Impact Damage Formation on Composite Aircraft Structures

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Impact Damage Formation on Composite Aircraft Structures

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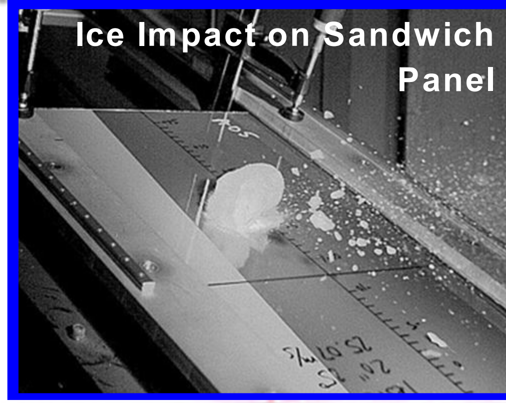
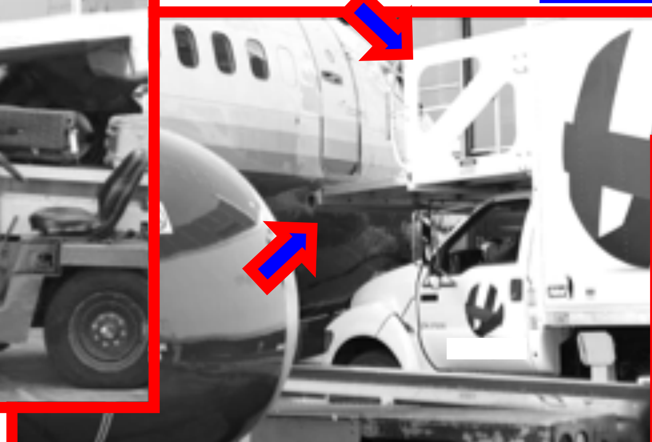
  - Lynn Pham
- **Other FAA Personnel Involved**
  - Larry Ilcewicz , Ahmet Oztekin
- **Industry Participation**
  - Boeing, Bombardier, UAL, Delta, DuPont, JC Halpin Consulting

Impact Damage Formation on Composite Aircraft Structures

- **Motivation and Key Issues**
  - impacts are ongoing and major source of damage
  - high energy ***blunt*** impact damage (**BID**) of main interest
    - involves large contact area
    - damage created can exist with ***little/no exterior visibility***
- **Sources of Interest:** those acting over wide area and/or across multiple structural elements
  - 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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Program Objectives

- **Understand blunt impact damage formation and visual detectability**
  - determine key phenomena and parameters controlling both internal and external/visual damage formation
    - internal vs. external damage formation vs. bluntness/contact-area size
  - identify and predict failure thresholds (useful for design)

- **Develop analysis and testing methodologies, including:**
  - full structure vs. sub-structure testing for HEWABI investigations
  - accurate modeling capabilities and tools validation
  - establish damage visibility criteria – surface crack, residual dent

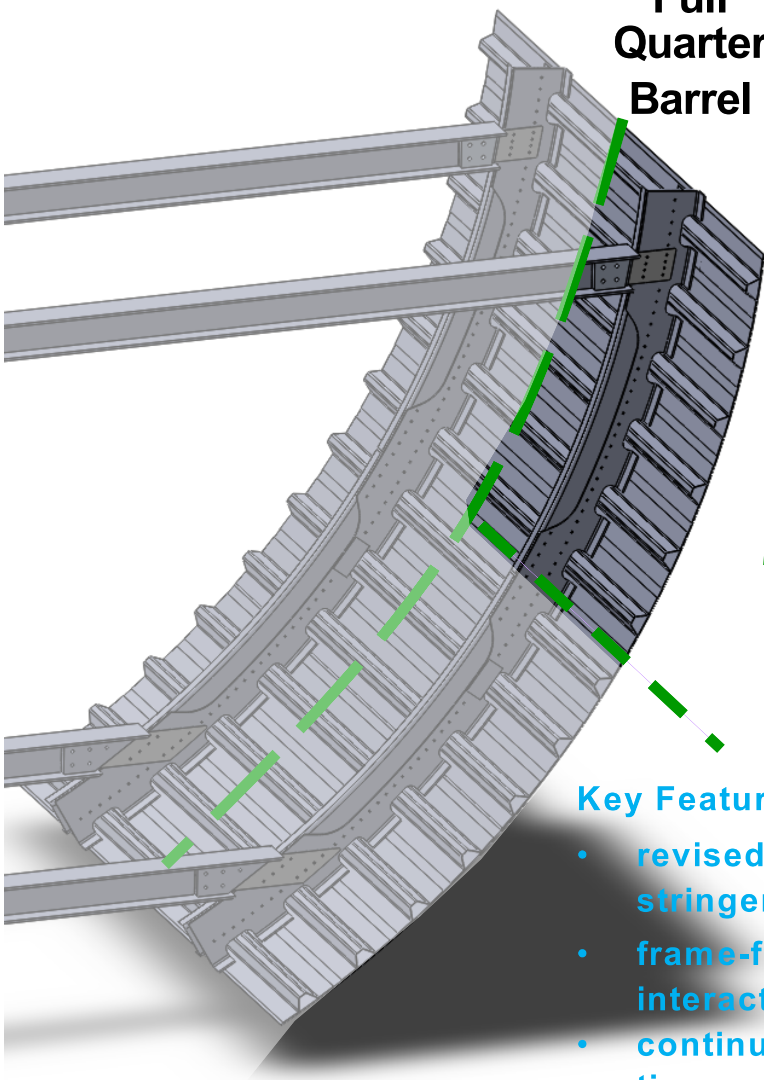
Outline

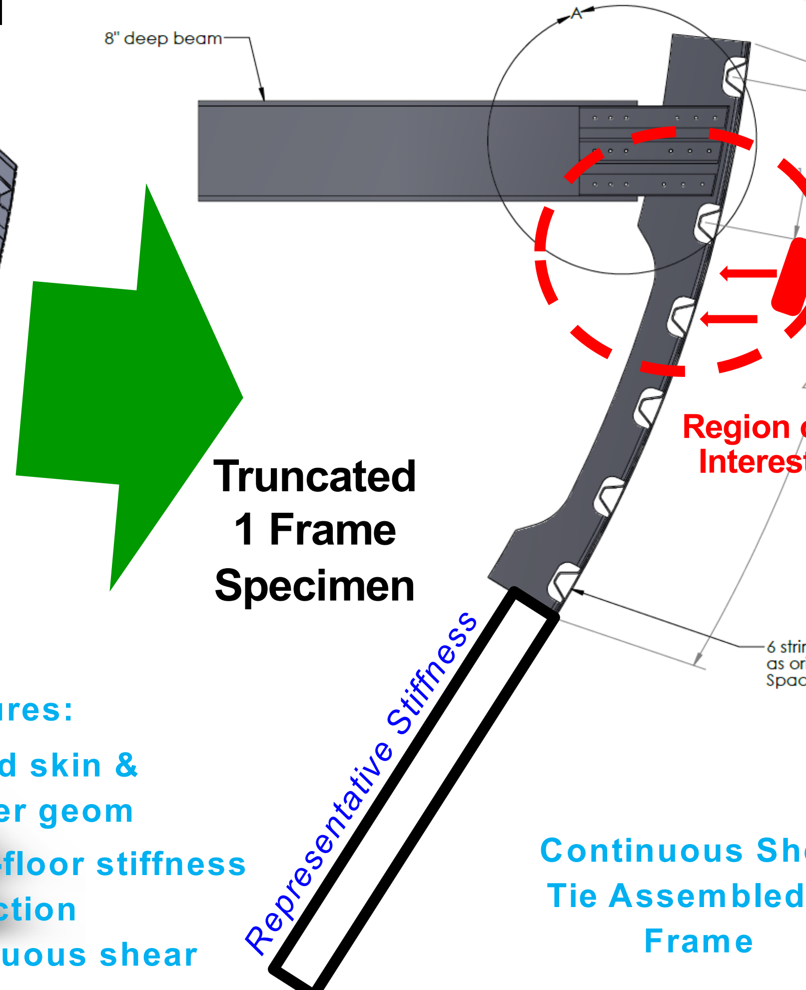
- Ground Service Equipment (GSE) High Energy Blunt Impact
- Impact Damage to Sandwich Panels & Core Crush Mechanics
- Summary, Benefits to Aviation, and Future Work

Next-Generation Specimen Blunt Impact Tests

Focus: Failure Near Floor Joint

Full Quarter Barrel





Truncated 1 Frame Specimen

Frame-to-Floor Stiffness Interaction

Key Features:

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

Continuous Shear Tie Assembled to Frame

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New Specimen Design & Test Matrix

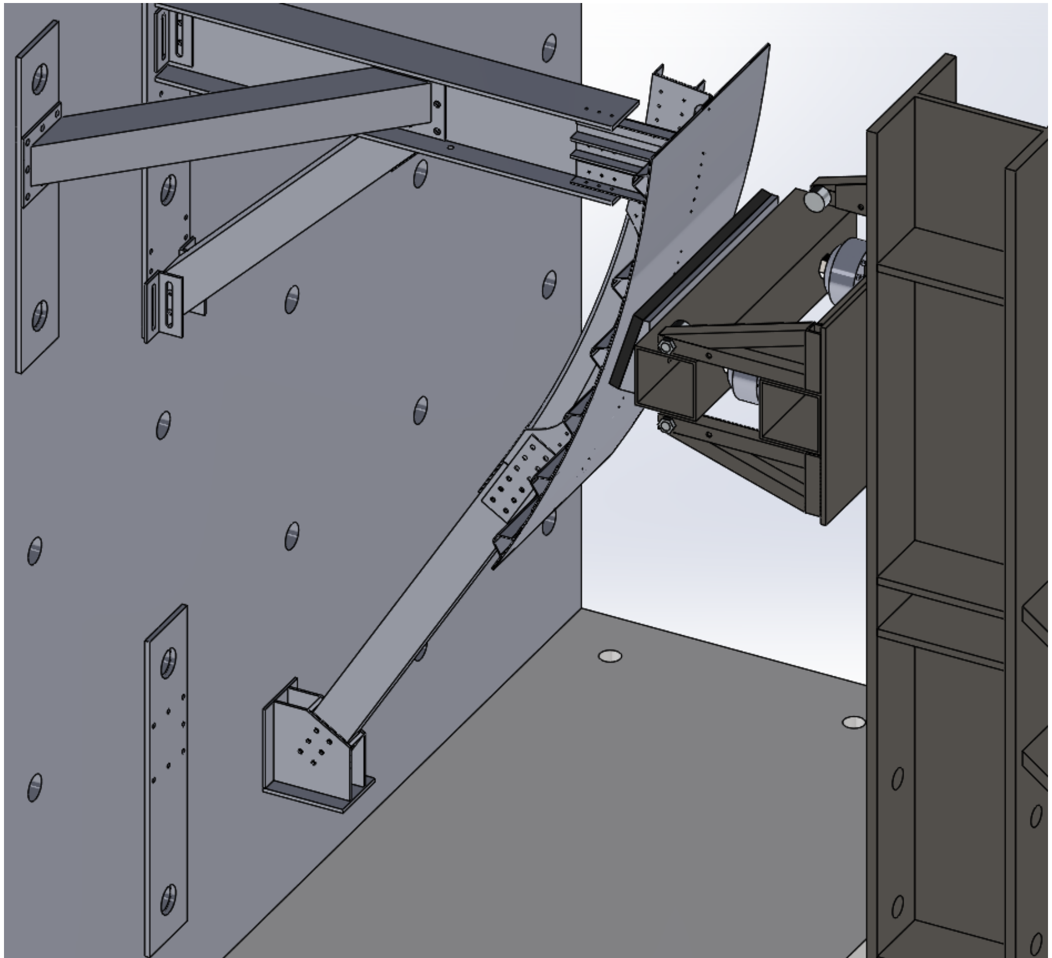
Part	Layup	THK (mm)
Skin	[0w/0/45/90/-45/0/90]s	2.79
Stringer	[0w/0/45/90/-45/0/90]s	2.79
C-Frame	[45/0/-45/45/0/-45]s (web) [45/0/0/-45/45/0/0/-45]s (flange)	2.64 3.53
Shear tie	[45/0/-45/0/45/0/-45/0]s	3.53

