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Impact Damage Formation on Composite Aircraft Structures

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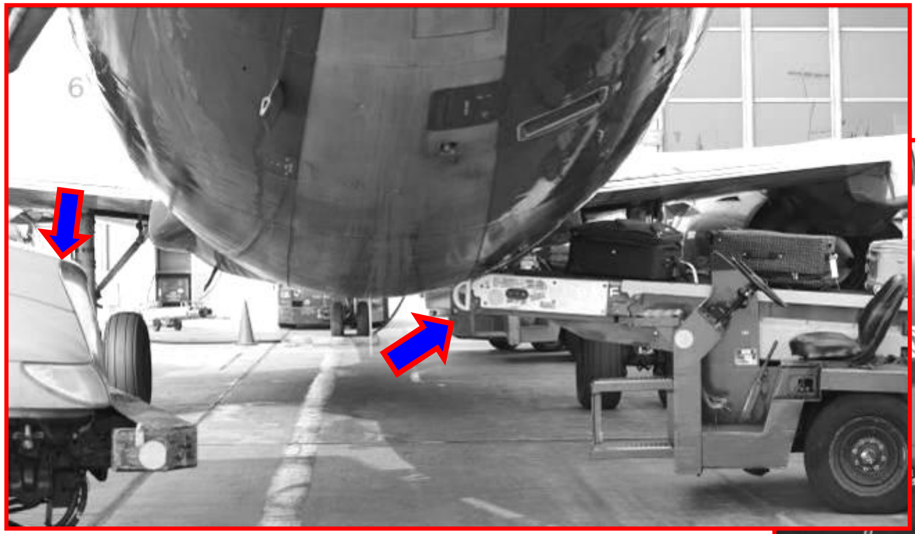
Impact Damage Formation on Composite Aircraft Structures

- **Principal Investigators & Researchers**
  - PI: Prof. Hyonny Kim, Professor, UC San Diego
  - Graduate Students
    - PhD:
      - HEWABI: Moonhee Nam, Chaiane Wiggers de Souza
      - Sandwich Core Crush: Konstantinos Anagnostopoulos
    - MS: none
- **FAA Technical Monitor**
  - Lynn Pham
- **Other FAA Personnel Involved**
  - Larry Ilcewicz , Ahmet Oztekin
- **Industry Participation**
  - Boeing, Bombardier, UAL, Delta, DuPont, JC Halpin Consulting

Impact Damage Formation on Composite Aircraft Structures

- **Motivation and Key Issues**
  - impacts are ongoing and major source of composite damage
  - High Energy Wide Area ***Blunt*** Impact (HEWABI) damage of main interest
    - involves large contact area
    - internal damage can exist with ***low/no exterior visibility***
- **Sources of Interest:**
  - ground service equipment (GSE) with rubber bumpers
  - railings, blunt/round corners, FOD of unknown geometry
  - hail ice, bird

Sandwich Blunt Impact
- core crush with low/non-visible dent
- low velocity: GSE, tools
- high velocity: ice, bird



Ground Vehicles & Service Equipment
- side & lower facing surfaces
- high mass, low velocity

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Overall Project Objectives

- **Understand impact damage formation; particularly for blunt sources and visual detectability**
  - Identify key phenomena
  - Understand controlling parameters
    - special attention to internal vs. external damage formation vs. bluntness/contact-area size
- **Develop testing methodology: full vs sub-structure and BC considerations**
- **Establish experimental database for analysis methods validation**
- **Develop progressive damage analysis methodologies predicting blunt impact**

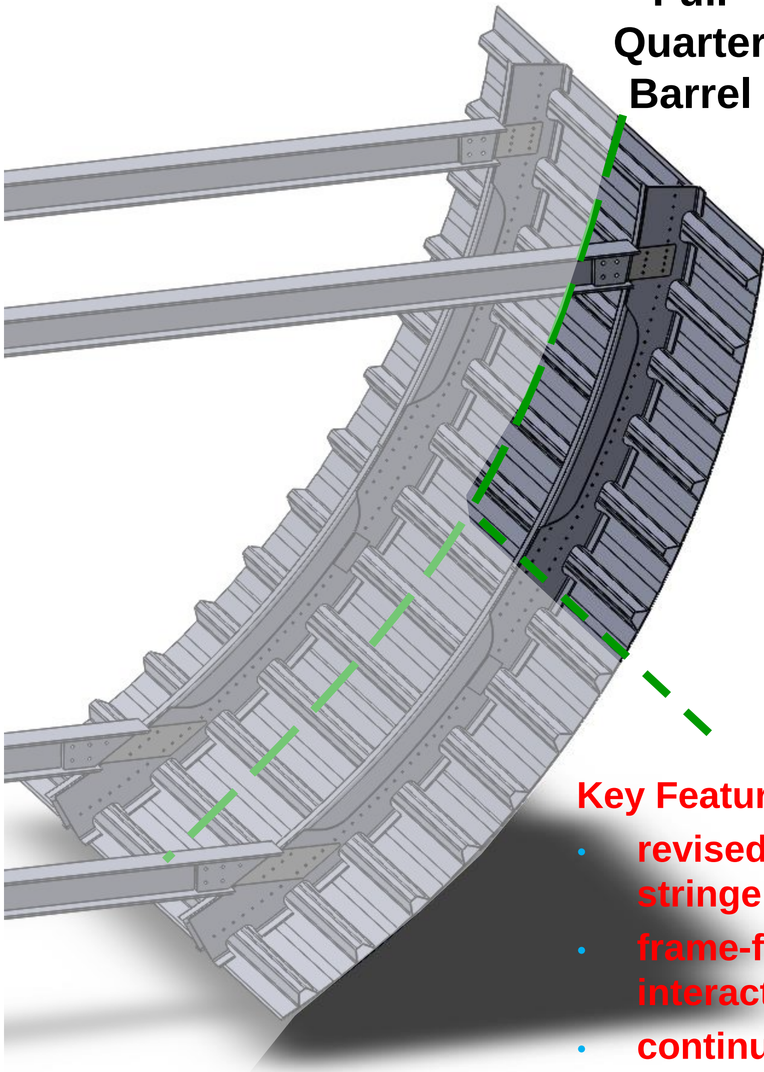
Outline

- Ground Service Equipment (GSE) High Energy Wide Area Blunt Impact (HEWABI)
- Impact Damage to Sandwich Panels & Core Crush Mechanics
- Summary, Benefits to Aviation, and Future Work

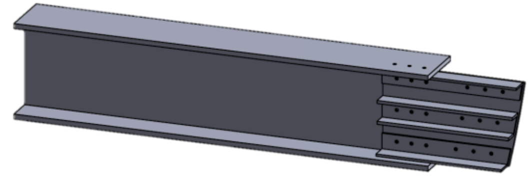
2nd Generation Specimen Blunt Impact Tests

Focus: Impact & Failure Near Floor Joint

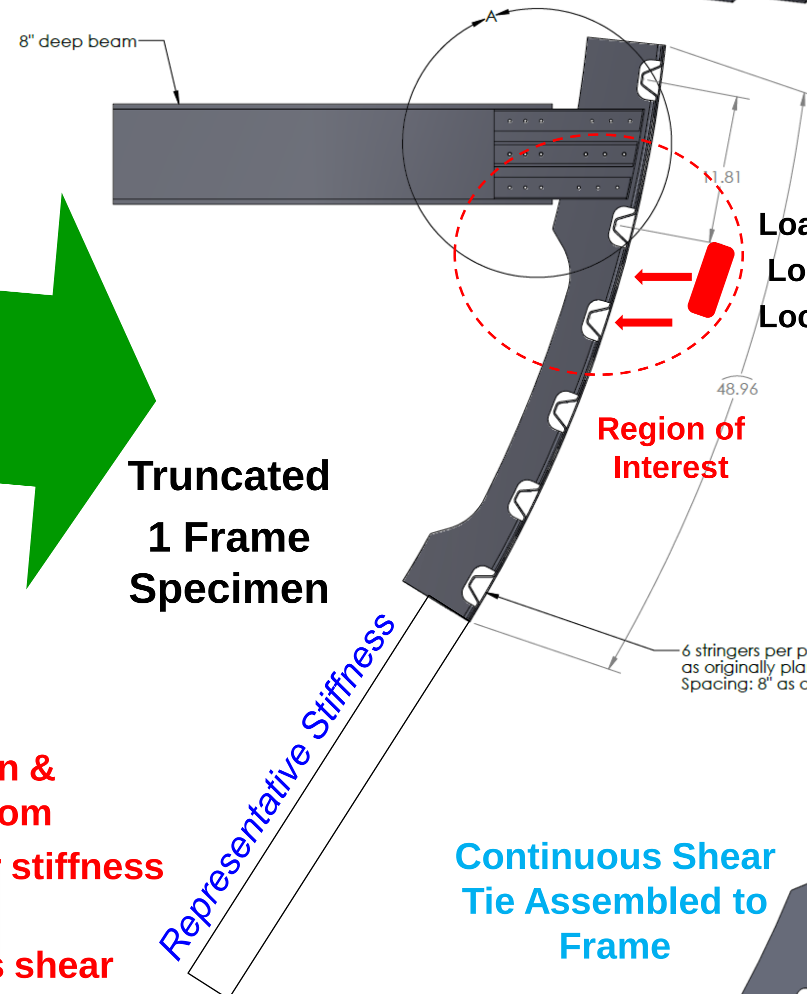
Full Quarter Barrel



Truncated 1 Frame Specimen

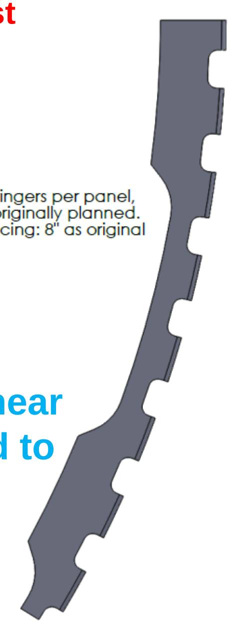


Frame-to-Floor Stiffness Interaction



Loading:
Loc 3
Loc 4

Region of Interest



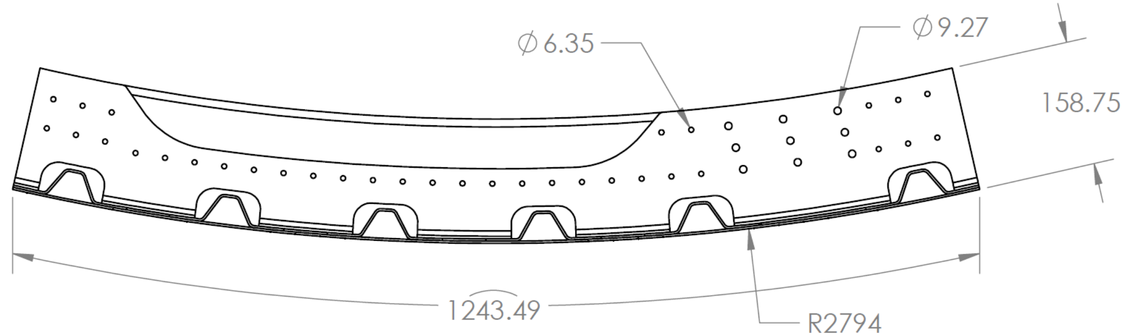
Continuous Shear Tie Assembled to Frame

Key Features:

