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Impact Damage Formation on Composite Aircraft Structures / Non-Destructive Evaluation Methods for Detecting Major Damage in Internal Composite Structural Components

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Impact Damage Formation on Composite Aircraft Structures / Non-Destructive Evaluation Methods for Detecting Major Damage in Internal Composite Structural Components

- **Principal Investigators & Researchers**
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  - Co-PI on NDE Project: Prof. Francesco Lanza di Scalea
  - Graduate Students
    - PhD: Konstantinos Anagnostopoulos, Moonhee Nam, Chaiane Wiggers de Souza, Eric Hyungsuk Kim, Margherita Capriotti
    - MS: none
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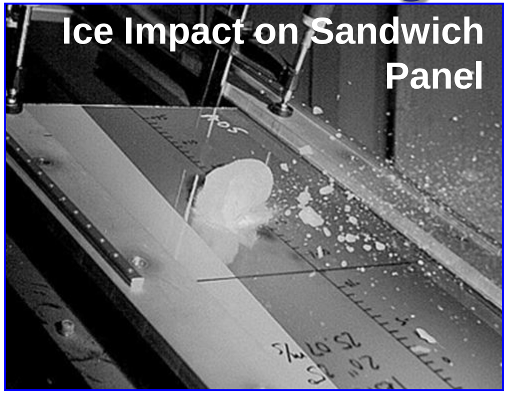
- **FAA Technical Monitors**
  - Lynn Pham, David Westlund
- **Other FAA Personnel Involved**
  - Rusty Jones, Curt Davies, Larry Ilcewicz
- **Industry Participation**
  - Boeing, Bombardier, UAL, Delta, DuPont, JC Halpin

Impact Damage Formation & NDE of Major Internal Damage

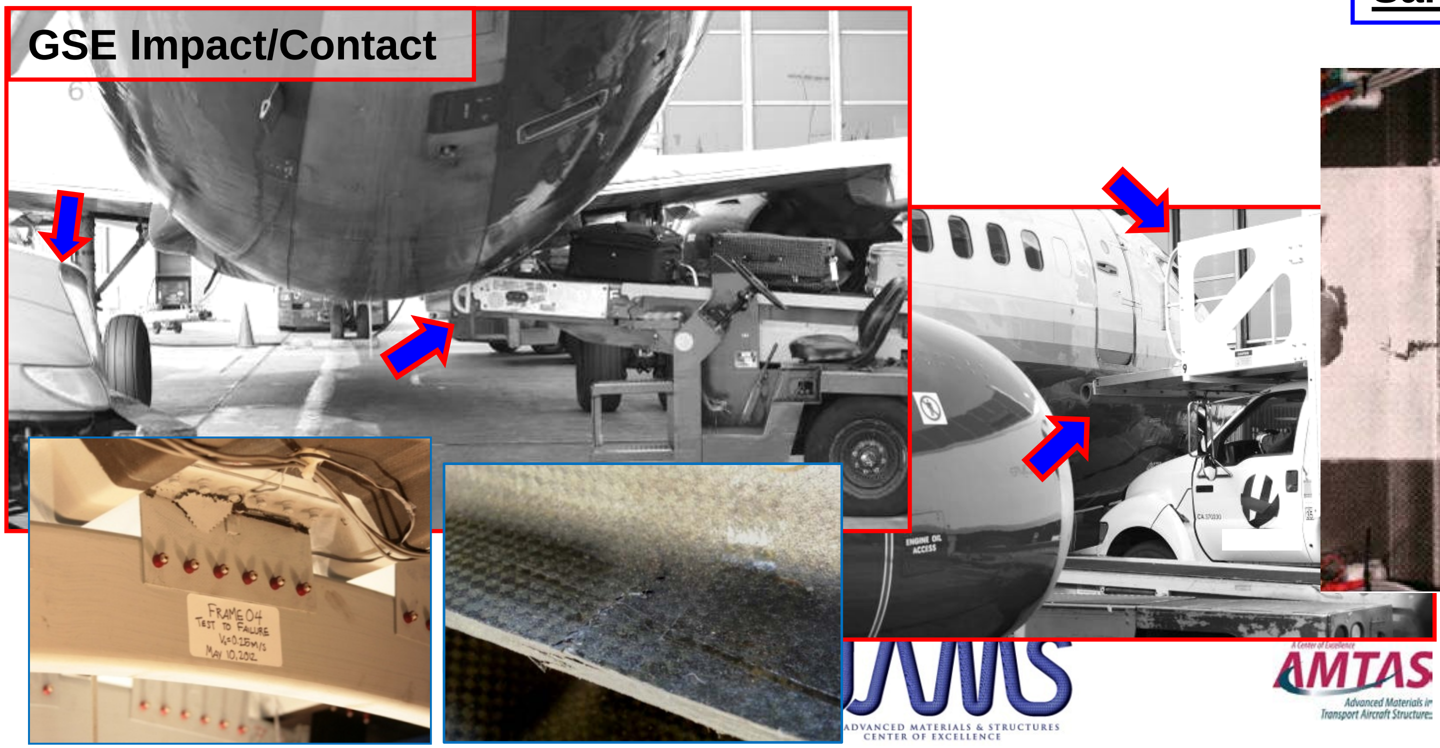
Motivation and Key Issues

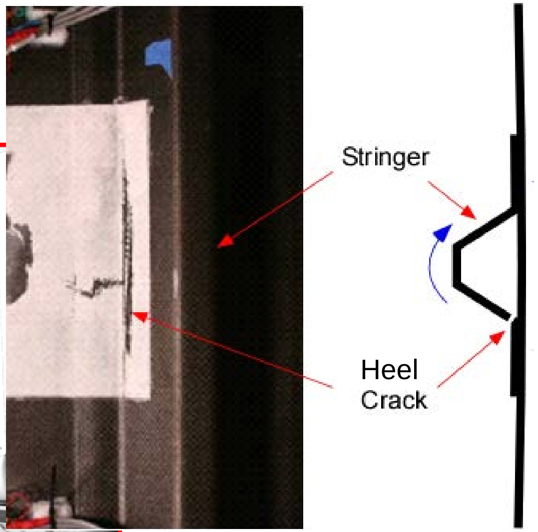
- high energy *blunt* impact damage (**BID**) of main interest
  - involves large contact area, multiple structural elements
    - GSE, FOD, railings/corners, hail ice, bird
  - internal damage can exist with ***little/no exterior visibility***
- damage to internal members not visible by typical one-sided NDE (e.g., UT scan)
  - cracked shear tie, frame, stringer heel crack
  - external-only NDE needed to find such damage



Sandwich Core Crush

GSE Impact/Contact





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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)

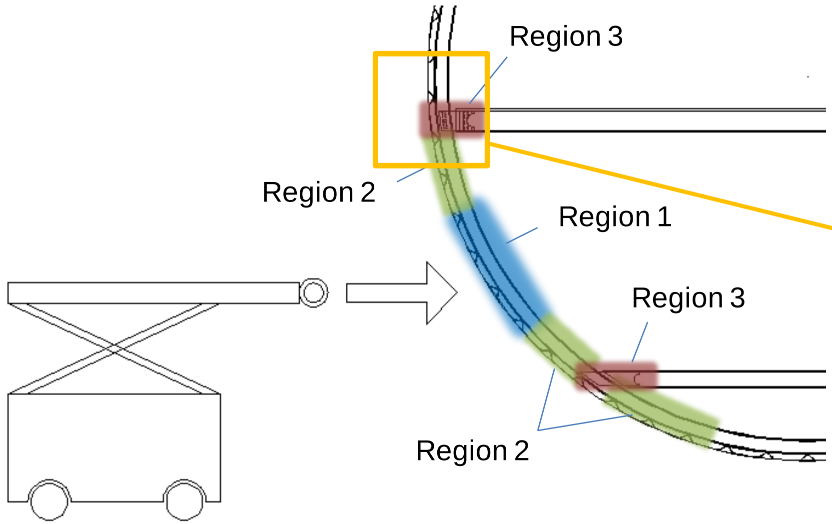
- **Develop analysis and testing methodologies, including:**
  - full structure vs. sub-structure testing for HEWABI investigations
  - accurate modeling capabilities
  - establish damage visibility criteria – surface crack, residual dent

