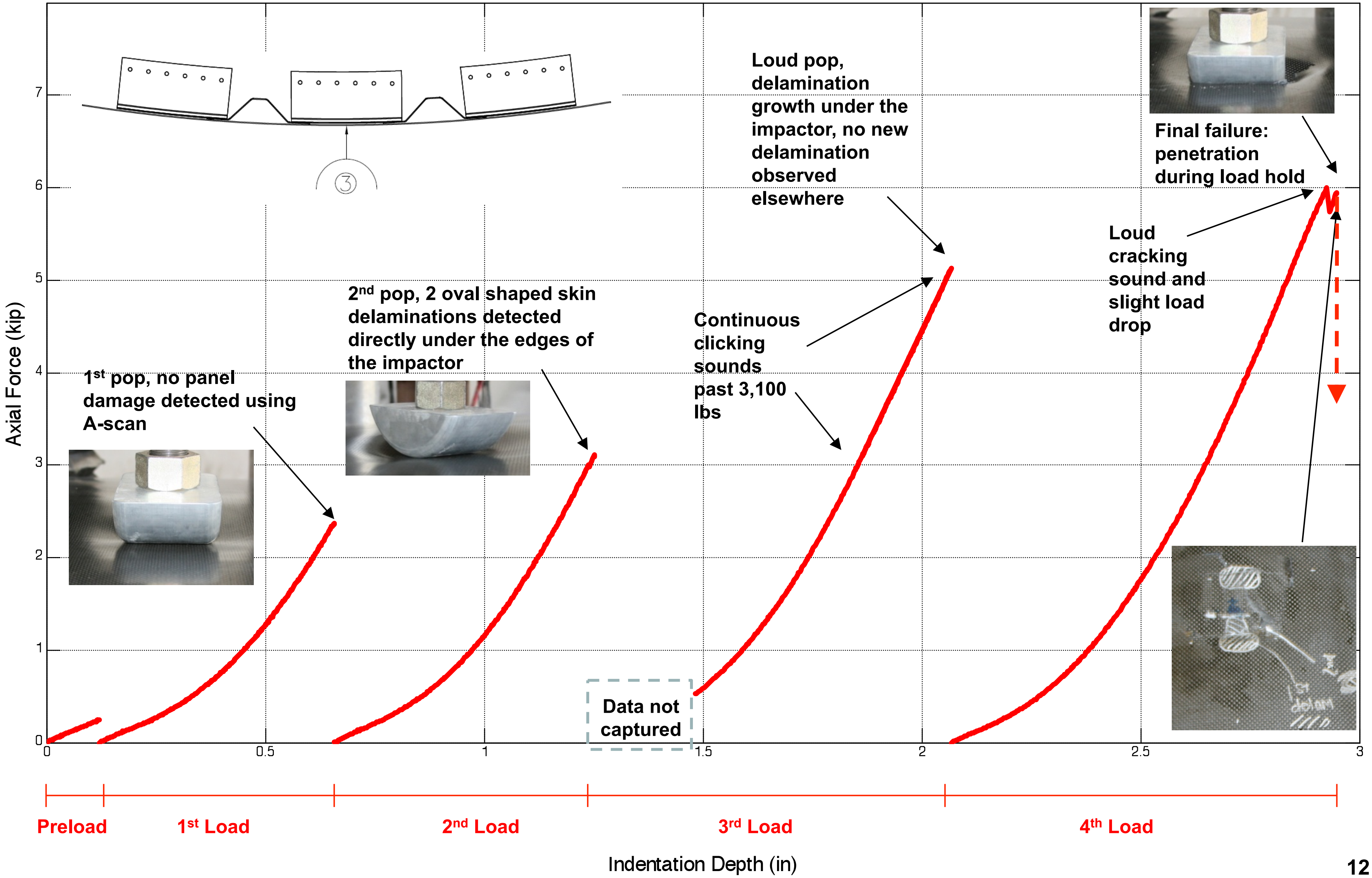
Three specimens tested to date:

- Stringer00 – rigid R3 in. directly above stringer
- **Stringer01 – rigid R3 in. on skin between stringers**
- **Stringer02 – rubber bumper on skin between stringers**



Stringer01 Results

Rigid 3 in. Rad. Indentor on Skin Between Stringers



1st pop, no panel damage detected using A-scan

2nd pop, 2 oval shaped skin delaminations detected directly under the edges of the impactor

Data not captured

Continuous clicking sounds past 3,100 lbs

Loud pop, delamination growth under the impactor, no new delamination observed elsewhere

