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Impact Damage Formation on Composite Aircraft Structures

Hyonny Kim,
Professor, Dept. Structural Engineering
University of California San Diego

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Impact Damage Formation on Composite Aircraft Structures

- **Principal Investigators & Researchers**
  - PI: Prof. Hyonny Kim, Professor, UCSD
  - Graduate Students
    - PhD: Konstantinos Anagnostopoulos, Moonhee Nam
    - MS: Chaiane Wiggers de Souza
- **FAA Technical Monitor**
  - Lynn Pham
- **Other FAA Personnel Involved**
  - Curt Davies
  - Larry Ilcewicz
- **Industry Participation**
  - Boeing, Bombardier, UAL, Delta, DuPont
  - San Diego Composites, JC Halpin

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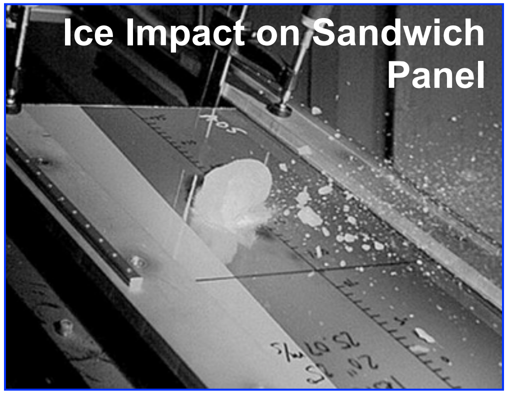
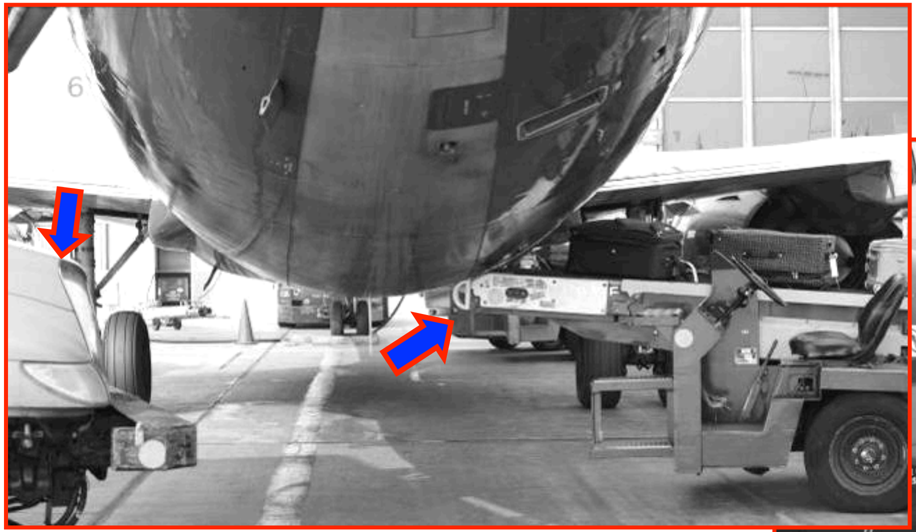
Impact Damage Formation on Composite Aircraft Structures

- **Motivation and Key Issues**
  - impacts are major source of aircraft 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



Ice Impact on Sandwich Panel

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 Program Objectives

General Objectives Applicable to Blunt Impact Sources of Interest:

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

- **Develop analysis and testing methodologies, including:**
  - physically-based modeling capabilities validated by element-level tests
    - selection of tests to excite key failure modes
    - further model validation via full-scale tests
  - establish how to predict damage visibility – surface crack, residual dent

Outline

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

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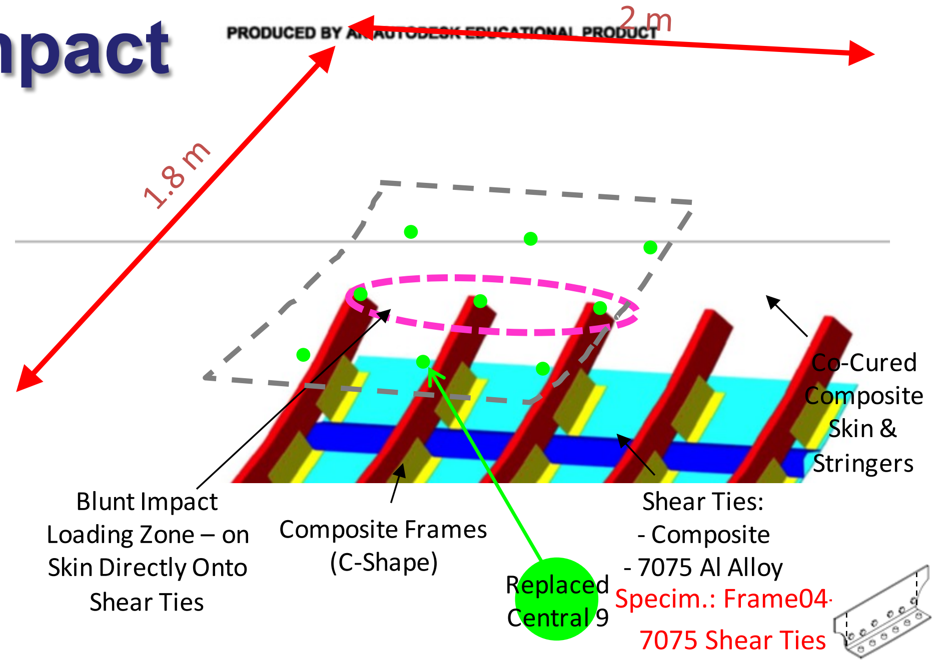
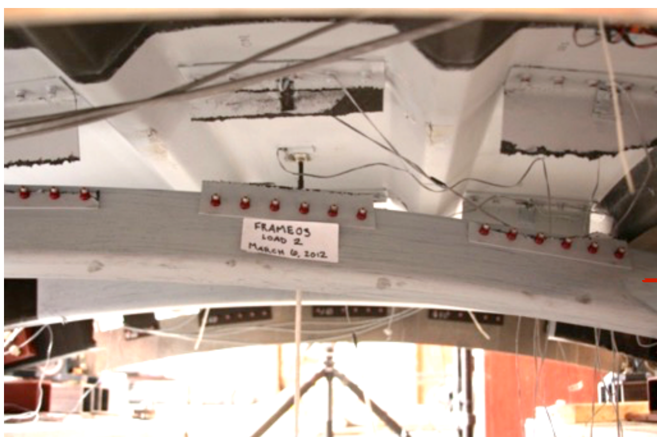
GSE High Energy Blunt Impact

Previous Results Summary I

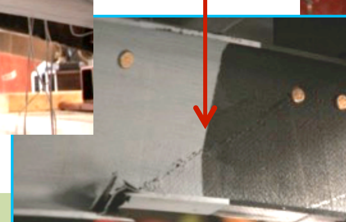
- series of large specimens tested (ID: Frame03, Frame04-1, Frame04-2)
  - internal damage to frames and shear ties
  - no skin cracking or external visibility
  - strength of shear ties strongly affects failure modes in frames
- element-level tests supporting modeling



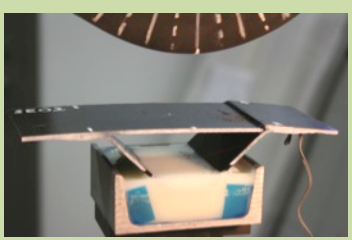
Large Panel Tests



Frame Failure Near Outer Shear Ties



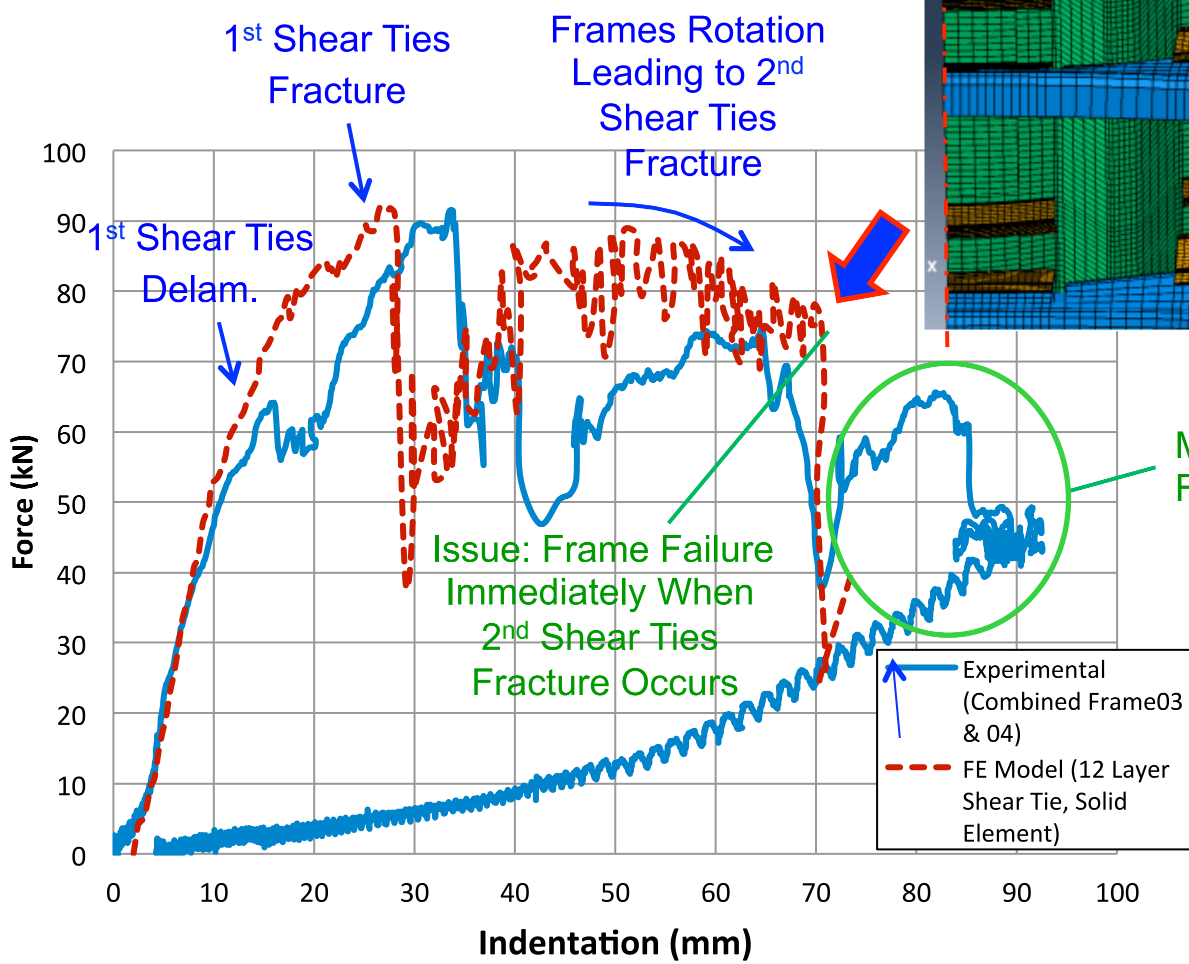
Element-Level Tests

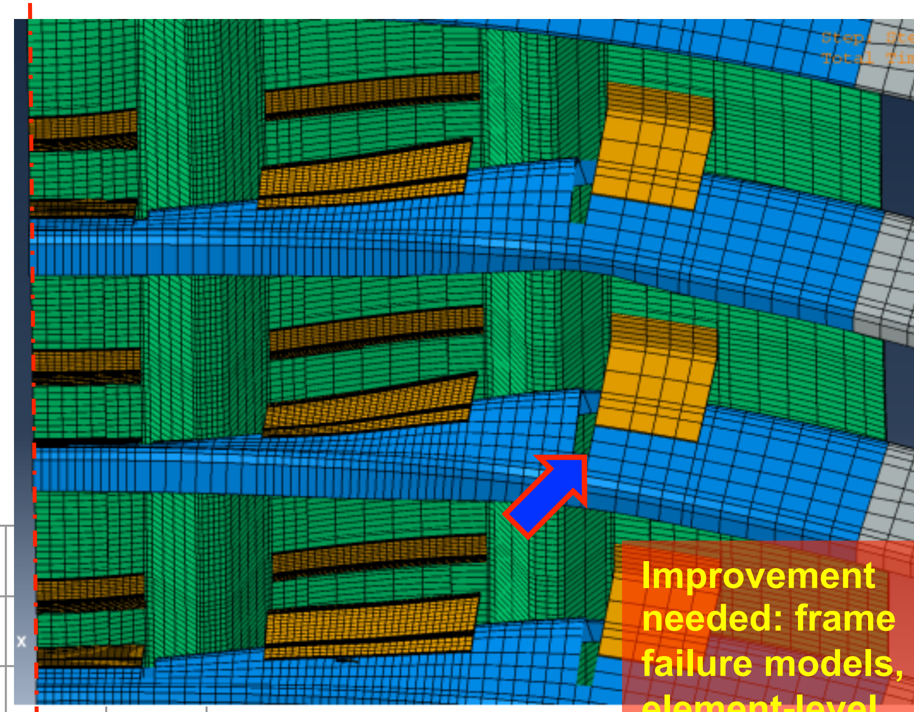


GSE High Energy Impact

Previous Results Summary II

Large Panel Simulation

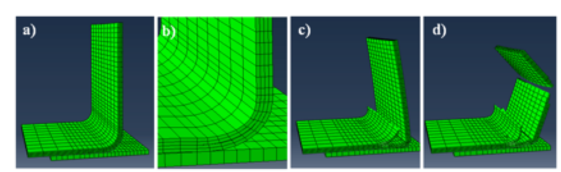




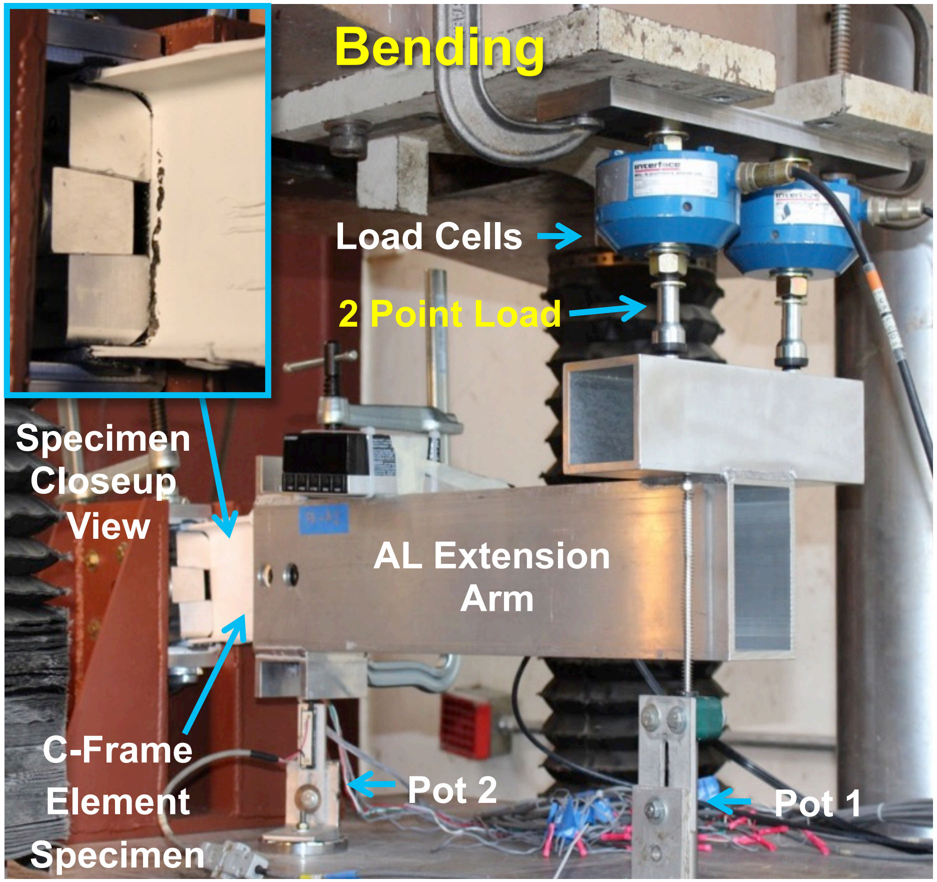
Improvement needed: frame failure models, element-level C-frame tests