- **Demonstrate detection method for finding major damage to internal structure**
  - detection performed from exterior skin-side only
  - relate NDE measurements with damage location, mode, and severity

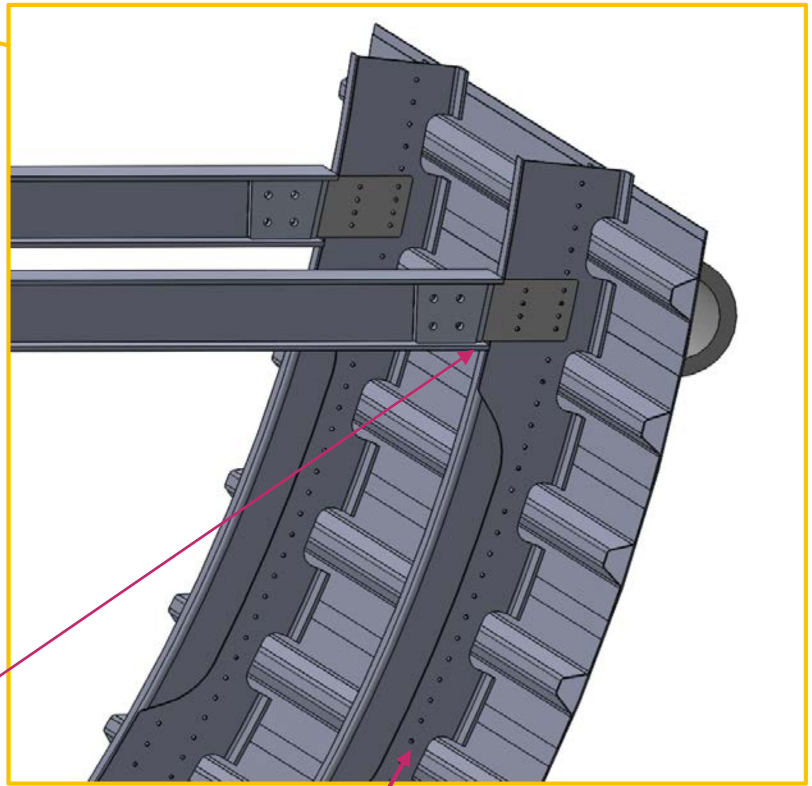
Outline

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

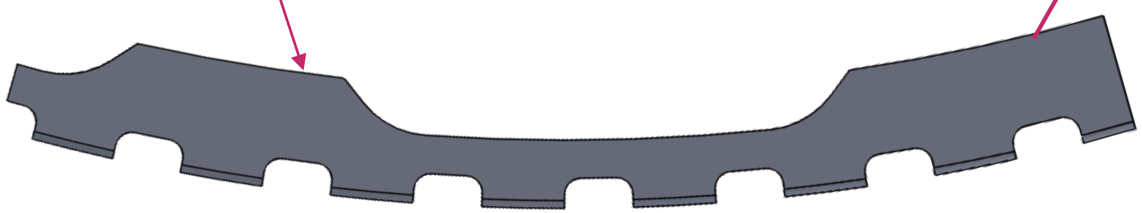
Focus: Frame-to-Floor Structure Joint Interaction



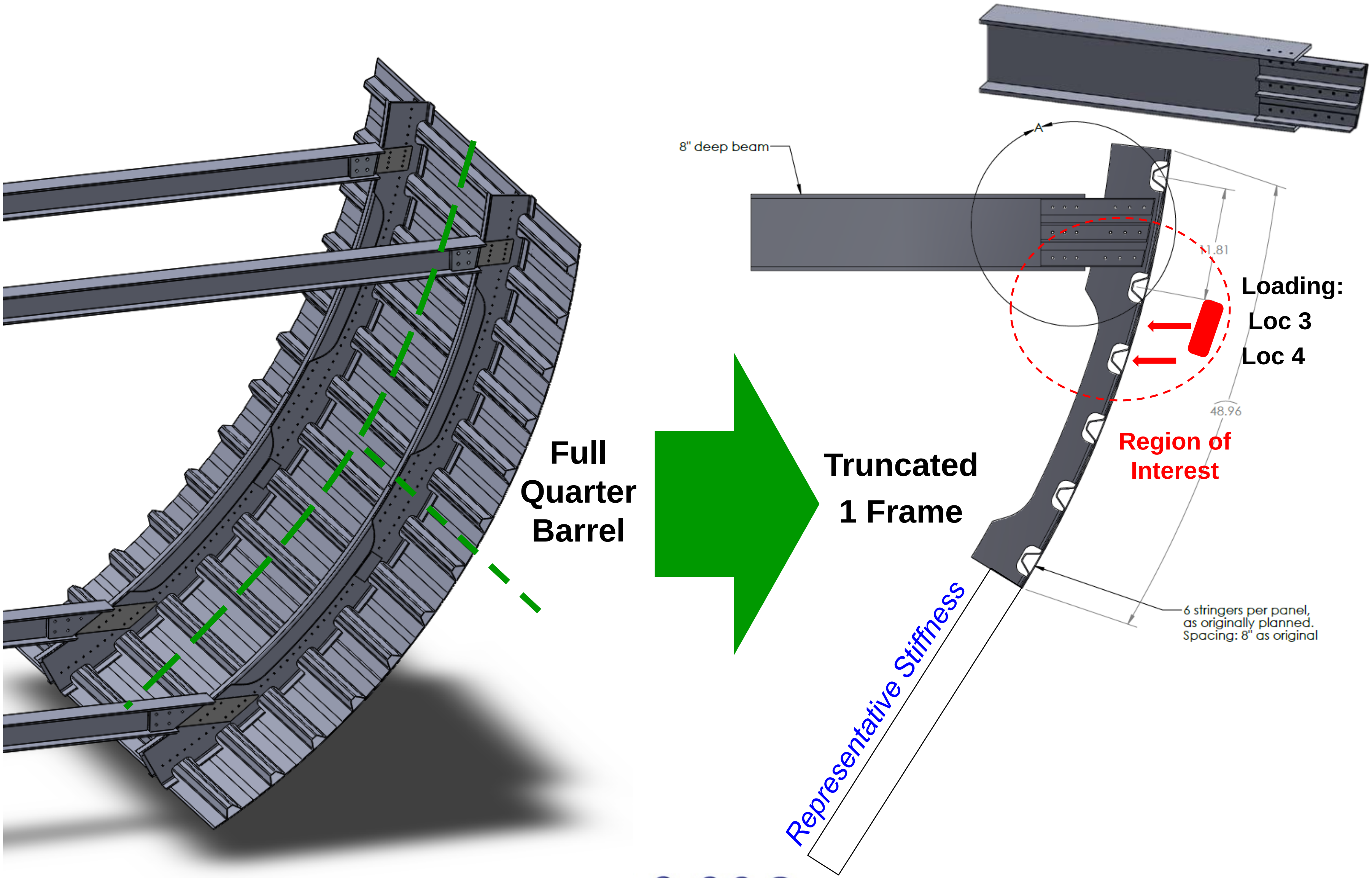
Specimen Design & Build: Impact at Region 2



- 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 represent frame-to-floor joint interaction
  - compliance of frame-to-floor connection
  - continuous shear ties