Loud cracking sound and slight load drop

Final failure: penetration during load hold

Stringer01 Exterior View After 4th Loading

Damage: Penetration & Localized Delamination

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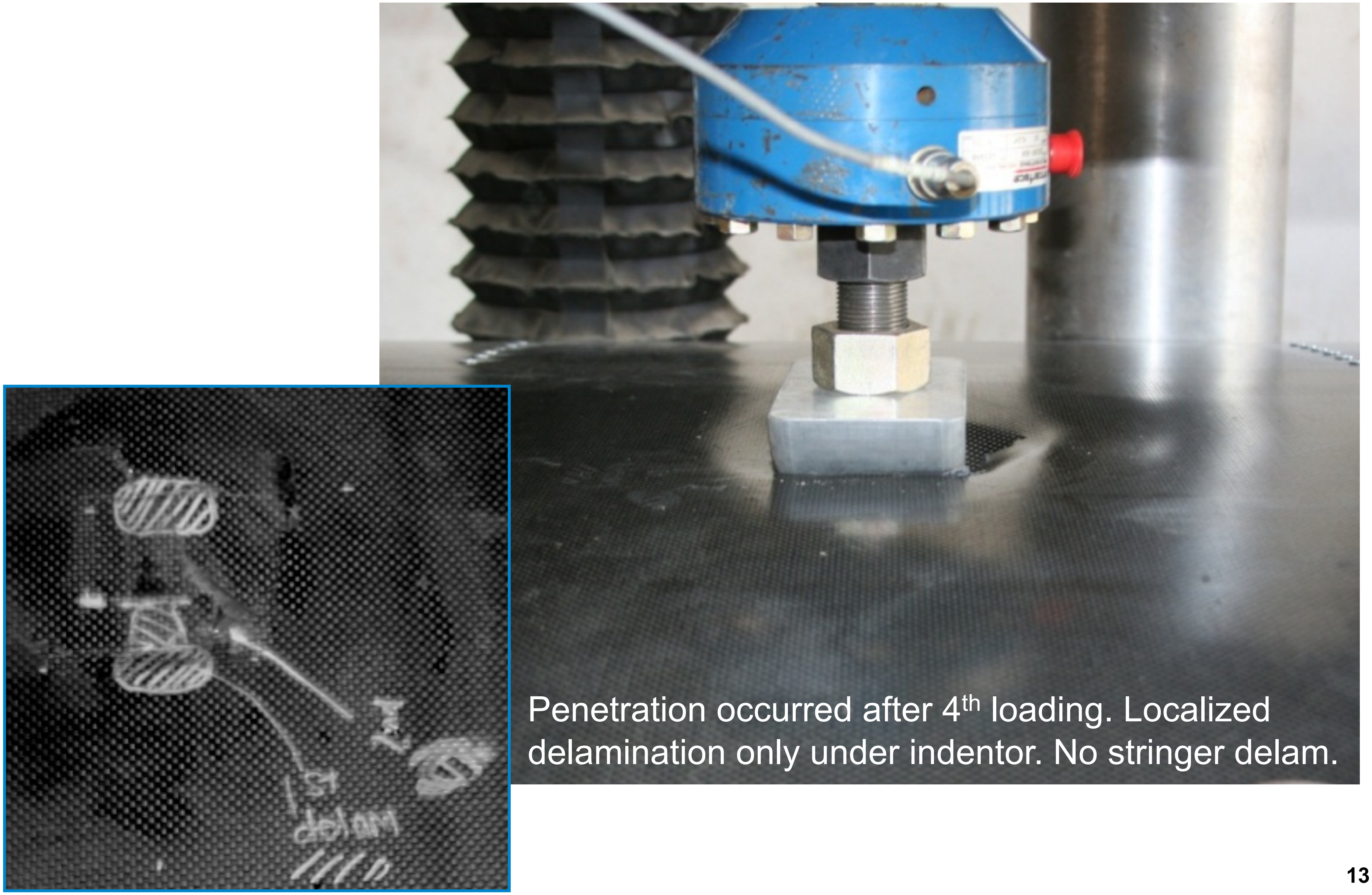
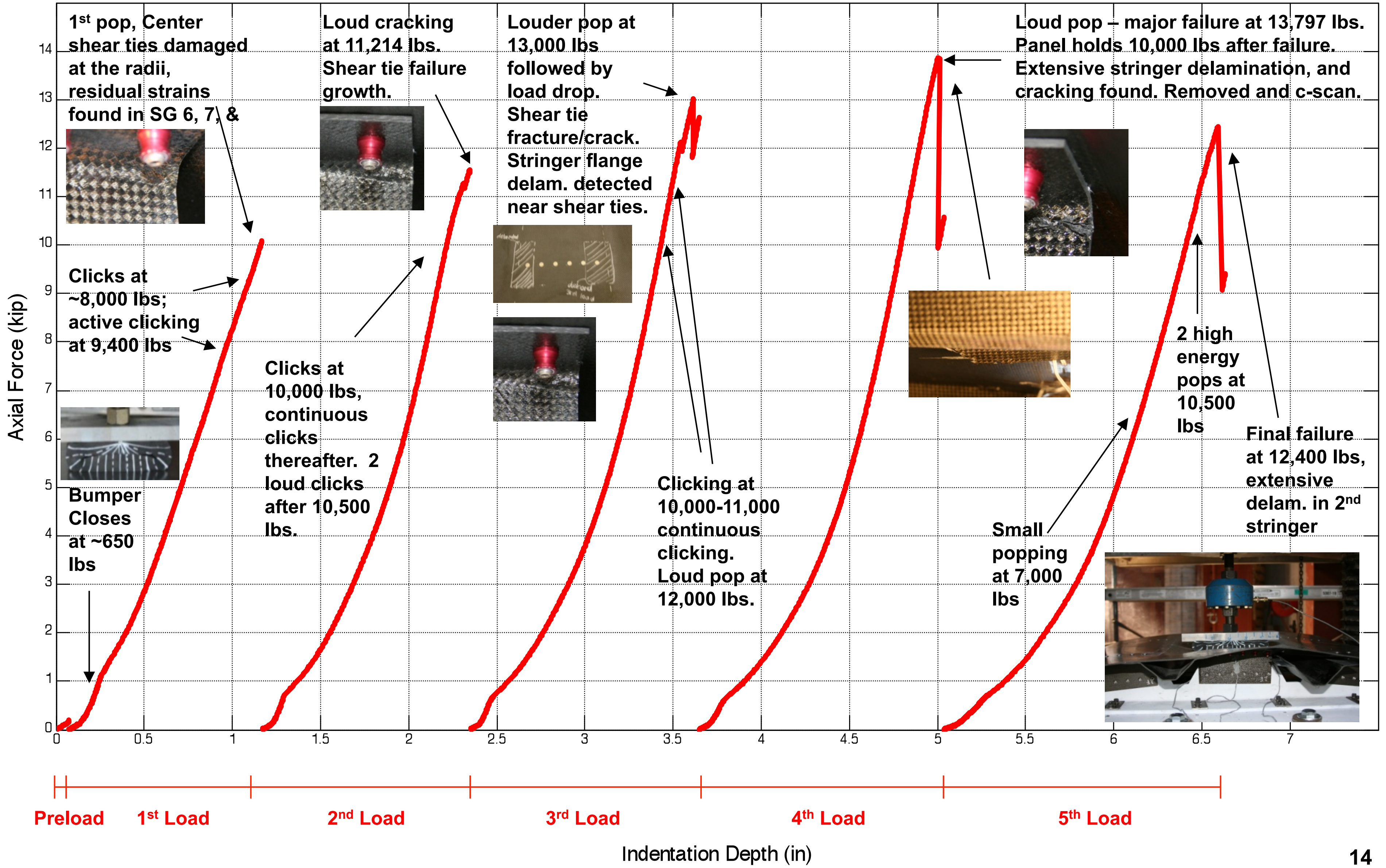


Penetration occurred after 4th loading. Localized delamination only under indentor. No stringer delam.

Stringer02 Results

Rubber Bumper on Skin Between Stringers



1st pop, Center shear ties damaged at the radii, residual strains found in SG 6, 7, &

Clicks at ~8,000 lbs; active clicking at 9,400 lbs

Bumper Closes at ~650 lbs

Loud cracking at 11,214 lbs. Shear tie failure growth.

Clicks at 10,000 lbs, continuous clicks thereafter. 2 loud clicks after 10,500 lbs.

Louder pop at 13,000 lbs followed by load drop. Shear tie fracture/crack. Stringer flange delam. detected near shear ties.

Clicking at 10,000-11,000 continuous clicking. Loud pop at 12,000 lbs.

Loud pop – major failure at 13,797 lbs. Panel holds 10,000 lbs after failure. Extensive stringer delamination, and cracking found. Removed and c-scan.

Small popping at 7,000 lbs

2 high energy pops at 10,500 lbs

Final failure at 12,400 lbs, extensive delam. in 2nd stringer

Stringer02 Exterior View After 4th Loading

Damage: Delamination in Both Stringers

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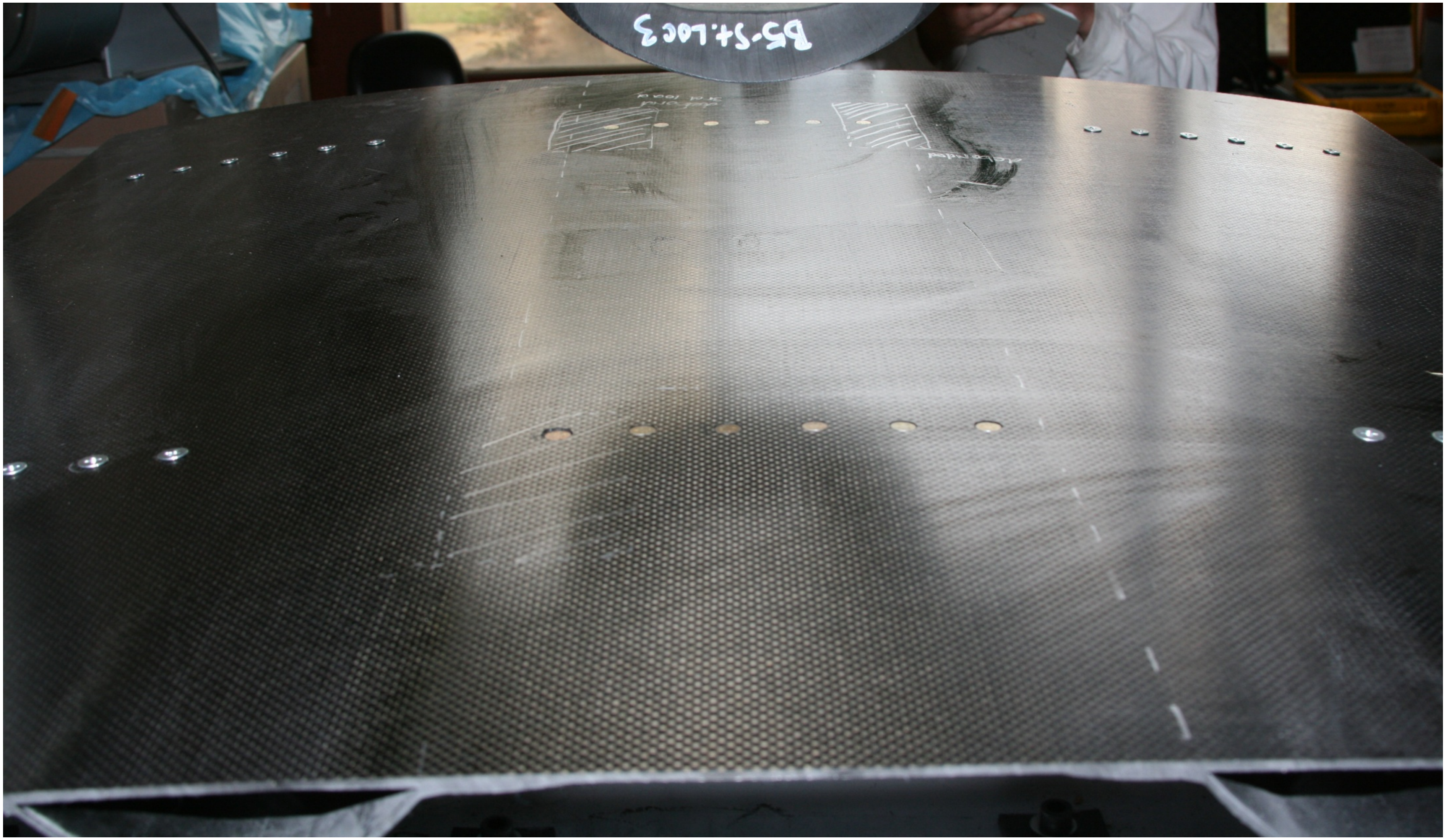
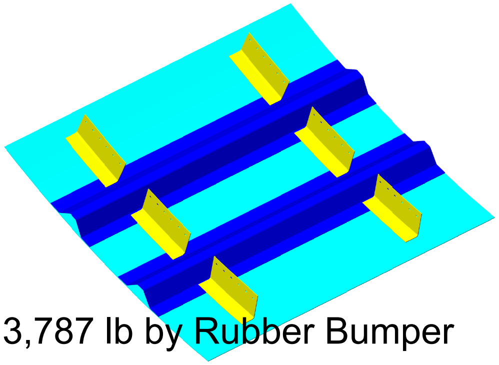