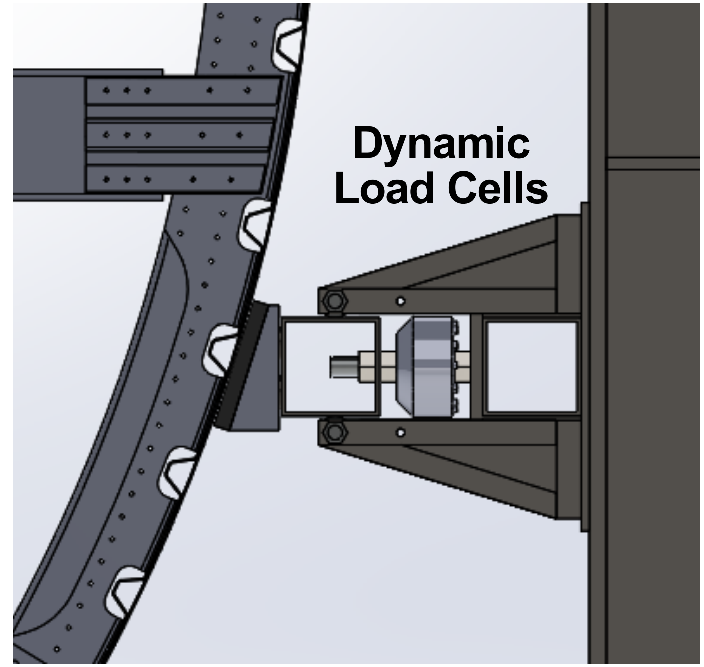
Specimen	Skin	THK (mm)	Shear Tie	THK (mm)	Load Loc	Load Speed
1	14 plies	2.79	16 plies	3.53	3	Quasi-Static
2	14 plies	2.79	16 plies	3.53	3	0.25 m/s
3	14 plies	2.79	16 plies	3.53	4	Quasi-Static
4	14 plies	2.79	16 plies	3.53	4	0.25 m/s

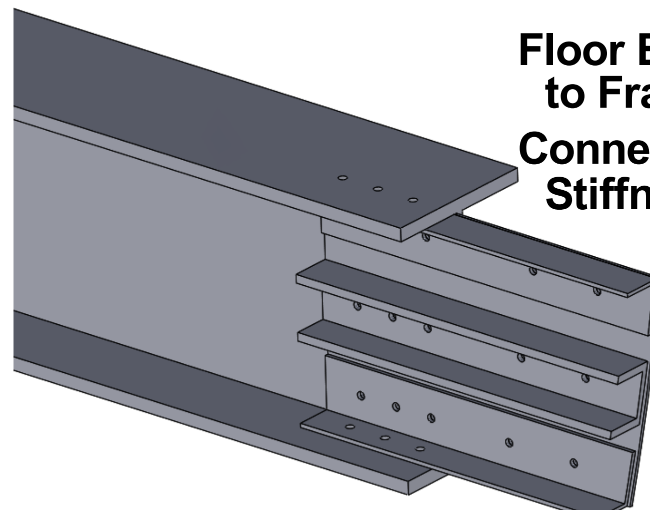
Load Speed “Quasi-Static” = slow speed until just past initial failure; stop & inspect; reload, stop etc.

Load Speed “0.25 m/s” = single load step until well past initial failure.

Test Setup







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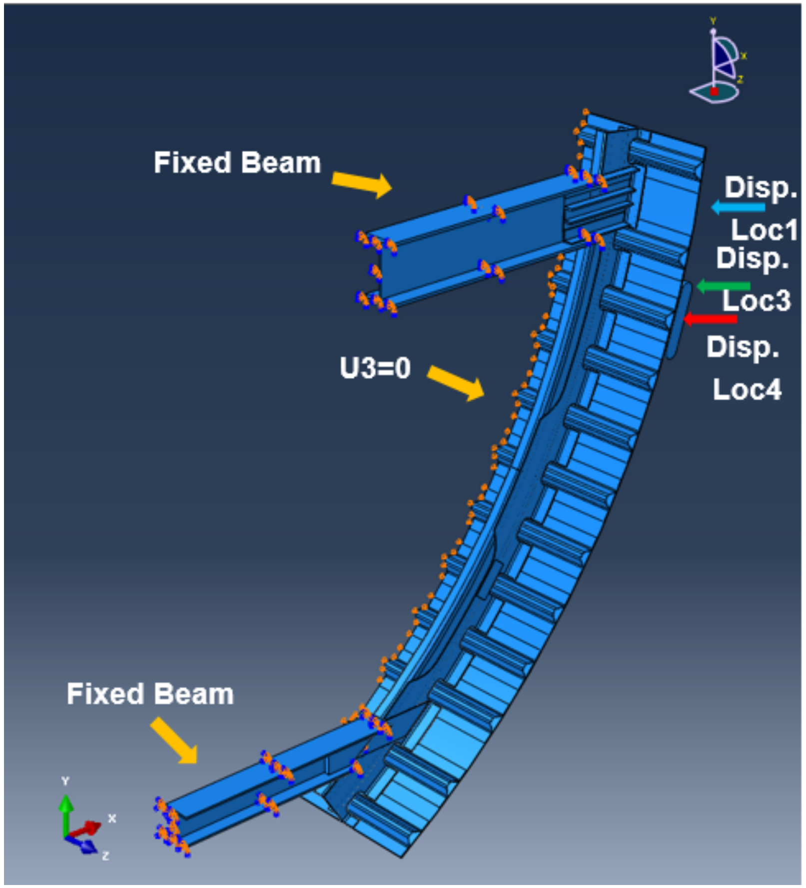
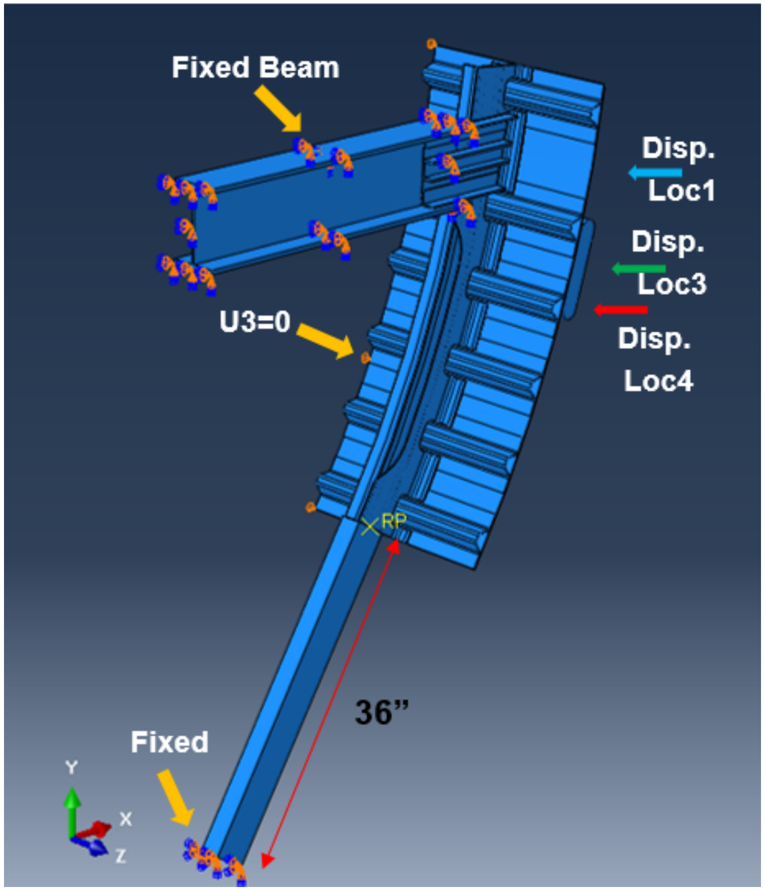
Truncated vs. Full ¼ Barrel Equivalency?

Assess via Finite Element Analysis



Full model



Truncated model

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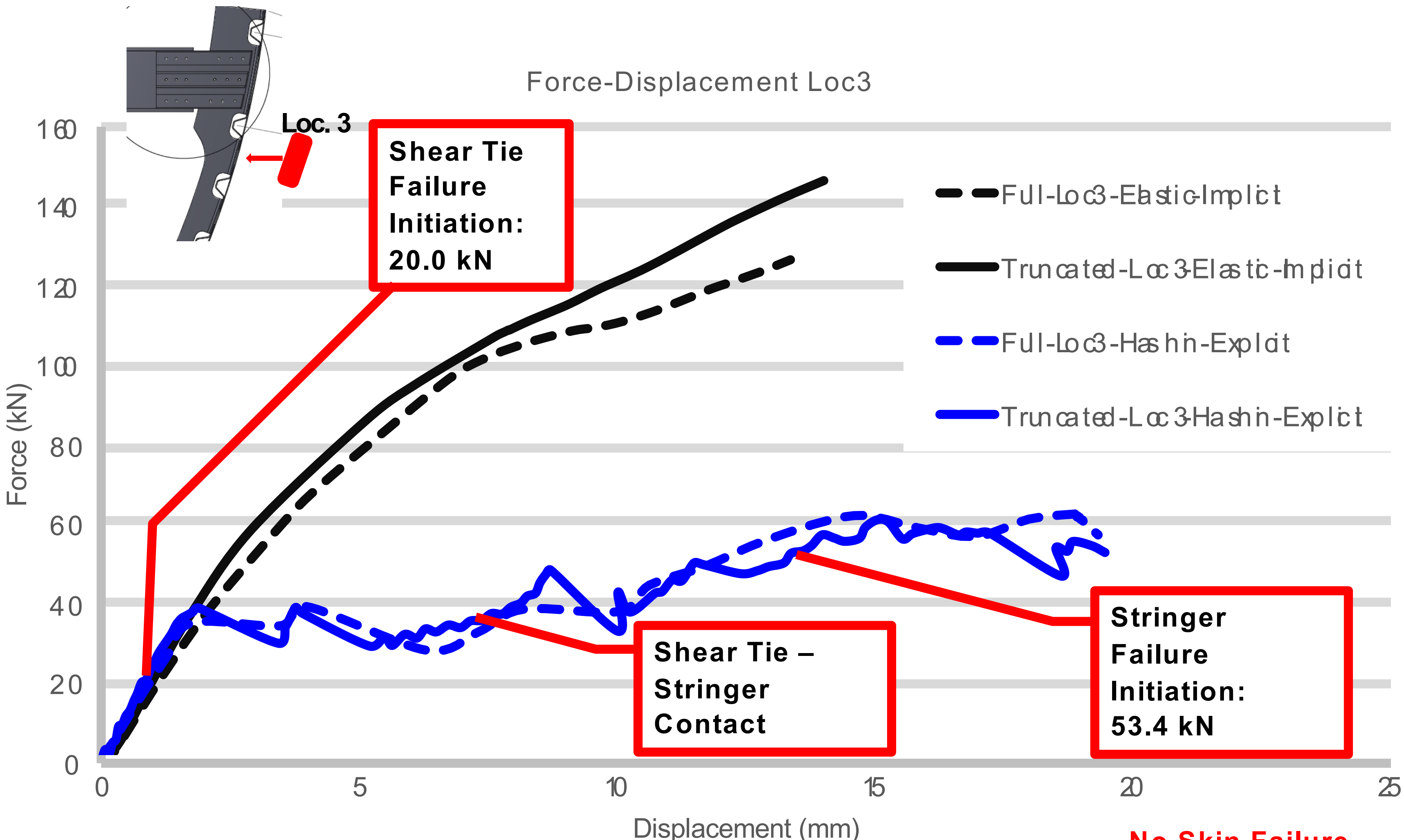
Loading Location 3 Response