- revised skin & stringer geom
- frame-floor stiffness interaction
- continuous shear ties

Large Specimen Design

- Qty: 4 panels
- Each Panel:
  - 6 co-cured stringers
  - 1 frame with continuous shear tie
  - floor joint compliance BC



Dimensions in mm

203 mm deep Alum I-beam represents passenger floor

Bracket representing compliance of floor-frame interaction

Part	Layup	THK (mm)
Skin	$[0w/0/45/90/-45/0/90]_s$	2.79
Stringer	$[0w/0/45/90/-45/0/90]_s$	2.79
C-Frame (all woven)	$[45/0/-45/45/0/-45]_s$ (web) $[45/0/0/-45/45/0/0/-45]_s$ (flange)	2.64 3.53
Shear tie (all woven)	$[45/0/-45/0/45/0/-45/0]_s$	3.53

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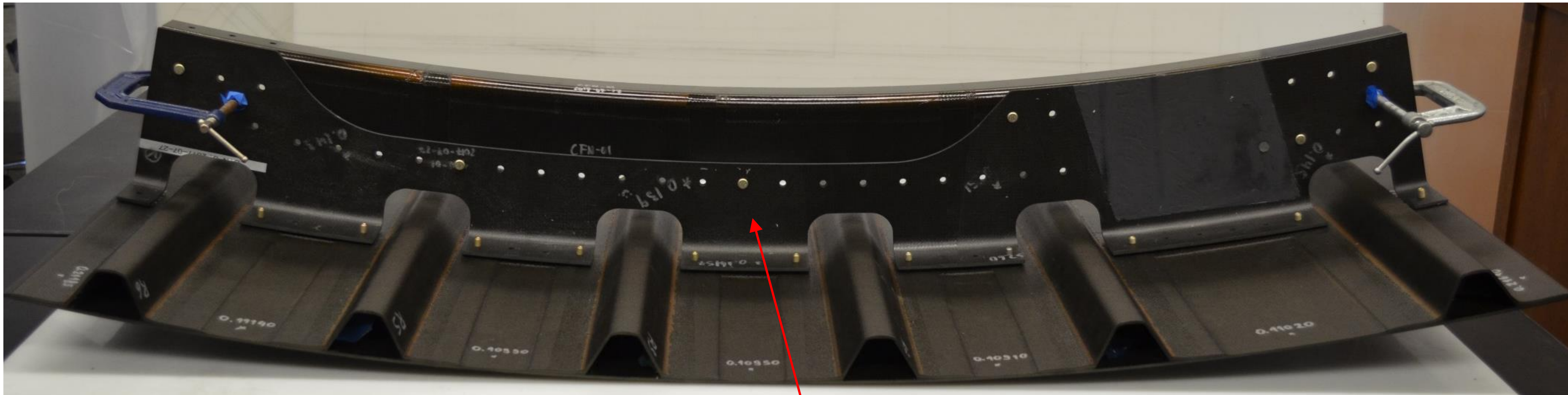
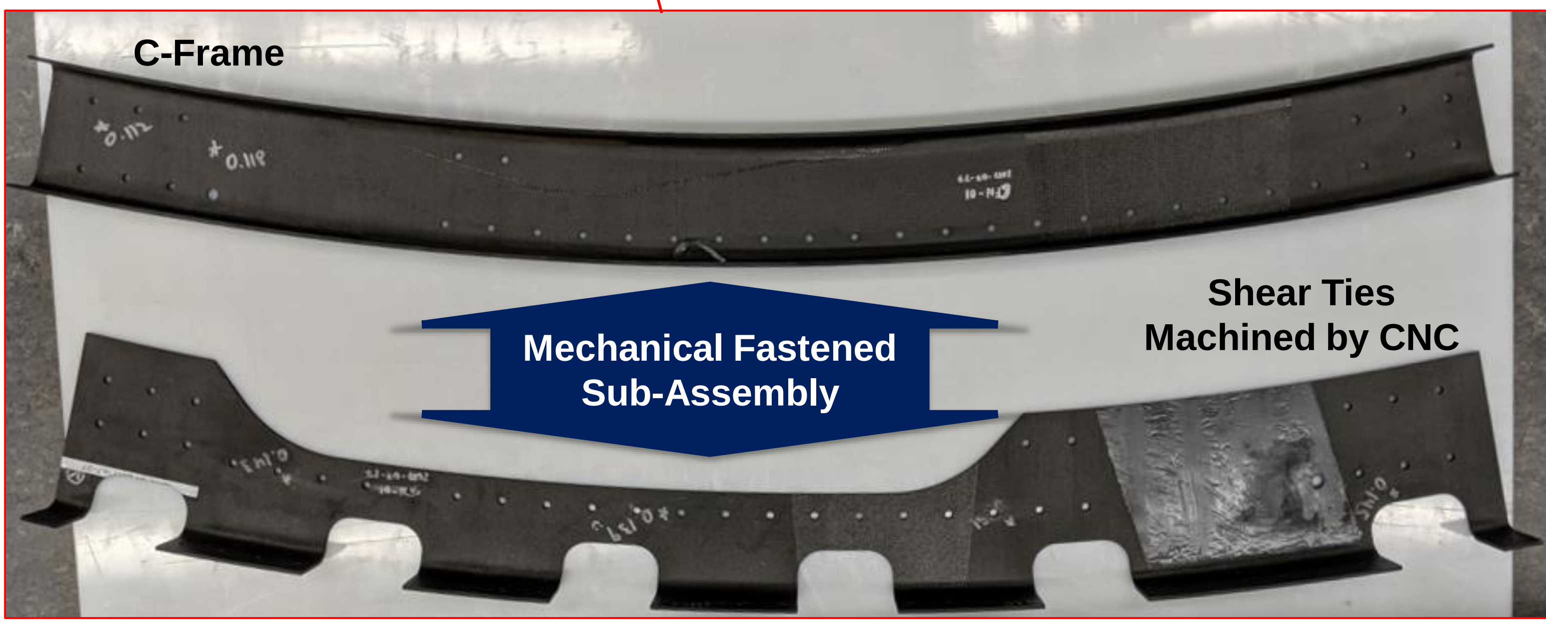
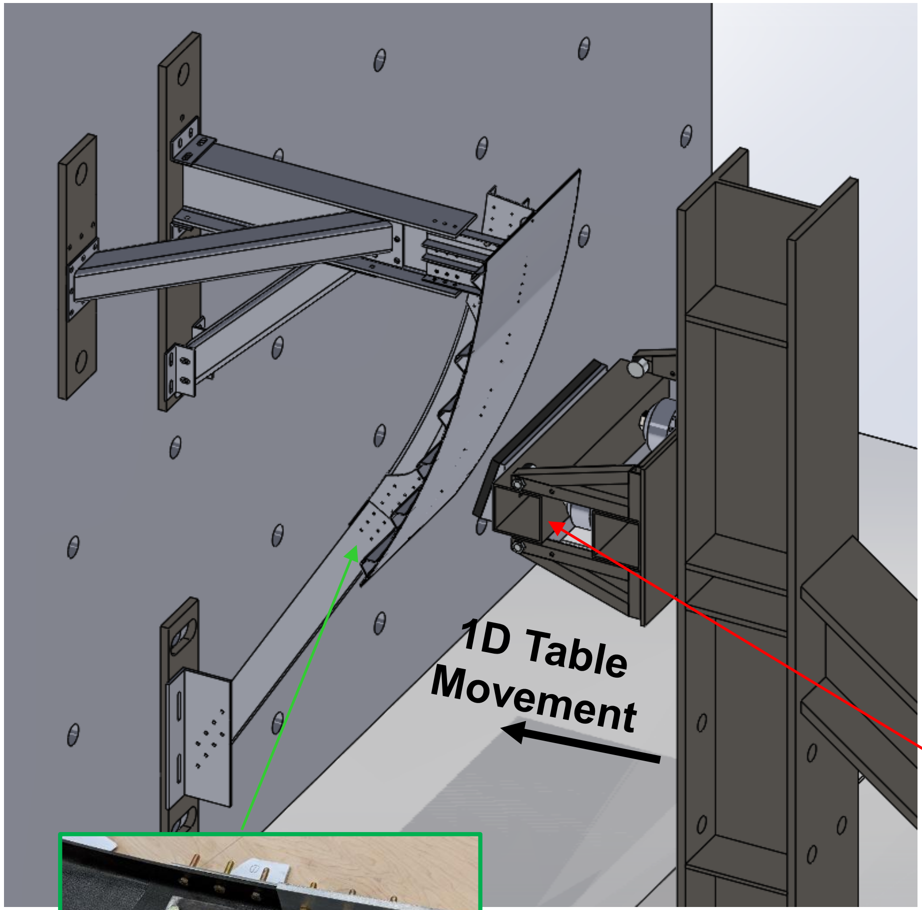
Fuselage Panel Assembly

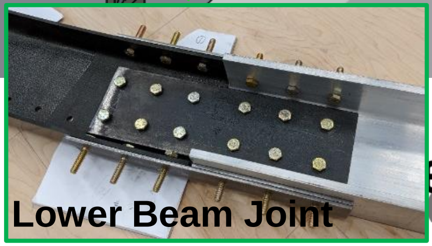




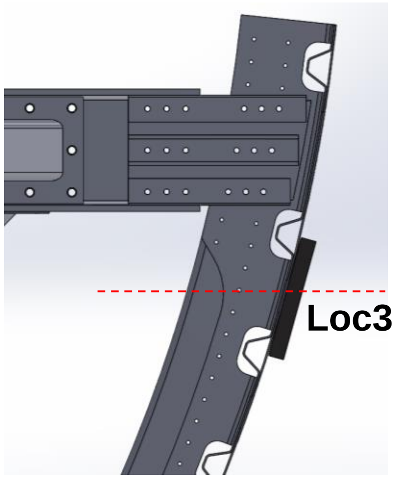
Test Configuration

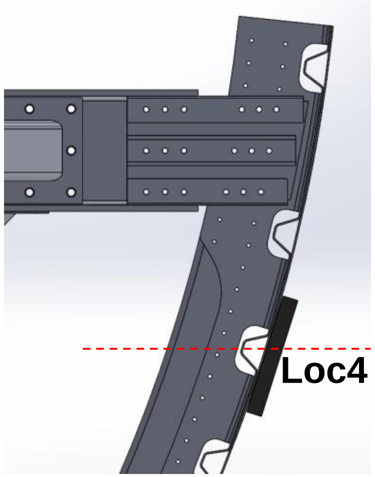
- Quasi-static loading only - table system tests found dynamic overshoot un-controllable due to high inertia