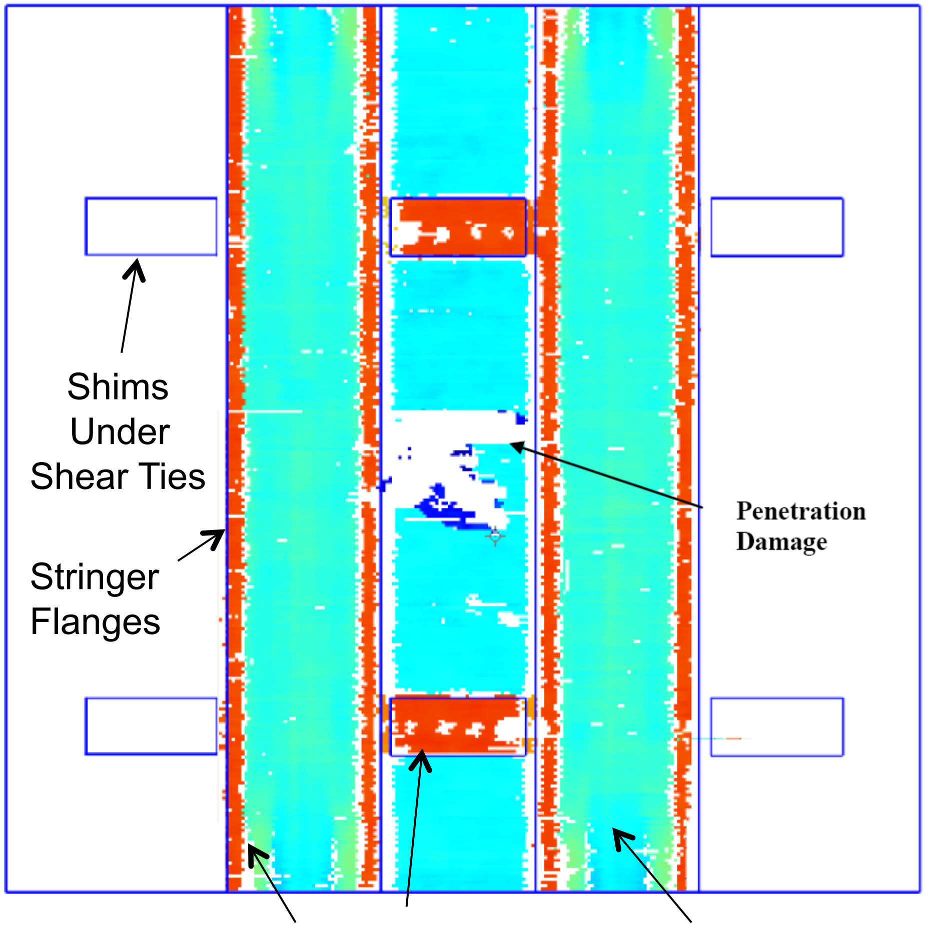
Widespread stringer delamination after 4th loading.
No visually-detectable signs of damage on external surface.

C-Scan Comparison: Stringer01 and 02 Rigid vs. Rubber Bumper at Same Location

- **for both, 4th Loading ended with major damage/load drop**



Stringer01 – Loaded to 6,004 lb by Rigid R3 in.