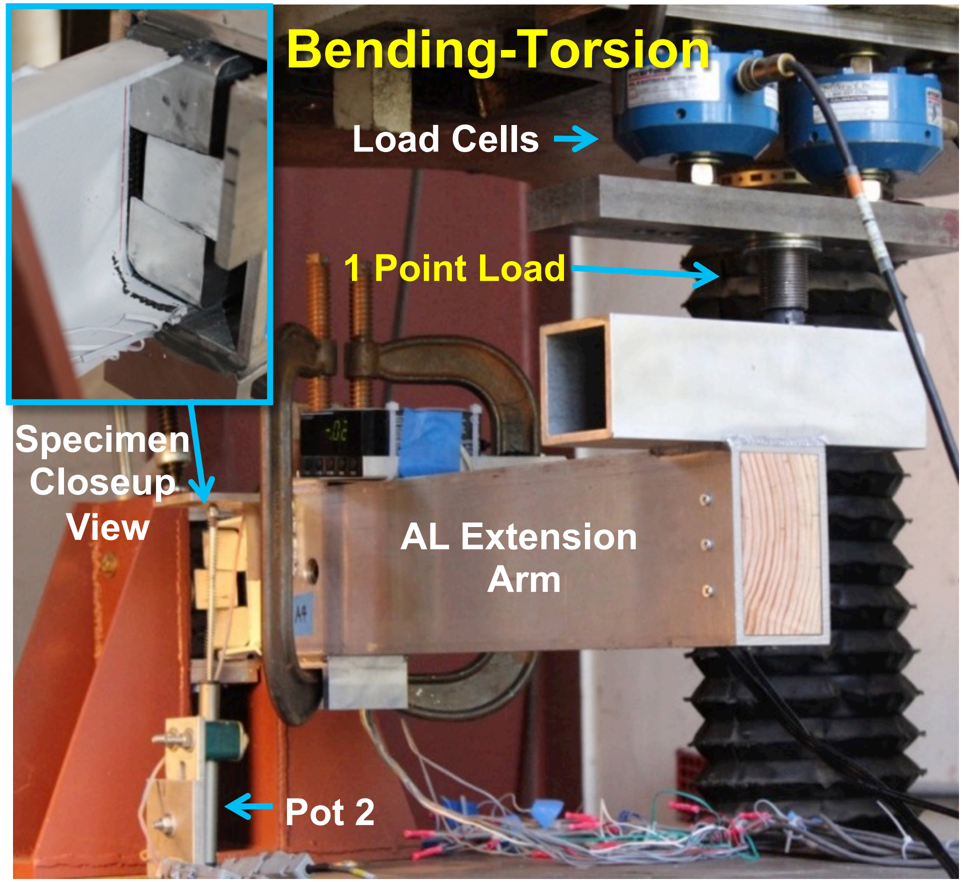
Shear Tie Modeling Details:

- continuum solid elements; 12 layers through the thickness
- cohesive surface interaction applied between elements
- 3D Hill failure criteria

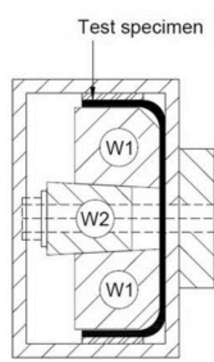


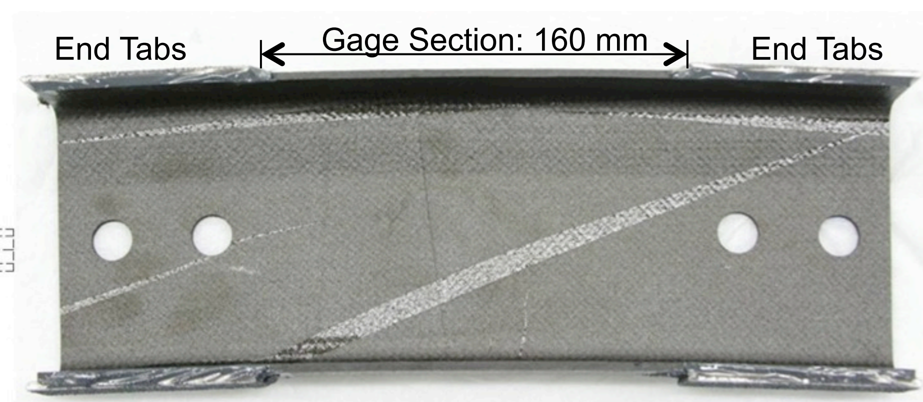
Element-Level C-Frame Tests





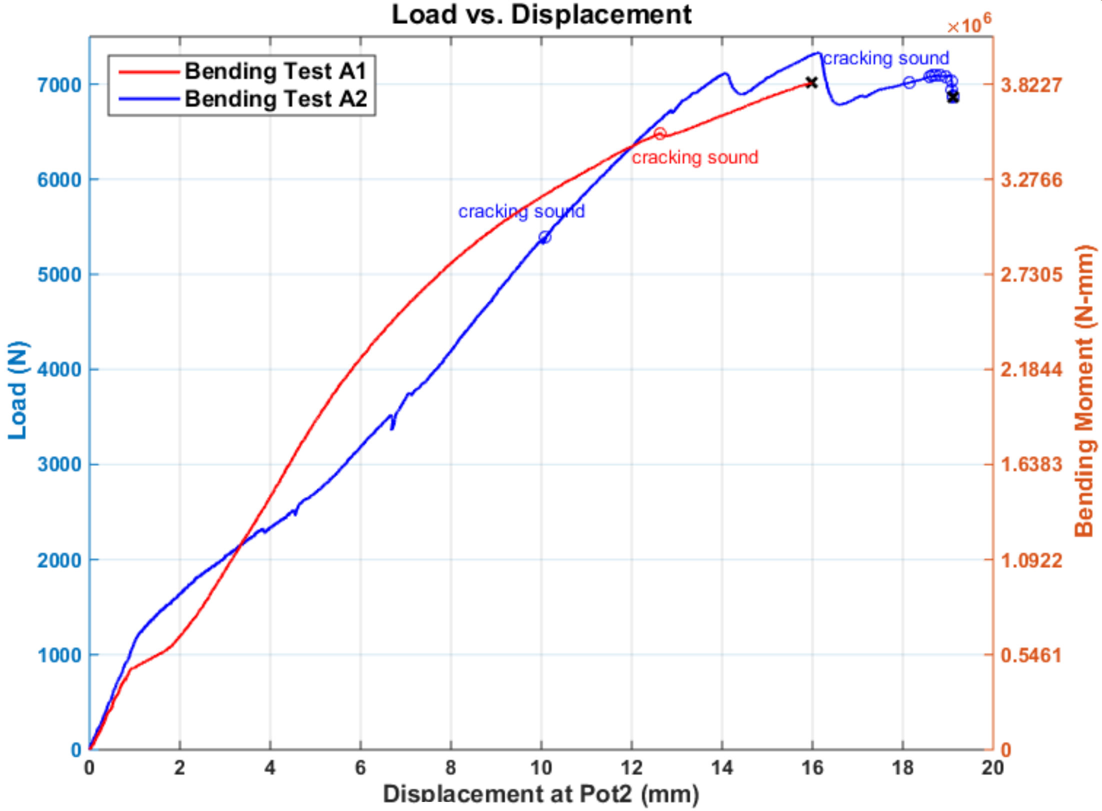
- C-frame test specimen
  - short section w/ extension arm
- fixed end boundary condition
- loaded end:
  - 2 point connection → bending
  - 1 point → bending + torsion