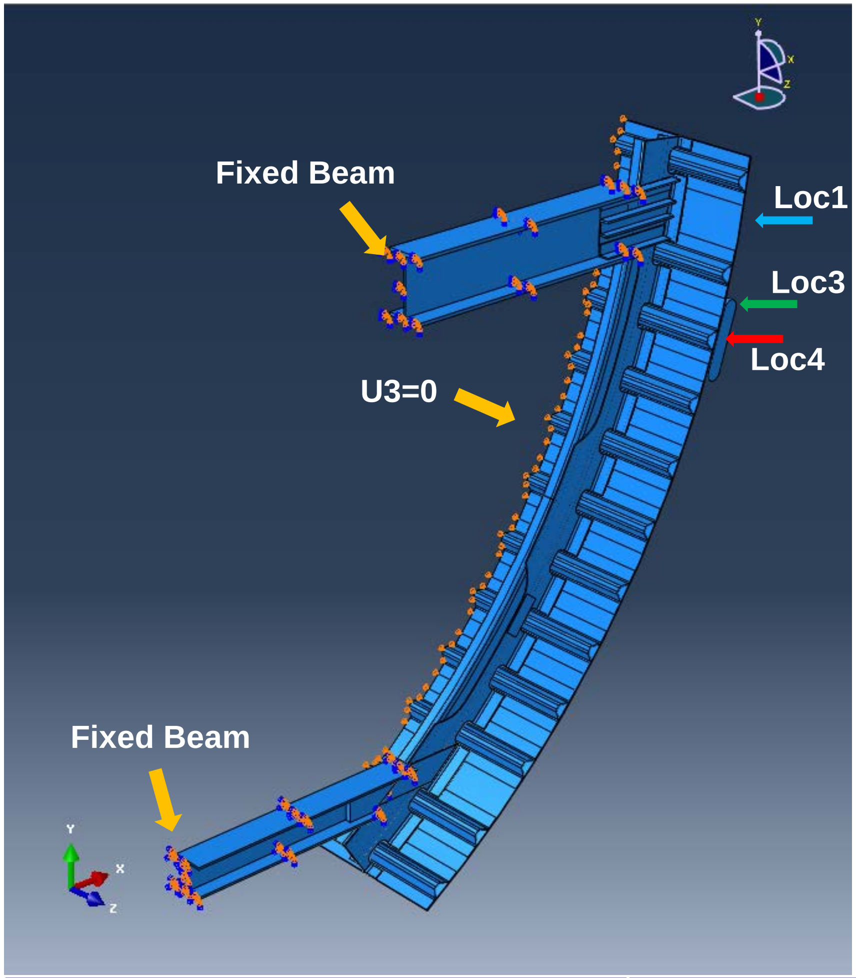


Simplification: Full to Truncated Specimen

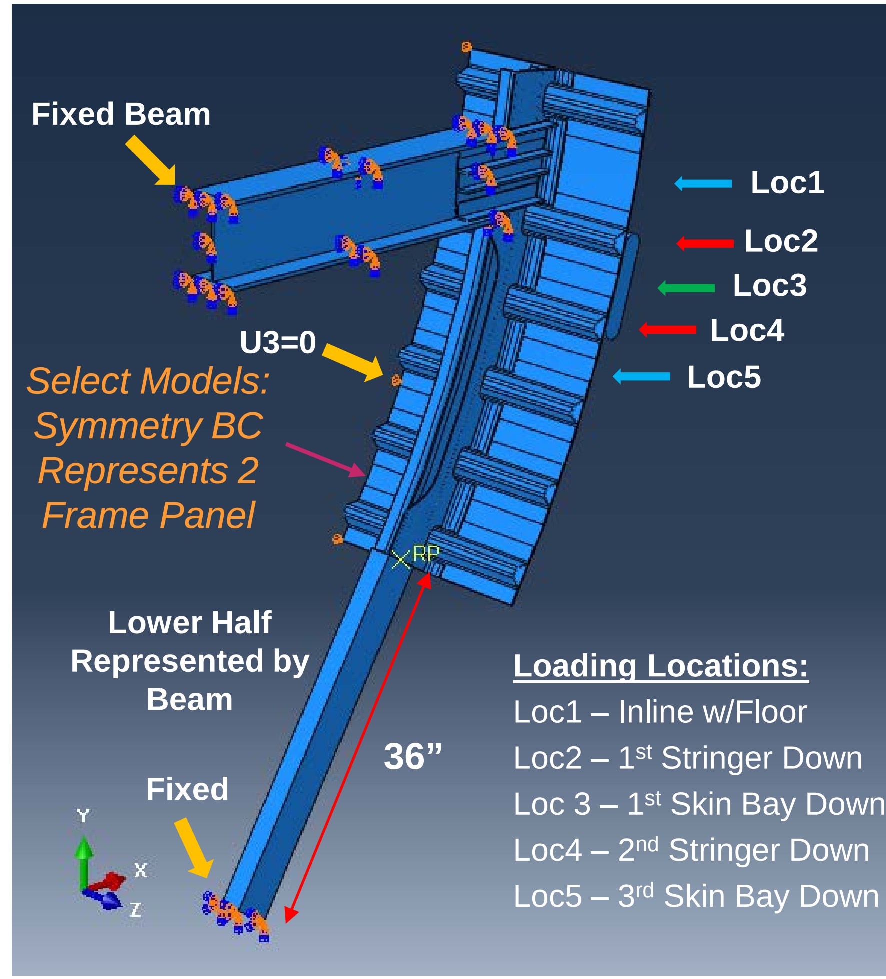


Boundary Conditions – Equivalence?