Test Loading Locations: Loc3 & Loc4

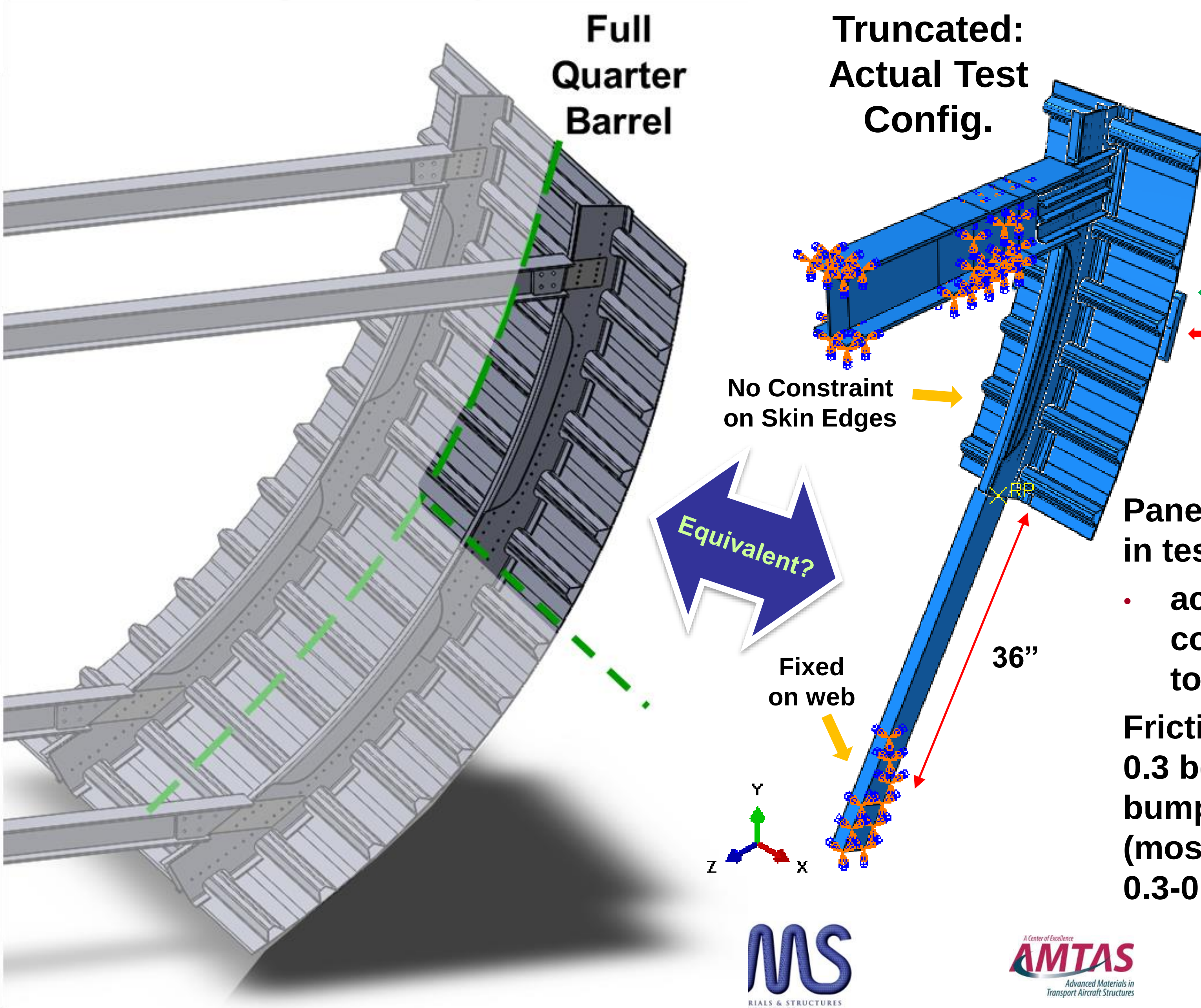




Four Specimens: Quasi-static, Inspect & Reload

Specimen	Load	Test Level
1	Loc3	First significant damage mode
2	Loc3	Major damage - frame
3	Loc4	First significant damage mode
4	Loc4	Major damage - frame

Modeling: Verify BCs Represent Quarter Barrel

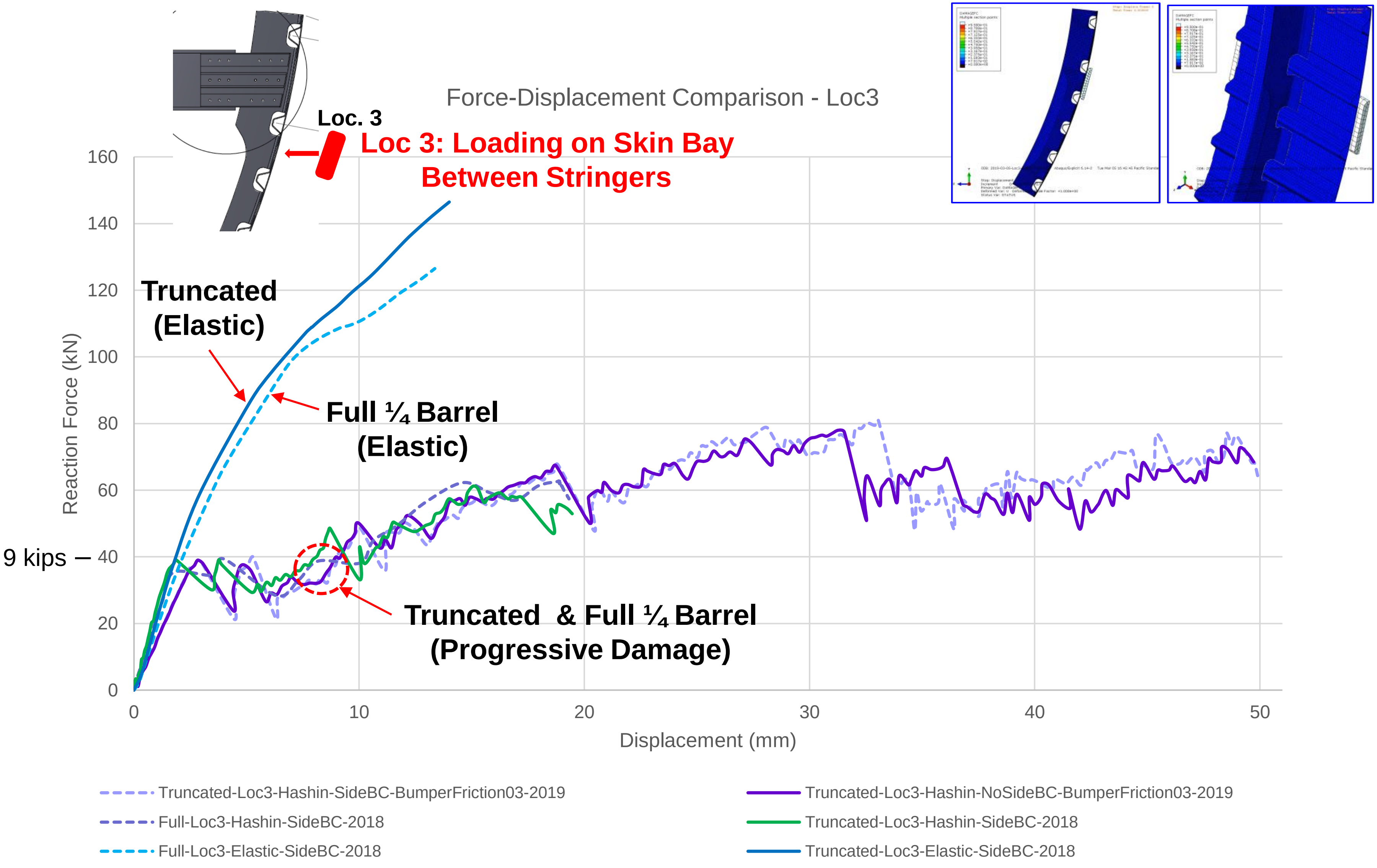


Panel skin edges free in test configuration

- actual edge condition difficult to replicate

Friction coefficient 0.3 between rubber bumper and skin (most dry contact 0.3-0.6)

Loading Location 3 Response Comparison



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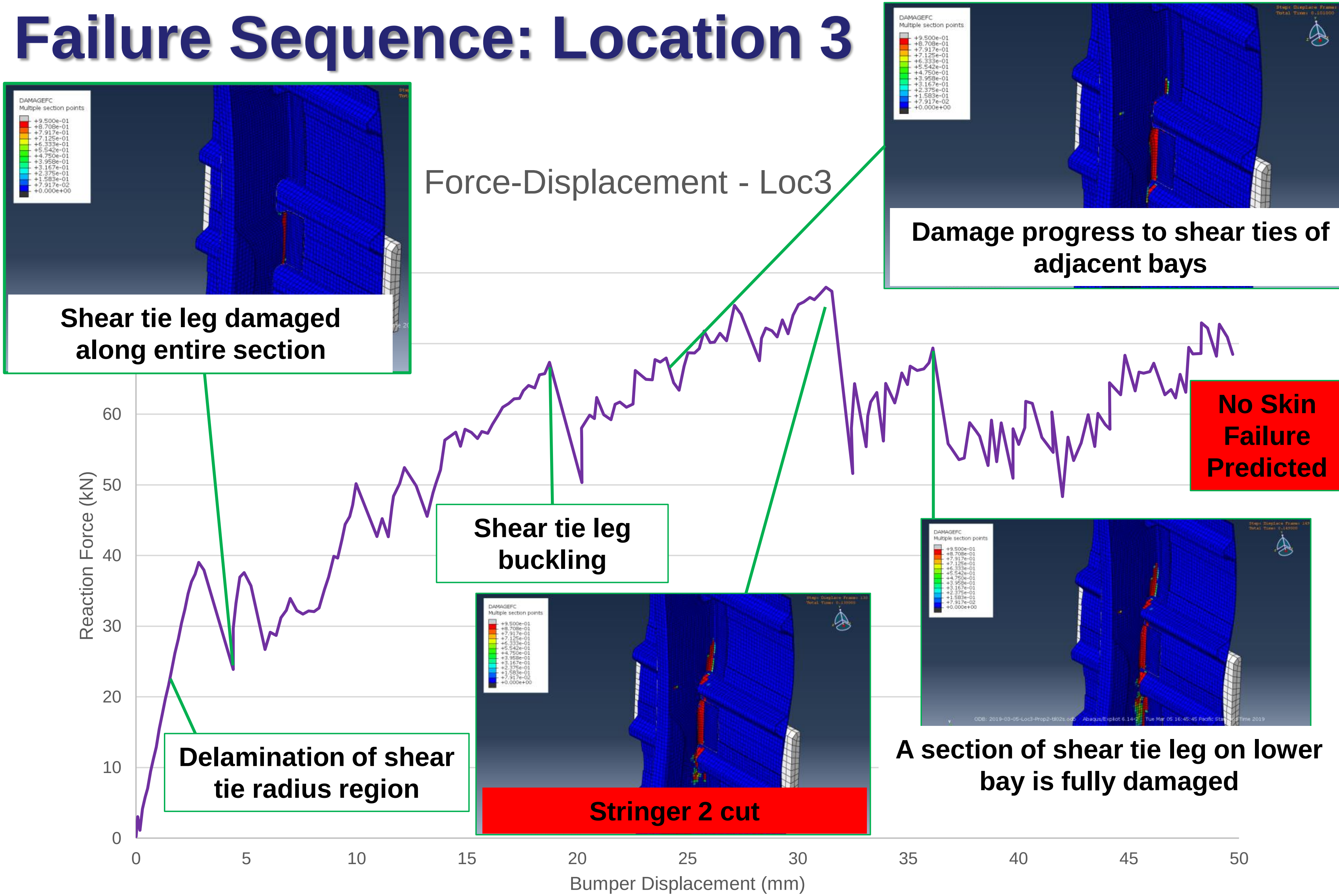
Failure Sequence: Location 3