No Skin Failure Predicted

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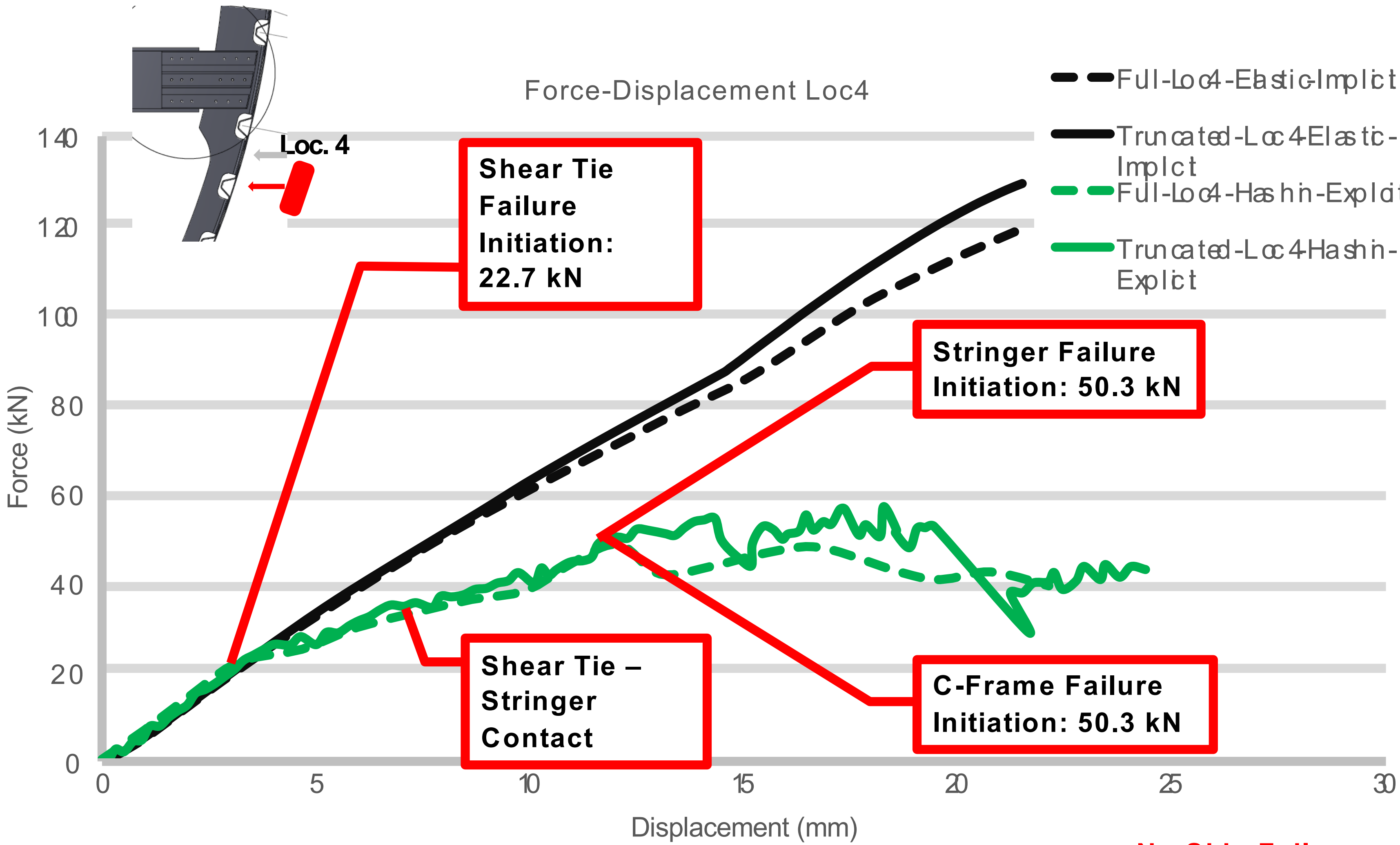
Loading Location 4 Response



No Skin Failure Predicted

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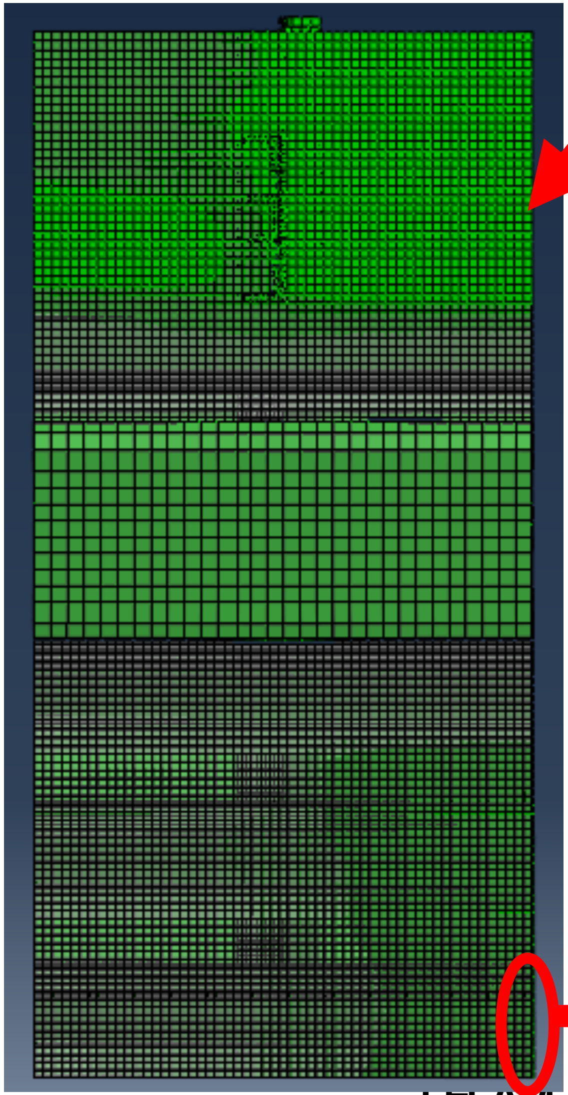
Panel Edge BC Consideration

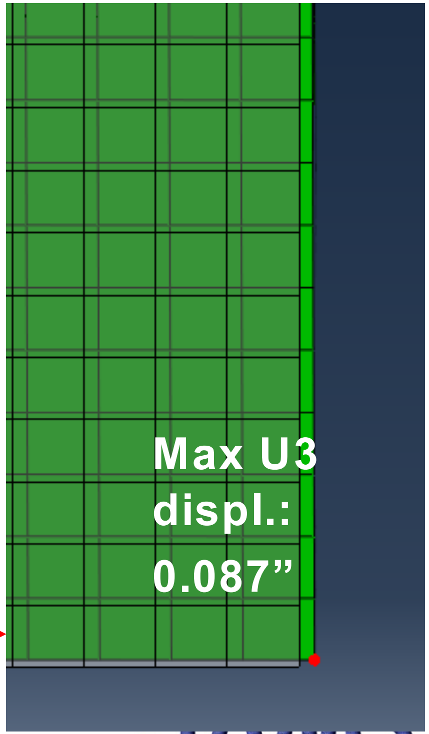
Consider the edge BC on panel long side

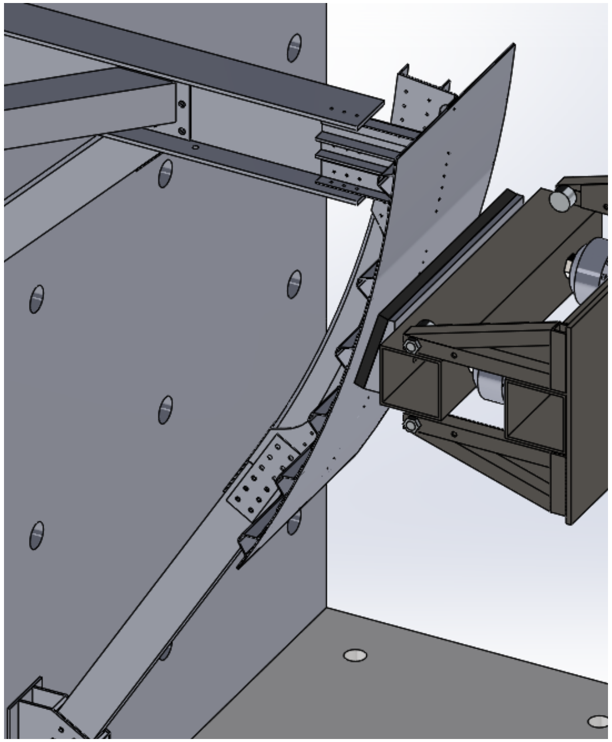
- In FEA, U3 = 0 for symmetry condition
- U3 = 0 difficult to replicate in the laboratory environment