Full Model

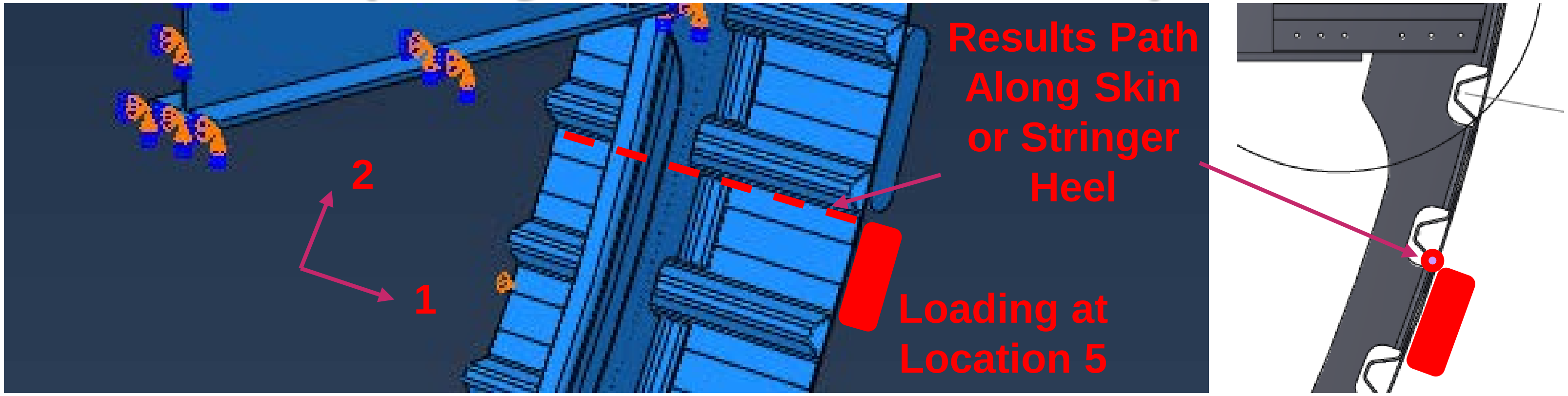


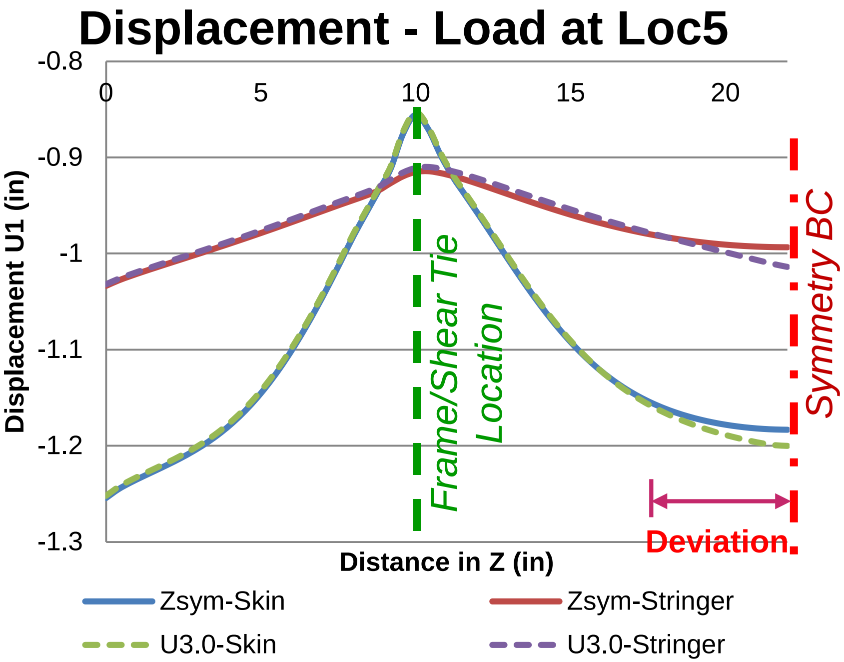
Truncated Model

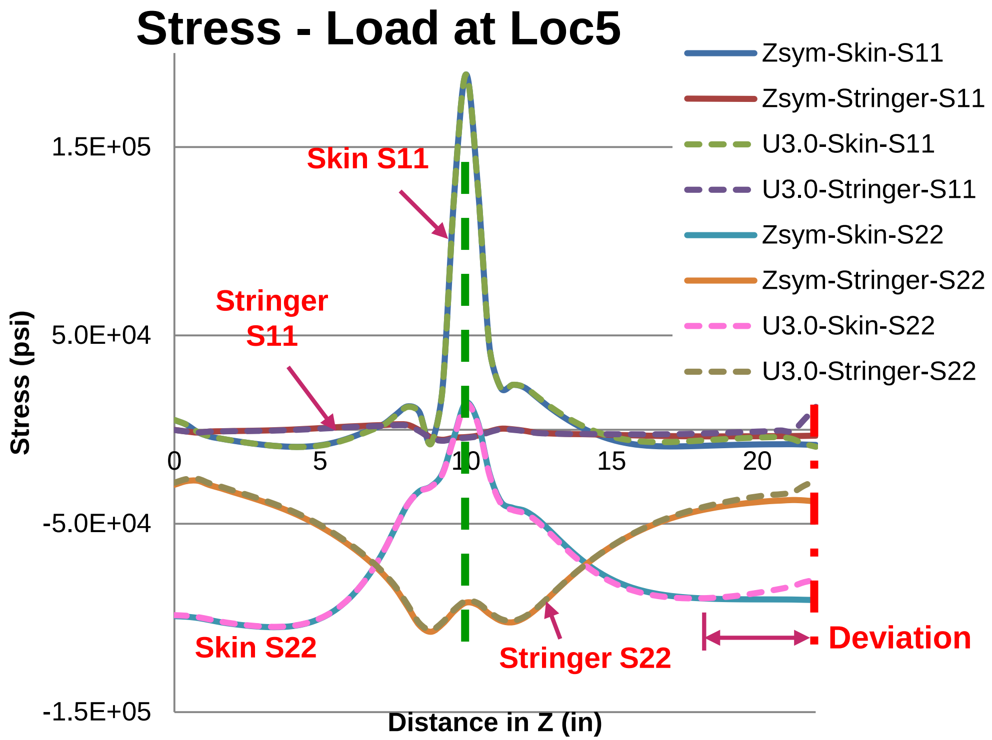


Code	Length	Loc.	BC
Full-Loc.X-RubBump-L15	Full	X= 3, 4	U3=0 on Skin Edge; Fixed Floor Beams
T-Loc.X-LowerBC-Sec3-L36	Truncated	X= 3, 4	U3=0 on Skin Edge; Al Channel BC

2 Frames (Z-Symmetric Model) vs 1 Frame

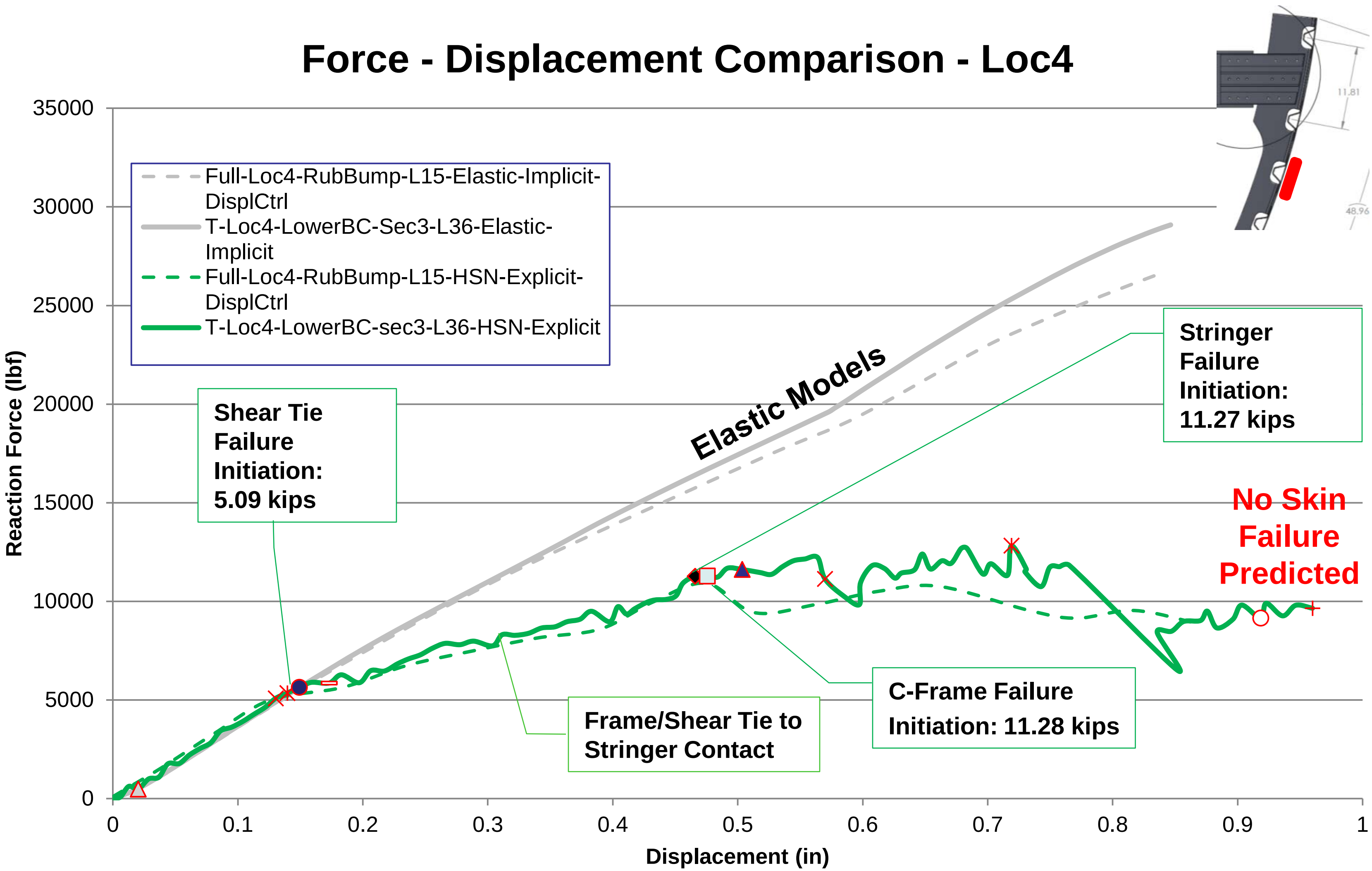






Conclusion: deviation only at edge of panel – can use 1-frame specimen to get same response.