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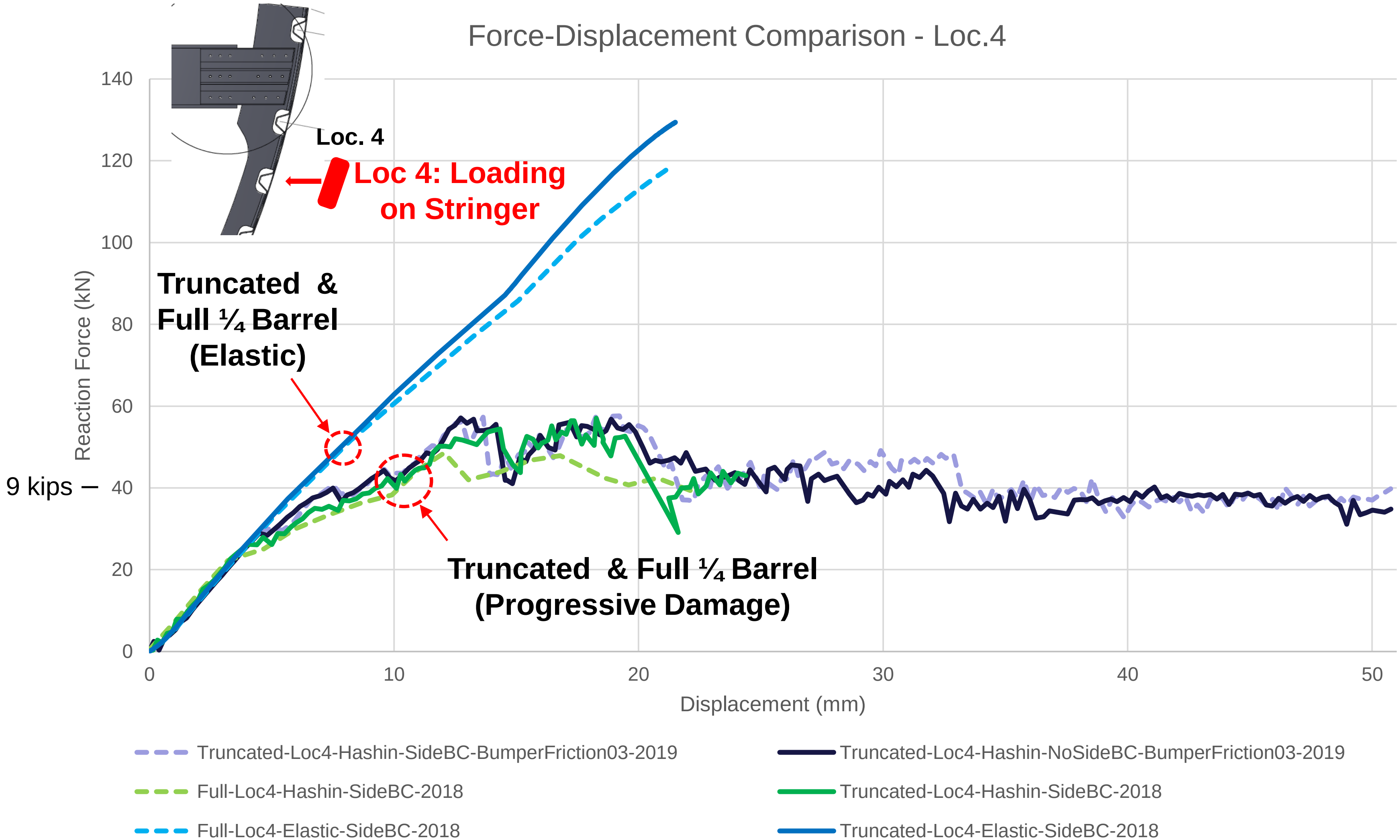
Loading Location 4 Response Comparison



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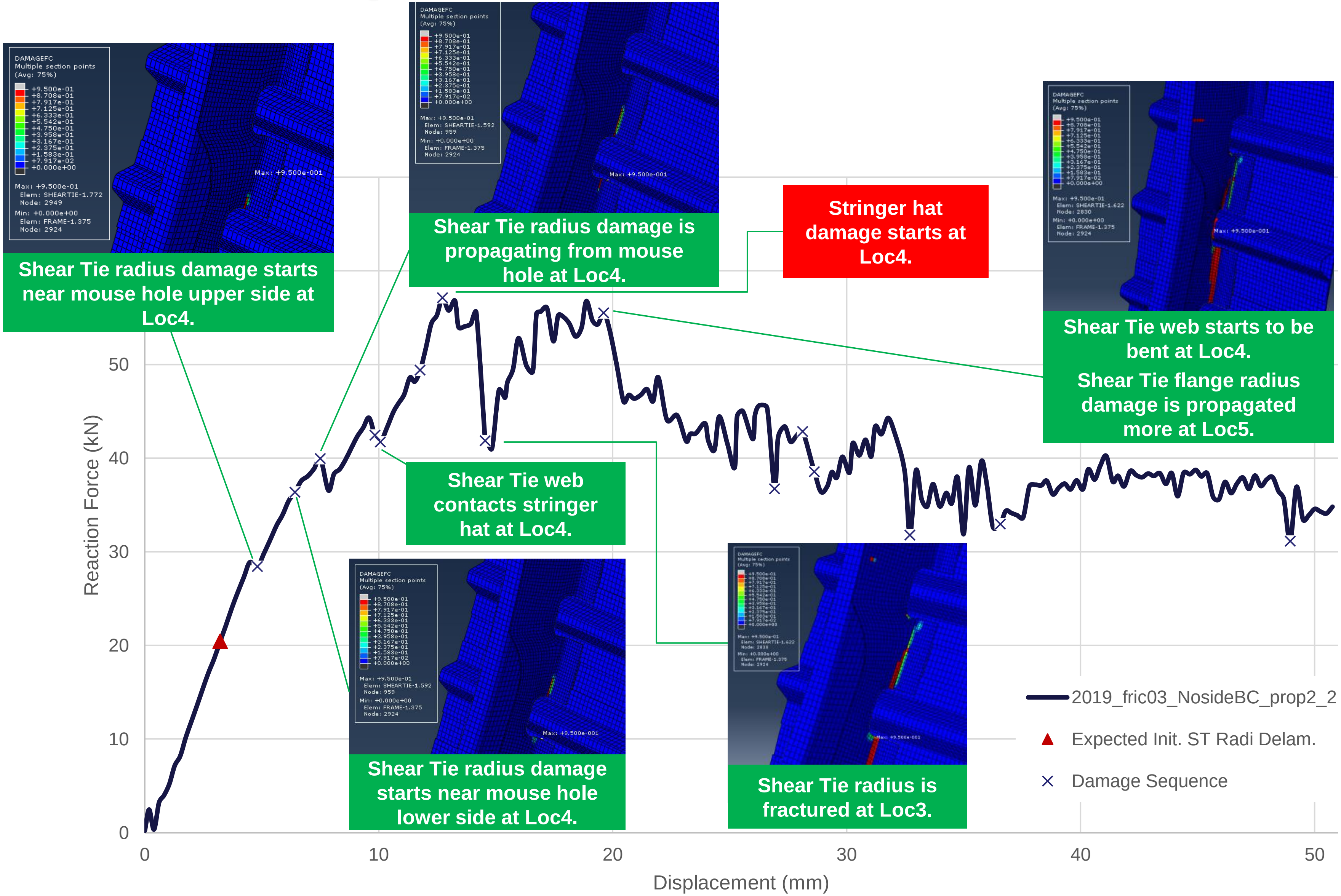
Failure Sequence: Location 4



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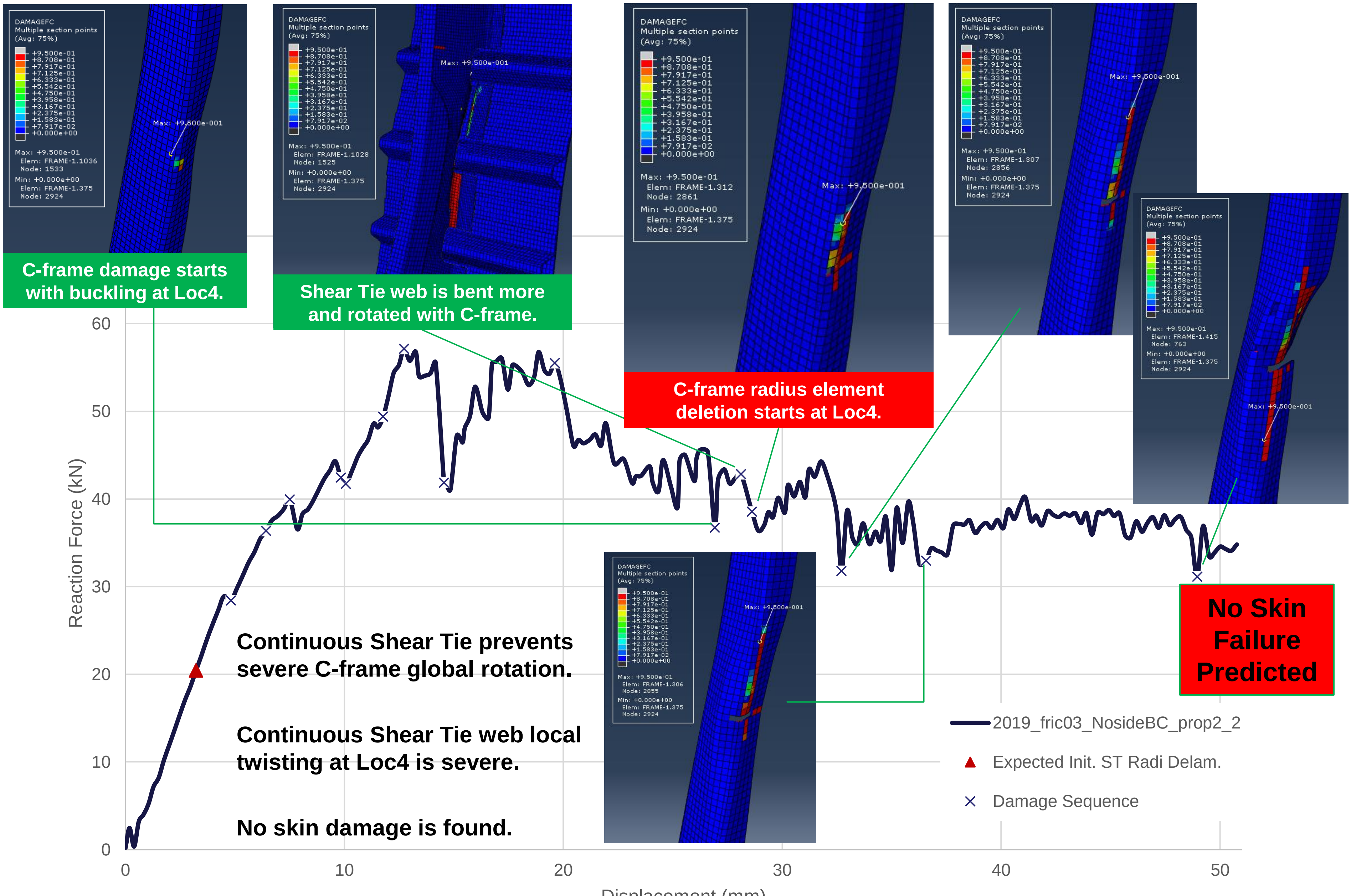