Account for friction between rubber bumper and skin

- Friction coefficient range: 0.3 to 0.6

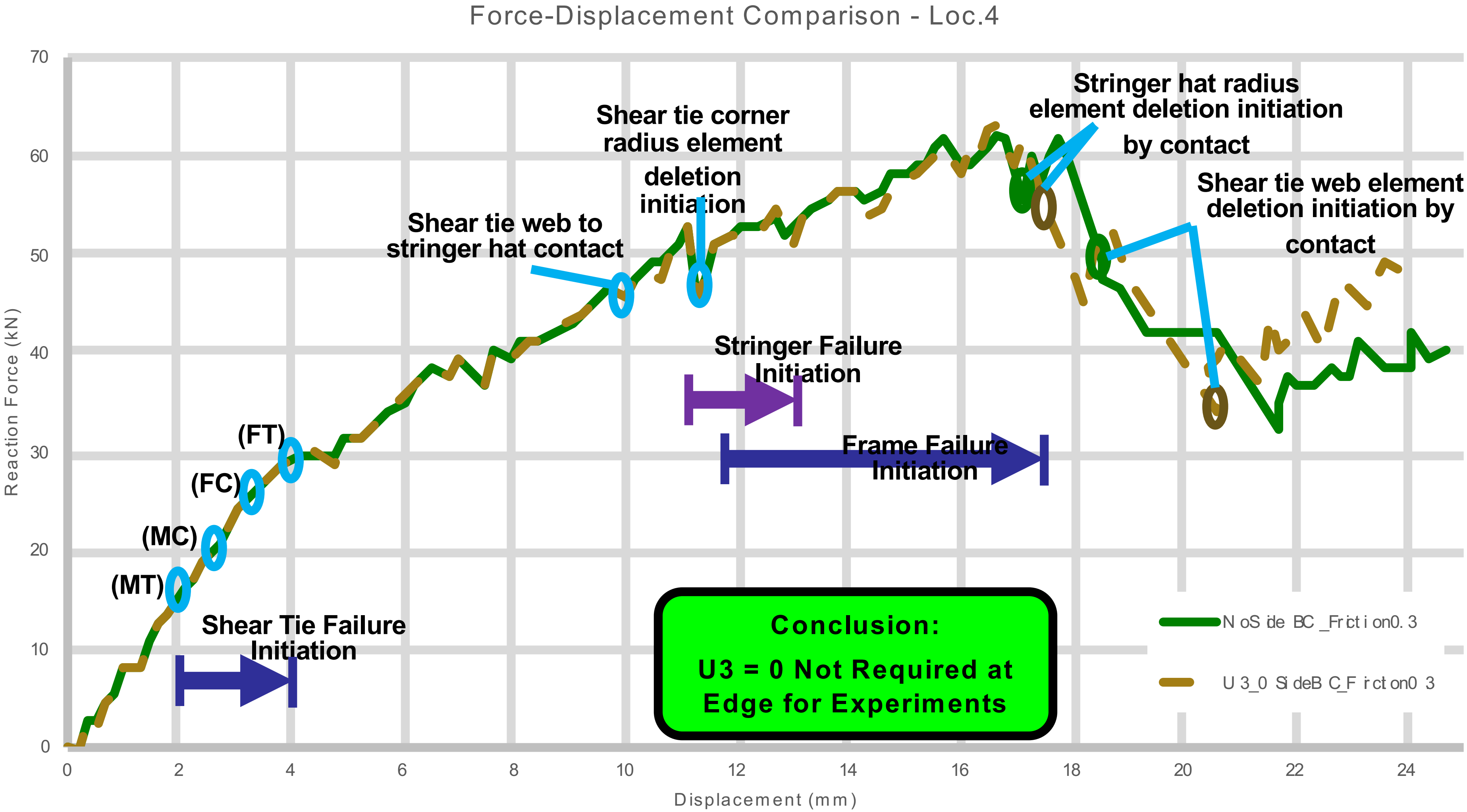






Panel Edge BC Comparison: U3 = 0 or Free

Loading Loc. 4, Friction Coefficient 0.3



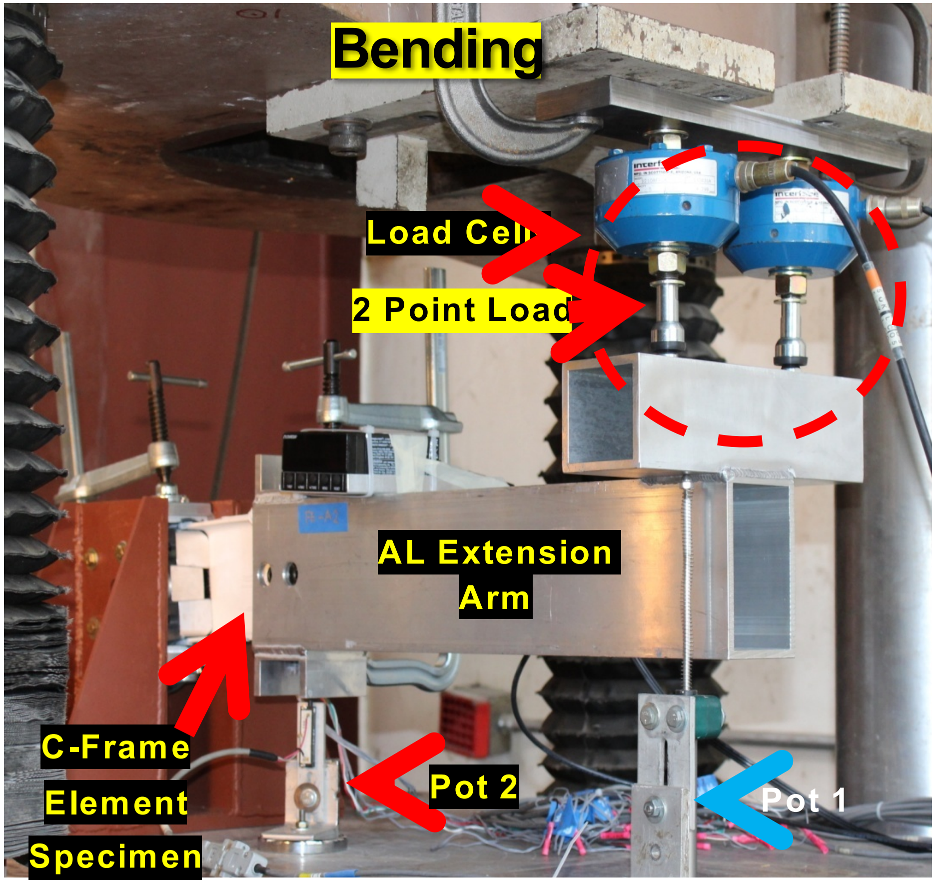
MT: Matrix tension

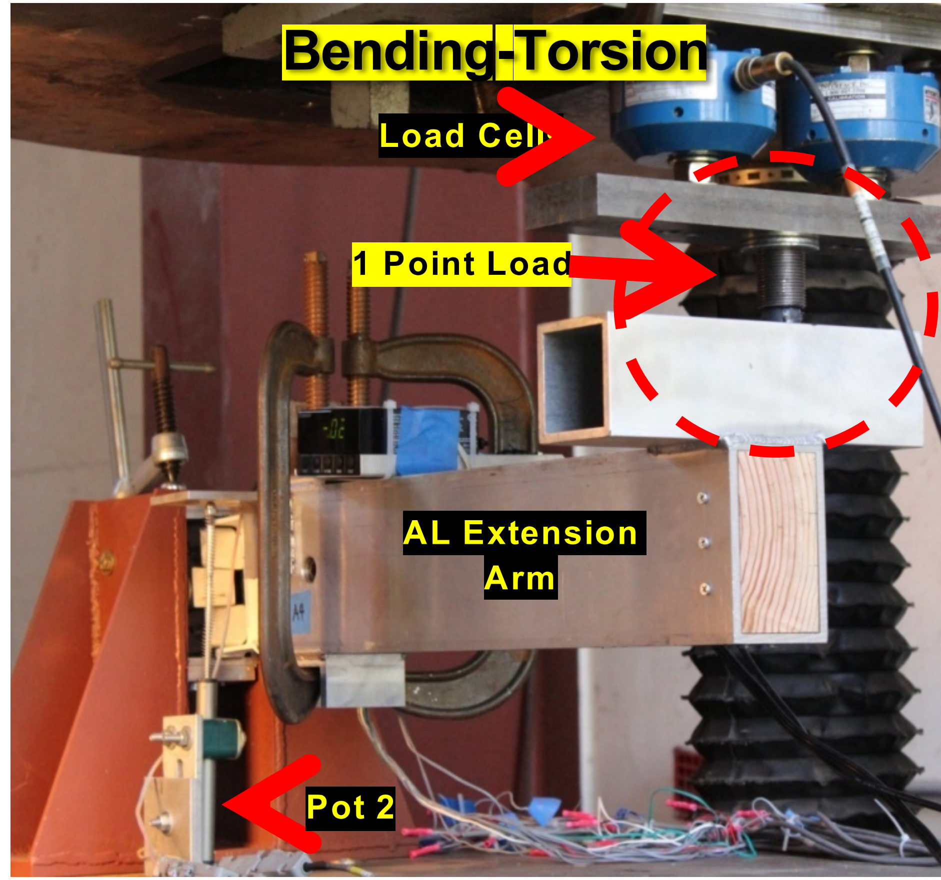
MC: Matrix compression

FC: Fiber compression

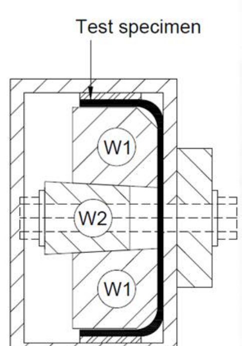
FT: Fiber tension

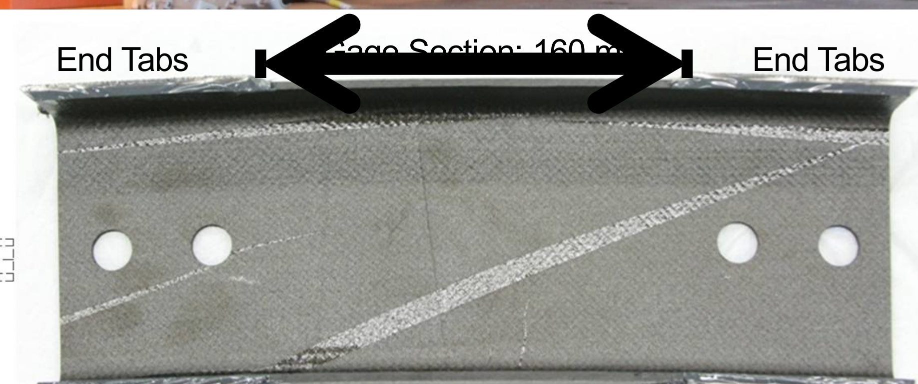
Element-Level C-Frame Experiments



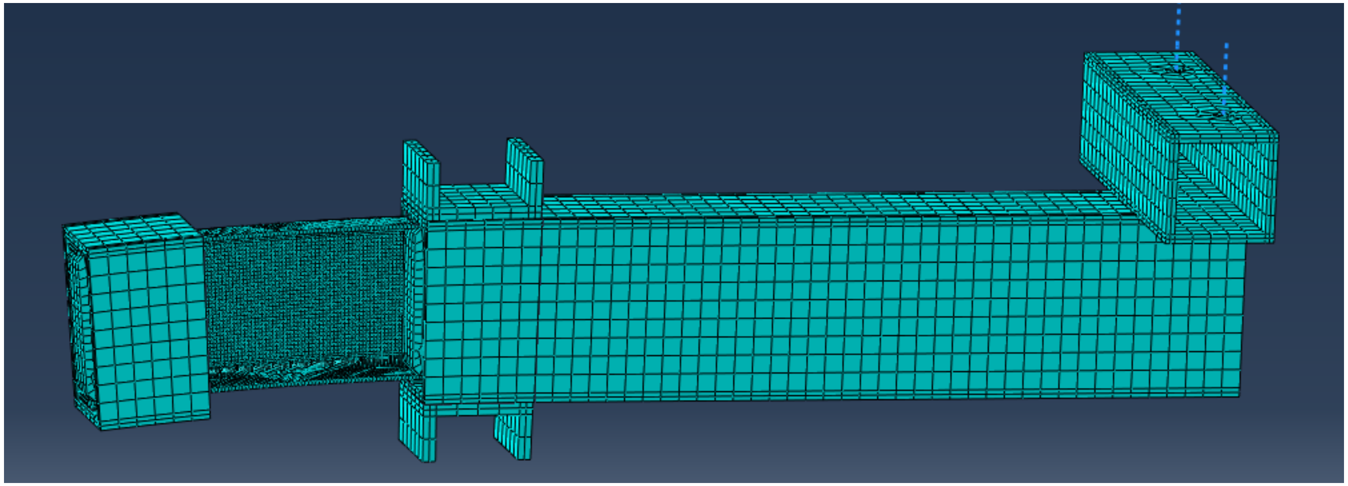


- C-frame test specimen
  - short section w/ extension arm
- Fixed end boundary condition
- Loaded end:
  - 2 point connection → bending
  - 1 point → bending + torsion

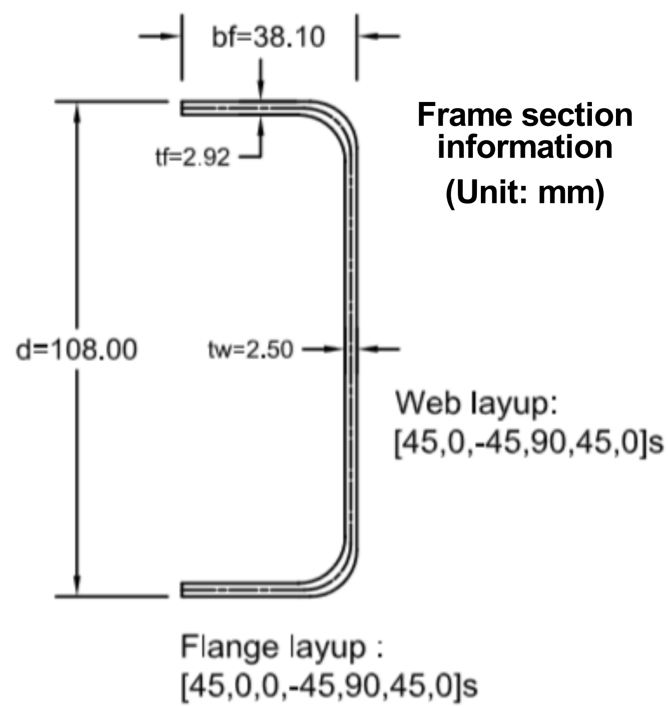




FE Modeling: Element-Level Validation



- Materials :
  - Cytec X840/Z60 6k woven carbon/epoxy with **Hill failure Criterion**
    - Failure criterion for woven composites
    - Examination of transverse shear effect
  - Aluminum 6061-T6 (box beam)
- Element type
  - **C-frame: Solid (C3D8R) – layer by layer modeling**
  - Aluminum: Solid (C3D8R)
- Abaqus/Explicit solver