Full vs Truncated Comparison at Location 4



Simulation: T-Loc4-EX.avi

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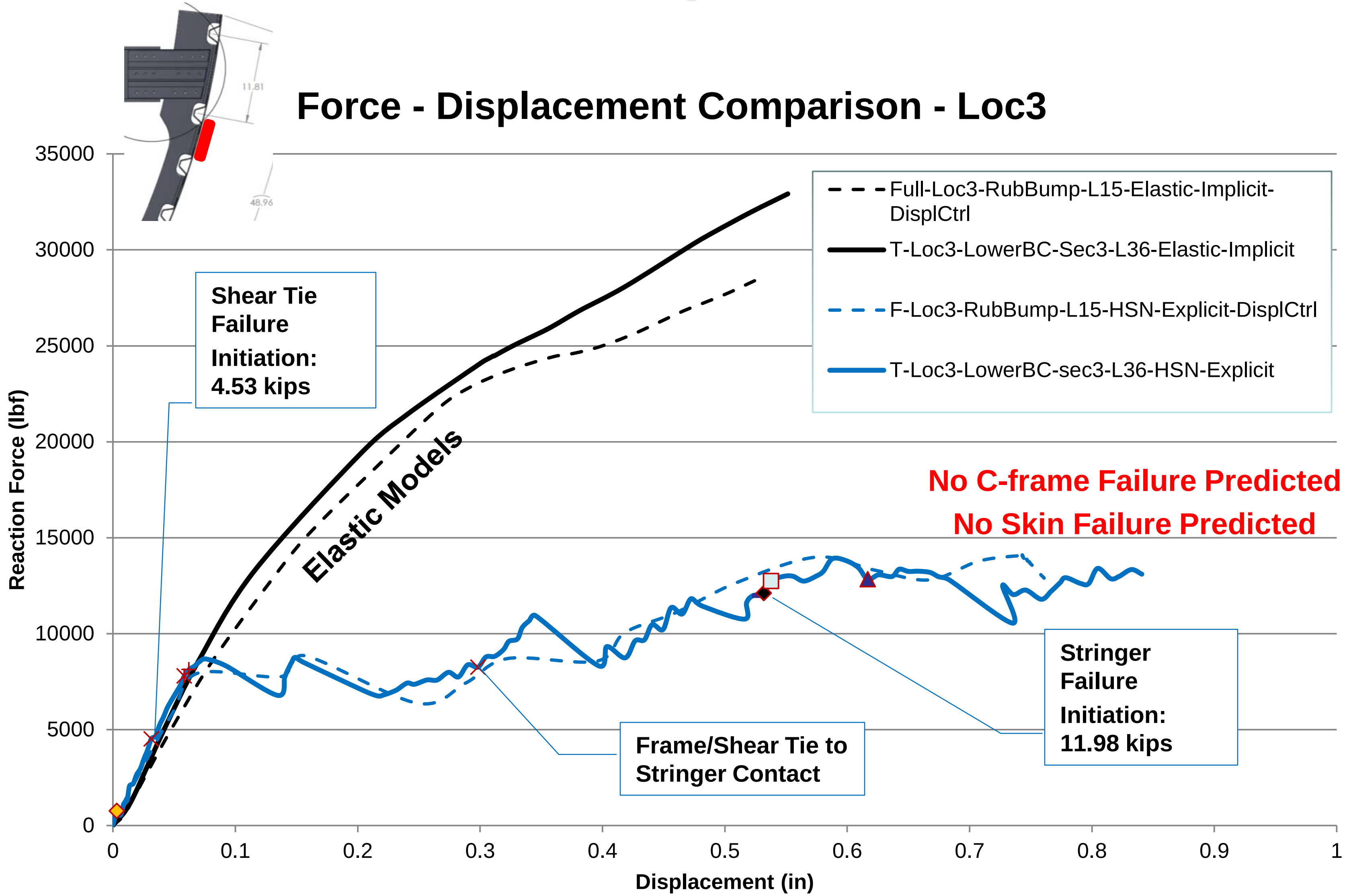
Simulation: Full Model

Full vs Truncated Comparison at Location 3



Simulation: T-Loc3-EX.avi

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Test Matrix

Specimen	Skin	Skin Thk (in)	Shear Tie	S. Tie Thk (in)	Load Loc	Load Type*
1	14 plies	0.11	16 plies	0.139	4	Quasi Static
2	14 plies	0.11	16 plies	0.139	4	Dynamic
3	14 plies	0.11	16 plies	0.139	3	Quasi Static
4	14 plies	0.11	16 plies	0.139	3	Dynamic
5	10 plies	0.079	12 plies	0.104	4	Chosen after Tests 1 to 4
6	10 plies	0.079	12 plies	0.104	3	Chosen after Tests 1 to 4
7	10 plies	0.079	16 plies	0.139	Chosen after Tests 5,6	Chosen after Tests 1 to 4
8	10 plies	0.079	16 plies	0.139	Chosen after Tests 5,6	Chosen after Tests 1 to 4

* Load Type: Quasi Static = increasing load until just past initial failure, stop & inspect, reload further to next major damage state, stop & inspect, repeat etc (multiple steps).
Dynamic = fast speed (0.25 to 0.5 m/s) until well past initial failure (one shot).

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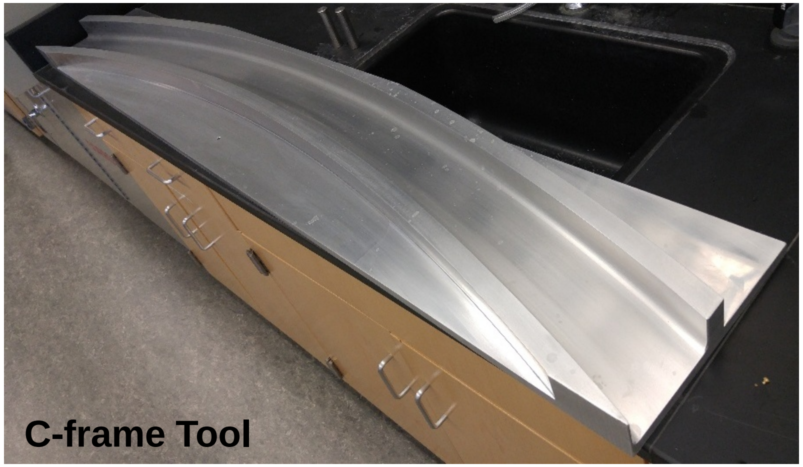
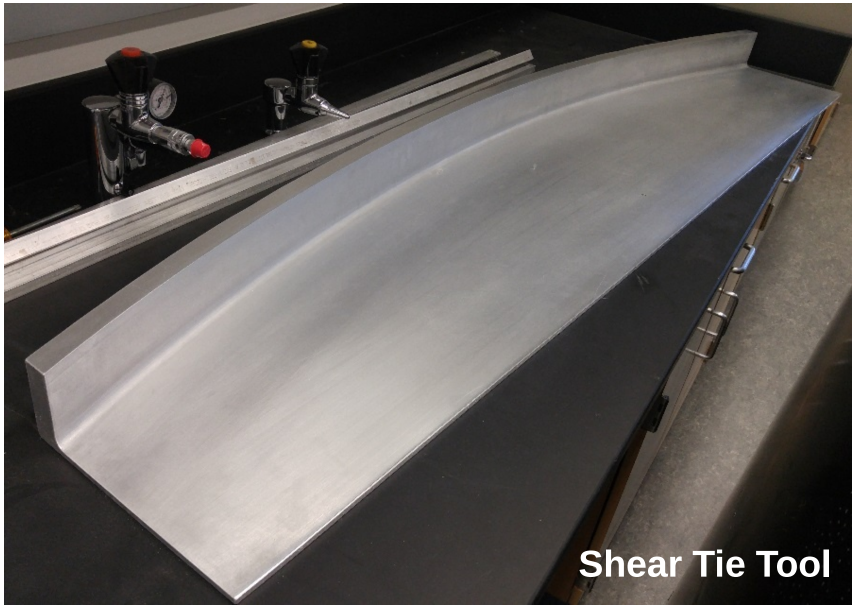
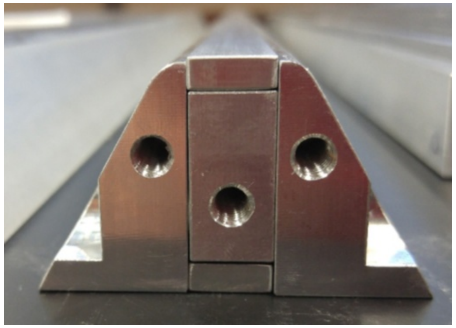
Specimen Manufacture