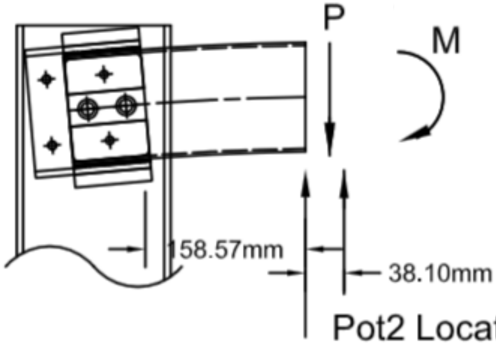




C-Frame Bending Test

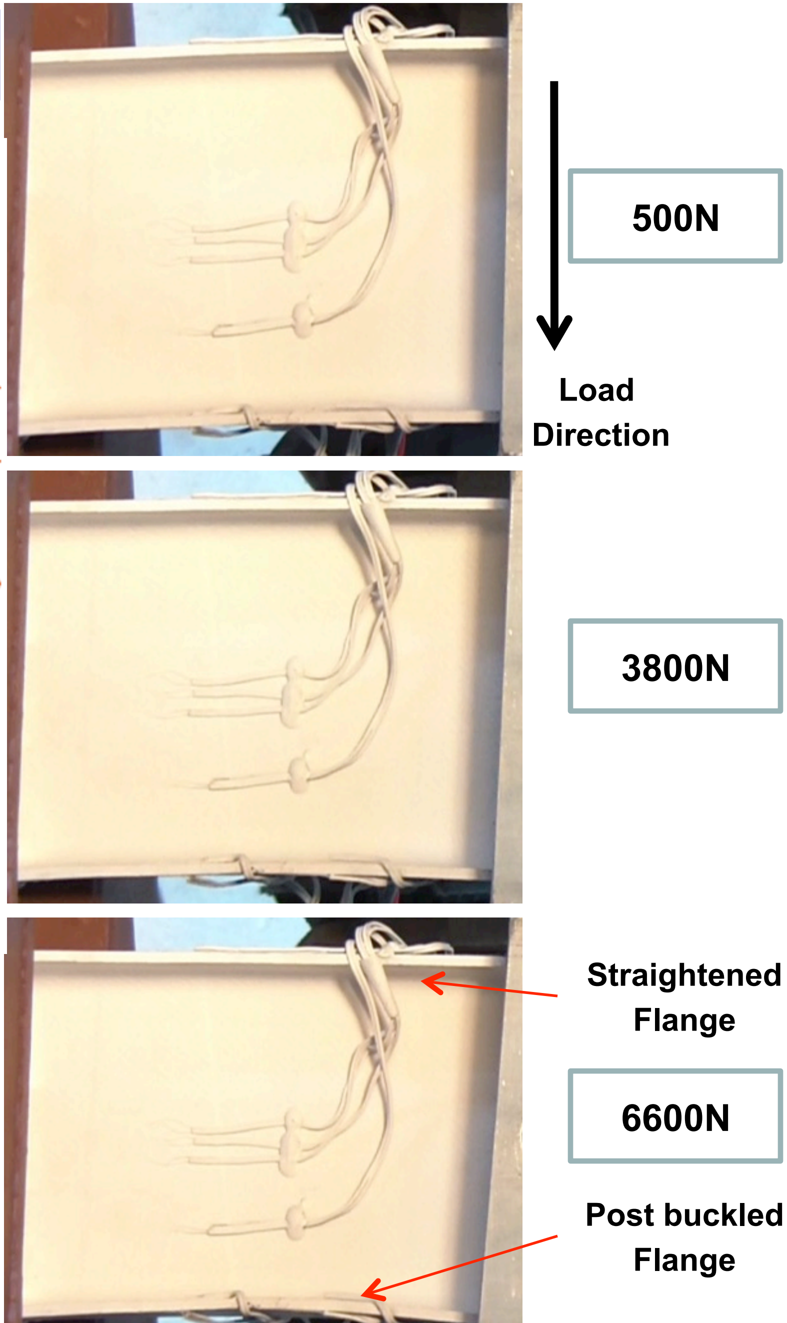
A2



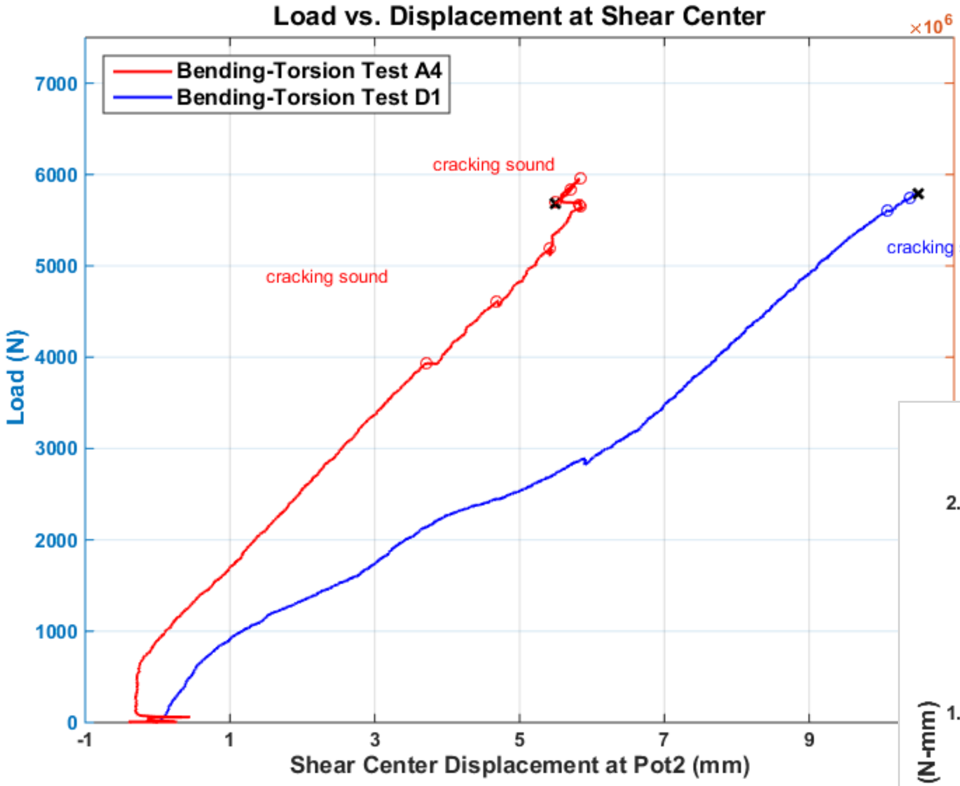


Pot2 Location for Bending Test A1, A2, A3

Pot2 Location for Bending-Torsion Test A4, D1

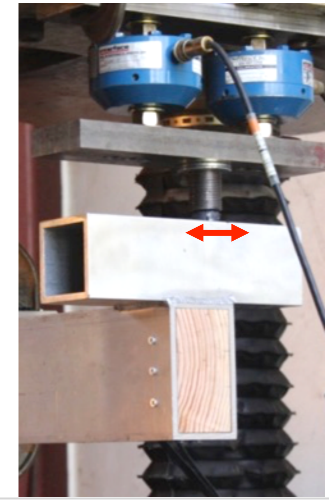


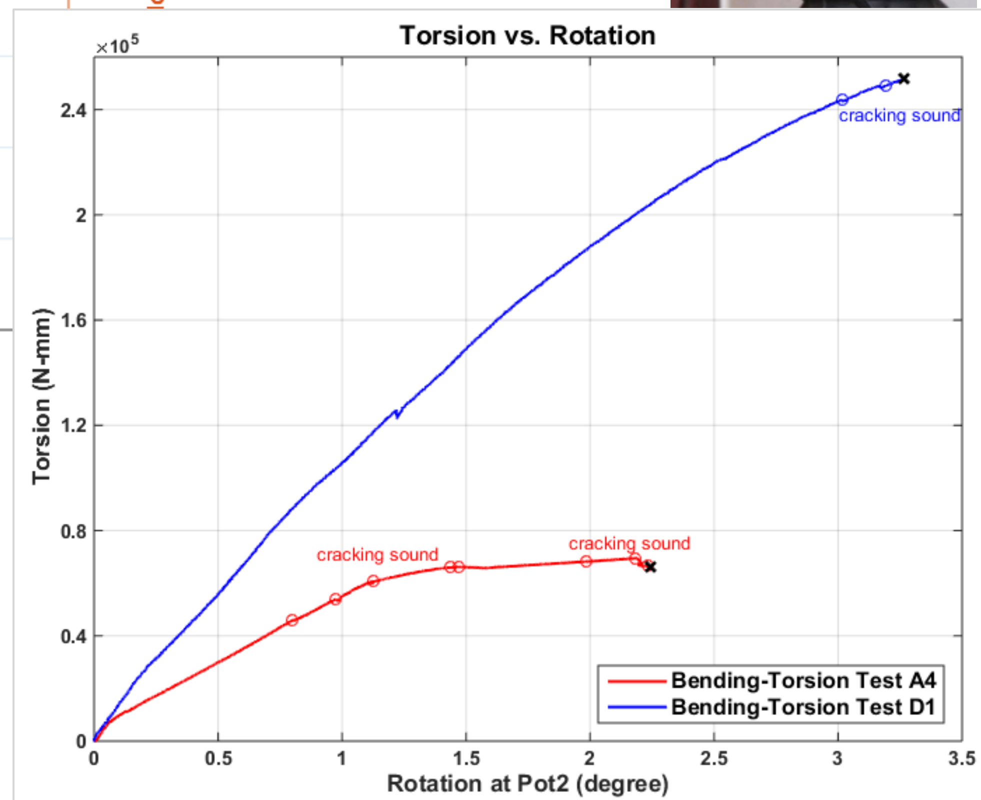
Combined Bending-Torsion Test

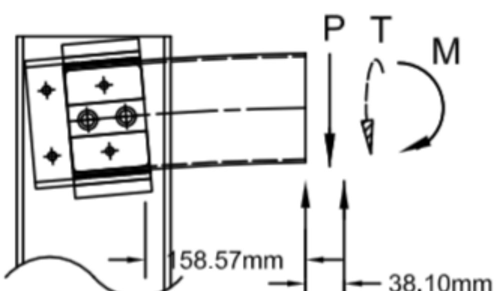


Specimens A4 and D1

- **More Torsion in D1**
- **Adjustment via Load Point Offset w.r.t. Shear Center**



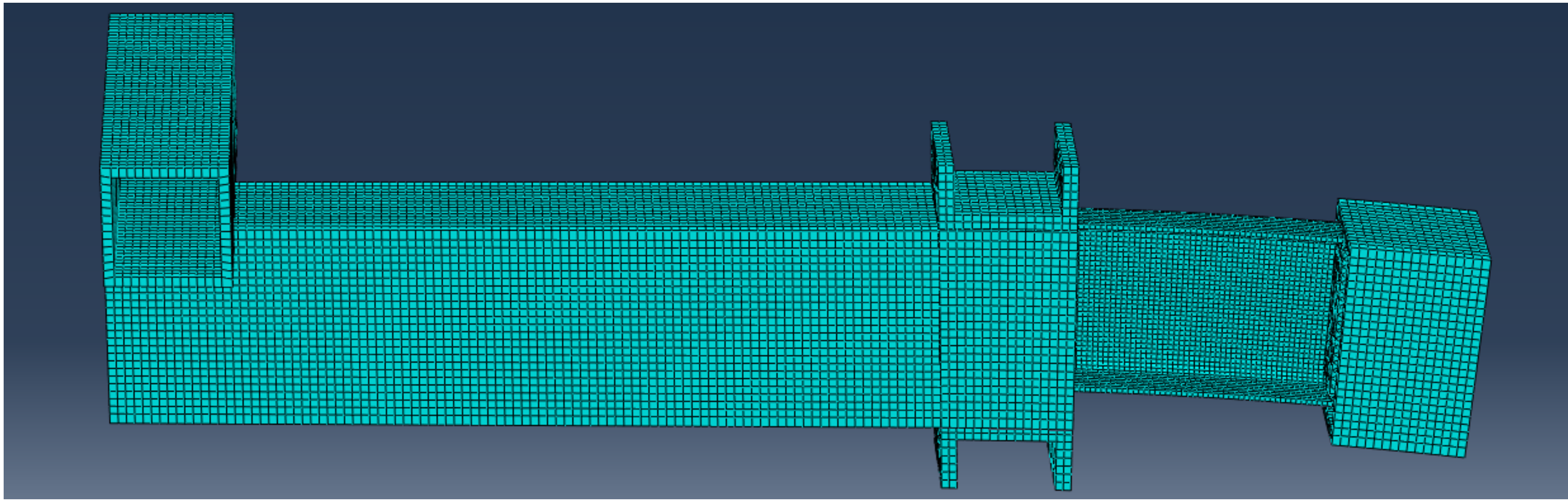




Pot2 Location for Bending Test A1, A2, A3

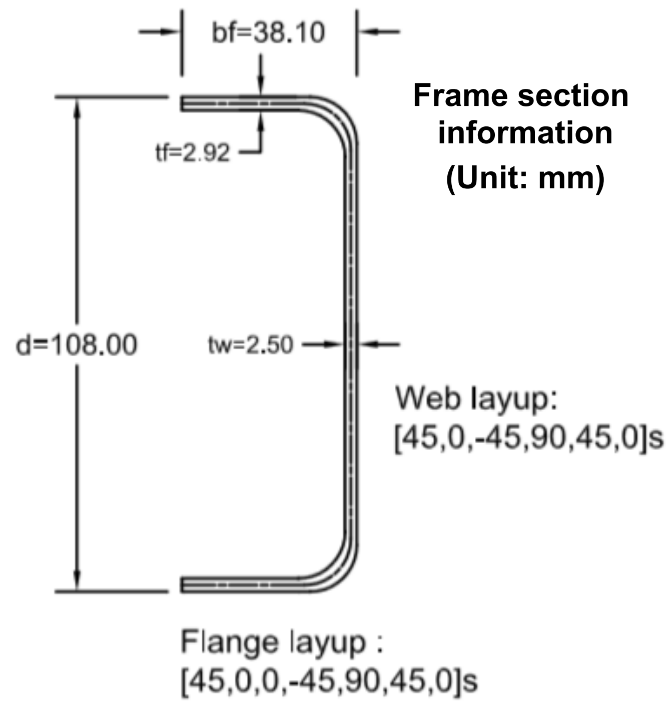
Pot2 Location for Bending-Torsion Test A4, D1

Finite Element Model: C-Frame Element Test

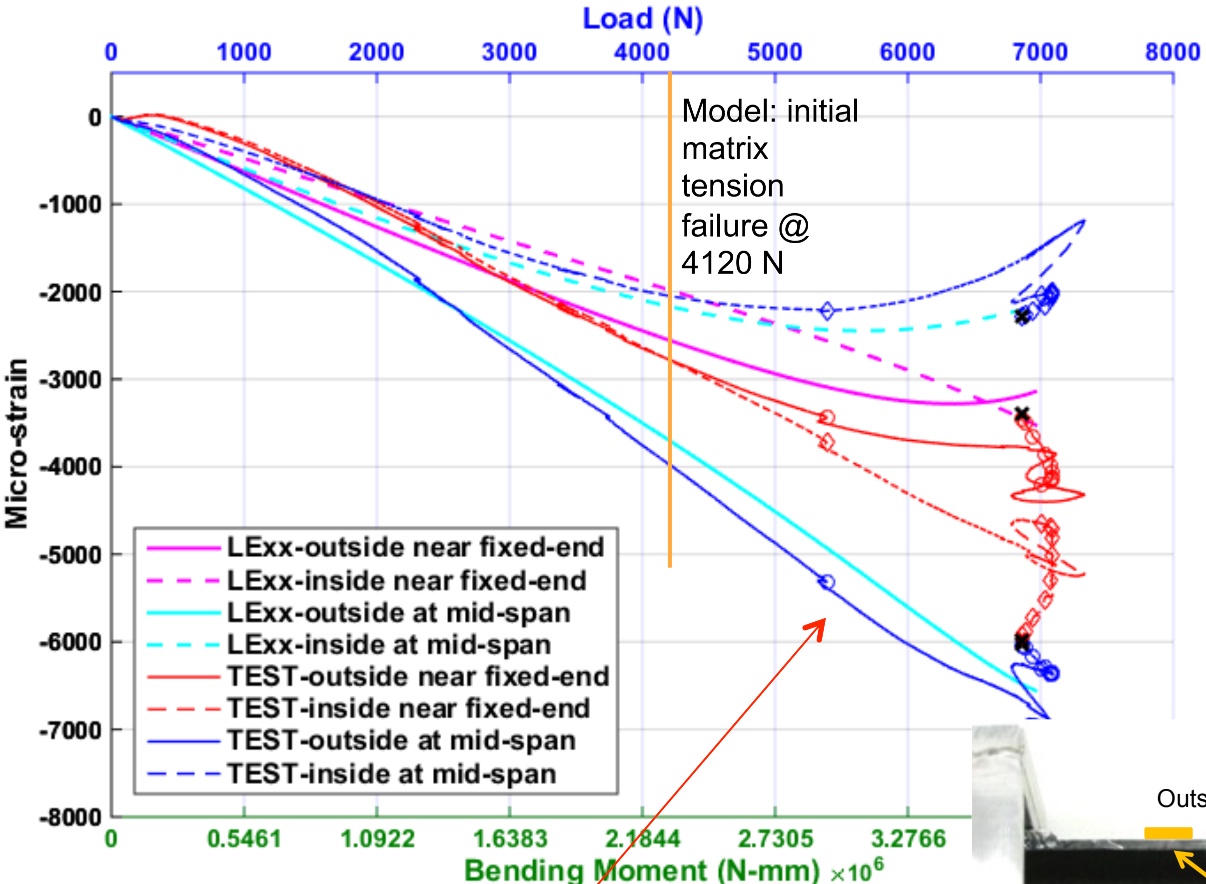


- Materials :
  - Cytec X840/Z60 6k woven carbon/epoxy with Hashin-Rotem failure
    - in-plane failures only, no delam represented
  - Aluminum 6061-T6 (box beam)
- Element type
  - C-frame: Continuum Shell (SC8R)
  - Aluminum: Solid (C3D8R)
- Tie interaction applied at interfaces

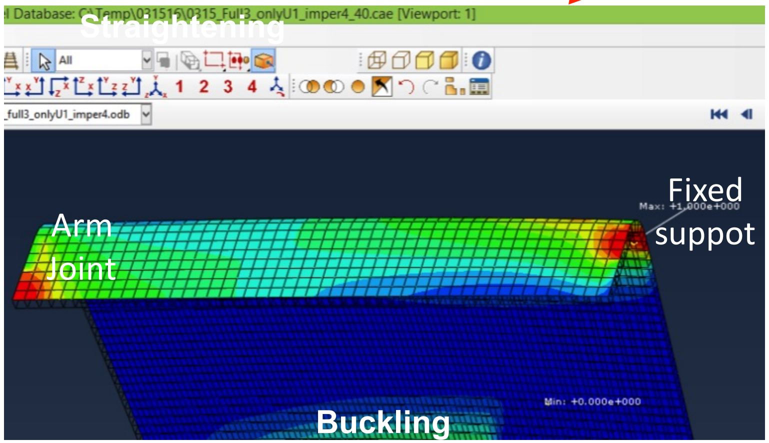
→ Incorporate validated models into large-sized five-frame panel simulations