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Test Schedule

- May 2019
  - Complete assembly (1st specimen)
  - Install strain gauges
  - Test site prep; fixtures install
- June 2019
  - Mount the first specimen in UCSD Powell Lab
  - Perform tests on first specimen
  - Assembly of all specimens (3 remaining specimens)
  - Install strain gauges
- July 2019
  - Perform testing on final 3 specimens

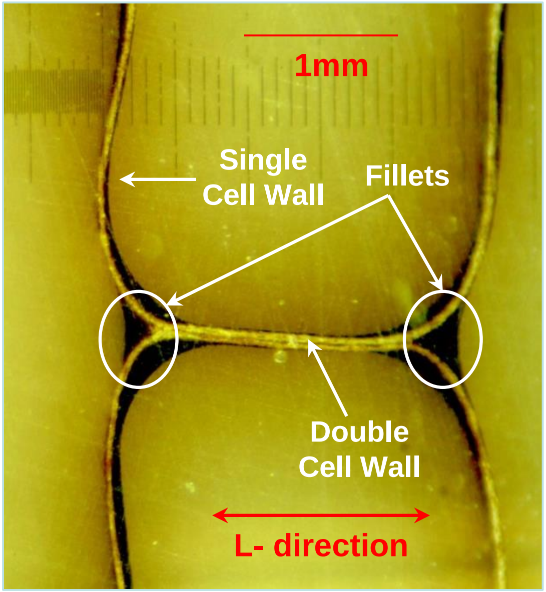
Outline

- Ground Service Equipment (GSE) High Energy Wide Area Blunt Impact (HEWABI)
- Impact Damage to Sandwich Panels & Core Crush Mechanics
- Conclusions, Benefits to Aviation, and Future Work

Introduction – Sandwich Core Crush

- Sandwich panel core crush/wall fracture affects residual strength
- Complex Nomex® core mesostructure ($\rho = 64\ kg/m^3$) affects core crush response

W-direction side view



Objectives:

- Determination of core damage extent under impact loads
  - focus on cellular core fracture mechanisms
- Employ image processing techniques to quantify core geometry imperfections
- Modeling core crush tests to include key features and manufacturing defects

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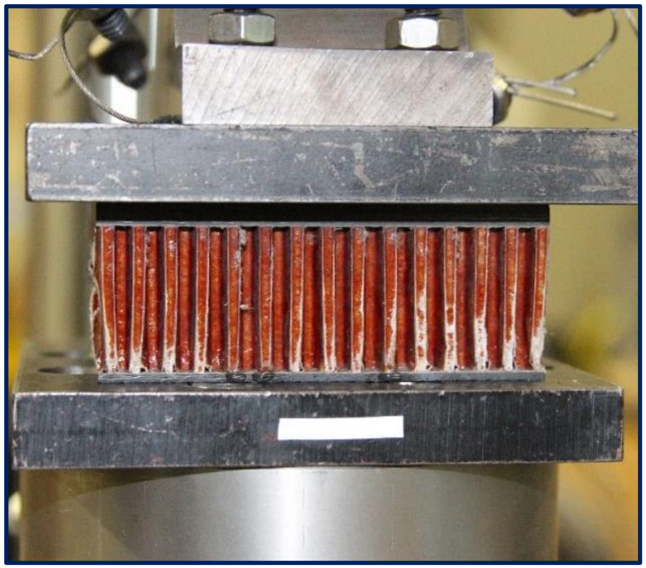
Approach

1) Core Crush Experiments

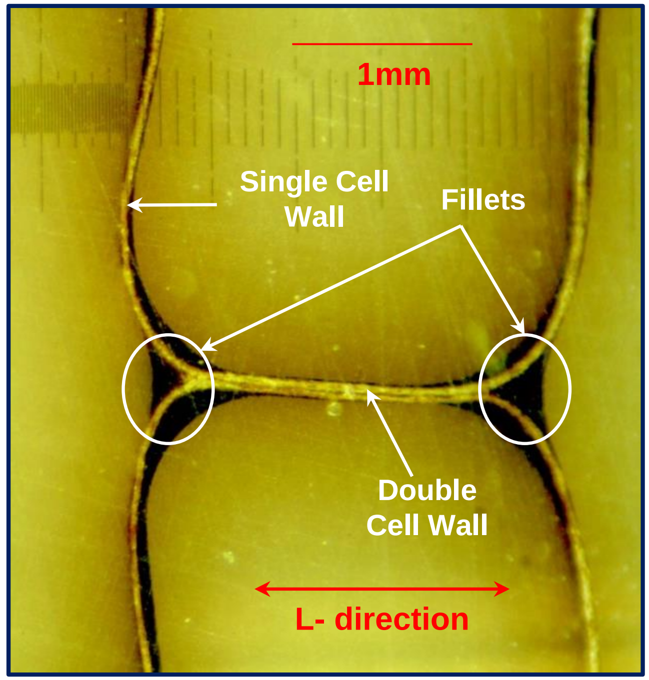
- Observe key mechanisms leading to cell collapse



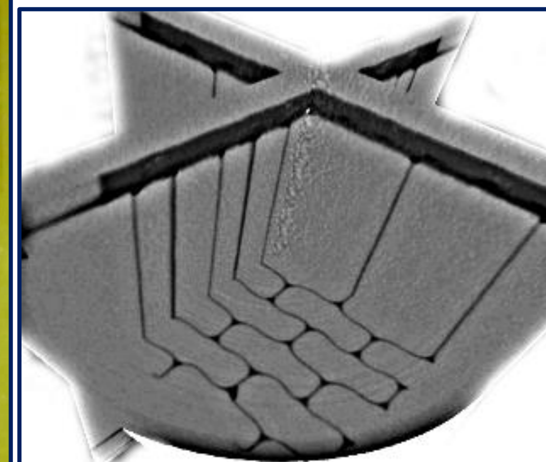
Flatwise compression test apparatus on Nomex® cores

2) *Actual* Geometry Quantification

- Metrics of geometry, including imperfections
- damage onset and evolution



Morphology of pre-impregnated Nomex® walls



X-Ray Computed Tomography (CT) scans on honeycomb core samples (Univ. Utah)

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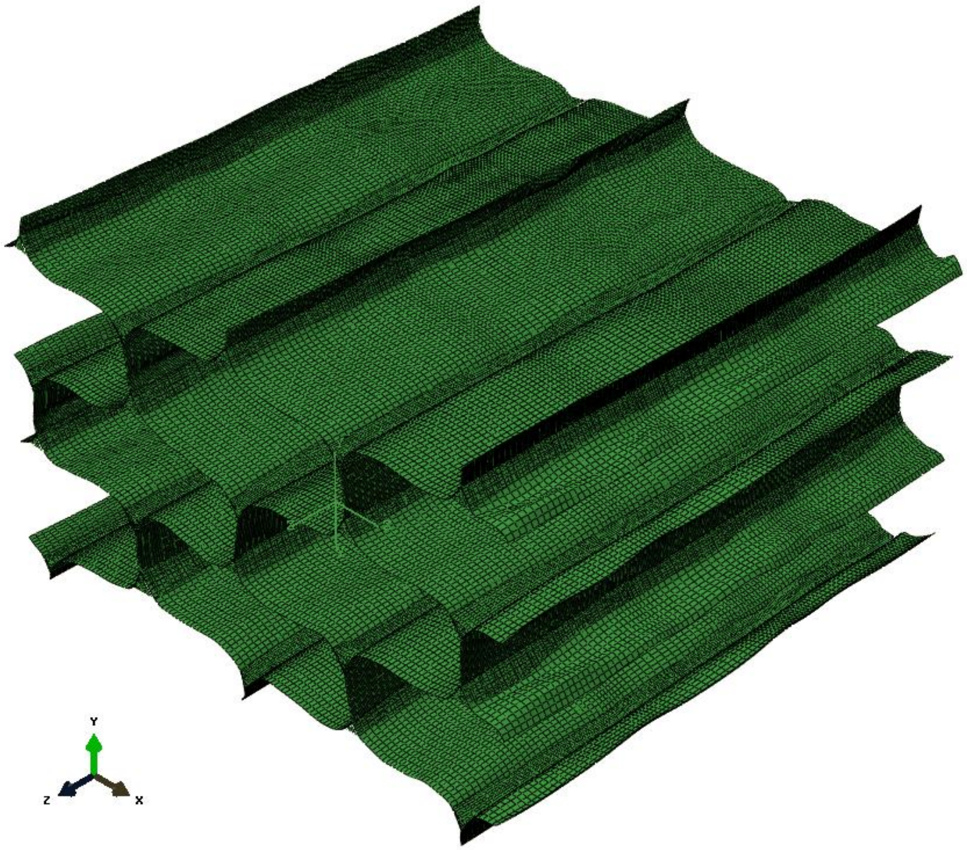
Approach

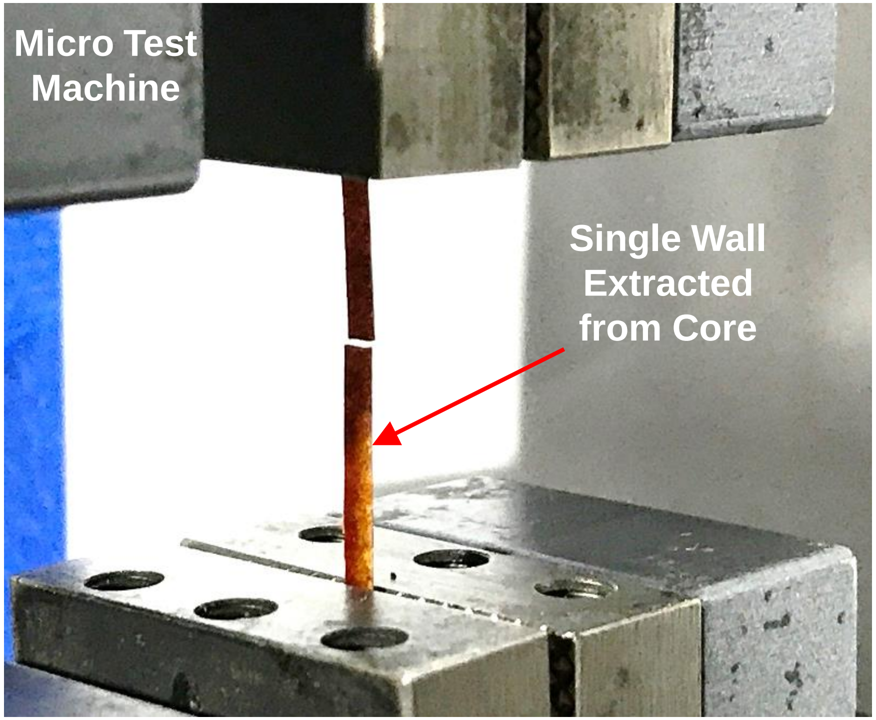
3) Finite Element Modeling

- Incorporate geometric defects



4) Basic Constituent Properties Determination

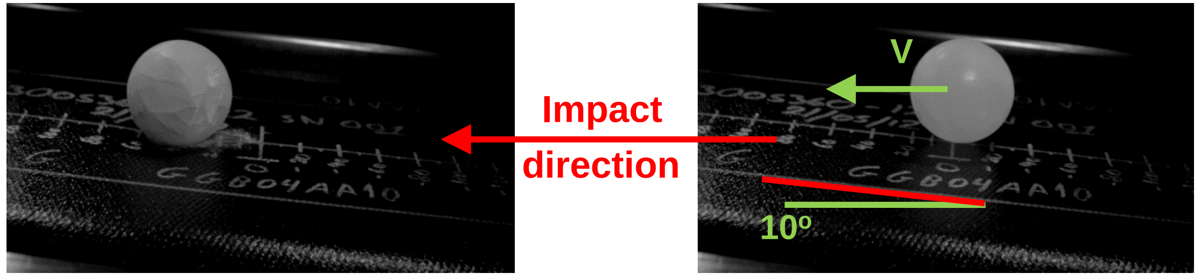
- Constitutive modeling & data gathering via single wall tests