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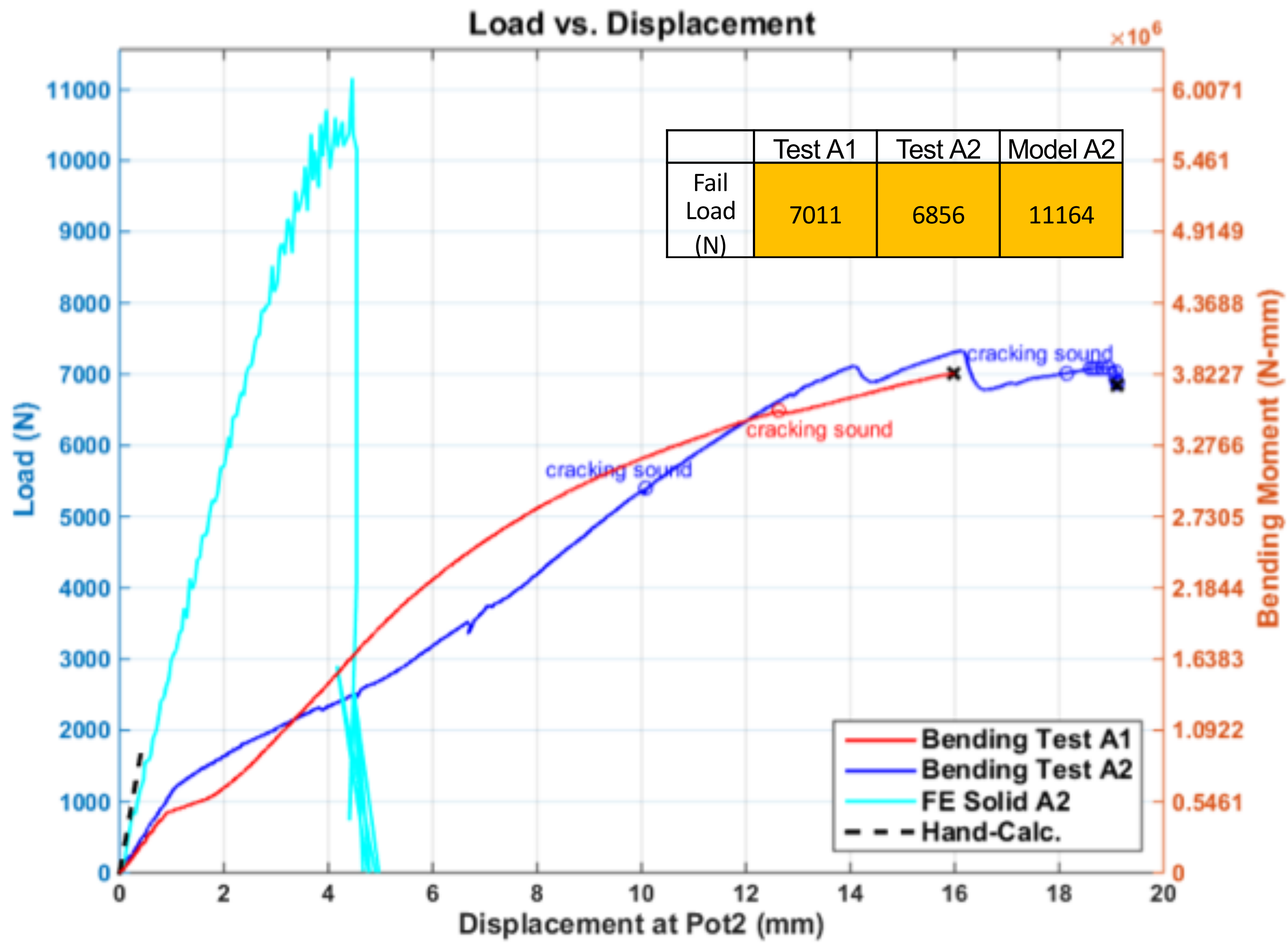
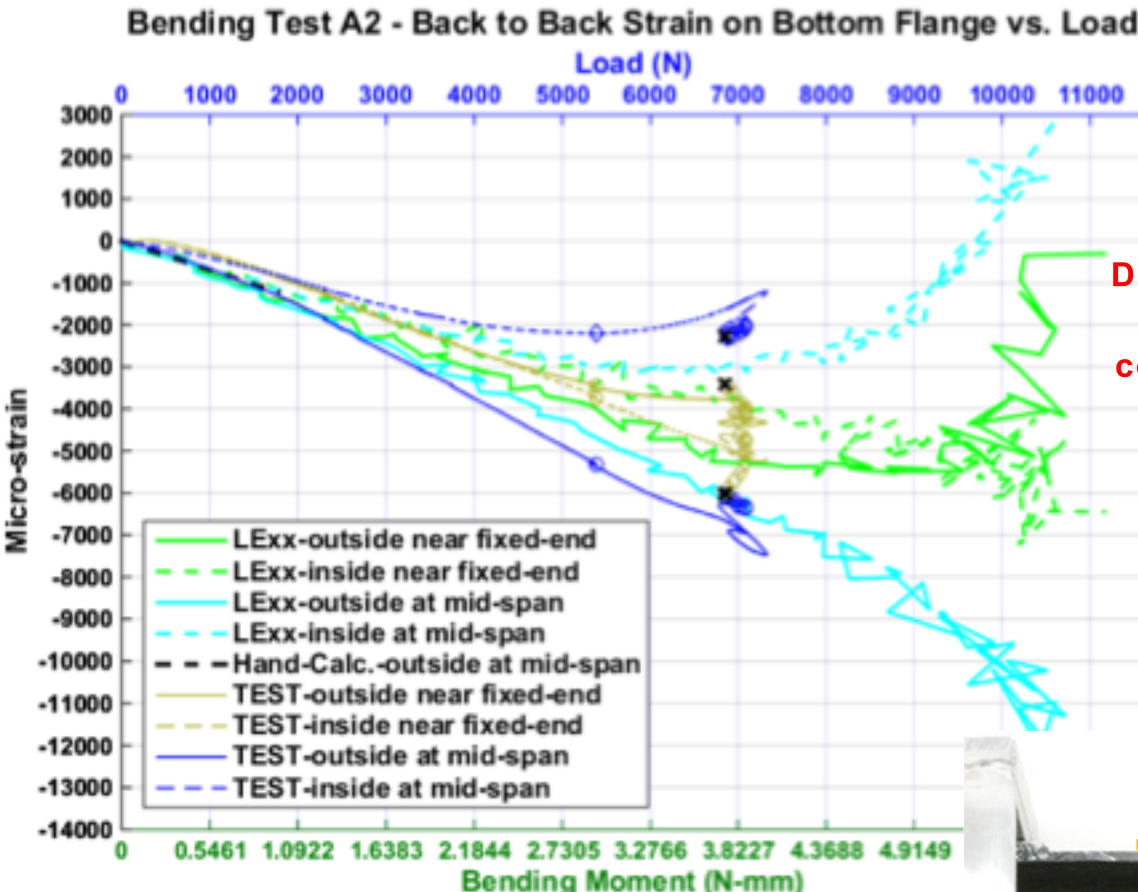
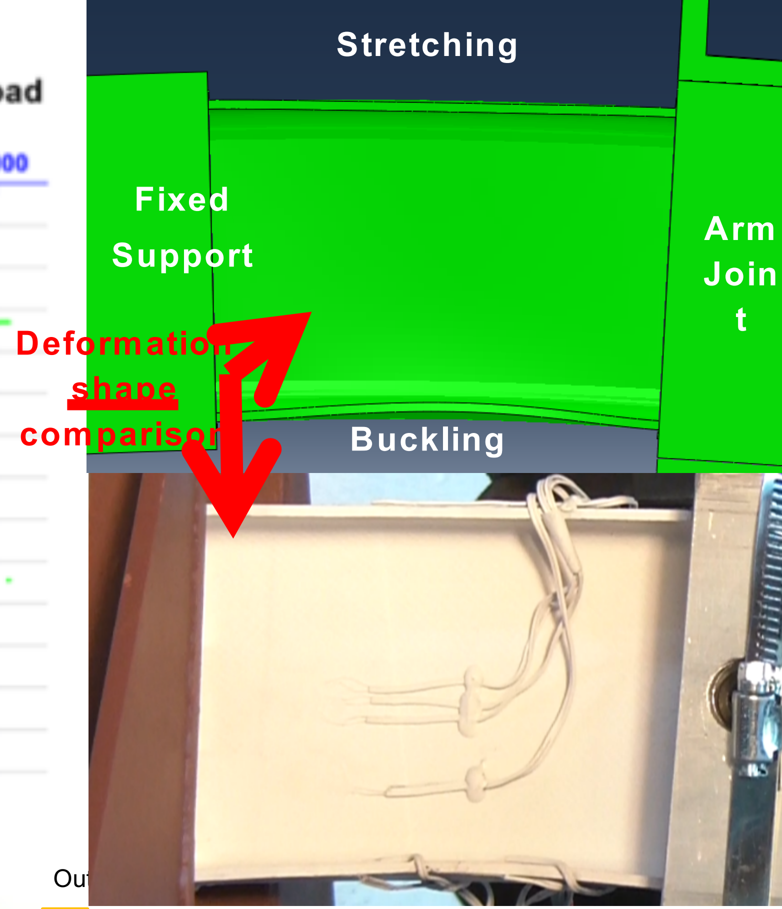
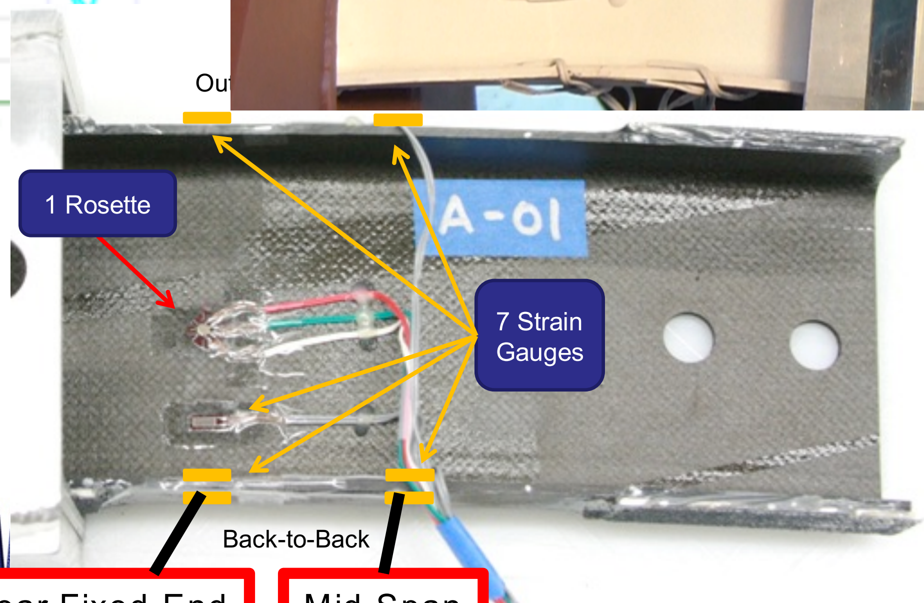
Bending A2 Model: Hill Failure Criterion Load – Displacement Curve



	Test A1	Test A2	Model A2
Fail Load (N)	7011	6856	11164







- Buckling mode from the measured strain curve on the compression flange.
- FE-predicted strain curve qualitatively agrees with the test result.

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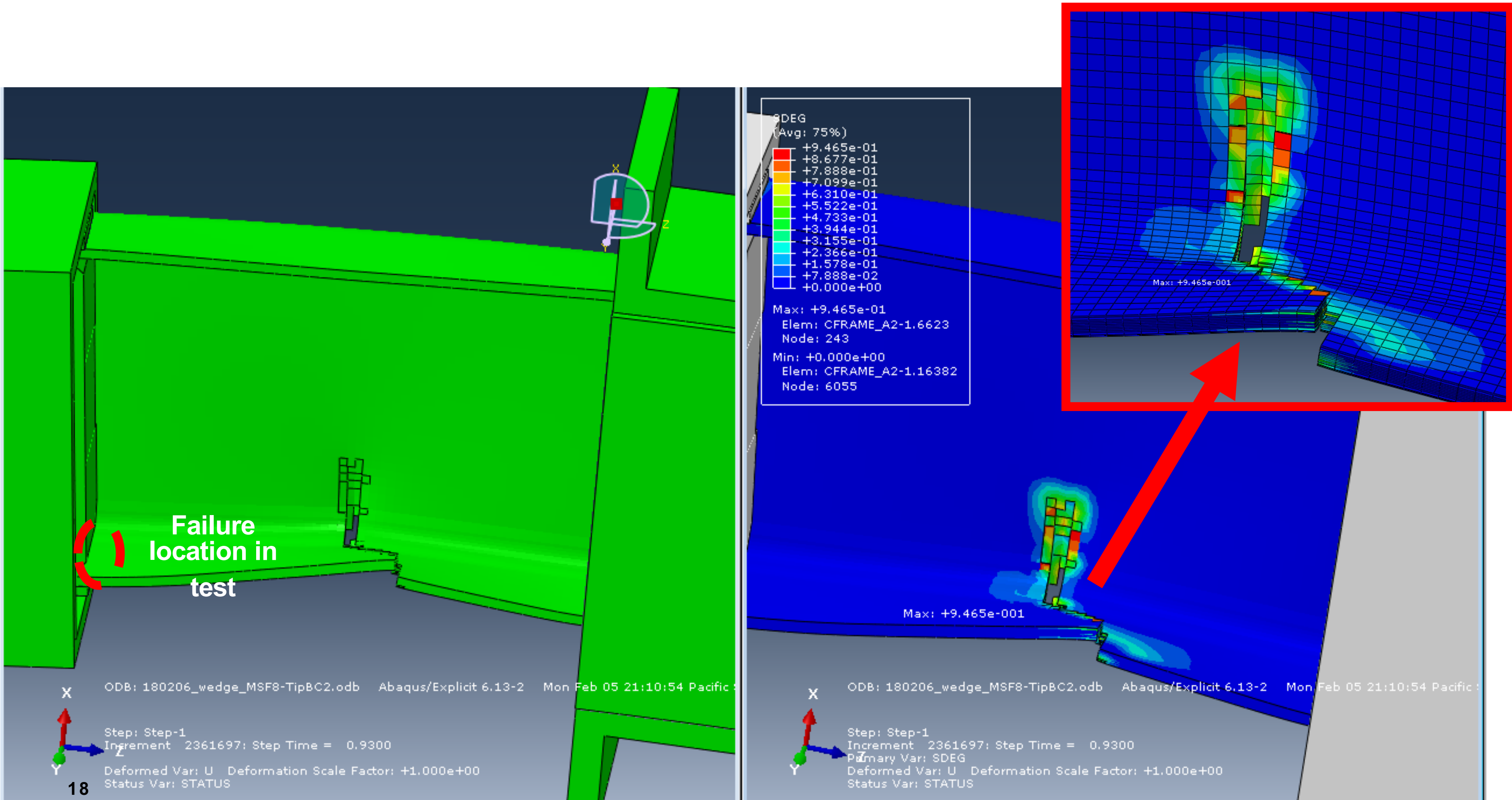
Bending A2 Model – 3D Hill Failure Criterion