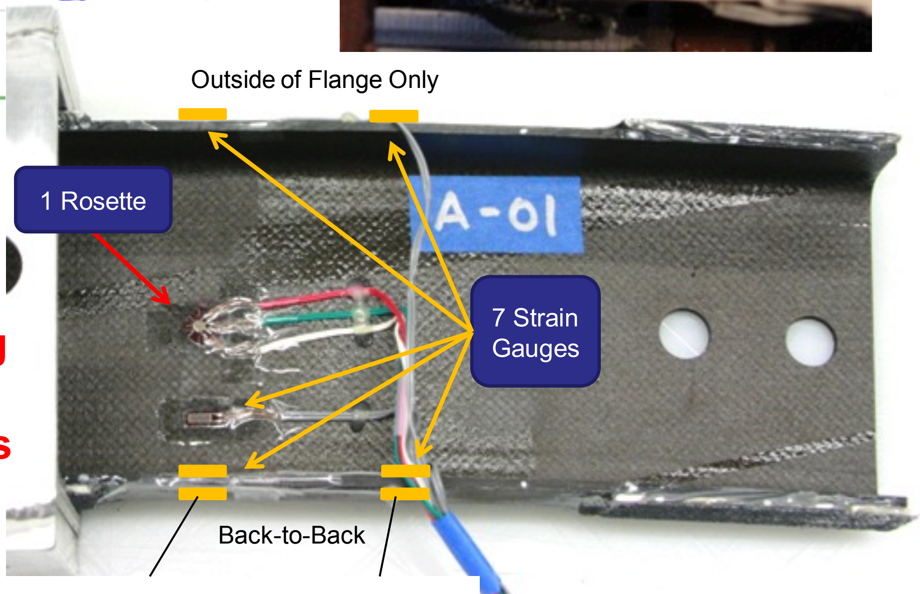
Bending Test A2 - Back to Back Strain on Bottom Flange vs. Load



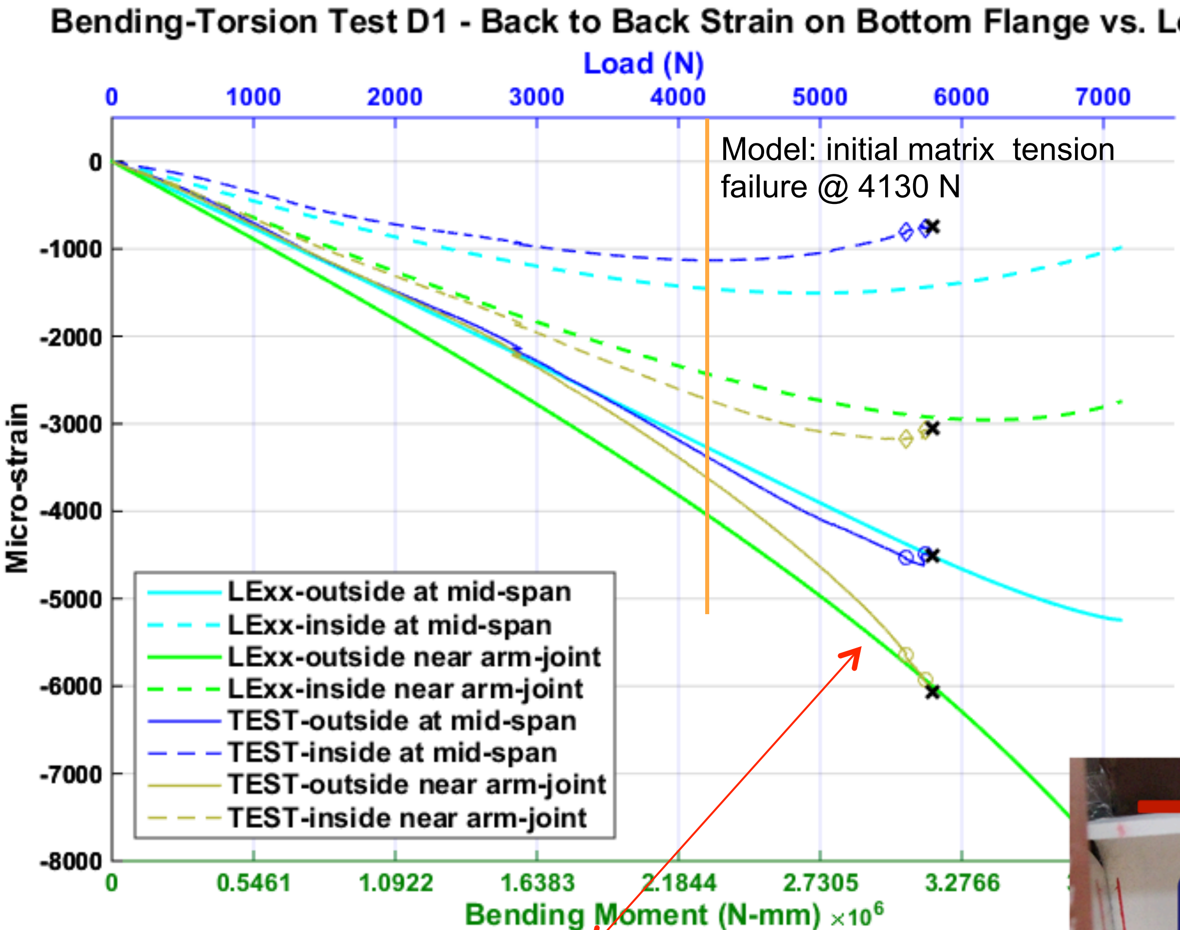
Bending Test, A2



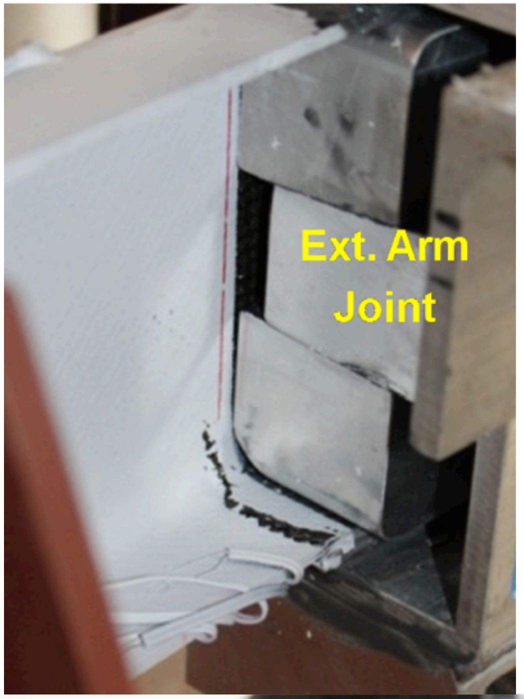
Modeling in Progress

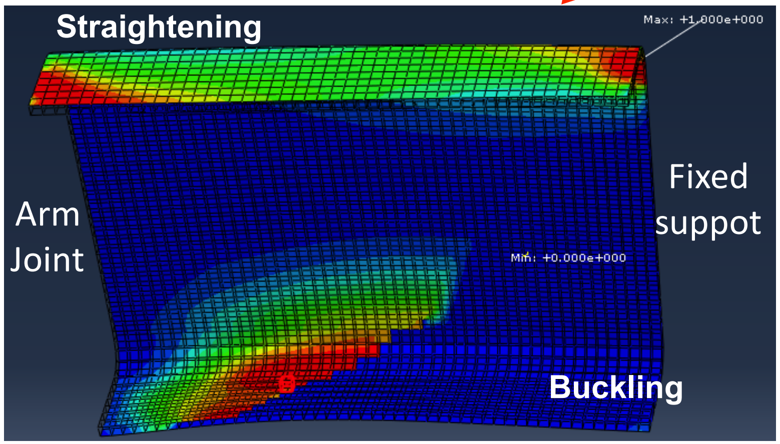


Near Fixed-End Mid-Span

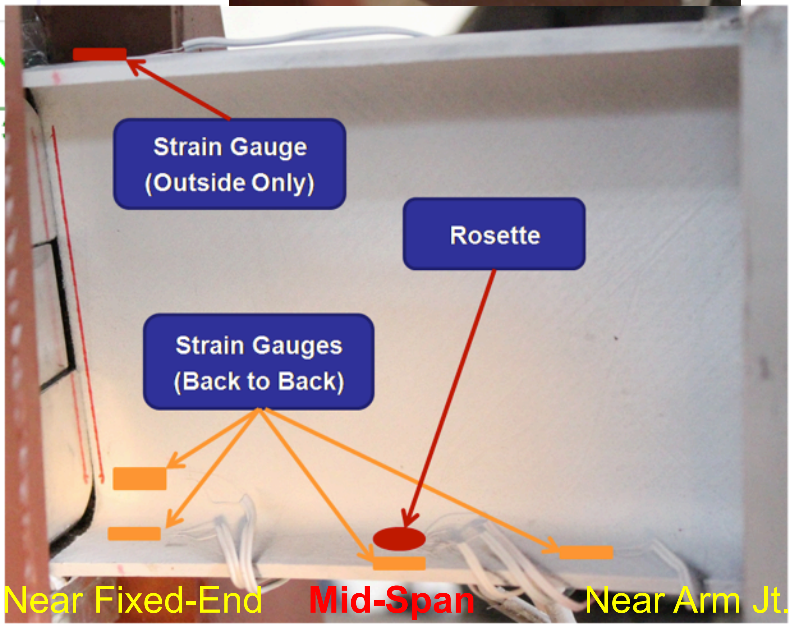


Bending- Torsion Test, A4

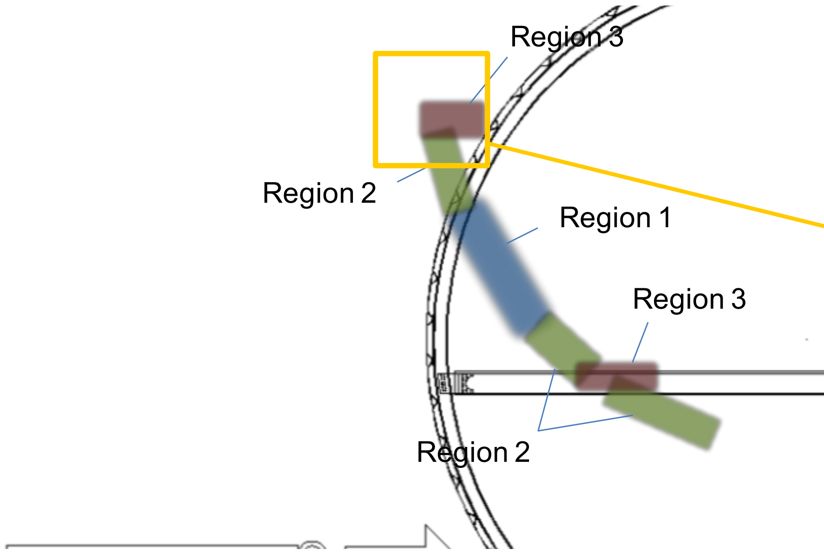




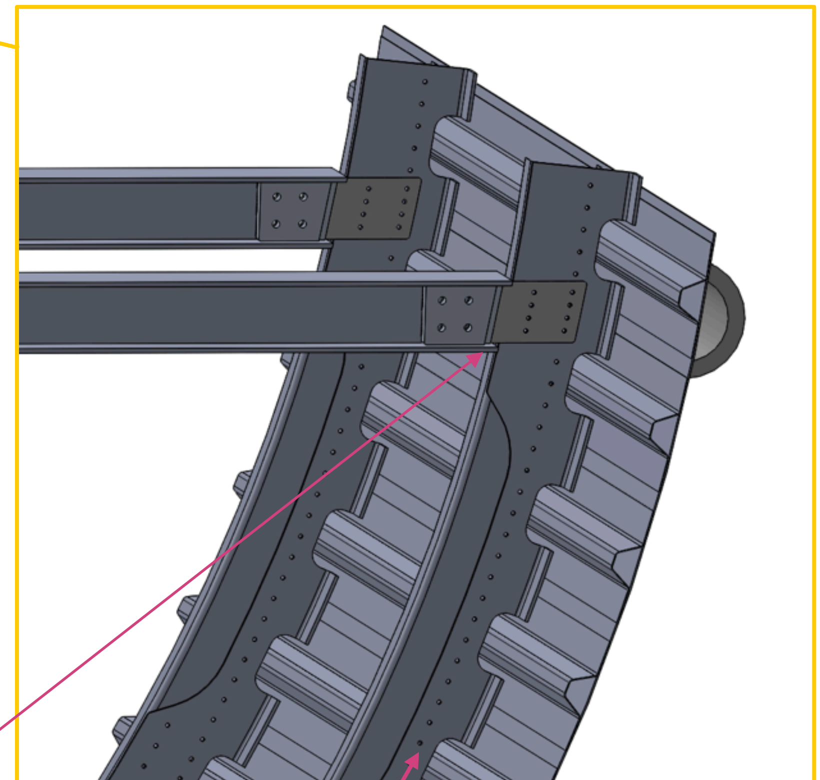
Modeling in Progress



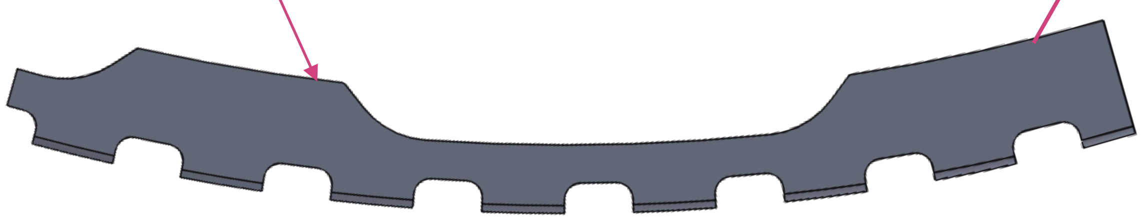
New Focus: Frame-to-Floor Structure Interaction