Toray T800/3900-2
Pre-Preg Purchased

Material	Quantity Rcvd (ft^2)
T800S 3900-2B UD	3010
T800H 3900-2D PW	1829

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Outline

- Ground Service Equipment (GSE) High Energy Blunt Impact
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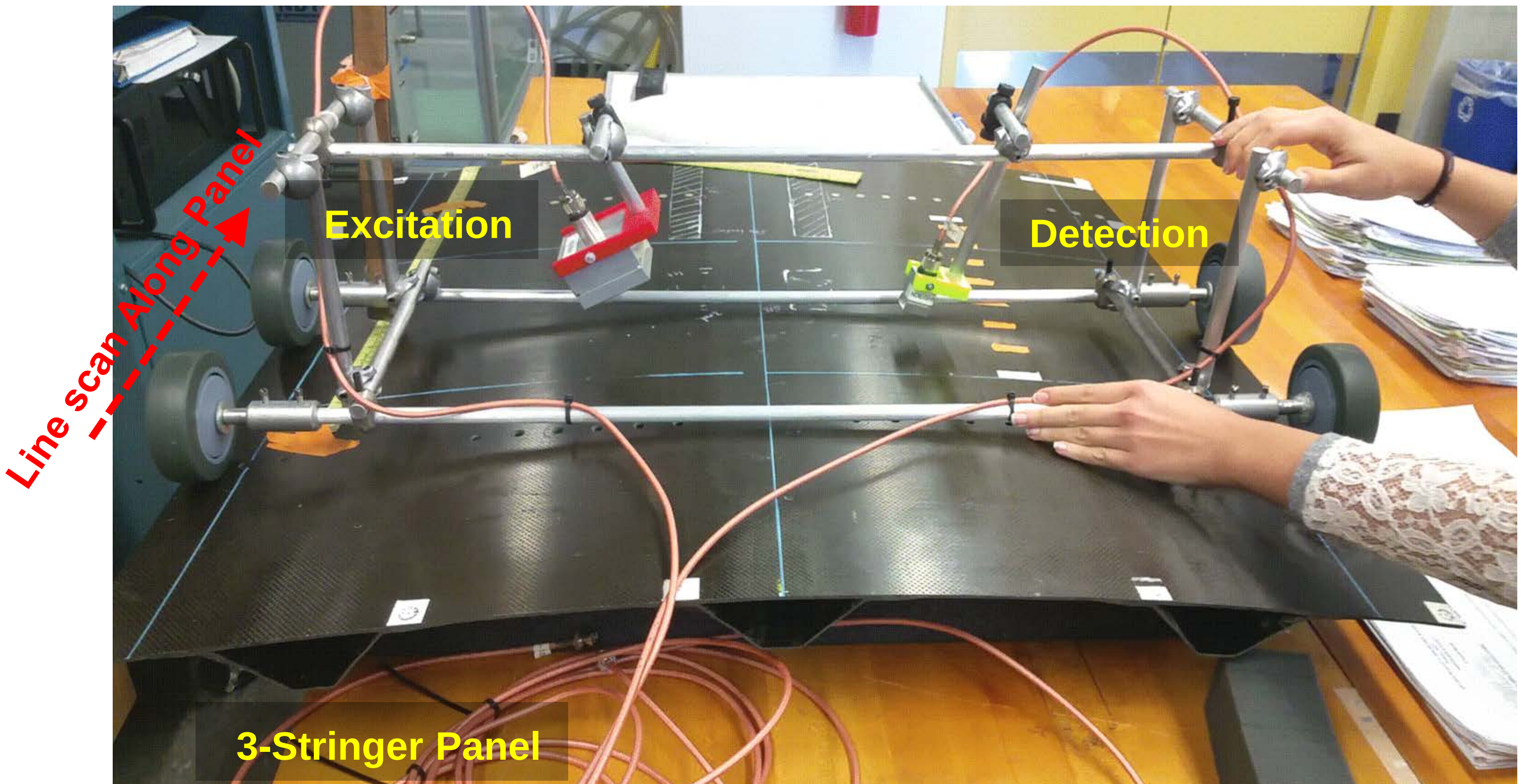
Non-Contact NDE Prototype

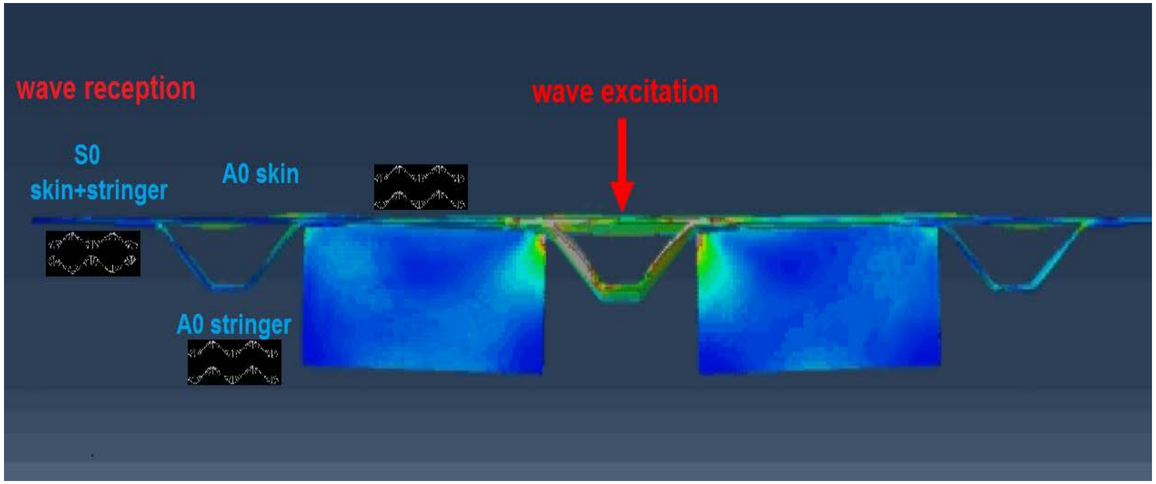
Non-contact system for panel scanning

- Line scan approach with non-contact sensors on moving carriage
- Air-coupled piezocomposite transducers: central frequency 170 kHz
  - no contact coupling dependency
- Pitch-Catch (NO differential):
  - 1 Cylindrically-focused transmitter + 1 unfocused receiver

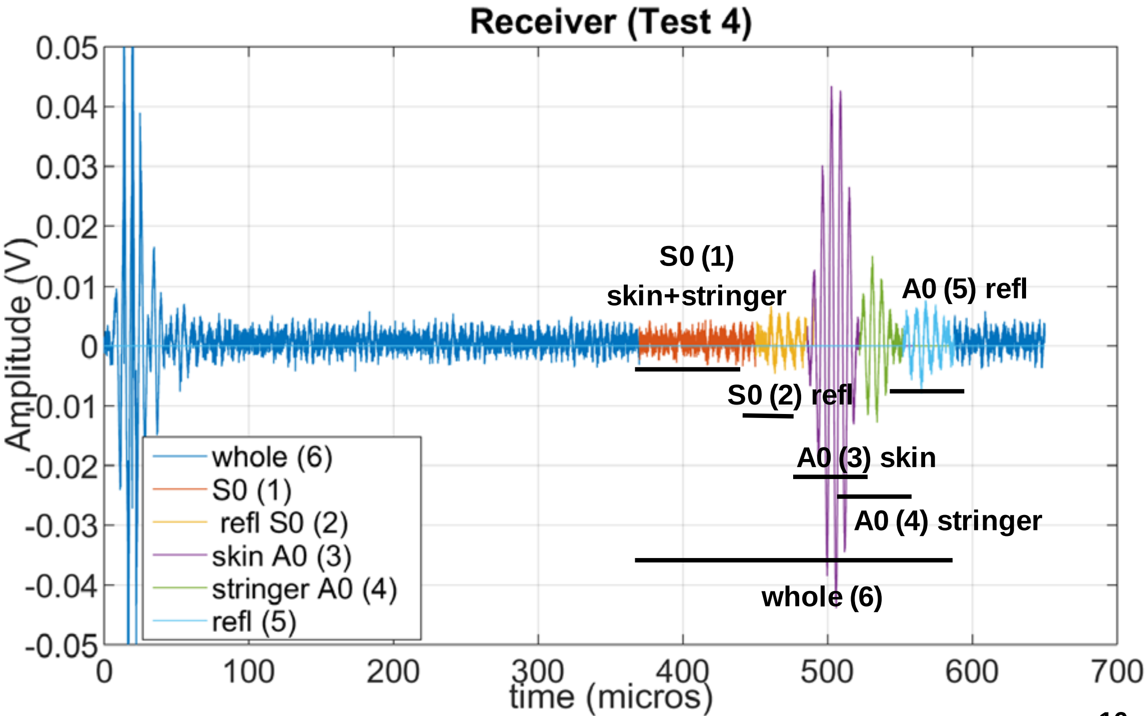


Non-Contact NDE Prototype

- Typical Signal:
  - Multi-mode: A0 & S0 in Skin/Stringer
    - confirmed by FEA
  - Time of Arrival computed from Group Velocity obtained from FEA