1) Core Crush: Ice Impact Tests

- 10º glancing angle, 80 - 160 m/s velocity; 275 - 590 J kinetic energy, 4-ply PW

50.8 mm ice bal in sabot

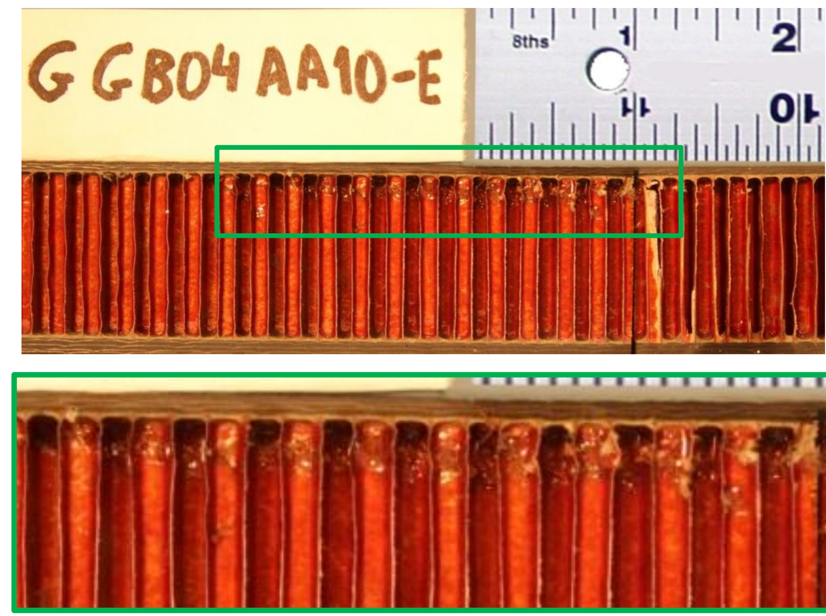


t = 1.665 ms from trigger

t = 1.332 ms from trigger

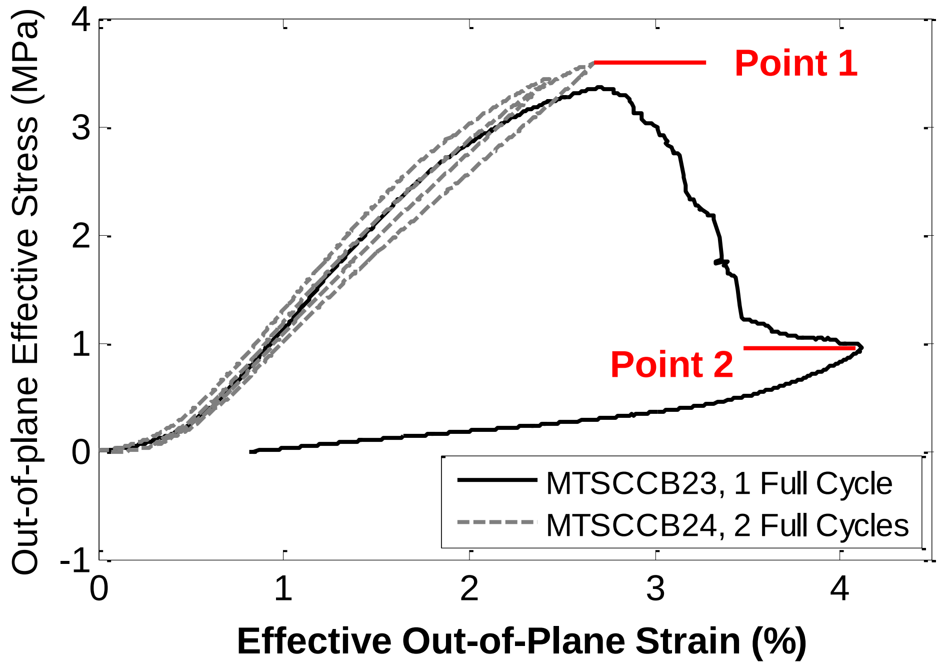
- High Speed videos from 590J impact (Velocity: 360 mph)

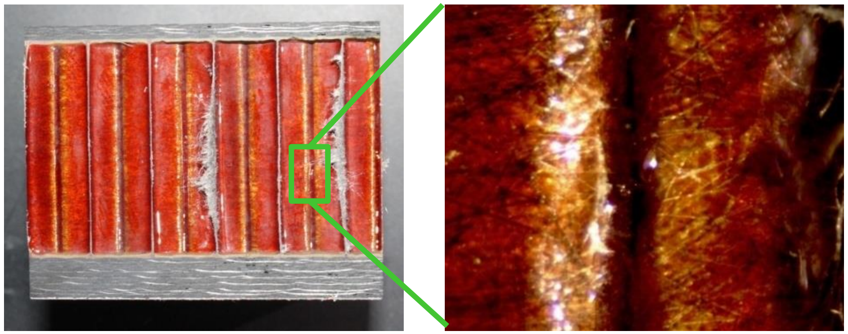
Highspeed camera #1: GGB04AA10 test



Core crushing span for 590 J energy: ~76 mm

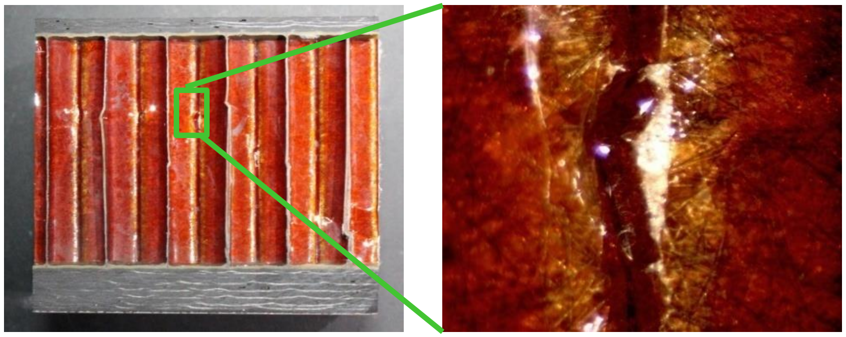
1) Core Crush: Flatwise Compression





Unloading at peak stress (Point 1):

- Onset of resin fillet disbonding from cell wall
- Strength is recoverable upon re-loading



Unloading at crushing region (Point 2):

- Fractured fillet leading to local cell collapse
- Strength and stiffness not recoverable

Sequence of crushing phenomena

1. Visual buckling of outer core corners
2. Visual post-buckling of single cell walls
3. Local disbond of fillet column
4. Kinking of single cell walls and fillet columns

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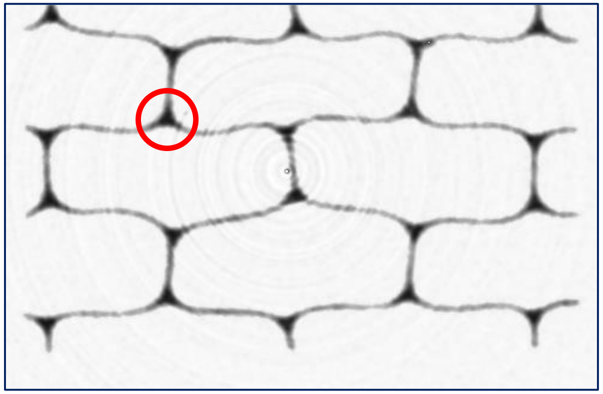
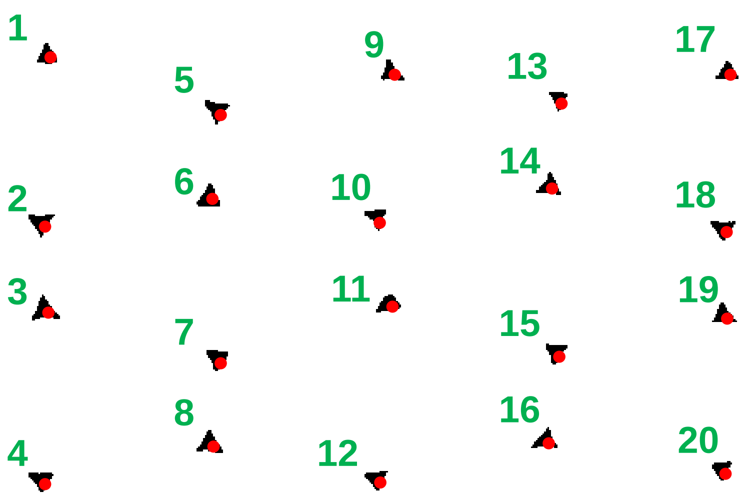
2) Actual Geometry: 3D Reconstruction From Imaging

1. Isolate critical pixels describing cell wall and fillet zone geometries



Through-thickness CT-scan slice



Resin-rich (Fillet) zones

2. B-spline surfaces and volumes to interpolate data points

$$C(u)=\sum_{i=0}^{n} N_{i,p}(u)P_i,\ u\in U,\ U=\{0,..,0,u_{p+1},..,u_{m-p-1},1,..,1\}$$

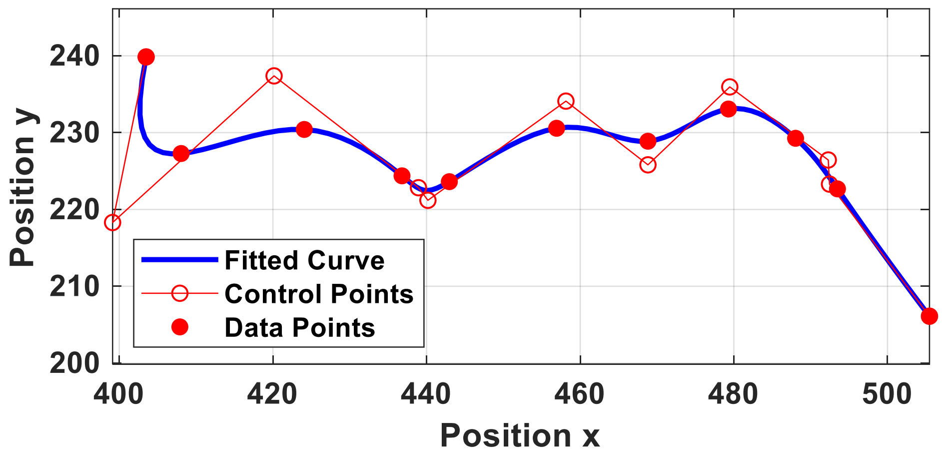
$$N_{i,p}(u)=\frac{u-u_i}{u_{i+p}-u_i}N_{i,p-1}(u)+\frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}}N_{i+1,p-1}$$