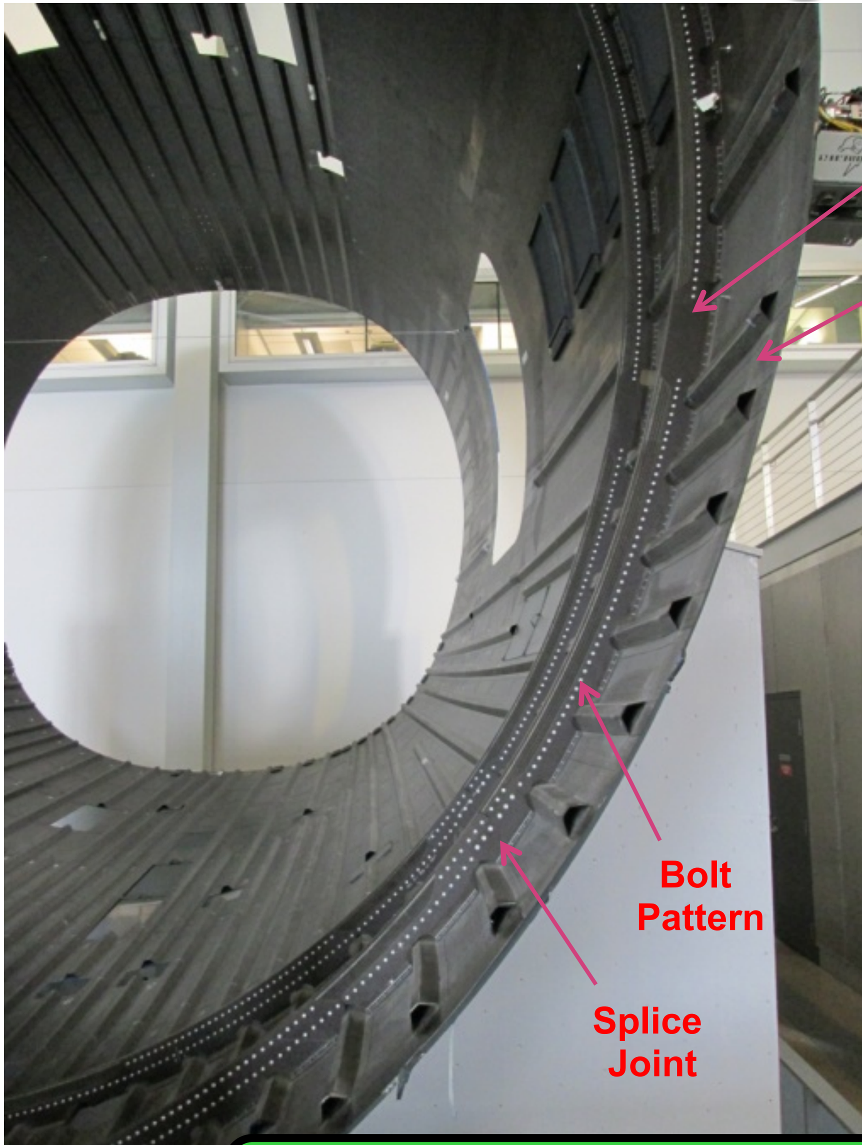
Specimen Design & Build: Impact at Regions 2 and 3



- GSE impact location relative to floor joint affects failure modes
  - **Region 1**: bending dominated
  - **Region 2**: more stiff – high beam shear
  - **Region 3**: most stiff – frame & joint crush
- must accurately represent frame-to-floor joint interaction
  - compliance of frame-to-floor connection
  - continuous shear ties



Benchmark Existing Configurations

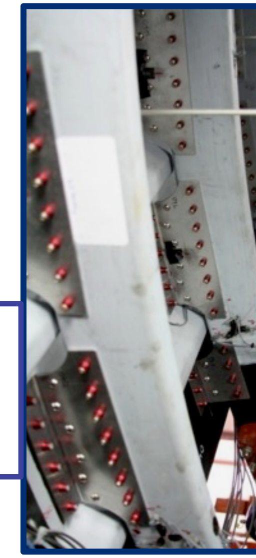


Considerations:

Continuous Shear Ties

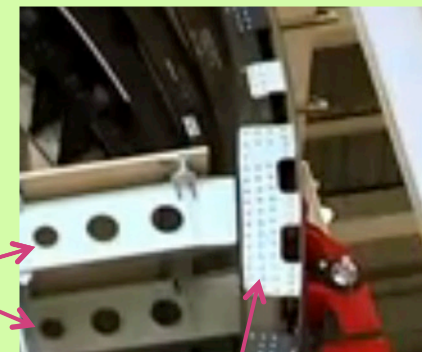
Stringer Spacing

Previous Specimen:
- discrete shear ties
- no floor beams



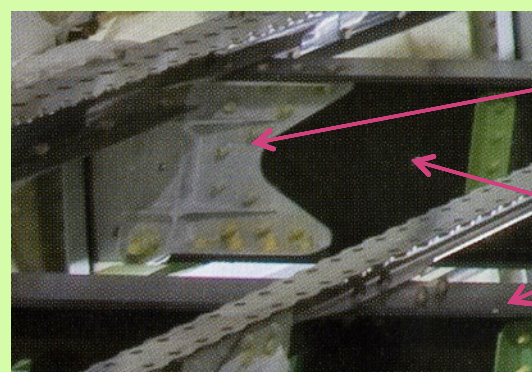
Frame-to-Floor Joint

Floor Beams



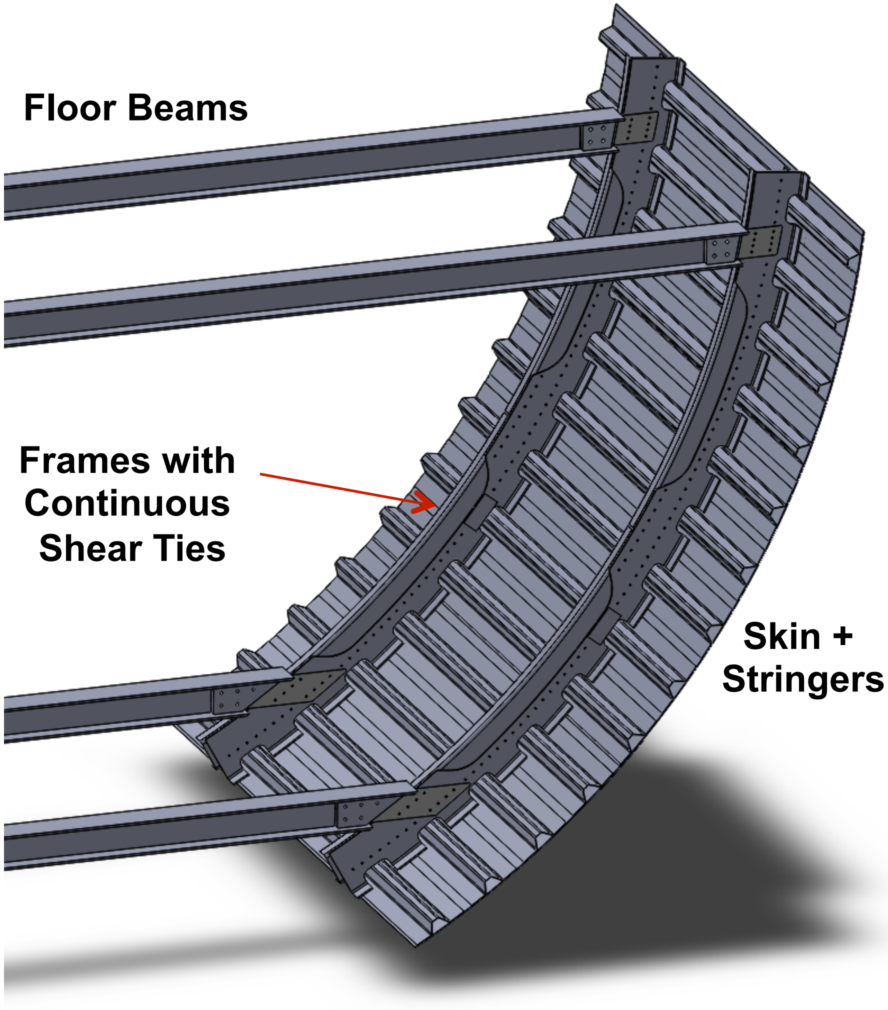
Bracket to Frames/Shear Tie

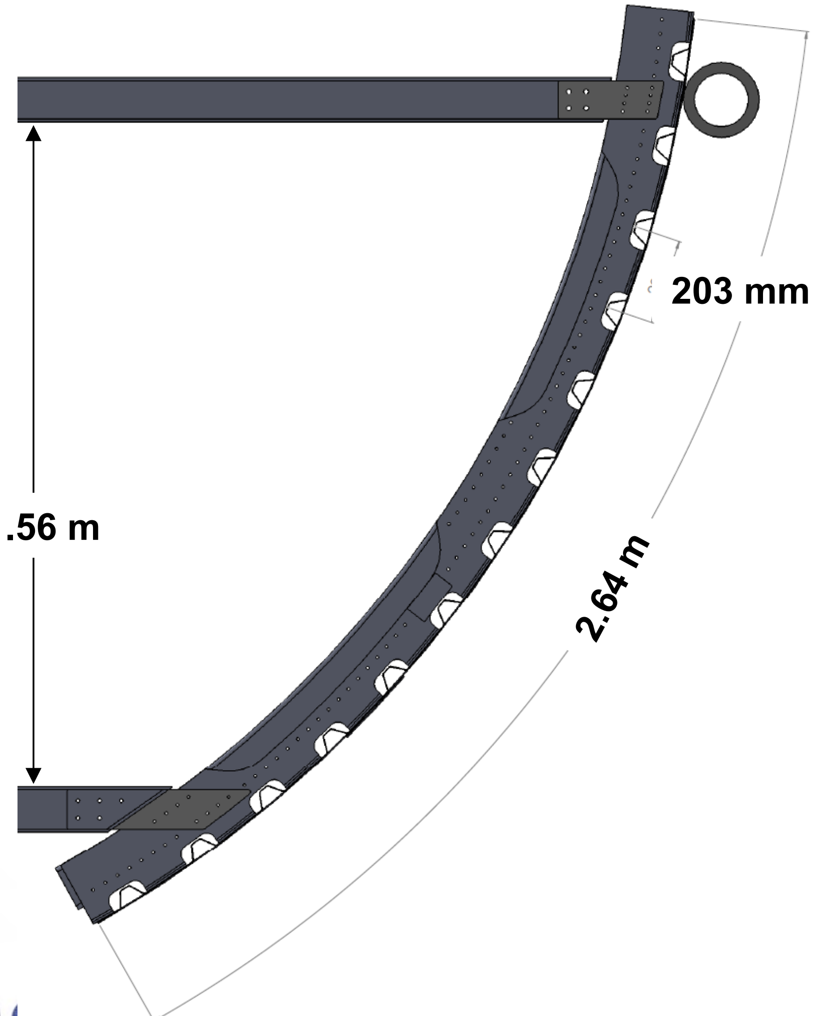
Floor Beams



Incorporate Features Into New Specimen Design

New Specimen:
Quarter Barrel With Floor Beams





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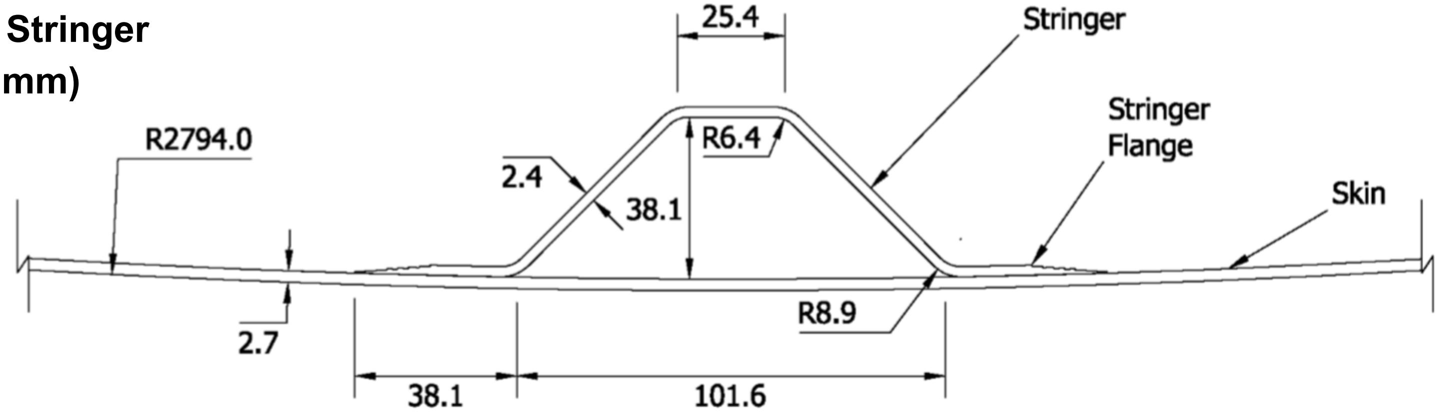
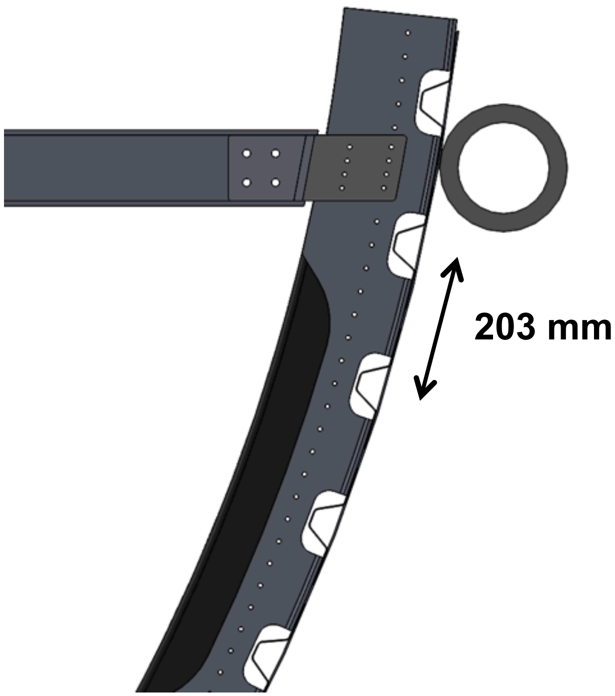
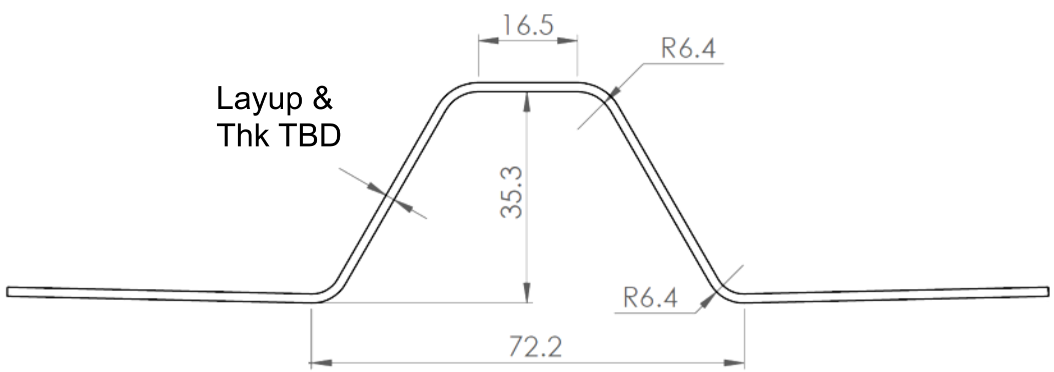
New Specimen Stringer Geometry