Shims Under Shear Ties

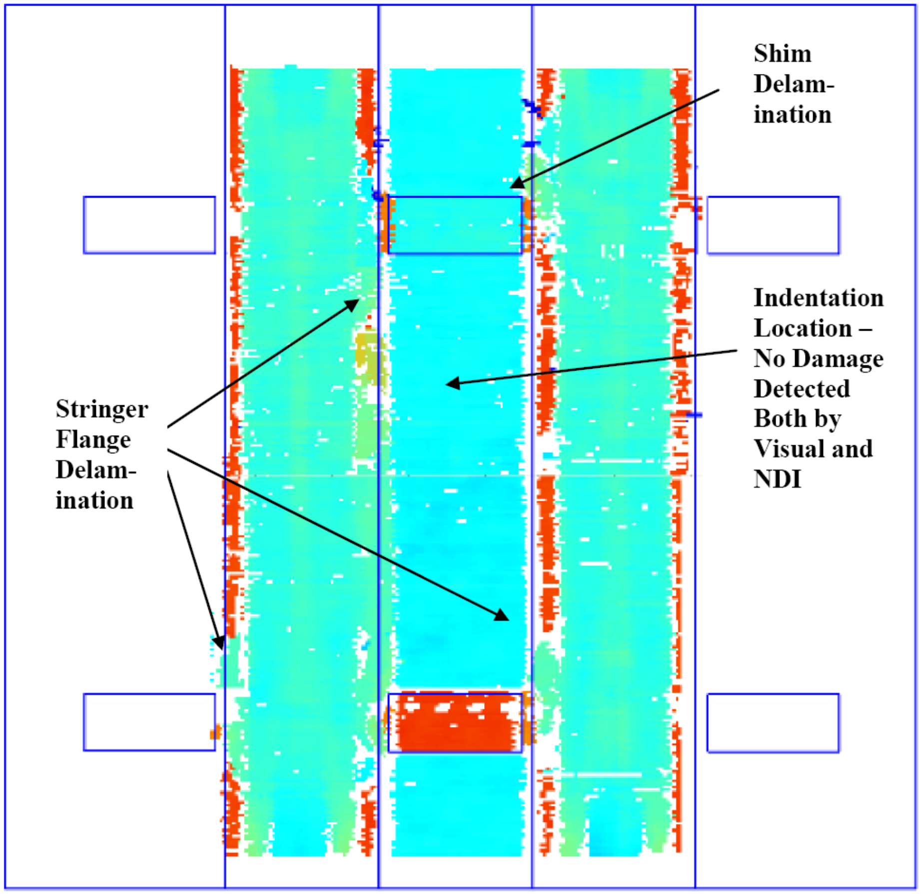
Stringer Flanges

Penetration Damage

Red: ~2X Panel Skin Thk

Light Blue/Green: Panel Skin Thk

Stringer02 – Loaded to 13,787 lb by Rubber Bumper



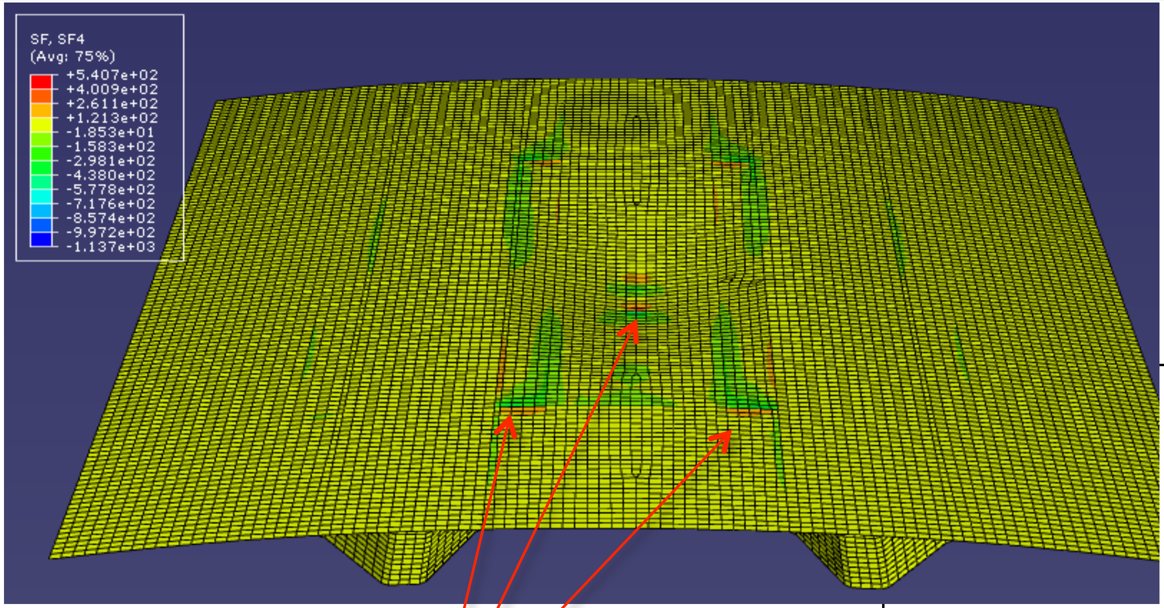
Shim Delamination

Indentation Location – No Damage Detected Both by Visual and NDI

Stringer Flange Delamination

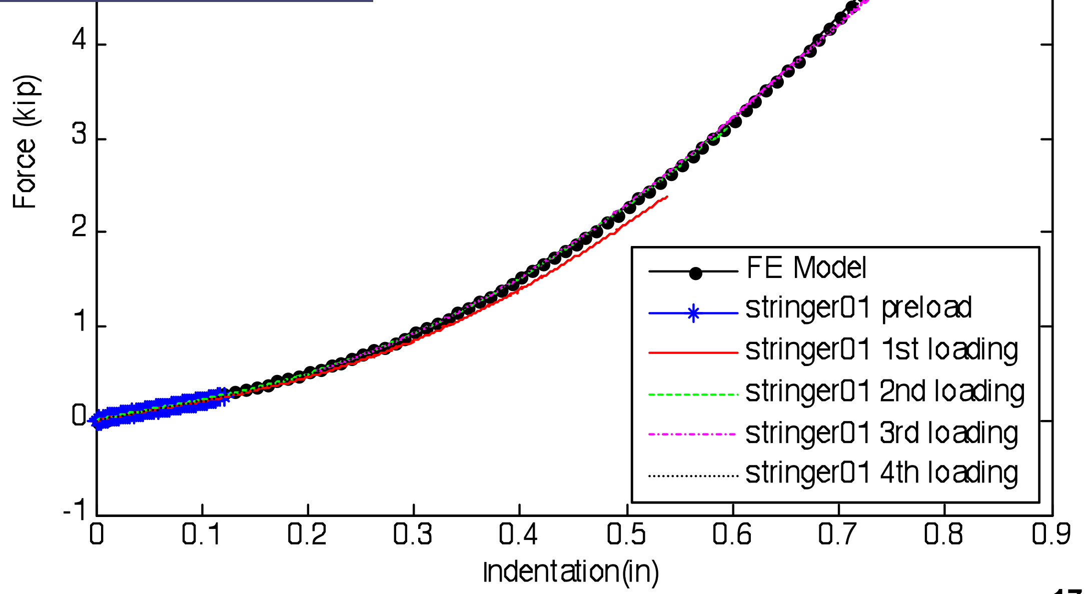
NDI Details: pulse/echo c-scan using manual x-y scanner; 5 MHz, 0.1x0.1 in.

Stringer Panel FEA Models



- 1st correlate with test data
- Extract additional quantities
  - internal forces and strains
  - interlaminar shear stress resultants

Model of Stringer01



Model results: high interlaminar shear stress (computed from ILS resultants):

-Rigid: in skin under indentor edges: 12-14 ksi at 3,000 lbs load

-Rubber Bumper: in stringer flanges at shear tie locations: ~14 ksi at 13,000 lbs load

Frame Specimens

Determining Boundary Conditions

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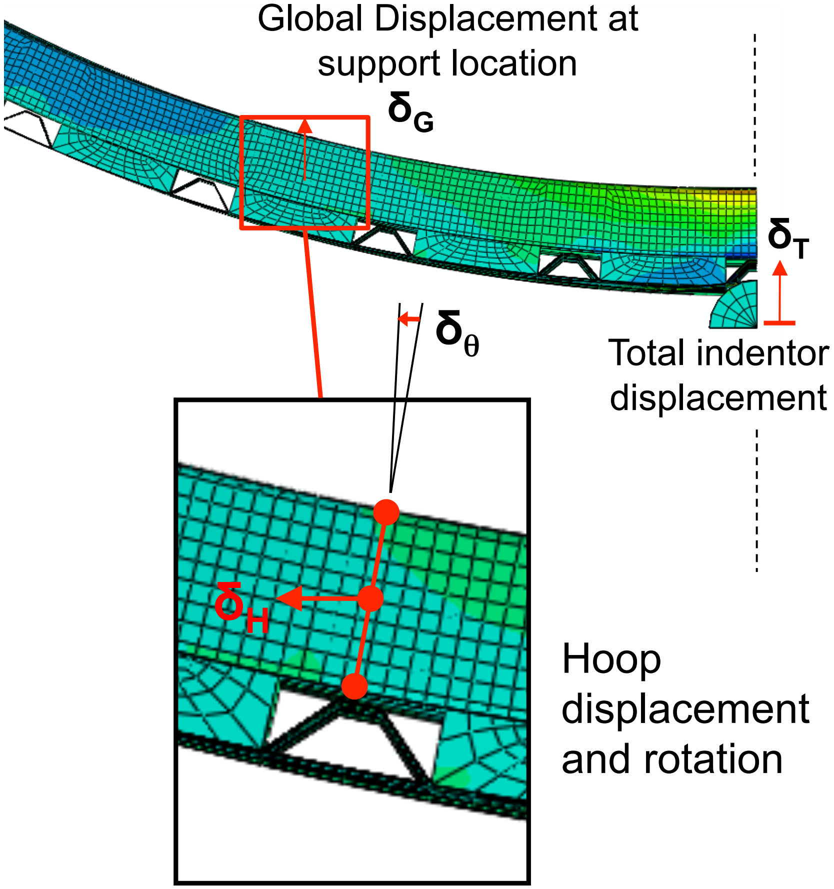
Full Barrel Model:

Local Indentor displacement, $\delta = \delta_T - \delta_G$

Frame Rotation, δ_θ

Hoop Displacement, δ_H

Symm Plane



Global Displacement at support location

Total indentor displacement

Hoop displacement and rotation

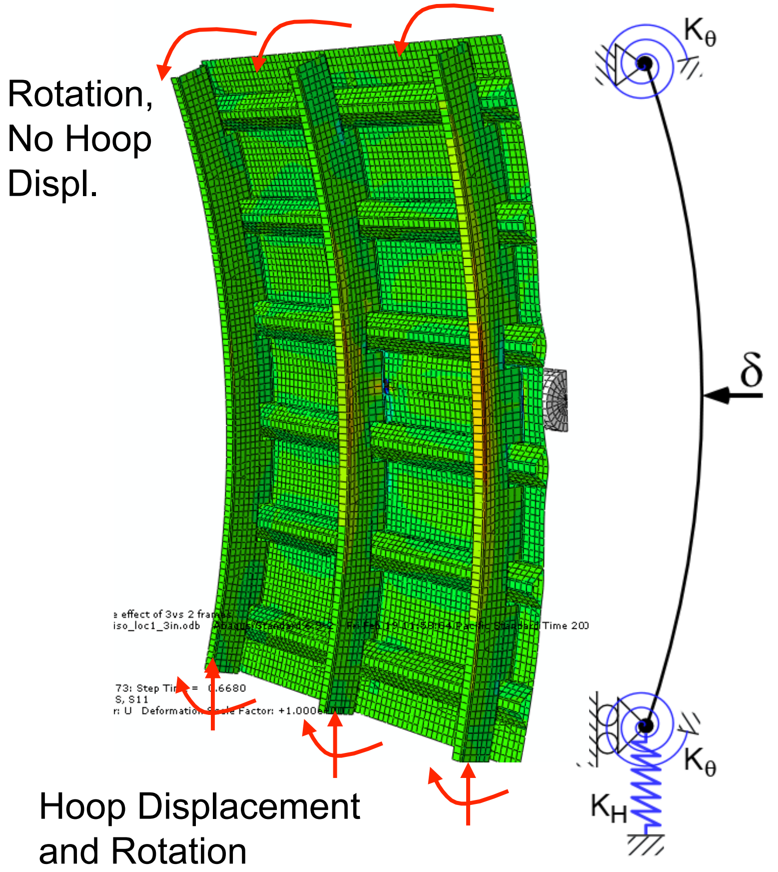
EQUIVALENCE?

Frame Specimen Model:

Apply trial values of K_H and K_θ

Compare with Full Barrel Model δ_H and δ_θ

Iterate spring stiffness values



Rotation, No Hoop Displ.

Hoop Displacement and Rotation

FE Model Determined Frame Specimen Rotational Stiffness

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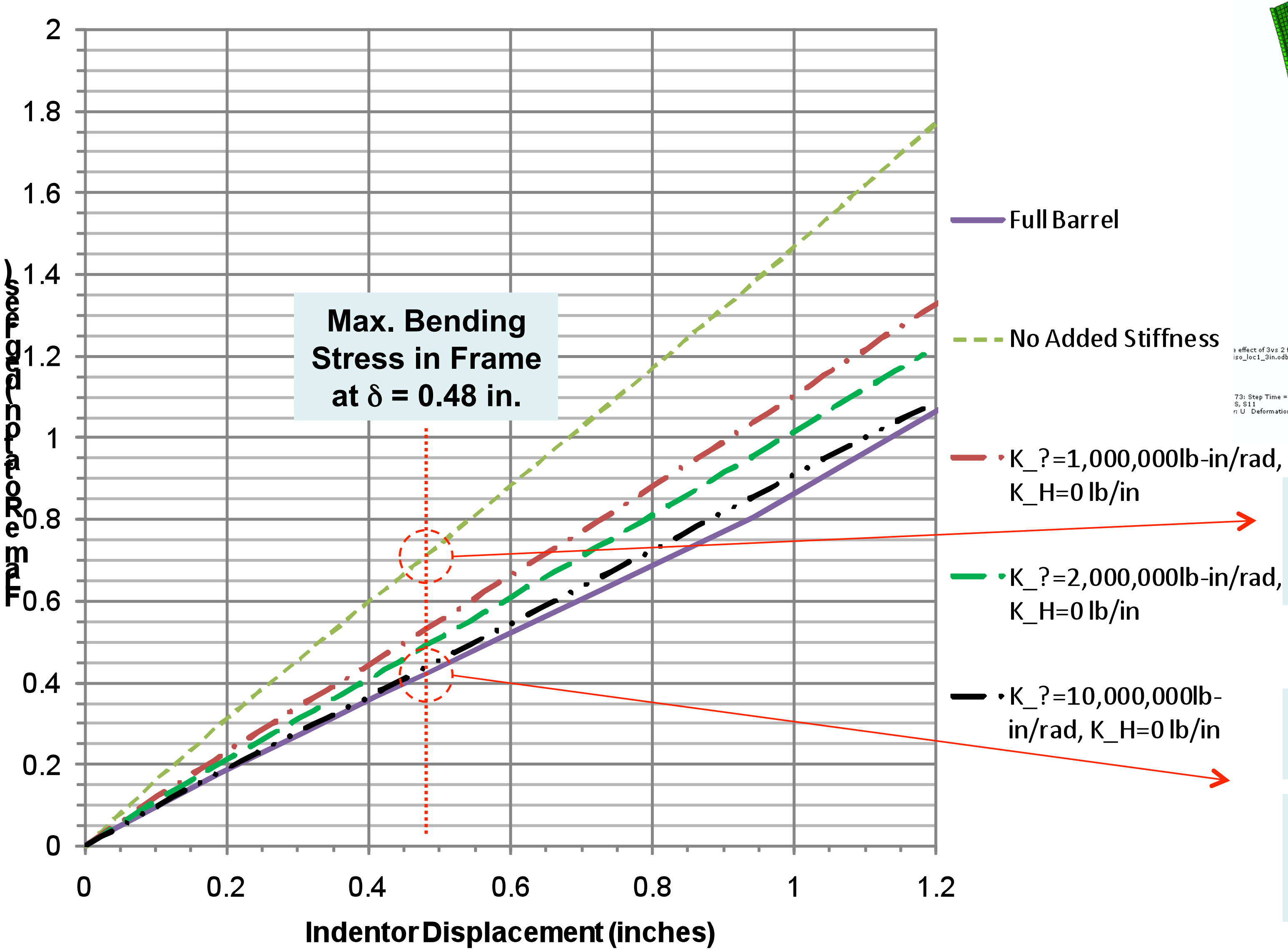
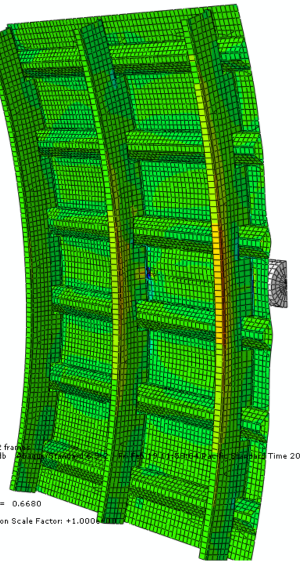


Max. Bending Stress in Frame at δ = 0.48 in.