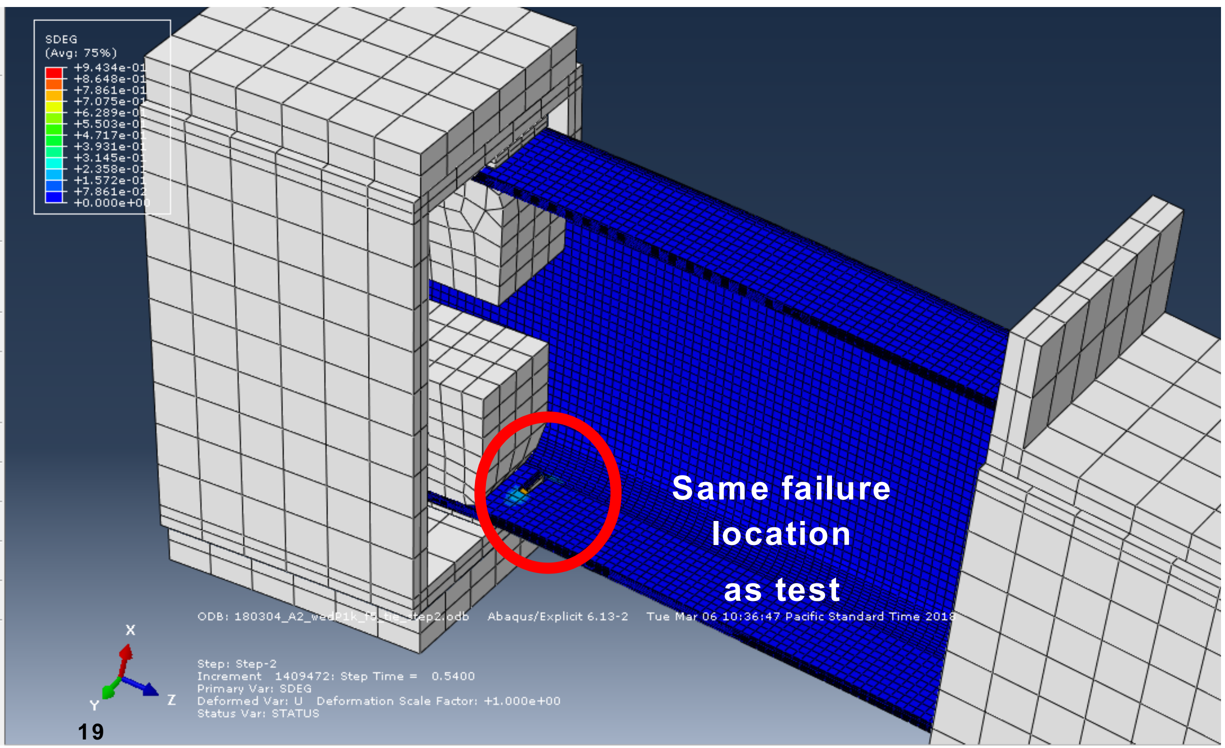
FE Model Failure mode:

- **Compression flange fractures at midspan**
- **Doesn't match with experiment location – slip and clamping effects need to be accounted for**



Refinement: Slip and Clamping Effects

- **Including slip in FE analysis**
  - **Need model refinement to account for fixture to specimen interaction (slip was observed in real tests).**
    - **Friction contact formulation is applied in detached adhesive zone between aluminum tab and c-frame.**
    - **Clamping effect is considered with 3D Hill criterion.**



1st trial :

Hypothetical wedge pressure and friction coefficient applied

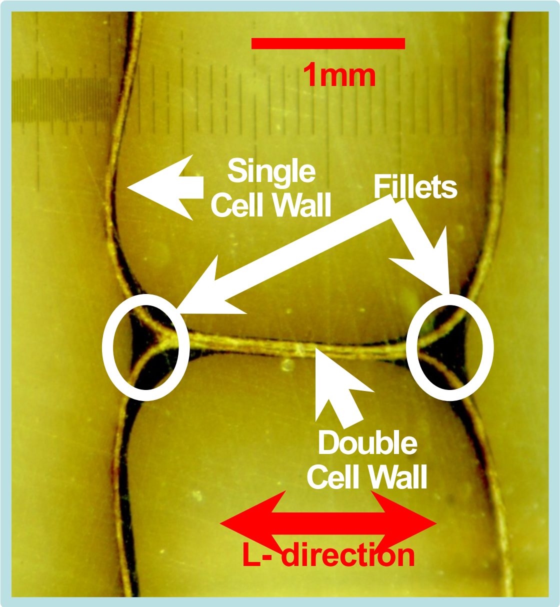
Outline

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

Introduction

- Complex Nomex® core mesostructure (ρ = 64 kg/m^3) affects core crush response

W-direction side view



Goals:

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

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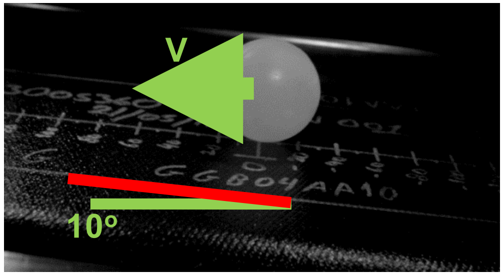
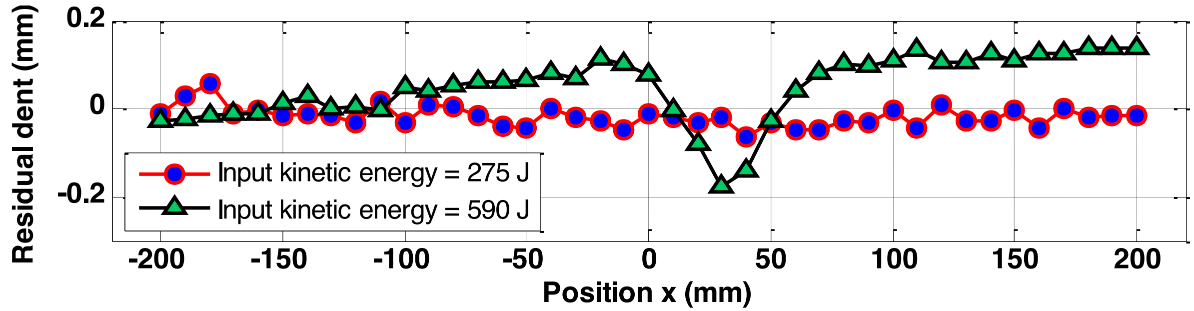
Example: Hail Impact on Low Glancing Angle Panels

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



t = 1.332 ms from trigger

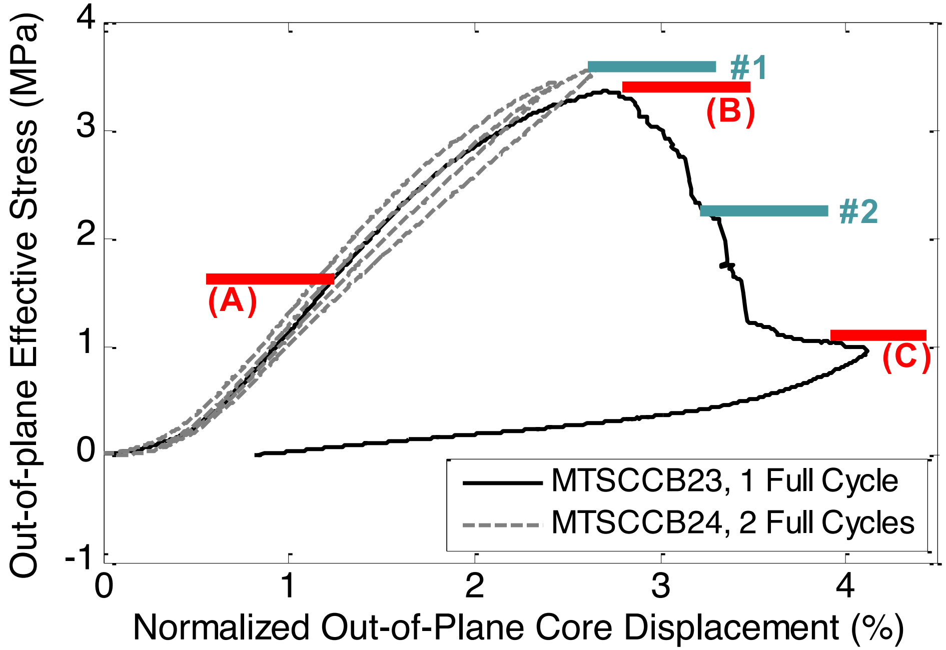


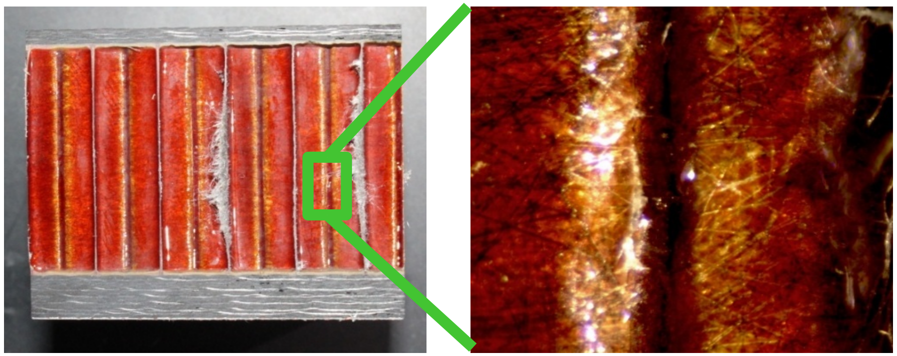
t = 1.665 ms from trigger

High speed video from 590J impact (velocity: 360 mph)

Impact direction

Damage on Nomex® Cores (Flatwise Compression)

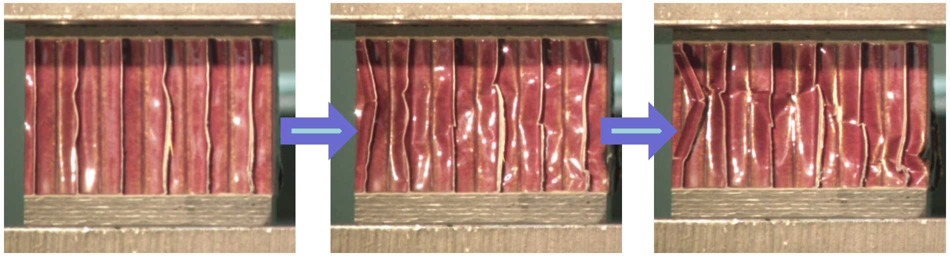




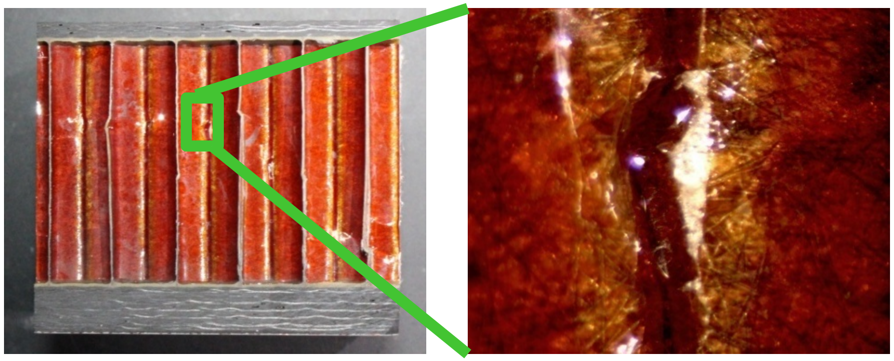
Unloading at peak stress (point #1):