Previous Specimen Stringer Dimensions (Units: mm)
Spacing 305 mm

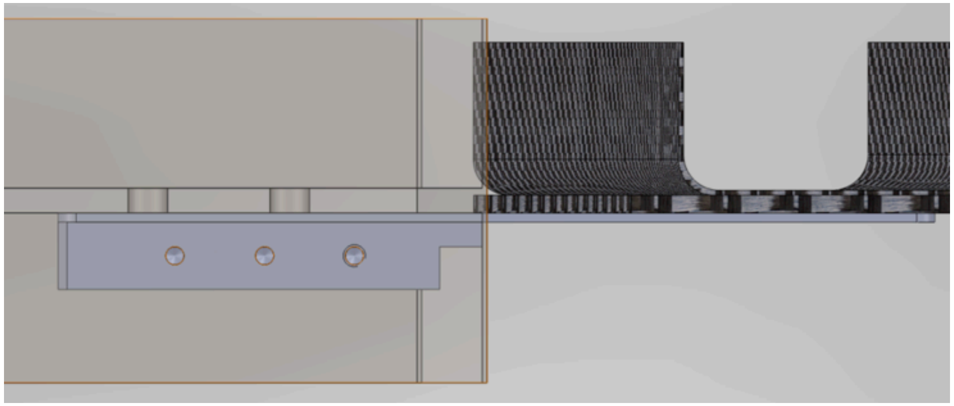




New Specimen Stringer Dimensions (Units: mm)

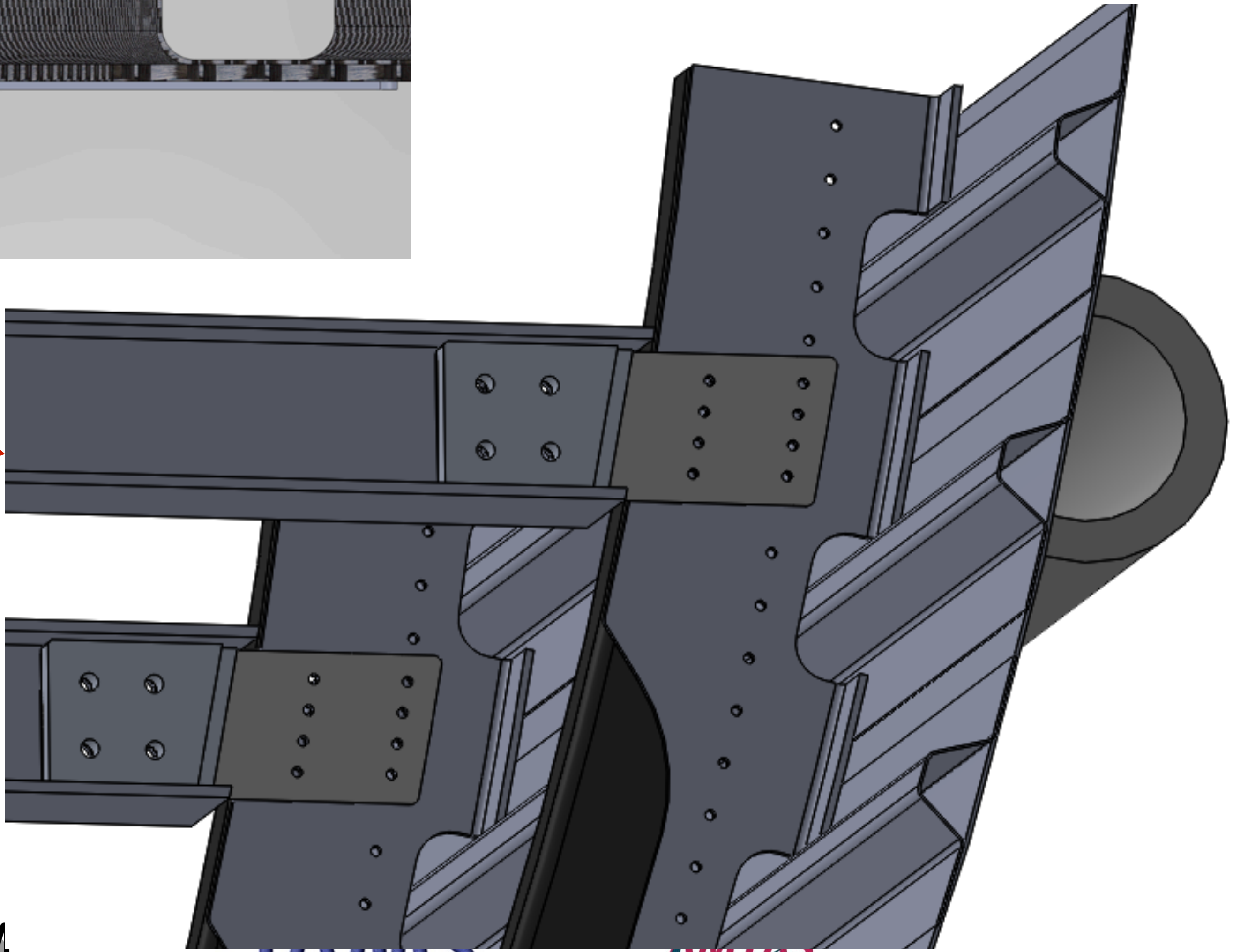


Floor Joint Connection



- Simplified model geometry aims to provide correct stiffness

Aluminum I-Beam Standard Section



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Outline

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

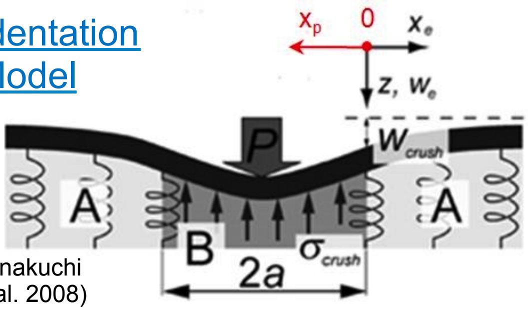
Sandwich Impact Activity Overview

- Investigate internal damage morphology of Nomex© honeycomb panels subject to blunt impacts & transverse loading:
  - Out-of-plane flatwise compression tests
  - Metal tip pendulum impact tests at 2-4 m/s
    - rounded metal tips vs flat impactor face
    - support conditions
    - facesheet thickness effect on core crush and dent
- Model complex mechanical behavior of Nomex© representative volume elements using *exact* honeycomb cell geometry

Previous Work Summary

- Local indentation model for sandwich beams

Identation Model



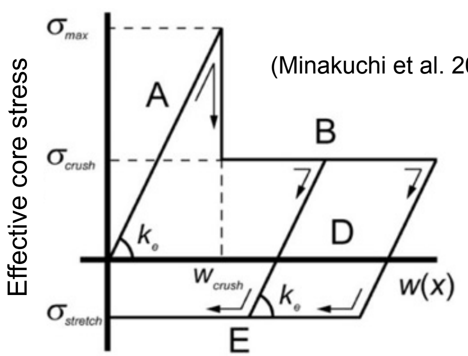
(Minakuchi et al. 2008)

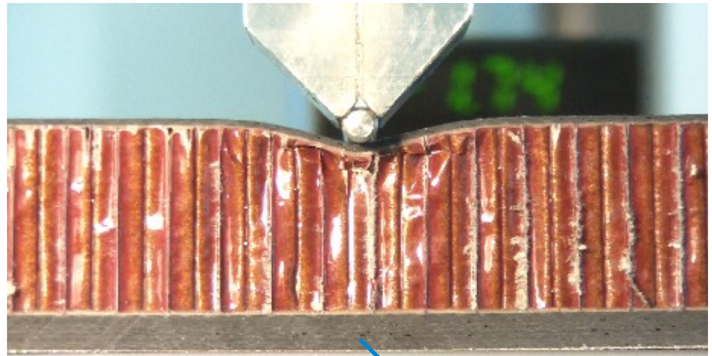
Elasto-Plastic Foundation

Indentation Model Assumptions

- Skin remains undamaged
- No shear interaction between cells
- Out-of-plane core response idealized as elasto-perfectly plastic spring:

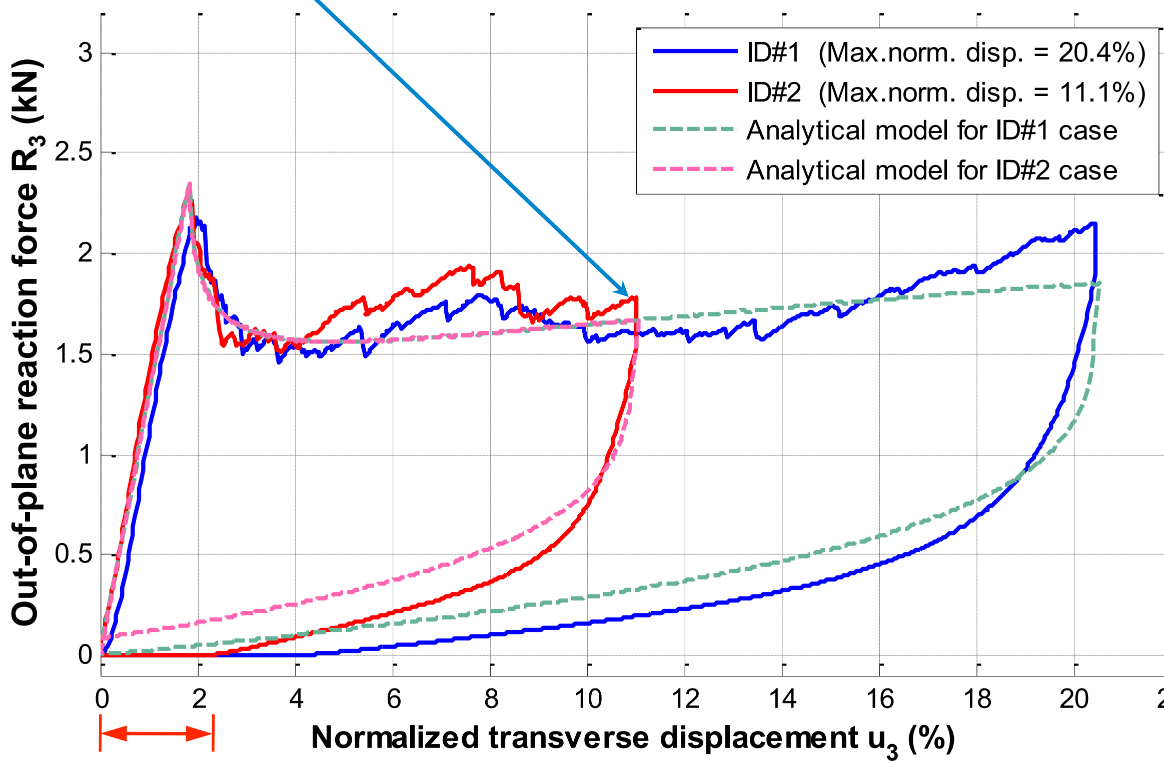
(Minakuchi et al. 2008)





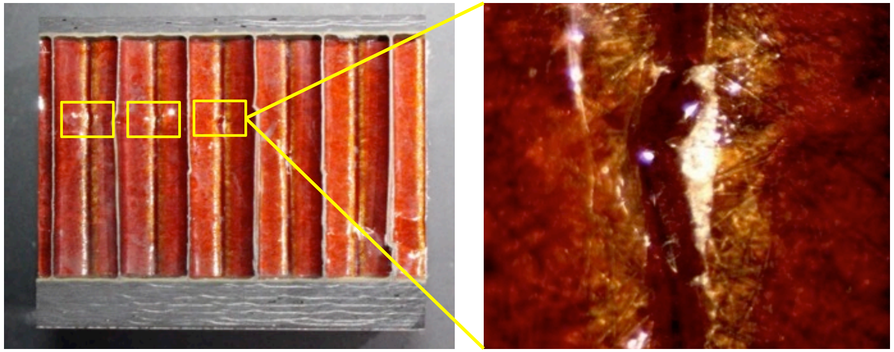
Model Correlation

- Crushing/ indentation accurately predicted
- Residual dent not predicted
  - simplistic unloading in core constitutive idealization

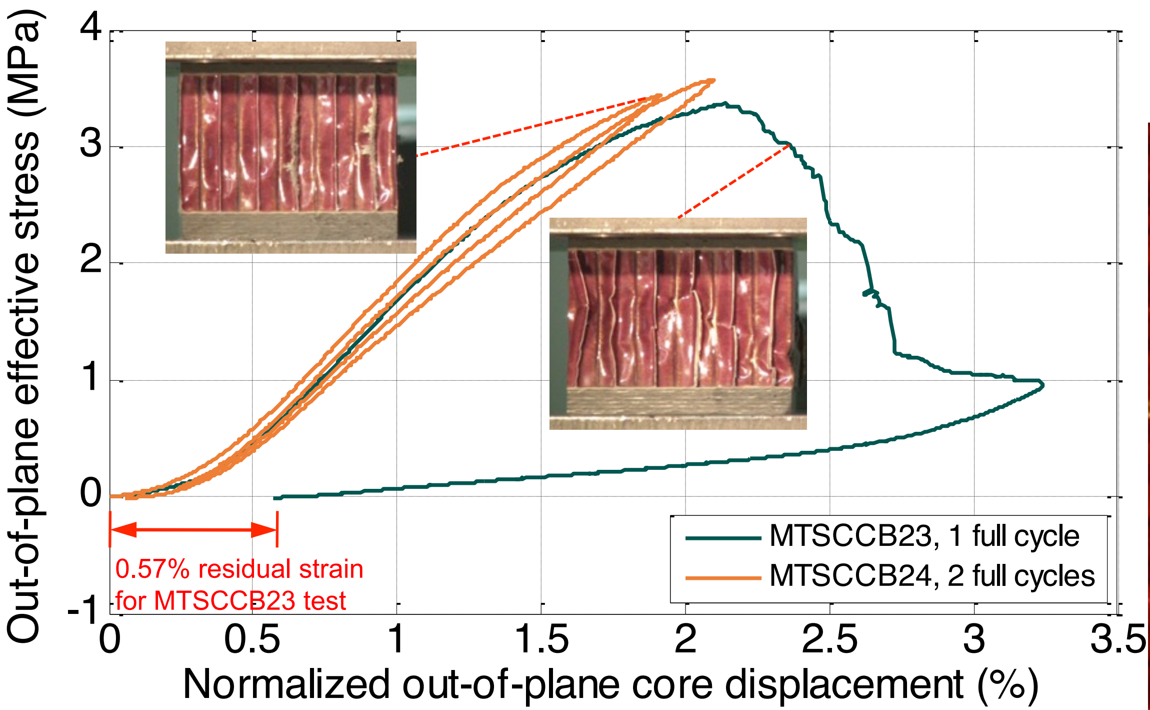


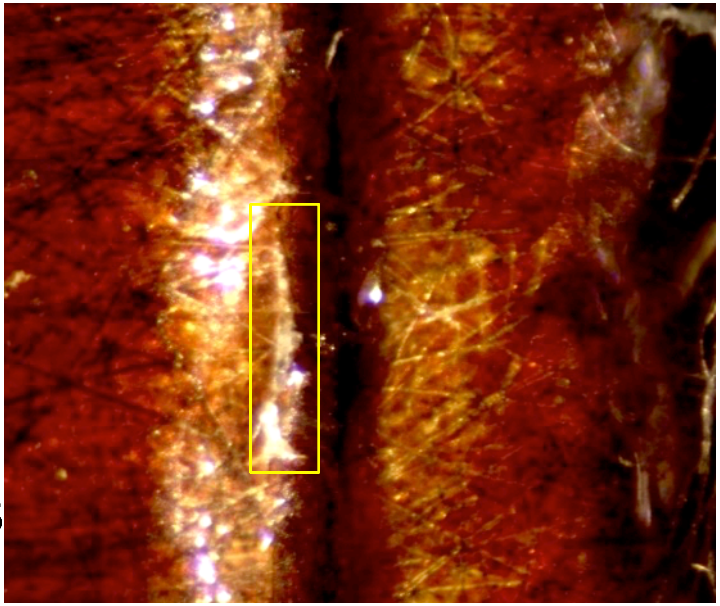
Flatwise Quasi-Static Core Crushing Tests