Panel Model No Added K 5792 psi

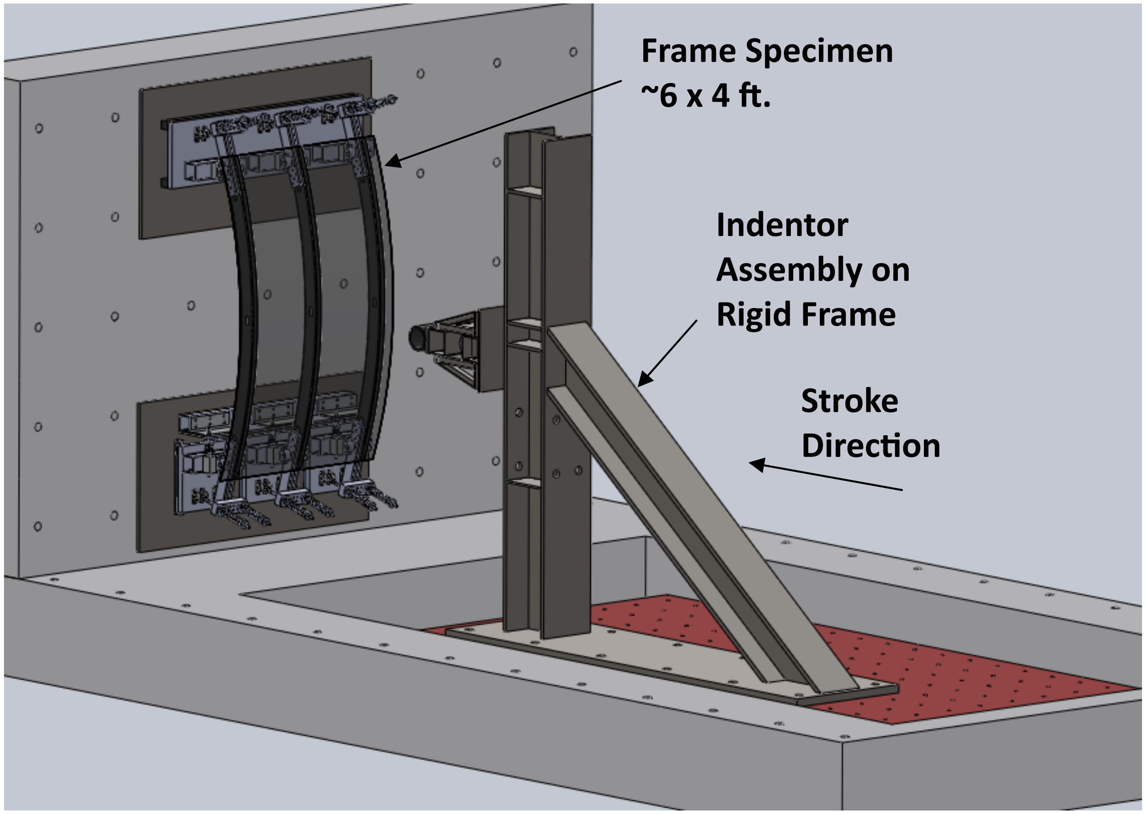
Full Barrel 4011 psi

Panel Model Kθ = 10M 4540 psi

Frame Specimen Test Configuration

Setup employing 1D table (shake table) with specimens mounted to strong wall. Indentor head moves into specimen – simulating GSE contact.

Rigid Strong Wall (full wall not shown)



Scaling Up:
Half Barrel Test Concept

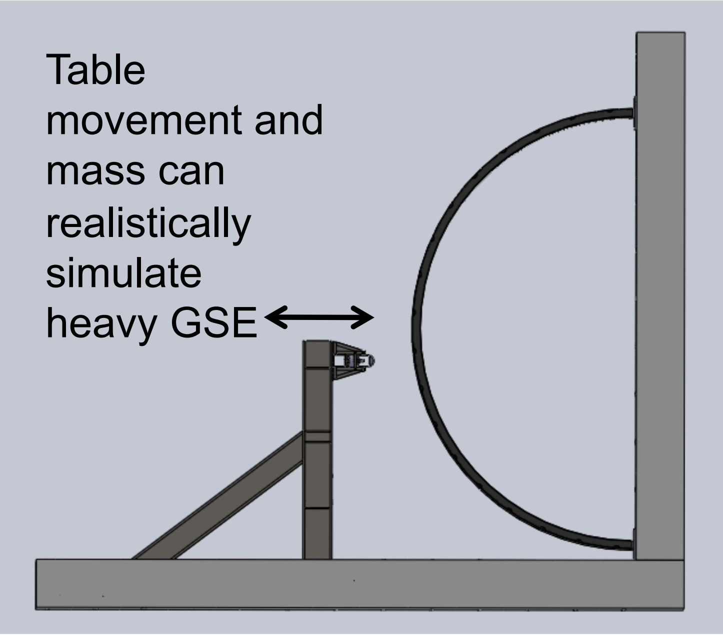
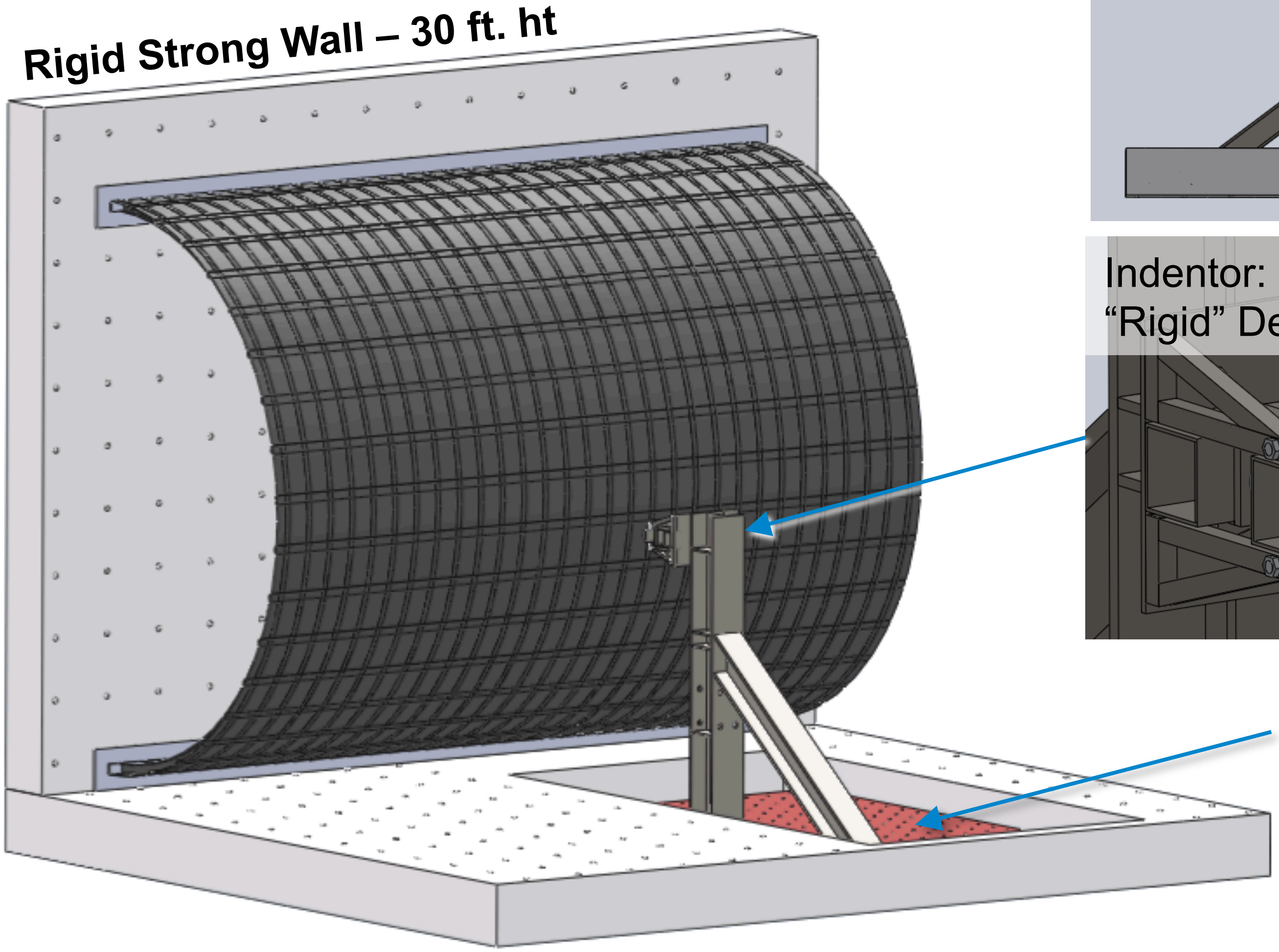
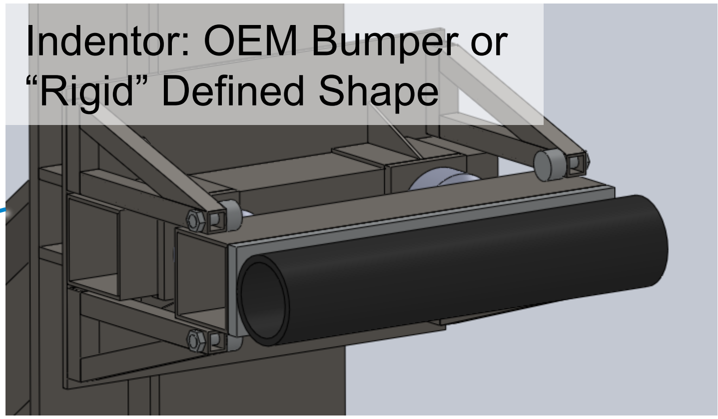