P_i: Control points, U = Knot vector

Inverse Problem

$$Q_k=C(\overline{u_k})=\sum_{i=0}^{n} N_{i,p}(\overline{u_k})P_i,$$

Find P_i and U by solving $(n+1)\times(n+1)$ system



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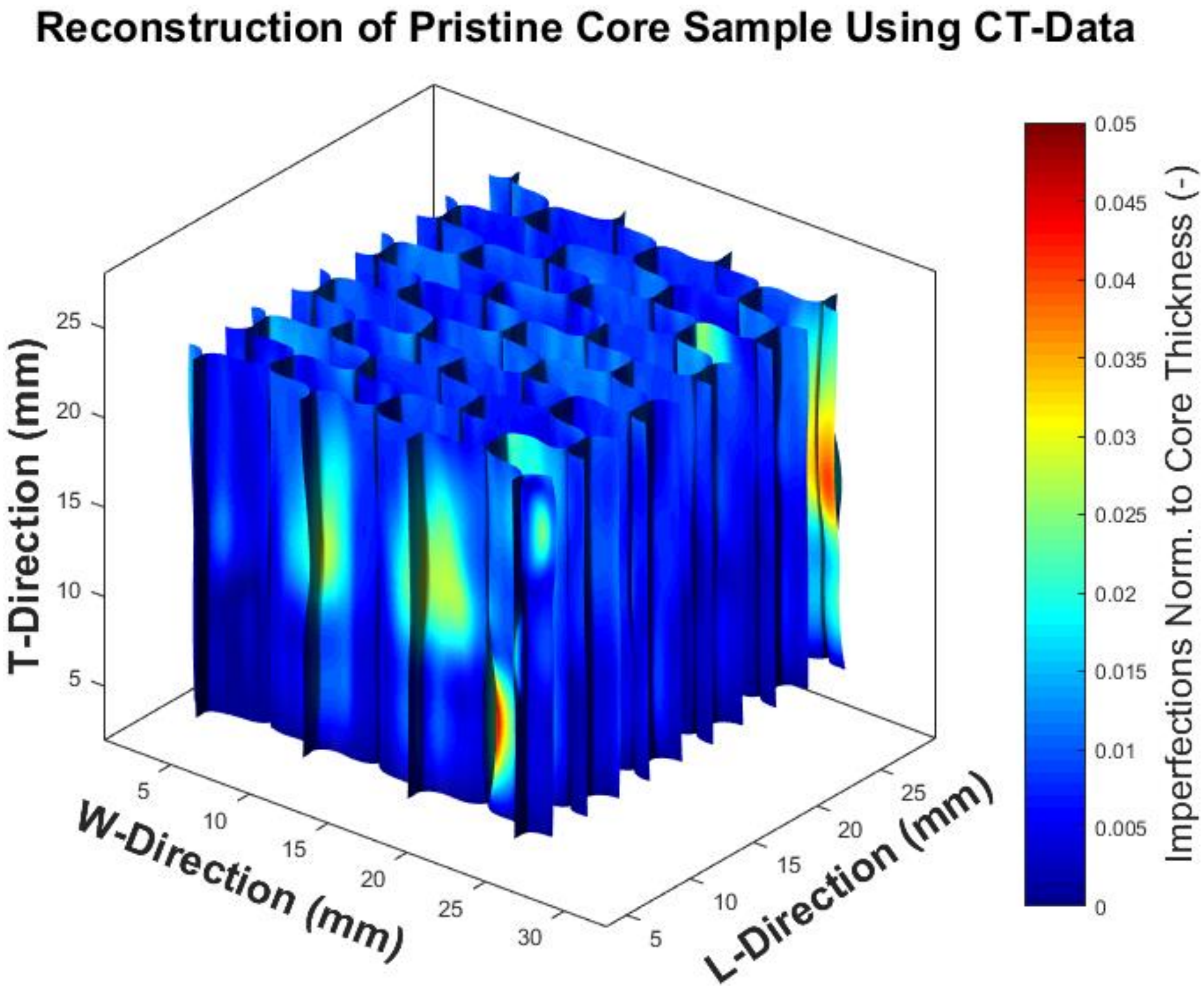
2) Actual Geometry: 3D Reconstruction From Imaging

- **7 CT-scan slices at different core thickness locations**
- **Interpolated to create 3D geometry model (for FEM)**



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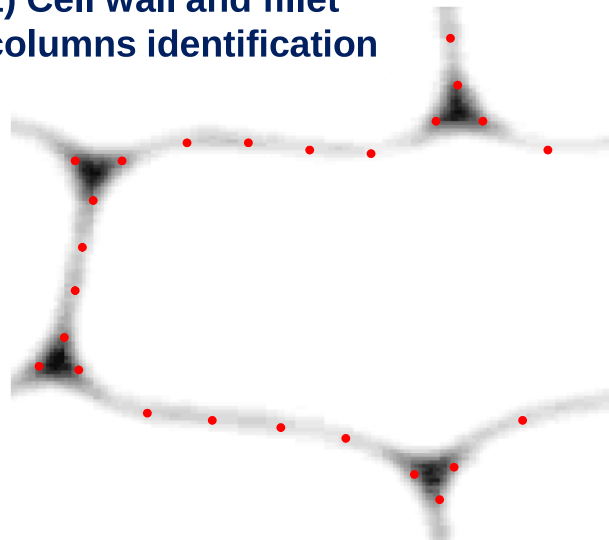
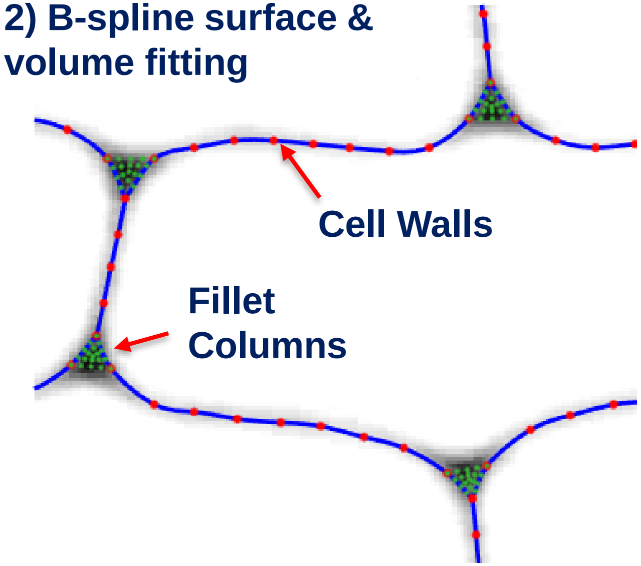
3) FEM: Automated FE Mesh Generation

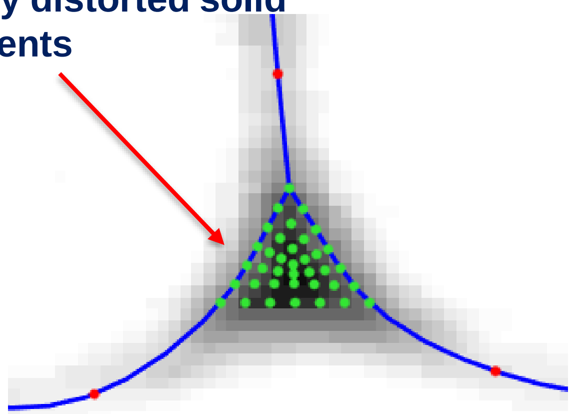
1) Cell wall and fillet columns identification