- Uniform flatwise compression tests on 35 x 35 mm core coupons with 0.5 mm/min applied displacement rate



MTSCCB23: Crushing damage state in W-direction after test (resin fillet fracture)

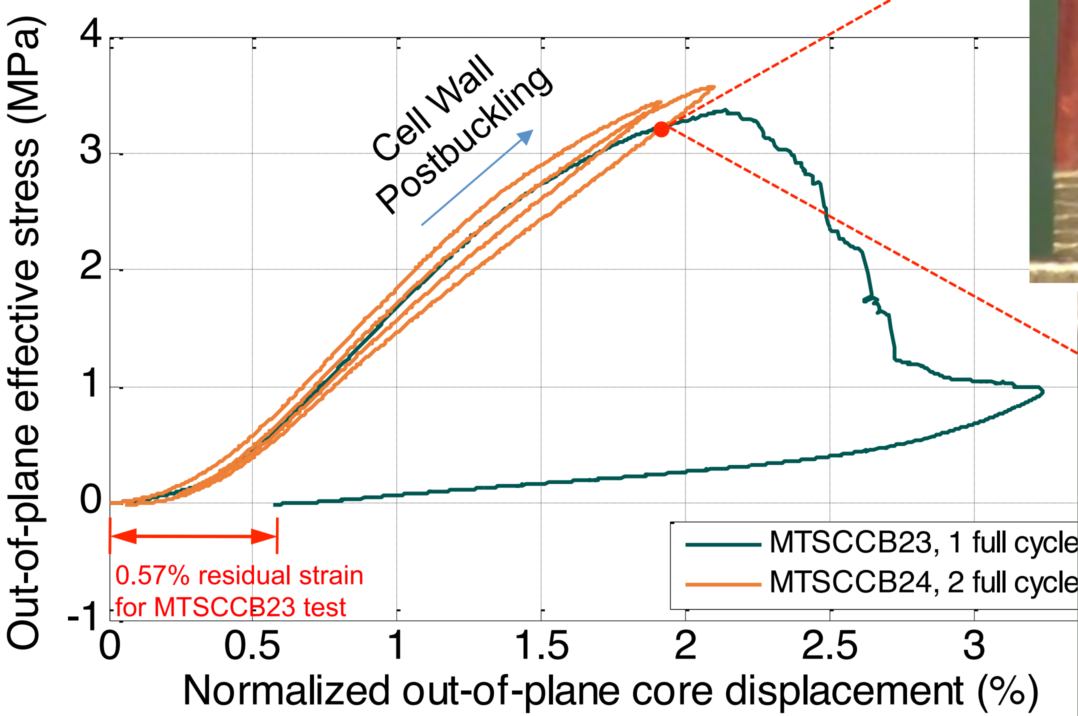




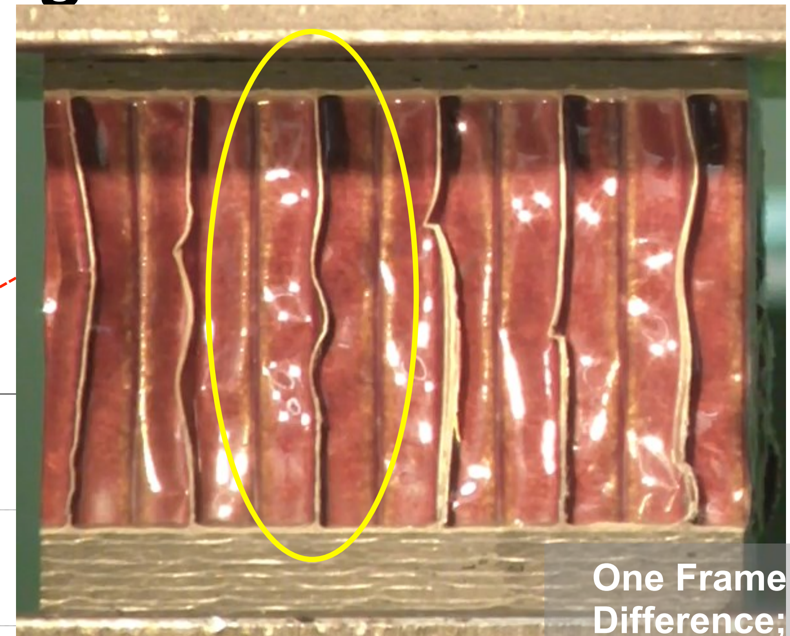
MTSCCB24: Onset of resin fracture; no residual strain

Wall Buckling & Core Snapping

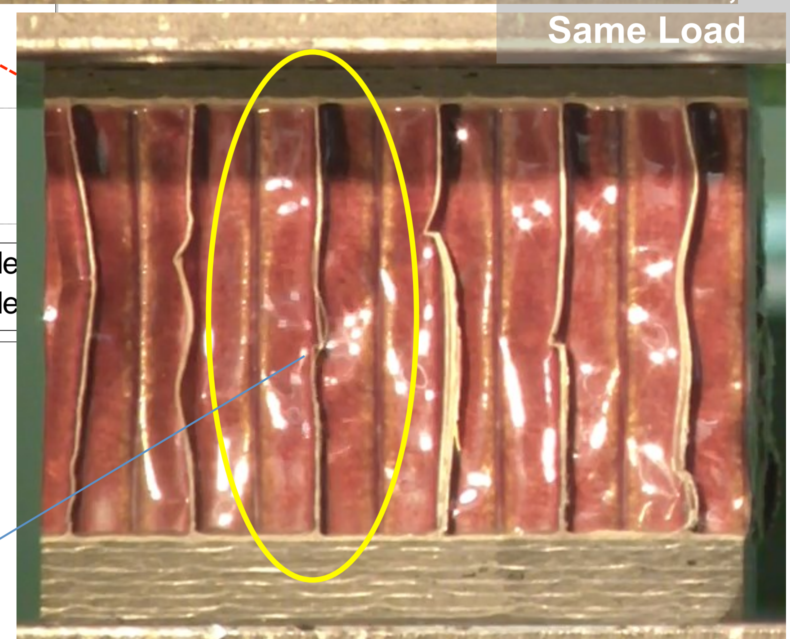
- Significant postbuckling of core walls prior to peak load; short wavelength low stiffness loss
- Approaching peak: resin fracture from kink → local wall separation causes mode change with audible snap; long wavelength with more stiffness loss



Video: Test MTSCCB23



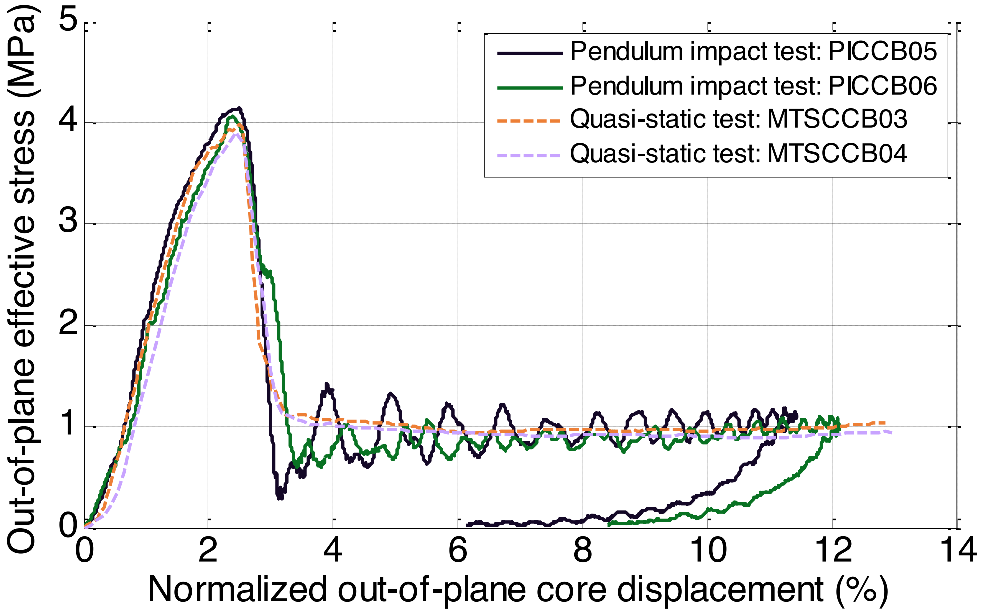
One Frame Difference; Same Load



Local Resin Fracture & Wall Separation

Low Velocity Impact Core Crushing Tests

- Strain rate effects: quasi-static vs. low-velocity flatwise impact tests

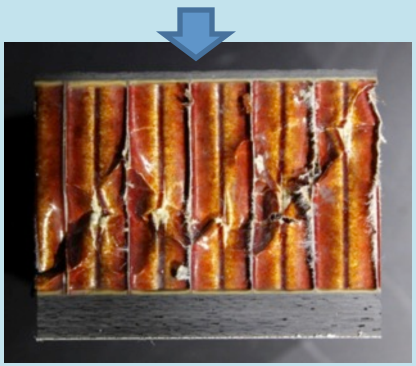


Test ID	Applied displacement rate	Peak stress (MPa)
PICCB05	Initial velocity 1.86 m/s	4.14
PICCB06	Initial velocity 1.85 m/s	4.07
MTSCCB03	Constant rate 5 mm/min	3.99
MTSCCB04	Constant rate 10 mm/min	3.90

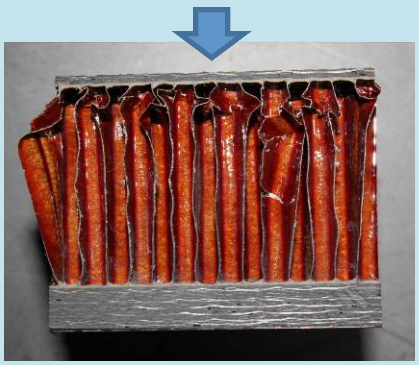
Not strongly rate dependent

- **Peak stress ~5% higher for pendulum tests**
- **Same level constant crush stress**

- Effect of impactor radius: flat tip vs. 152.4 mm radius tip



Flatwise impact compression test (PICCB06)



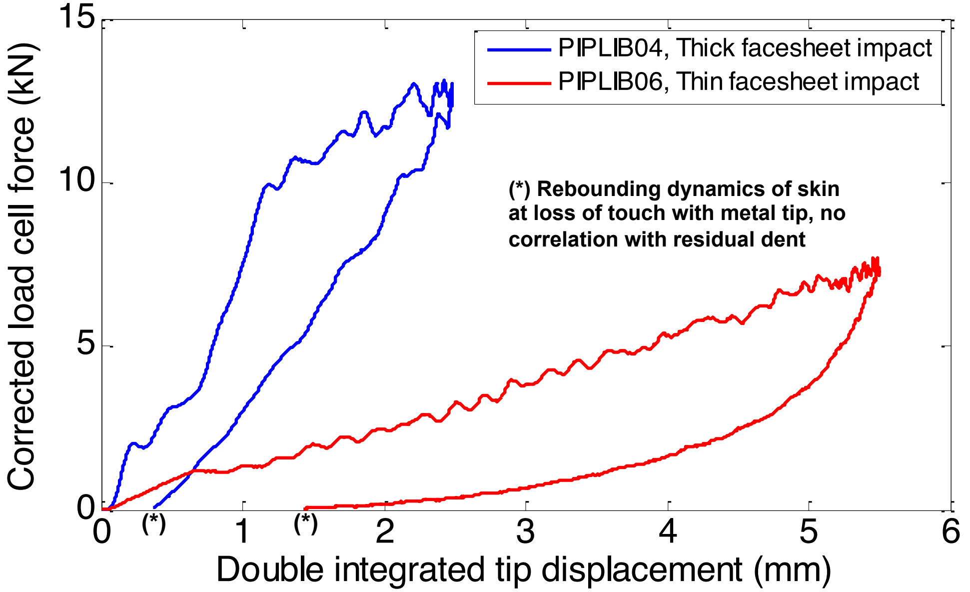
152.4 mm radius tip impact compression test (PICCB14)

PICCB14 test: Highspeed camera video (15,000 fps)

Radius-tip impact induces core crush at near-impact facesheet.