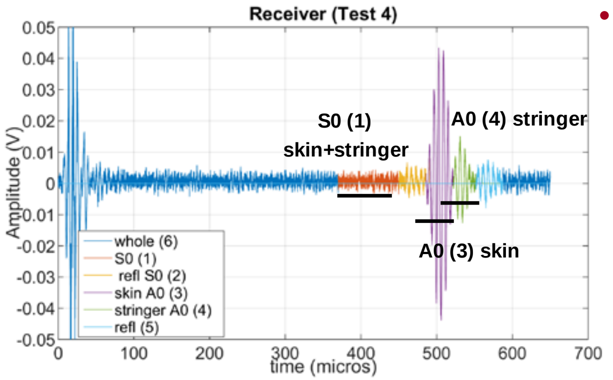
Gating in 6 different exploitable packets to isolate different modes



Non-Contact NDE Prototype

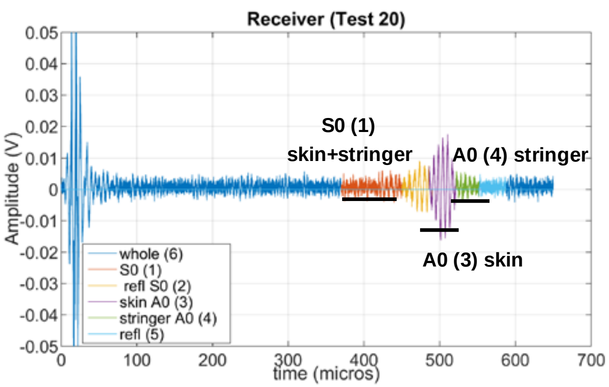
- Outlier Analysis:
  - Multivariate
  - Multi-mode

Super-Vector for mode compounding



Baseline Signal
(six possible time gates)

Test Signal
(six possible time gates)



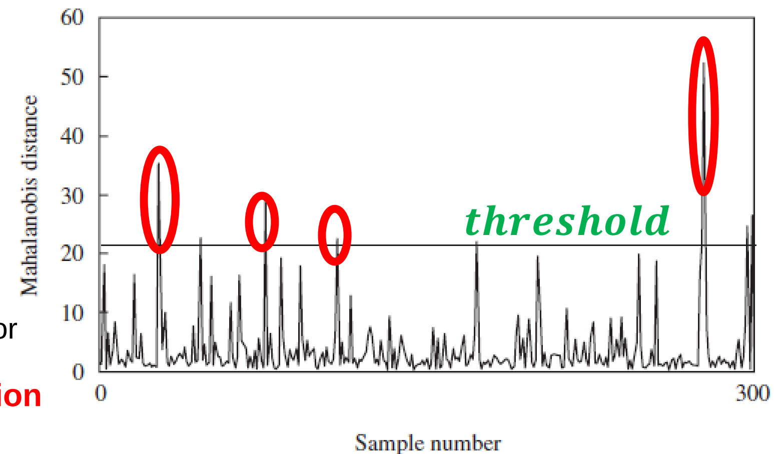
Feature Super-Vector

$$x = \left\{ \begin{bmatrix} Max\ Ampl \\ Max\ Ind \\ Variance \\ Kurtosis \\ \dots \end{bmatrix}_{m1} \begin{bmatrix} Max\ Ampl \\ Max\ Ind \\ Variance \\ Kurtosis \\ \dots \end{bmatrix}_{m2} \begin{bmatrix} Max\ Ampl \\ Max\ Ind \\ Variance \\ Kurtosis \\ \dots \end{bmatrix}_{mN} \right\}$$

Known Undamaged Region:
Baseline Vector
Average, Covariance
$\bar{x}, C$

Test Vector
x
Any Location

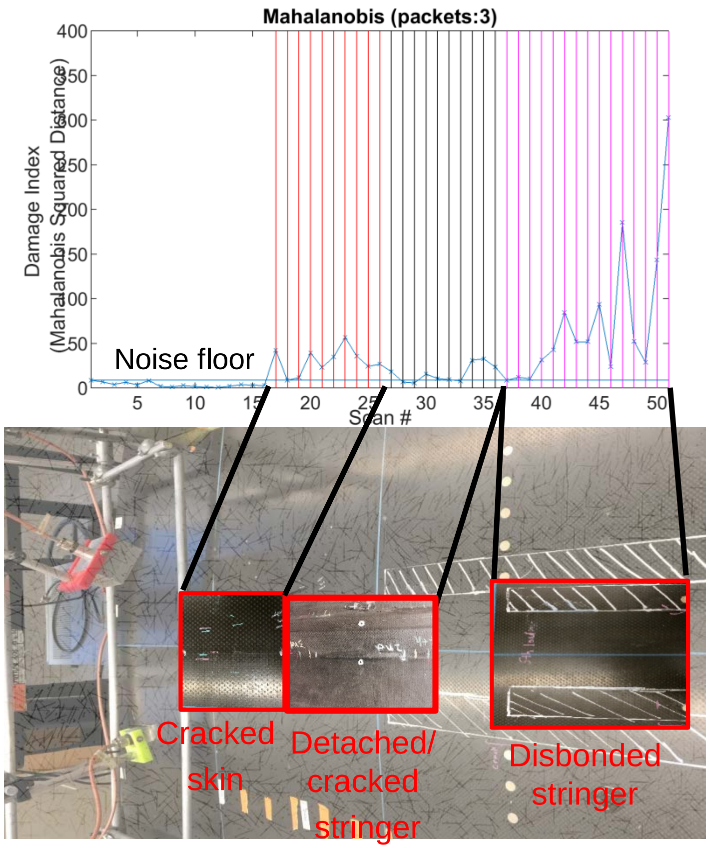
Damage Index (DI) :
(Mahalanobis Squared Distance)
$(x - \dot{x}) * C^{-1} * (x - \dot{x})^T$



$$If\ DI > threshold \Rightarrow \textbf{DEFECT}$$

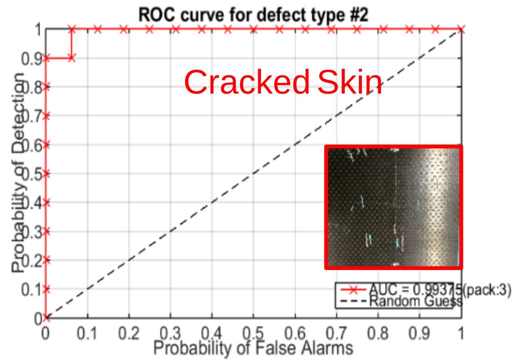
Non-Contact NDE Prototype

- Outlier Analysis Results:
  - **Skin** modes only



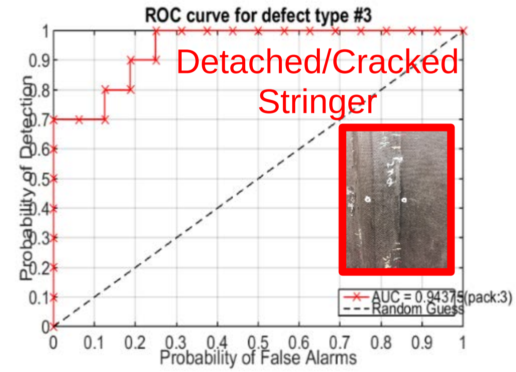
ROC curves

for performance assessment



Excellent detection :

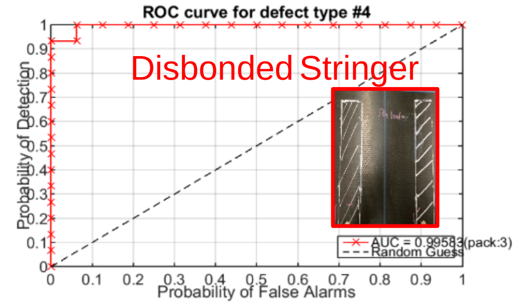
90% POD with 0% PFA



Ok detection :