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

Sequence of failure events

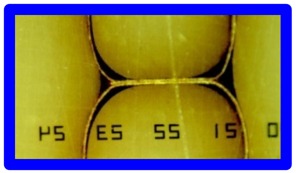


(A): Onset of post-buckling | **(B): Onset of resin fracture** | **(C): Core crushing plateau**



Unloading at unstable region (point #2):

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



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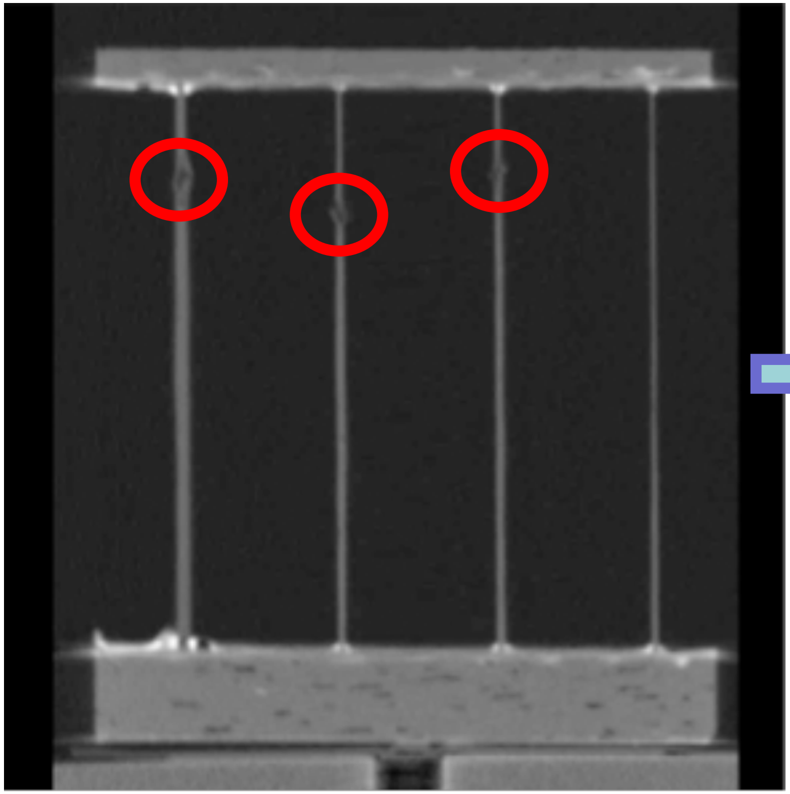
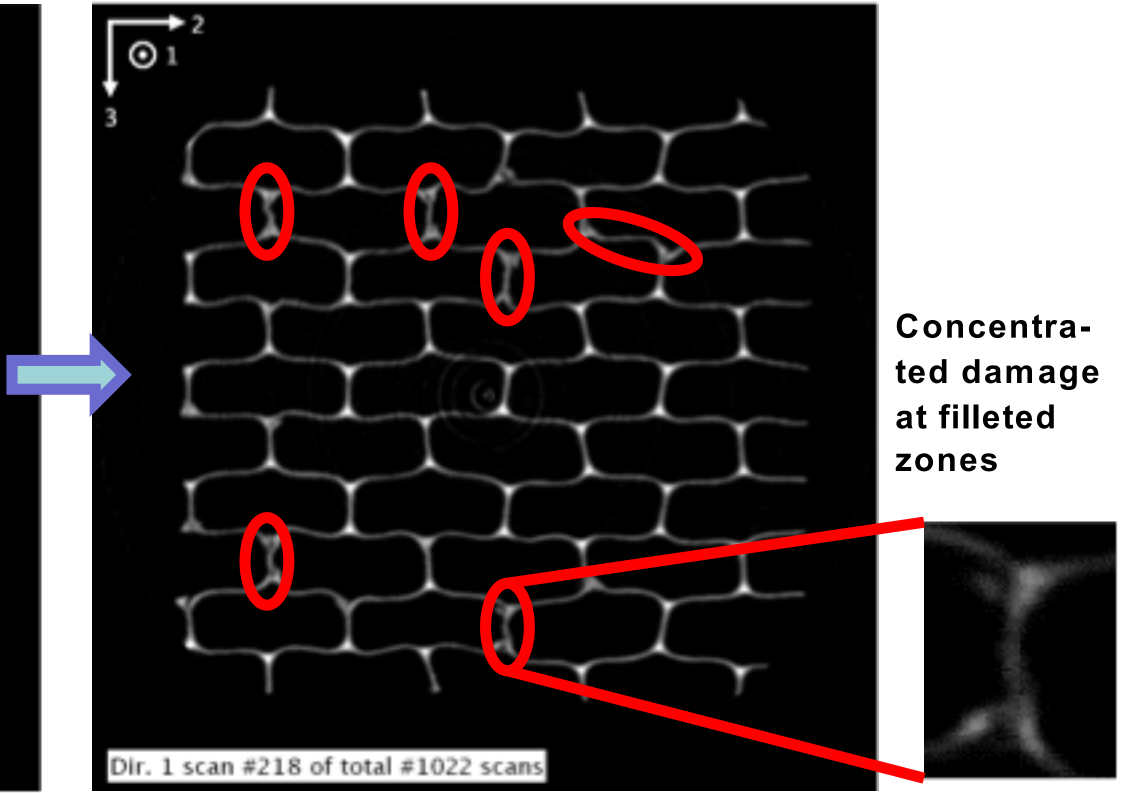
Computed Tomography Scans for Initial Damage Level in Flatwise Compression Coupons

- Collaboration with University of Utah: CT-scans provided by Prof. M. Czabaj
- Through thickness scans provide clear description of damage
- Fillet fracture and detachment from paper walls are the prevailing modes (right figure)

Cross-sectional slice #302 of tested coupon





Concentrated damage at filleted zones

Imperfect Core Geometry Effects
FE Model construction from CT Images

Automated procedure utilized in Matlab

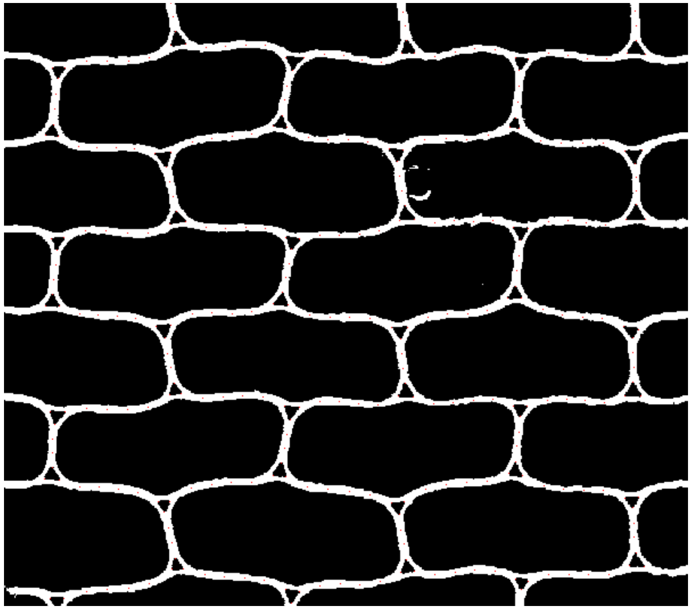
1) Image processing of each slice to obtain pixels representative of the shape of the cellular structure

- Pixels at triangular fillets
- Pixels at cell walls

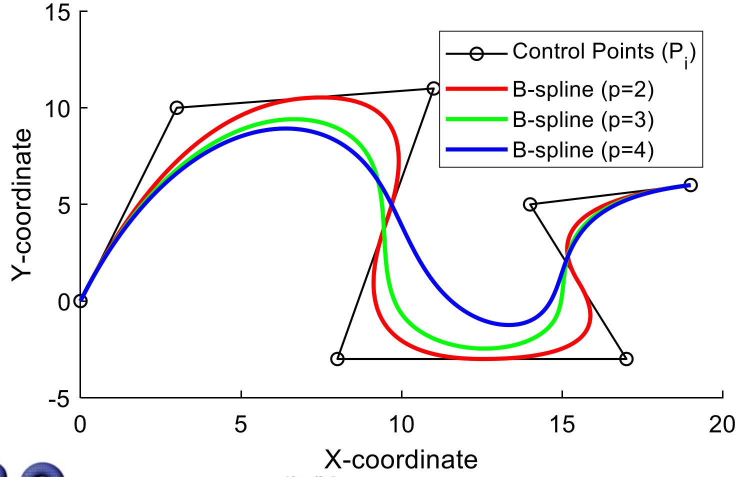
2) Repeat steps 1 at different through-thickness CT-slices

3) B-spline surfaces fitted through data pixels obtained in steps 1) and 2)

- Characterize imperfection metrics of pre-buckled walls
- Perform collapse/post-buckling computational analysis on actual geometry honeycomb structure