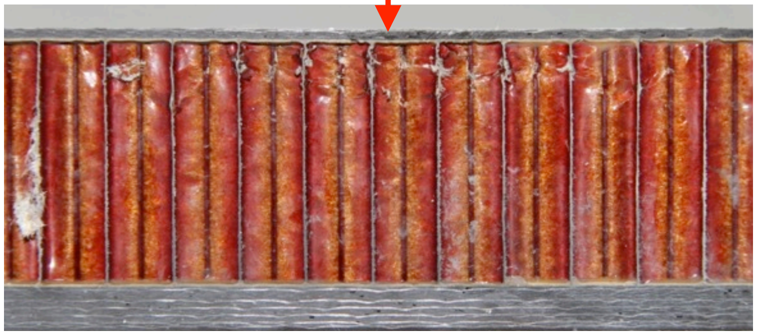
Effect of Facesheet Thickness:
Impact on Full Back-Supported Panels (145 x 95 mm)

- R50.8 mm metal tip impact
- Input energy = 20 J
- Skin thickness:
  - Thick side nominal thickness = 4.85 mm
  - Thin side nominal thickness = 1.68 mm
- Flip specimen to investigate effects of skin stiffness on core damage
- Depth indicator used to measure actual dents along panel surface



Impact sites

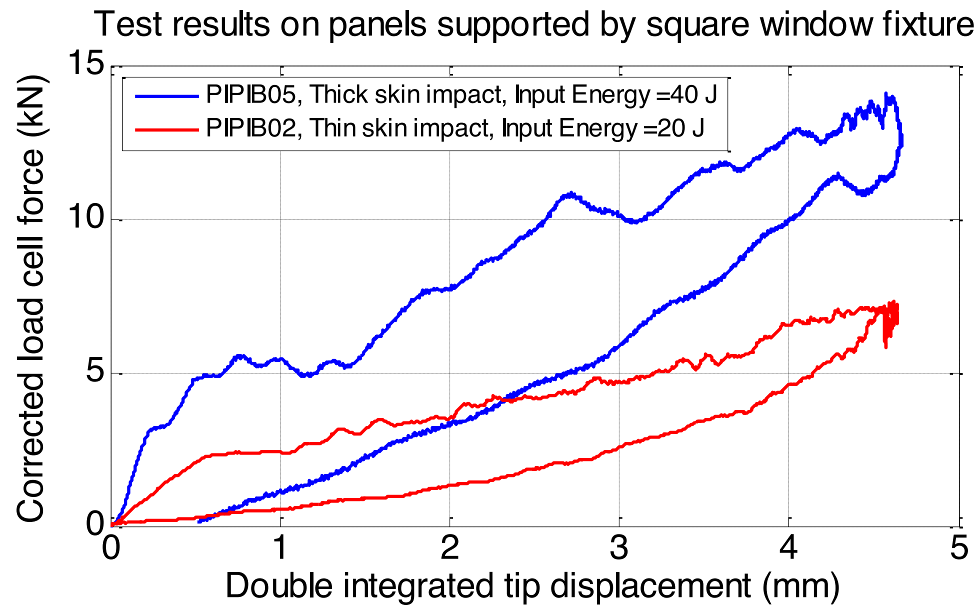
Local indentation impact on thick site impact -> no residual dent



Local indentation impact on thin site impact -> peak residual dent 0.4 mm

Impact Tests on Picture Frame Supported Panels
(195 x 195 mm, 165 mm Square Opening)

- R50.8 mm metal tip impact
- Input energy range: 14 – 40 J
- 40 J impact on thick side facesheet produced slight core fracture – more stiff facesheet → more restoring force
- All thin skin impacted specimens experienced core damage
- Thin skin specimens revealed cell wall snapping, while thick skin tests also exhibit more core wall fracture

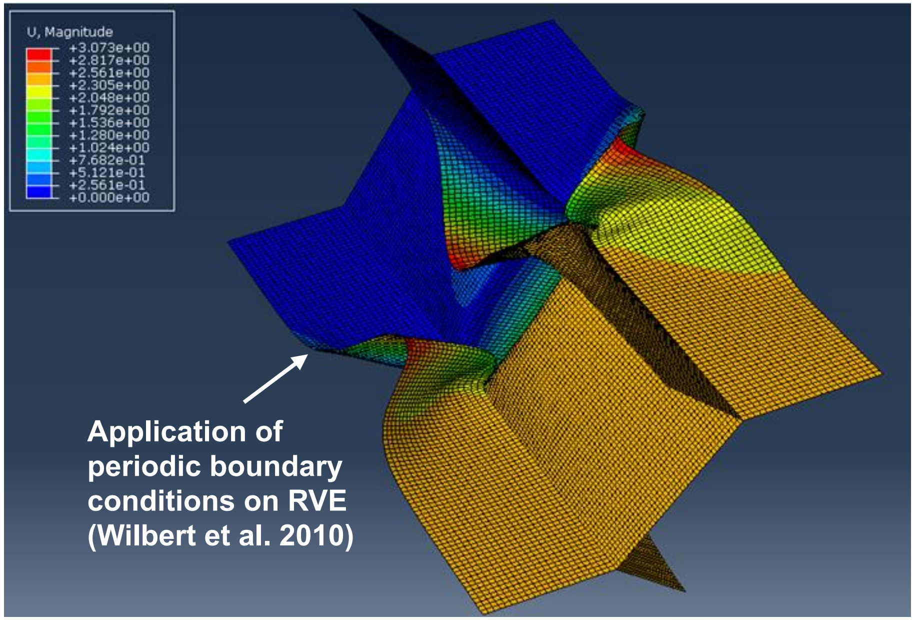


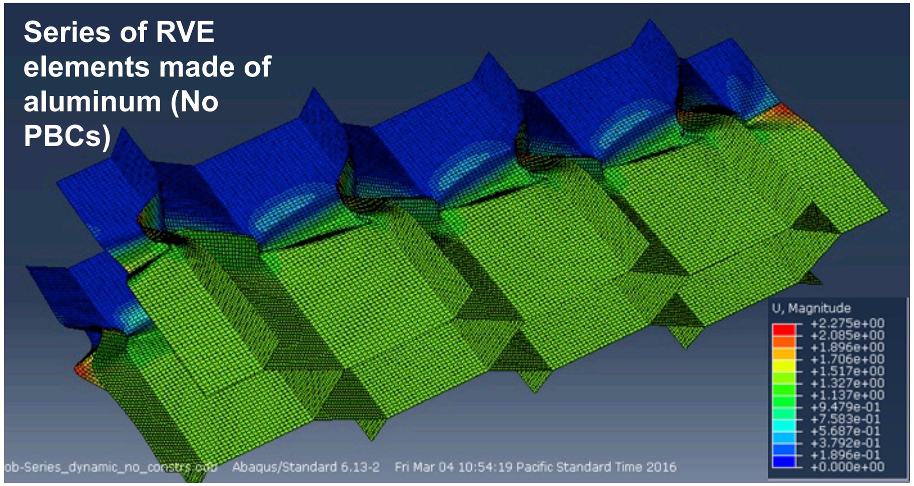
Pendulum impact on thick impact site with 40 J input energy

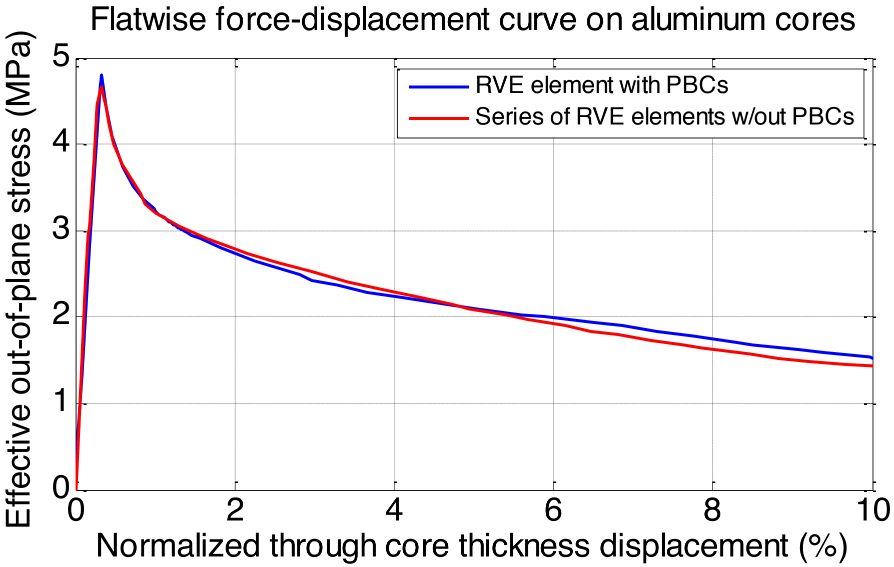
Pendulum impact on thin impact site with 20 J input energy; peak residual dent 0.33 mm

Current Modeling Activity: Core Failure

- Simulate flatwise compression tests
- Exact representation of cell geometry with and without periodic boundary conditions (PBC)
- Elasto-plastic aluminum material; will change to Nomex©







Outline

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

Summary/Conclusions

Ground Service Equipment (GSE) High Energy Blunt Impact

- Element-level C-frame bending and bending-torsion tests completed
  - excited relevant failure modes observed in past large panel blunt impact test
- FE models capture key response of element-level tests: flange post buckling, initial matrix tension failure, matrix compression and fiber compression failure of bottom flange (model development still in progress)
- Quarter barrel specimen design – includes floor joints to gain more accurate frame torsion response and allow investigation of impact near floor location

Blunt Impact Damage to Sandwich Panels

- Flatwise core compression quasi-static tests reveal that onset of Nomex© core damage is attributed to local fracture of phenolic resin rich zones, followed by cell wall snapping (local wall separation + mode change) and successive wall folding
- Radius-tip impacts result in core crushing close to impact-side facesheet
  - by contrast, flatwise compression (static & dynamic) shows crush/kinking initiating anywhere through core depth
- Impacts of stiff facesheet produce less visible damage (low/no dent)
  - cell walls tend to fracture in tension due to higher spring-back forces
- Accurate Nomex © core simulation requires very fine RVE computational model with fracture capabilities and consideration of geometric irregularities

Benefits to Aviation

Ground Service Equipment (GSE) High Energy Blunt Impact

- Understanding of prospective damage resulting from GSE impact events
  - awareness of phenomena and possible internal failure modes
  - provides information on mode and extent of seeded damage, particularly non-visible impact damage (NVID) from blunt impact threats
  - how design parameters (layup, thickness, etc) affect damage formation and propagation; influence of stiff regions (floor area)
- Accurate FEA modeling capability of blunt impact
  - predict damage modes, size, and locations
  - external visibility – residual dent level, surface cracking

Blunt Impact Damage to Sandwich Panels

- Insight into properly seeding damage for damage tolerance assessment
  - Knowledge of internal core damage state as a function of skin bending stiffness
  - Detailed understanding of instability phenomena during core crushing mechanism and fracture during facesheet spring-back
- Modeling capability for predicting core impact-crushing and residual dent depth

Looking Forward

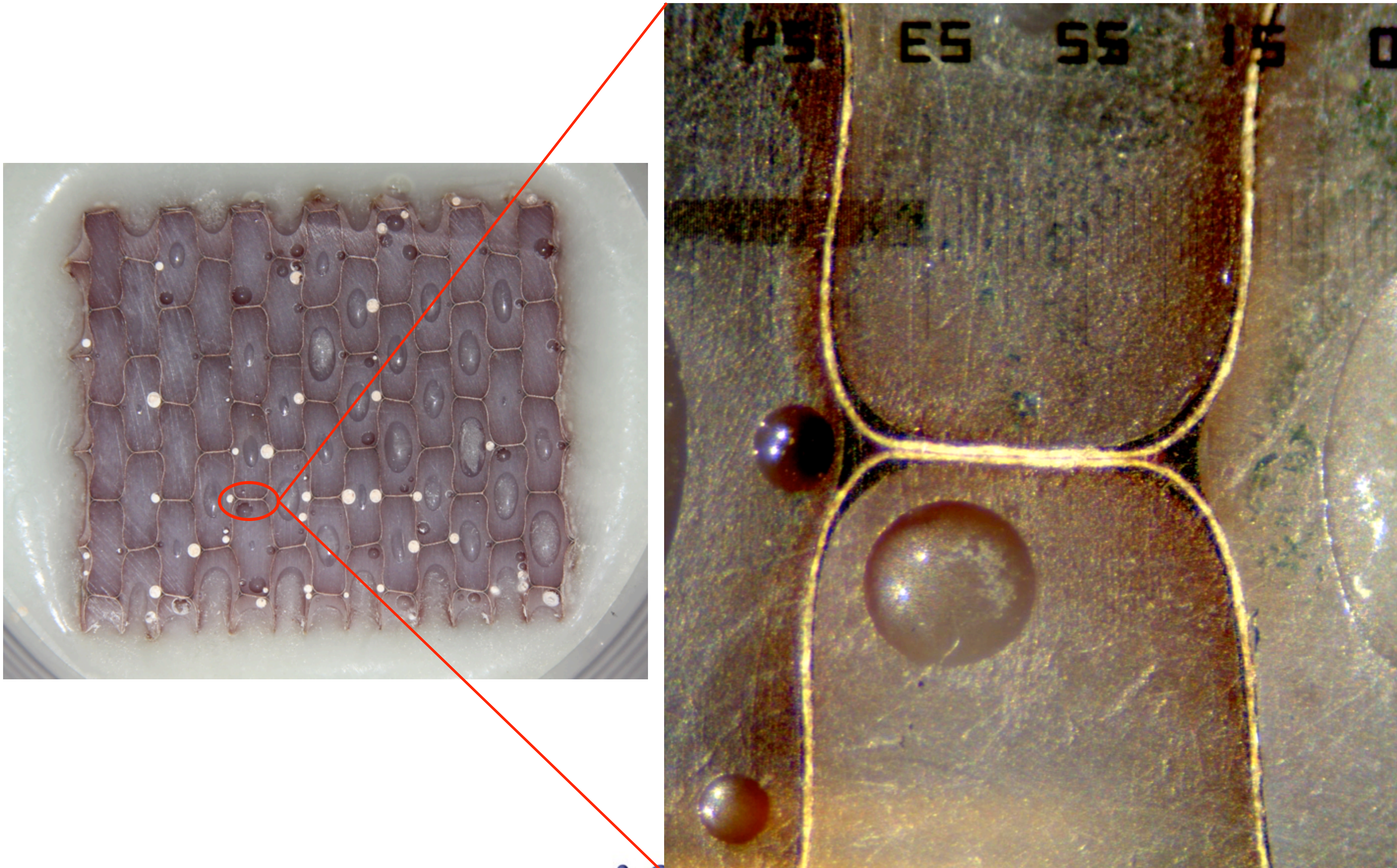
Ground Service Equipment (GSE) High Energy Blunt Impact

- Continued development of high fidelity FEA modeling capability – validated at element level
  - incorporate C-frame failure models into previous specimen simulation
- Quarter-barrel specimen analysis – assess for improvement of specimen design
- Quarter barrel specimen detailed design finalization and manufacturing
- Quarter-barrel or half-barrel fuselage tests; effect of near-floor impacts and glancing impact (underbody)
- Direct C-frame crushing element tests – impacts at floor beam level
- Multiple fasteners modeling within impact progressive failure analysis

Blunt Impact Damage to Sandwich Panels

- Enhance experimental database with more tests & observations – emphasis on relating core damage extent to face sheet stiffness, dent/visibility
- Conduct hail ice impacts and investigate structural performance of panels in high strain rate regime
- Initiate more accurate representation of core geometry using actual honeycomb cell size as well as introduce phenolic resin fillets in the intersection of double and single walls (resin columns)

Core Exact Geometry & Resin Rich Columns



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