Table movement and mass can realistically simulate heavy GSE





Indentor: OEM Bumper or “Rigid” Defined Shape

1DOF Table System
-capable of quasi-static and fast dynamic motion (35 in/s)

Low-Velocity High-Mass Wide-Area Blunt Impact

- ground vehicles and ground service equipment (GSE) impacts

High Velocity Hail Ice Impact

- Investigate damage formation to composites
- Establish methodology for damage initiation prediction and failure threshold force scaling
- Develop models predicting impact damage extent

Hail Impact Failure Threshold Energy (FTE) and Damage Modes

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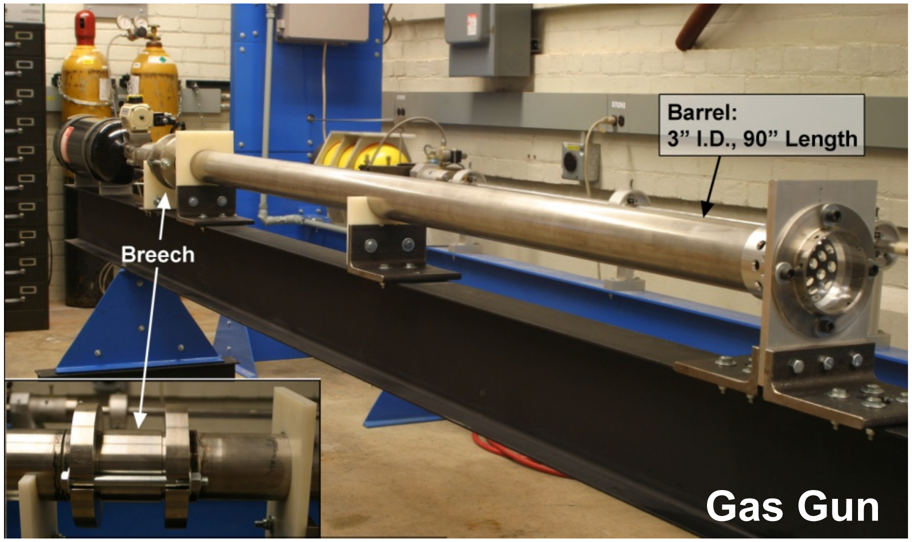
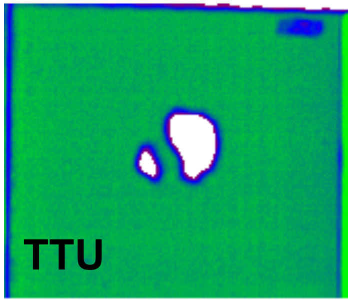
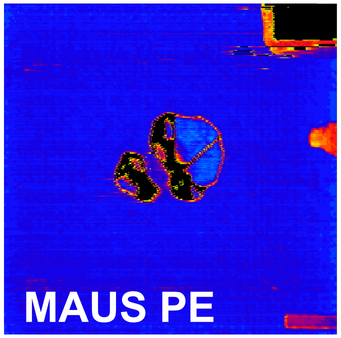
🟩 Completed 🟪 In Progress 🟧 Upcoming	SHI 38.1 mm	SHI 50.8 mm	SHI 61.0 mm	SHI 50.8mm Angle 1	SHI 50.8mm Angle 2
8 plies	304 mm x 304 mm [0/45/90/-45]_s				
FTE	🟩 3	🟩 3	🟪 3	🟧 3	🟧 3
Damage, > FTE	🟪 3+3	🟪 3+3	🟪 3+3	🟧 3+3	🟧 3+3
16 plies	304 mm x 304 mm [0/45/90/-45]_2s				
FTE	🟩 3	🟩 3	🟩 3	🟧 3	🟧 3
Damage, > FTE	🟪 3+4	🟪 3+4	🟪 3+4	🟧 3+3	🟧 3+3
24 plies	304 mm x 304 mm [0/45/90/-45]_3s				
FTE	🟪 3	🟪 3	🟩 3	🟧 3	🟧 3
Damage, > FTE	🟧 3+3	🟧 3+3	🟧 3+3	🟧 3+3	🟧 3+3

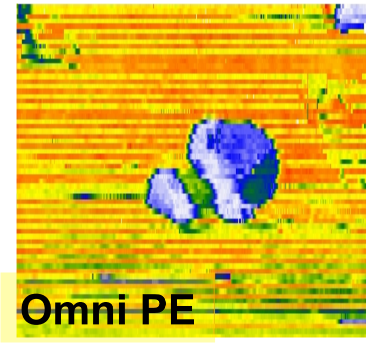


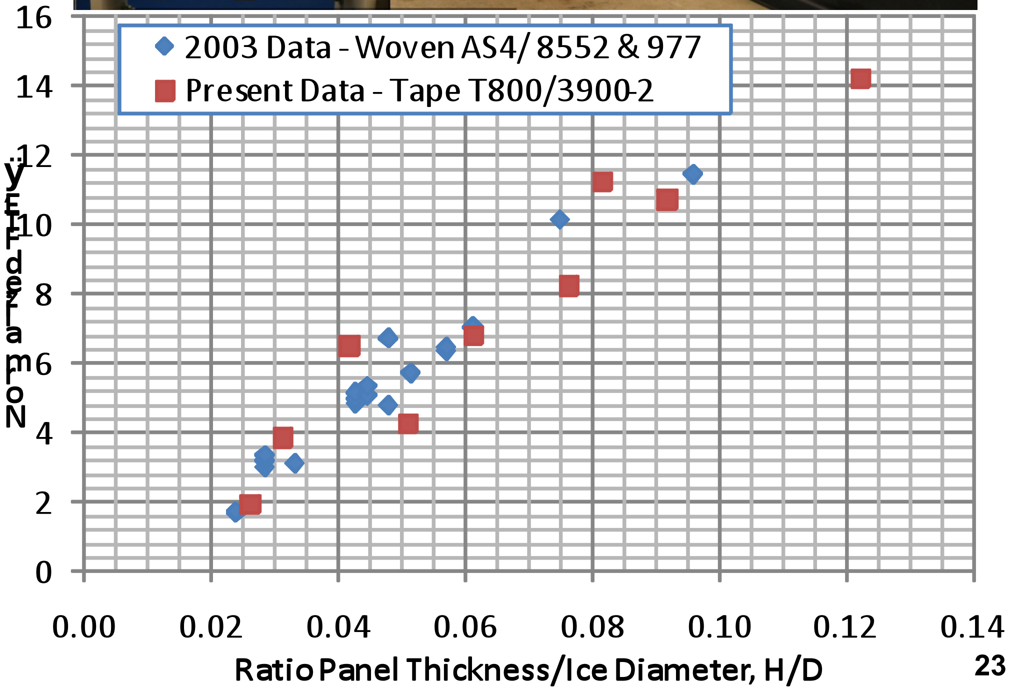
Sandia Lab Collaboration
Advanced NDI Studies

Scans of 16 ply panel impacted with 38.1 mm ice at 162 m/s (332 J)