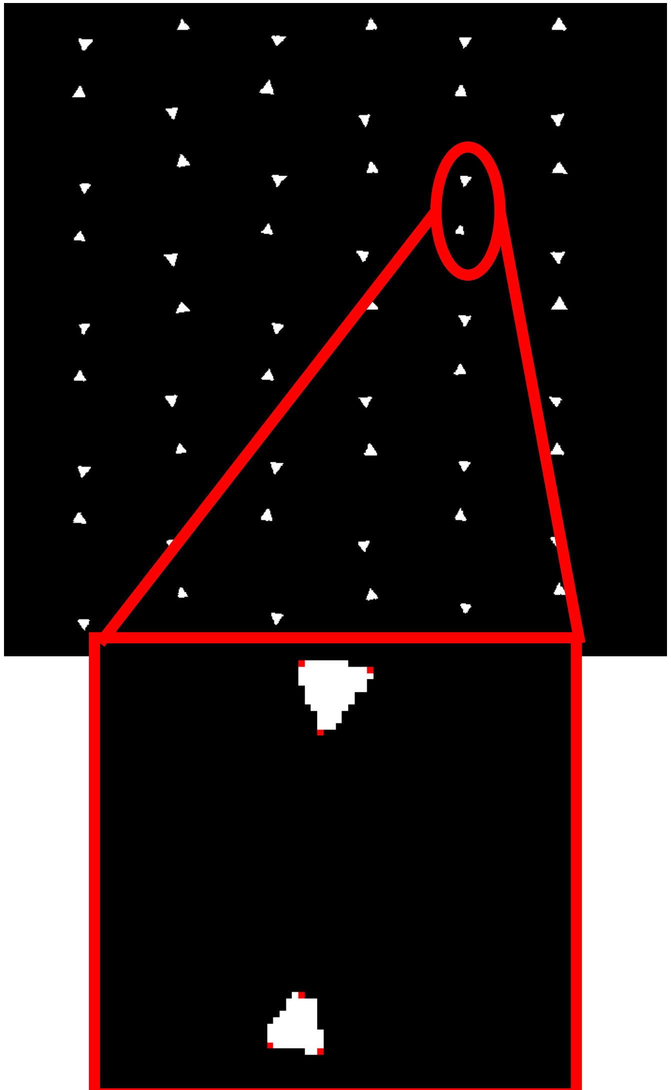


B-Spline Curve Fit

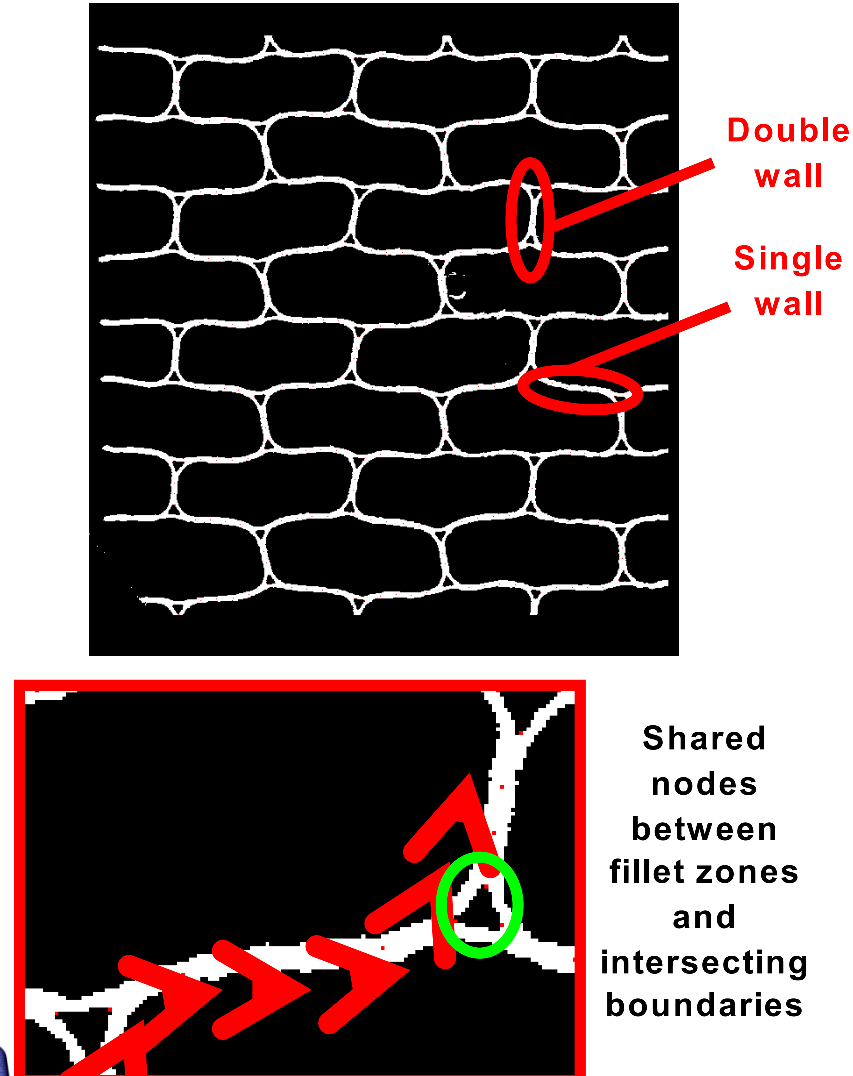


Extract cell interpolated pixels from CT-scan slices

1) Get corner pixels of triangular-shaped fillets using threshold color segmentation



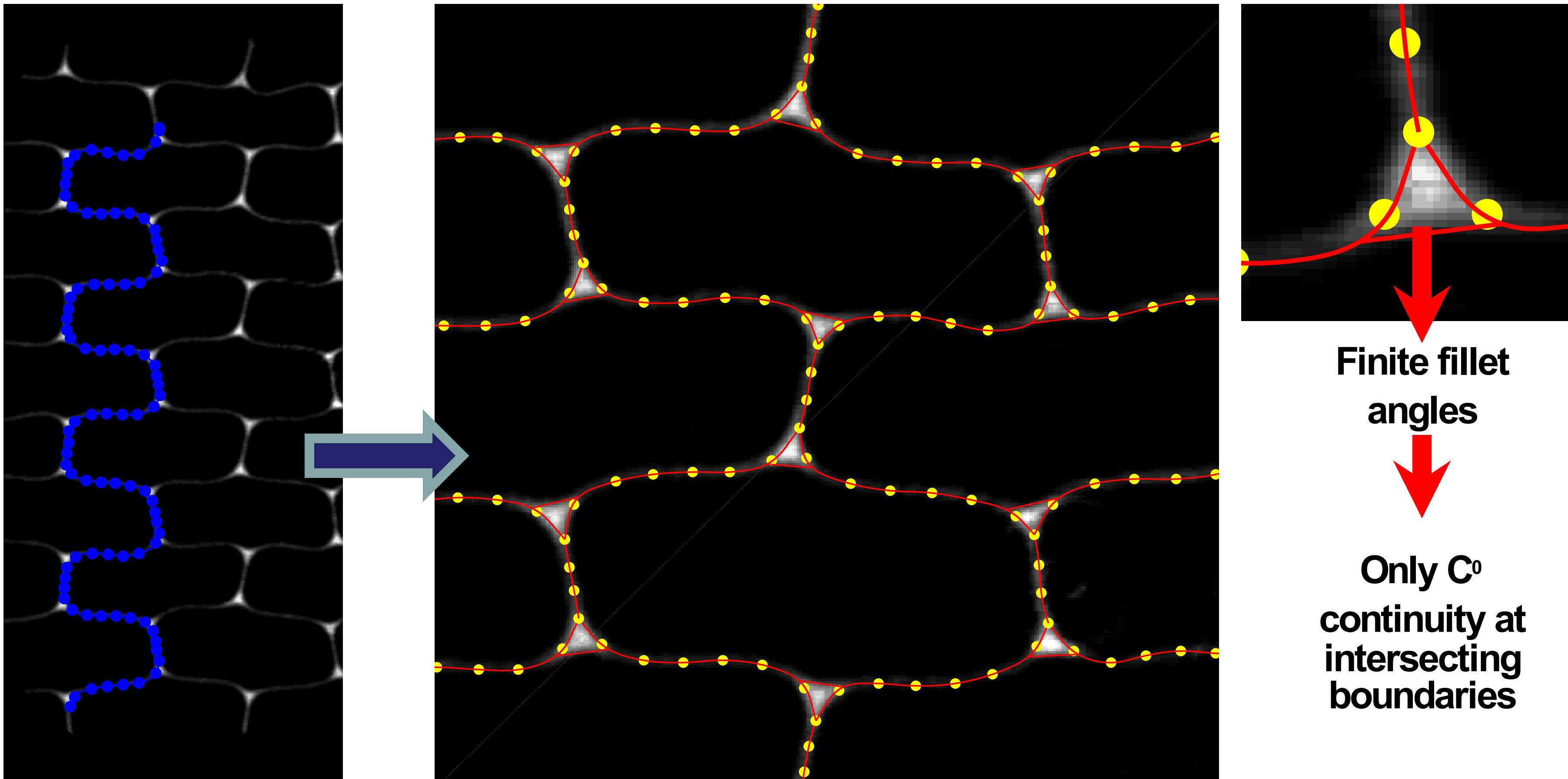
2) Get pixels of cell wall structure using matrix color segmentation



Application of B-spline curves (one CT-slice)

3) Use B-spline curve fit to extract planar honeycomb geometry

- Obtain the spline of each paper ribbon (as in expansion process)
- B-splines at double wall region match perfectly between adjacent layers



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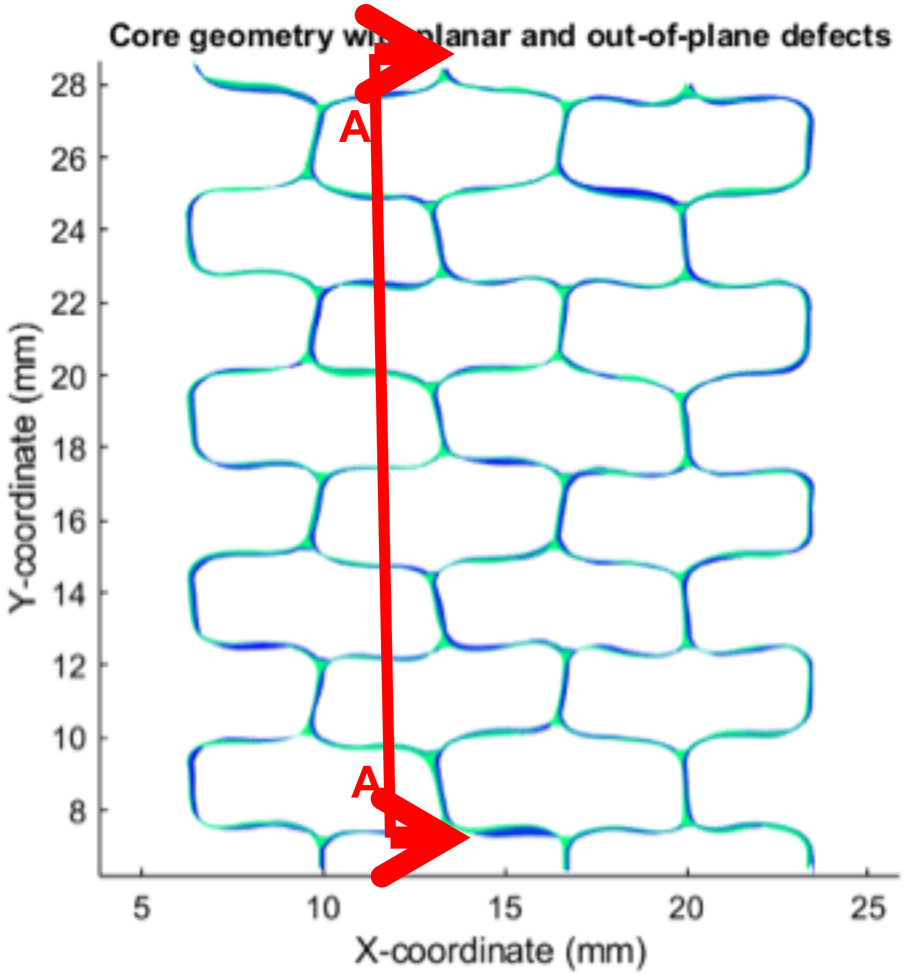
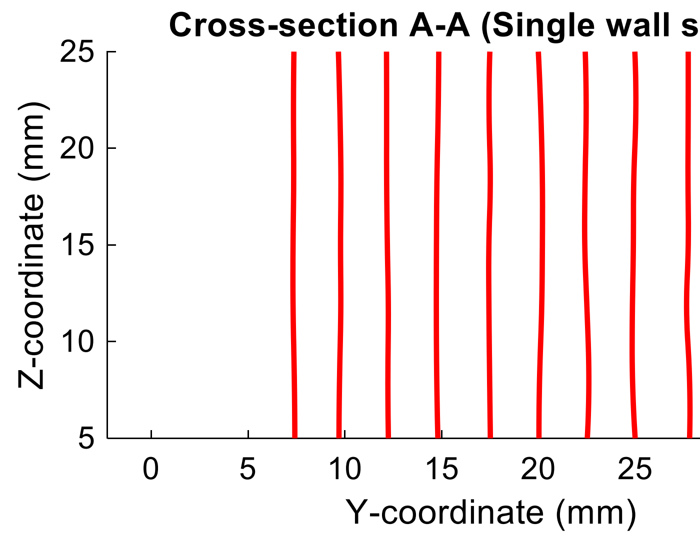
3D Core Reconstruction & Imperfection Metrics

Extend into many slices and reconstruct 3D geometry based B-spline surfaces





Distorted Cell Wall Geom

- Pre-Buckled

Exact 3D Actual Geom FE Model

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Outline

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

Summary

Ground Service Equipment (GSE) High Energy Blunt Impact

- Next Generation HEWABI specimen design completed and parts fabricated
  - focus on blunt impact tests near floor beam locations
- Simulations of blunt impacts near floor beam completed
  - predict sequence of failure modes; no skin failure
  - truncated specimen geometry shows equivalence to full quarter barrel
- Element-level C-frame FE models developed for bending and torsion
  - to be incorporated into large panel blunt impact models

Impact Damage to Sandwich Panels

- Core damage has been experimentally documented via ice sphere impact gas gun tests at low angles of attack; no dent visible with core crush/fracture.
- For Nomex® paper based cores, phenolic resin pre-impregnated paper cells exhibit mesoscale structural complexity
  - Phenolic resin accumulation zones around wall intersection boundaries significantly improve stability of system during flatwise compression tests
  - CT-scans on post-tested compression coupons revealed partial detachment of fillet columns due to cell wall post-buckling
- CT-scans on untested configuration provides insight on actual in-situ geometric imperfection state of Nomex® core in sandwich

Benefits to Aviation

- Understanding the damage resulting from HEWABI through element level and structural level studies – particularly for impacts near floor beams
  - 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
  - resin thickness coating cell walls
  - geometric imperfection of walls
  - more accurate modeling representation of core
- Understand effects of manufacturing defects/variability on core mechanics – FE model generation by CT-scan permits accurate actual geometry definition

Looking Forward

- Complete HEWABI specimen machining, drilling, assembly
- Test HEWABI specimens
- Continued development of high fidelity FEA modeling capability – validated at element level.
- In large-scale FE models, define effective representation of fasteners and its influence in damage initiation and progression.
- Simulation of core crush response with actual geometry defined by CT scans.