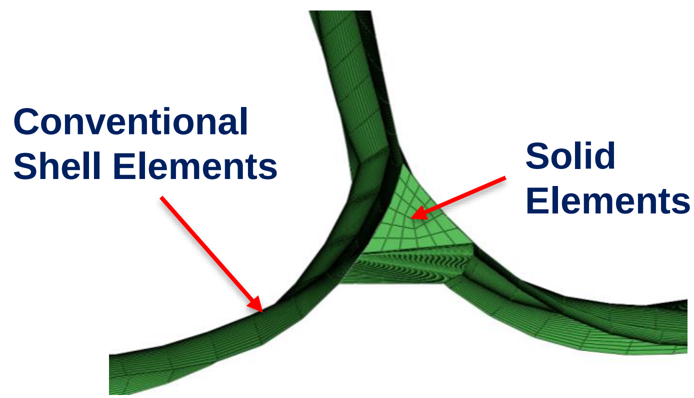
2) B-spline surface & volume fitting



3) C^0 continuity to avoid highly distorted solid elements

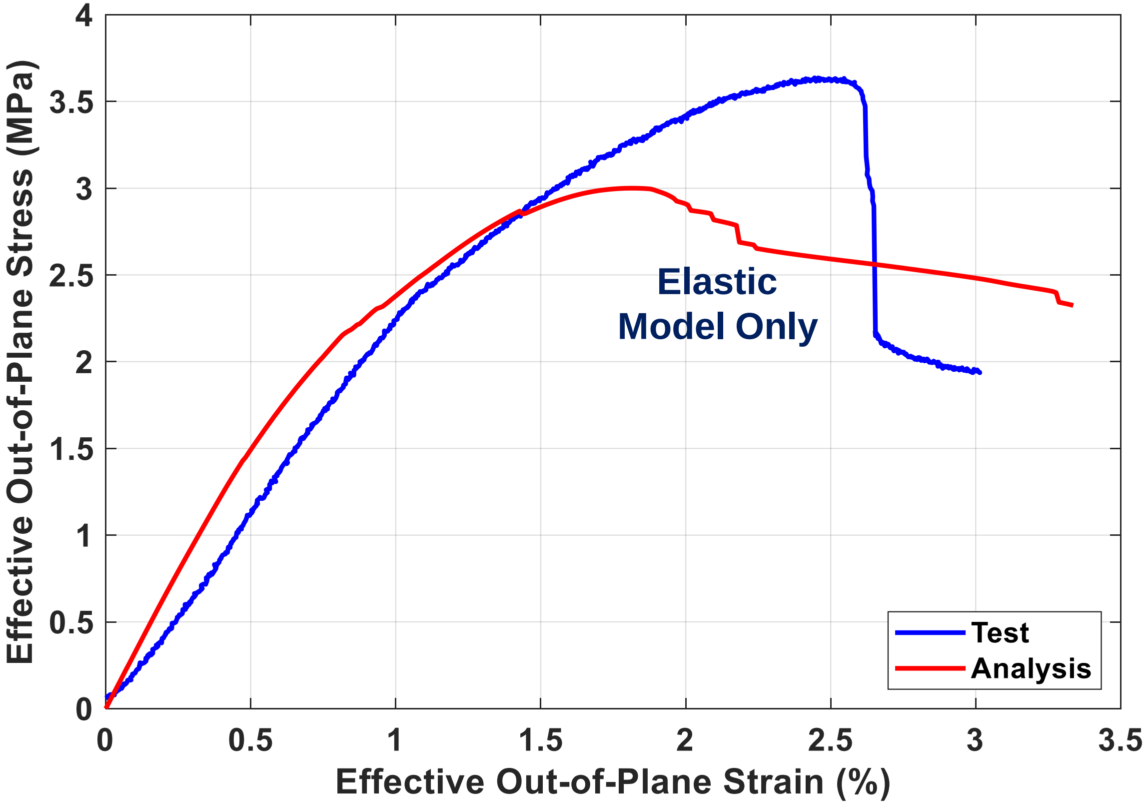


4) Automatic mesh generation of B-spline surfaces and volumes

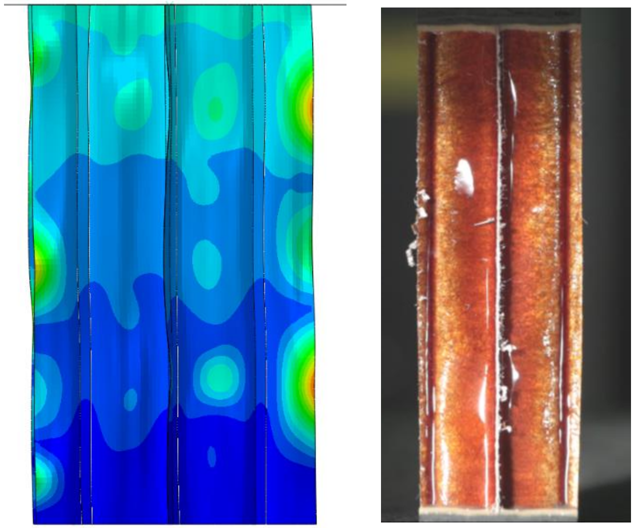


3) FEM: Simulation Results – Single Cell Geometry

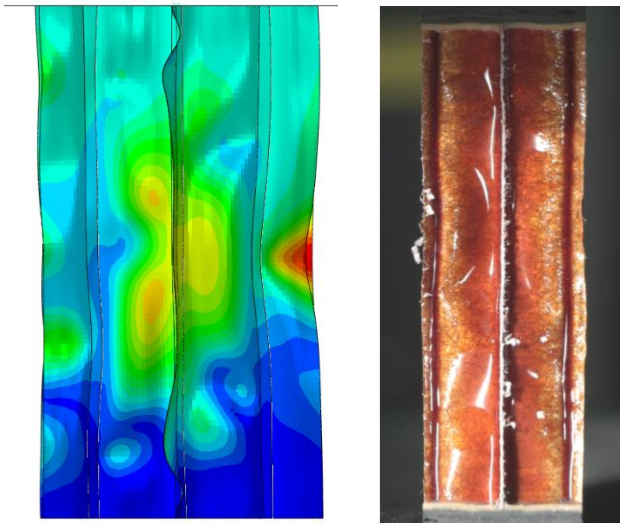
- Elastic properties from literature (limited available data)
- Cellular geometry extracted from CT-scans
- Underestimation of collapse strength (~80% of tests)
  - need improved material properties



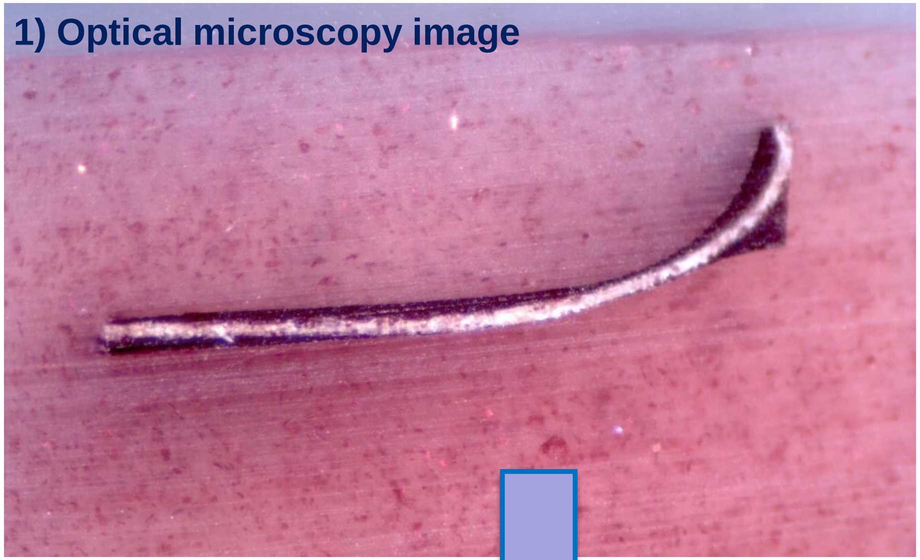
Effective Strain = 0.6%

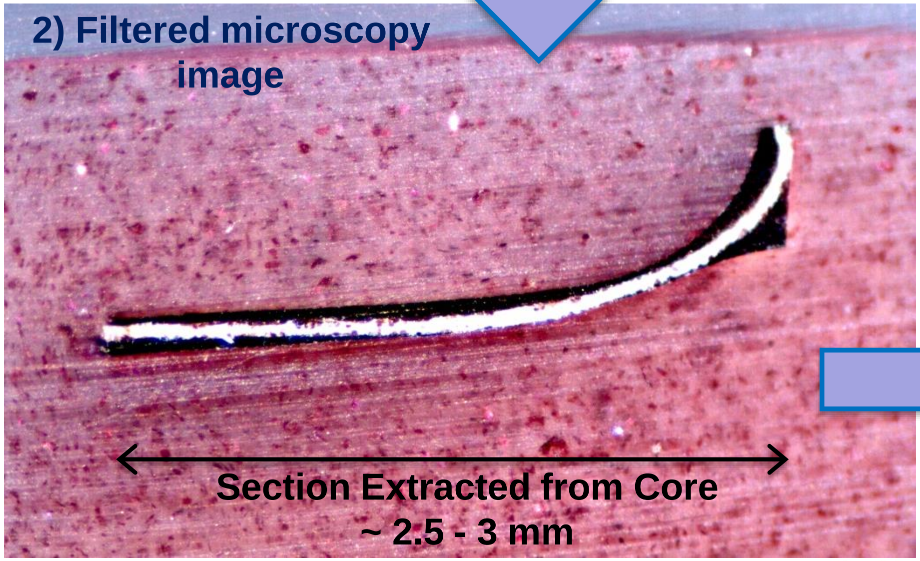


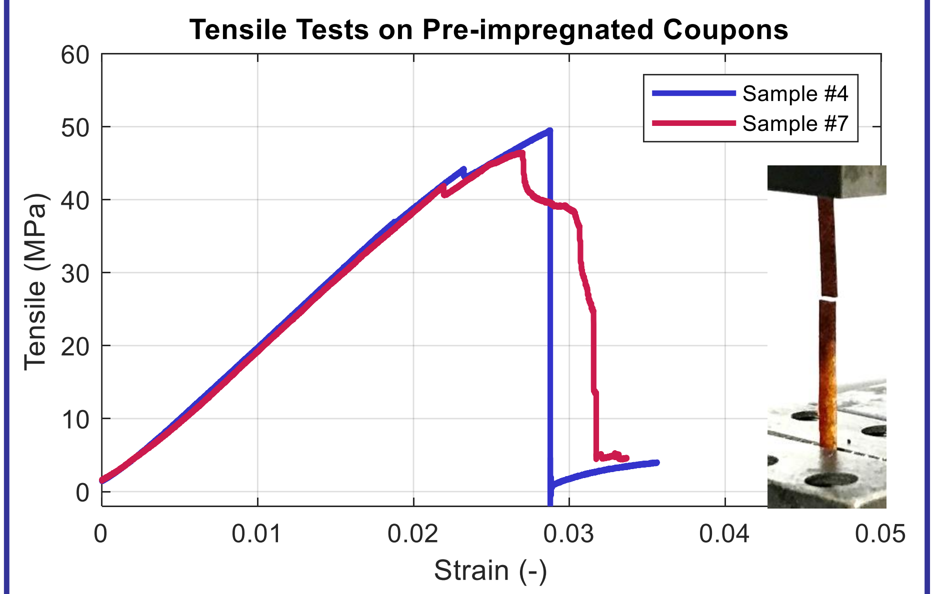
Effective Strain = 1.6%



4) Basic Constituent Properties: Nomex Cell Walls

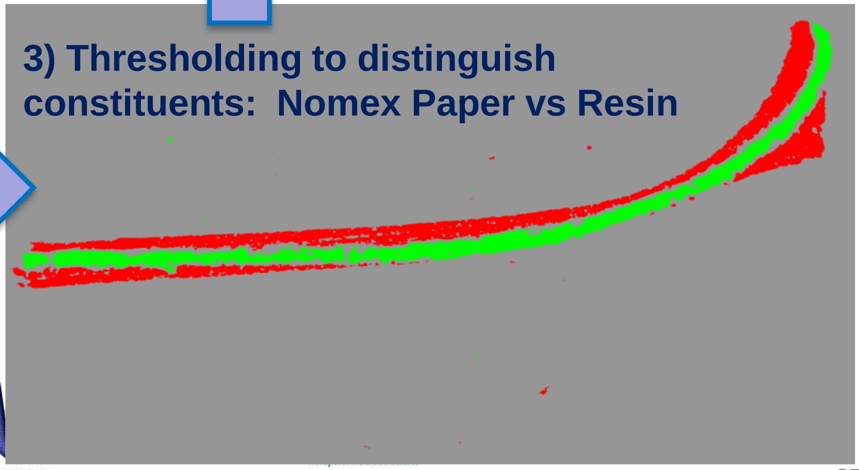






Accurate Volume Fraction Info – enables paper vs phenolic properties extraction

Improved Test Understanding



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Outline

- Ground Service Equipment (GSE) High Energy Wide Area Blunt Impact (HEWABI)
- Impact Damage to Sandwich Panels& Core Crush Mechanics
- Summary, Benefits to Aviation, and Future Work

Summary

Ground Service Equipment (GSE) High Energy Blunt Impact

- 2nd Generation HEWABI specimen design & fabrication + assembly nearly completed, test fixtures ready
- FE simulations of blunt impacts near floor beam completed
  - predict sequence of failure modes; major internal damage w/ no skin failure
  - truncated specimen geometry shows equivalence to full quarter barrel
- Prediction & sub-structure test methodology established for HEWABI testing

Impact Damage to Sandwich Panels

- Nomex® based core cells exhibit mesoscale structural complexity
  - Phenolic resin-rich zones around wall intersection boundaries (fillet columns) strongly affect core crush stability
- Image analysis used for 3D reconstruction of actual geometry using CT-scan data
- Numerical models are underestimating collapse strength of cores
  - non-uniform phenolic resin coating & fillet columns
  - effects of actual imperfect geometry

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Benefits to Aviation

- Understanding damage resulting from HEWABI
  - key phenomena awareness and possible internal damage modes can be predicted
  - guides inspection strategies and location definition
  - permits more accurate model representation, could influence design
- Improved FE modeling methodology and validation for blunt impact damage
- Demonstrate techniques for effective boundary conditions definition for smaller sub-structure specimens to represent larger full structure.
- Establish relationship between core features vs crushing and fracture
  - resin fillet columns
  - non-uniform resin thickness coating cell walls
  - geometric imperfection of walls
- Understand effects of manufacturing defects/imperfection on core mechanics

Looking Forward

HEWABI:

- Complete HEWABI specimens assembly and testing
- Continued development of high fidelity FEA modeling capability for HEWABI
  - validated at element and full scale structure levels
  - define effective representation of fasteners and its influence in damage initiation and progression

Sandwich Core Crush:

- Simulation of core crush response with actual geometry & complexity (from microscopy, CT scans)
- Run parametric computational studies on the effect of the resin-rich zones on the out-of-plane crushing response of Nomex® based cores

Write Final Reports – Both Topics