Ice Impact Models Development

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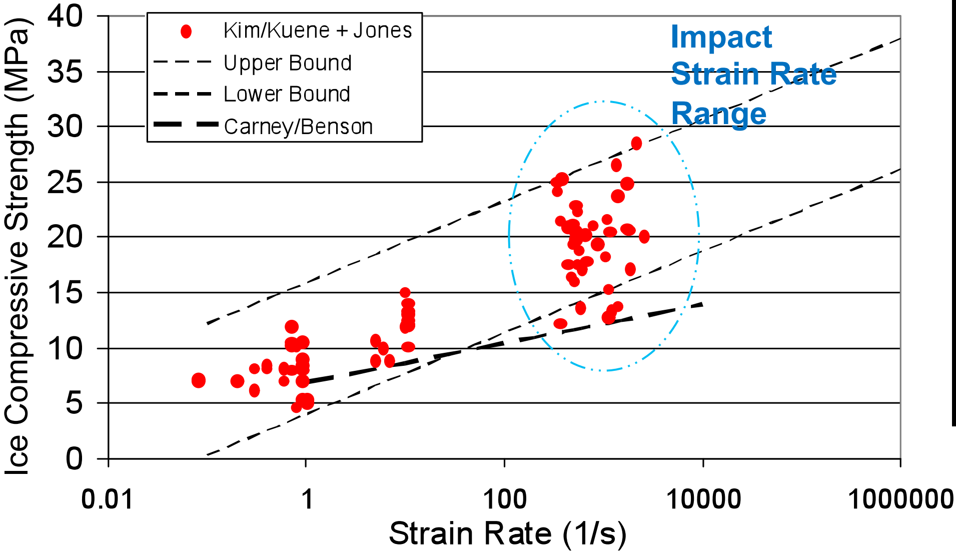
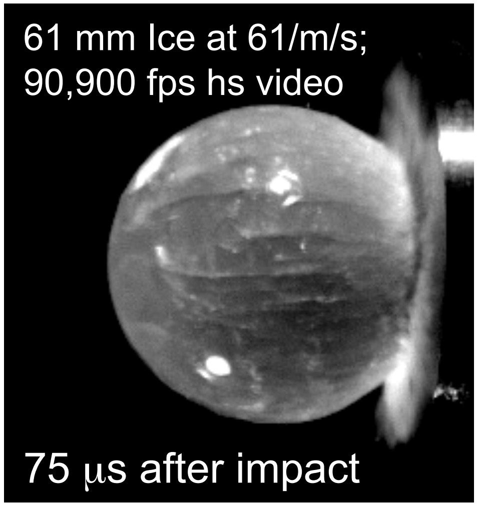
- Develop accurate, strain-rate sensitive ice projectile material model – use to simulate impacts onto composite targets/structures

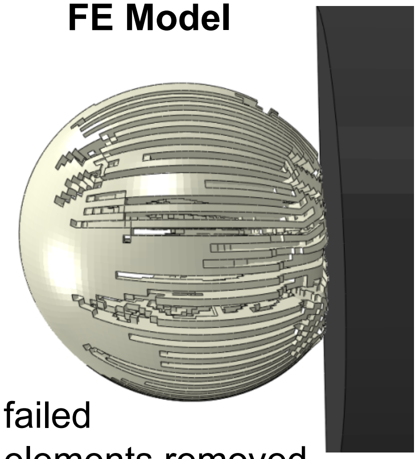




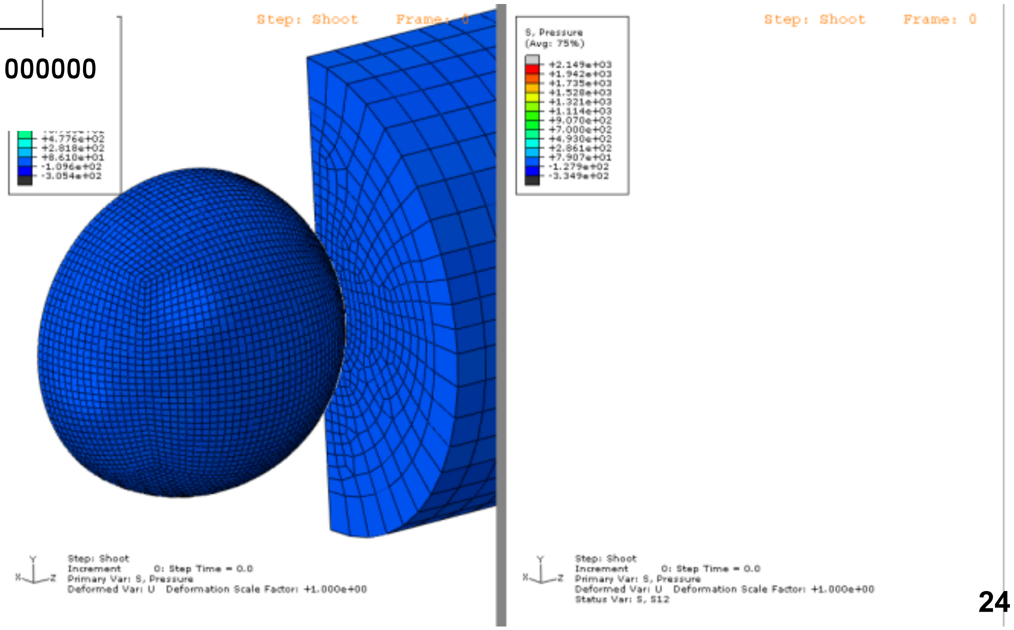
61 mm Ice at 61/m/s; 90,900 fps hs video

75 µs after impact

FE Model



failed elements removed



- Elastic-plastic with failure model
  - tensile pressure cutoff – failed elements behave as fluid
- Compressive strength based on high-rate (10^3 s^{-1}) ice test data (Kim and Keune 2006)

Conclusions/Discussion

- **Wide Area Blunt Impact**
  - **Rubber bumper indentor produces internal distributed damage**
    - » develops much higher contact area with no localized damage
    - » delamination of stringers originate at internal reaction/hard points (at shear ties)
    - » damage initiation at over 3X loading than “rigid” indentor, peak force 2X higher
    - » no permanent deformation or externally visible damage
  - **Rigid 3 in. radius indentor produces localized damage**
    - » penetration w/ no delamination of stringer flanges
    - » initial damage is localized delamination in skin under indentor edges
  - **Models confirm high interlaminar shear develops at observed damage locations**
  - **Frame specimen test system setup – amenable to larger-scale specimens**
- **High Velocity Hail Ice Impact**
  - **FTE for tape pre-preg materials can be established**
    - » delamination is initial mode – no exterior damage visible
    - » data for T800/3900-2 tape found to overlap with woven AS4/8552 & 977 data
  - **Basic physics of ice sphere fracture during impact understood**
    - » longitudinal crack formation with peak contact force corresponding to crack saturation
  - **FE models able to represent basic physics – models to be applied to composite panel specimens & made available for public domain**

A Look Forward

- **Benefit to Aviation**
  - Can assist in improving the resistance of composite structures to blunt impact threats – in particular GSE and large hail
    - provides critical information on mode and extent of seeded damage, particularly non-visible impact damage (NVID) from blunt impact threats
    - establishes: modeling capability and methodology for reduced-sized specimen testing
  - Aids in assessing whether a blunt impact incident could have caused damage
    - if so, what inspection technique should be used? where?
- **Future needs**
  - Transition to Phase II and III testing of larger-sized articles:
    - 4 or 5 bay stringer+frame-stiffened skin, ¼ or ½ barrel
    - large sandwich panel structure (Beech Starship section at UCSD)
  - Establish modeling capability simulating damage & stiffness loss – incorporate into shell-type elements which can be used in global/full-structure models
  - Understanding of dynamic effects – low velocity impact vs. quasi-static indentation, strain rate dependent material behavior; ***relate to field operations***
  - Investigate glancing impacts – confirm previous FE study predictions of angle effects
  - Consideration other primary structure types – e.g., wing, tail
  - Hail ice: investigate damage resistance of sandwich construction and stiffened skin