90% POD with 20% PFA

Every point is different threshold level – typically, lower threshold yields higher detection but more false alarm



Excellent detection :

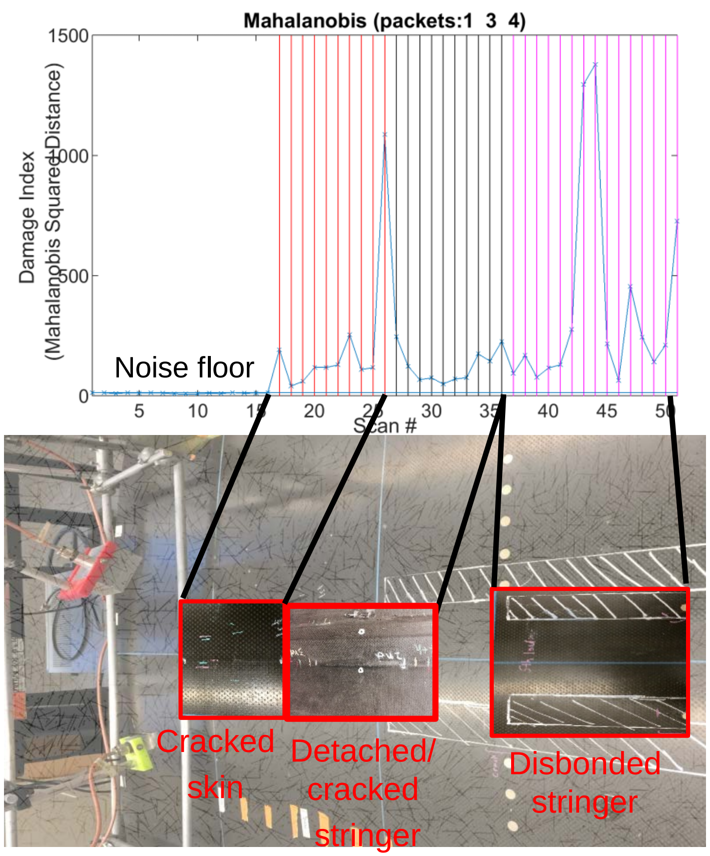
93% POD with 0% PFA

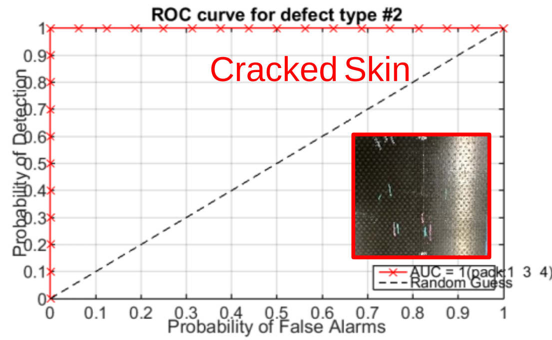
Non-Contact NDE Prototype

- Outlier Analysis Results:
  - **Skin** + **Stringer** modes (best combination)

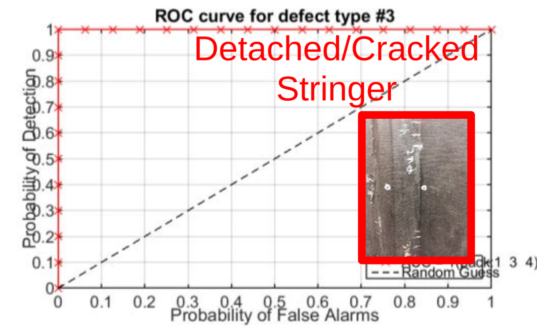
ROC curves

for performance assessment

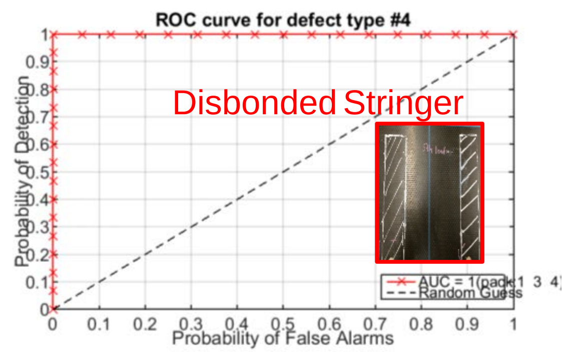




Perfect detection



Perfect detection



Perfect detection

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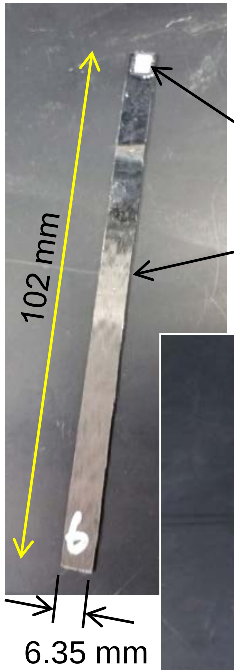
NDE Excitation by Mini Impactor – Portability

Impact based excitation desirable for ease of use and high amplitude/intensity

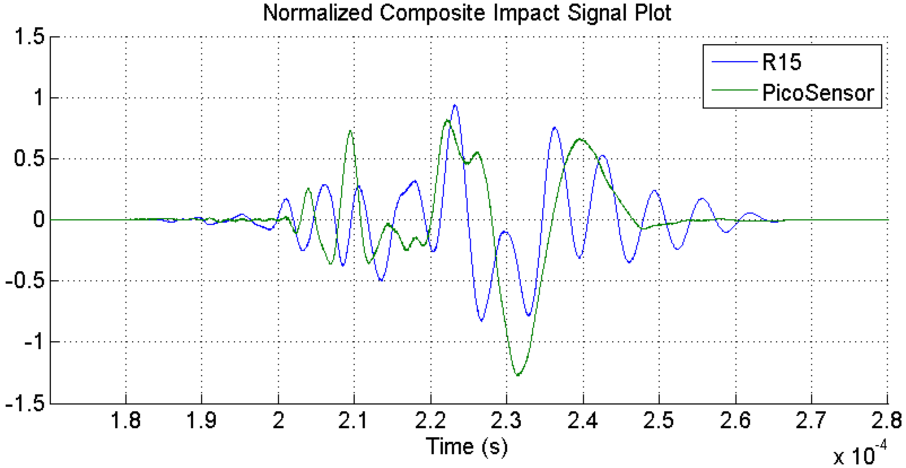
- transducers need high power and couplant, lasers bulky & damage surface

Typical impulse hammer excitation has frequency content < 20 kHz.

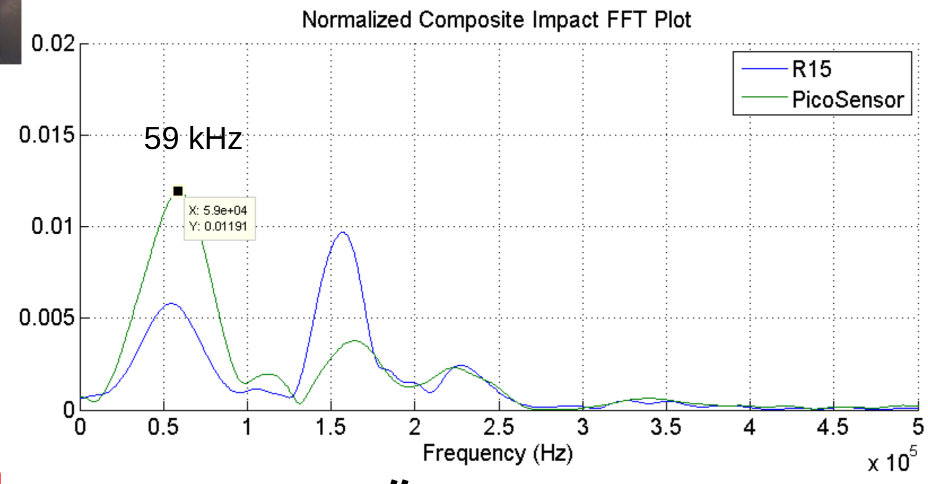


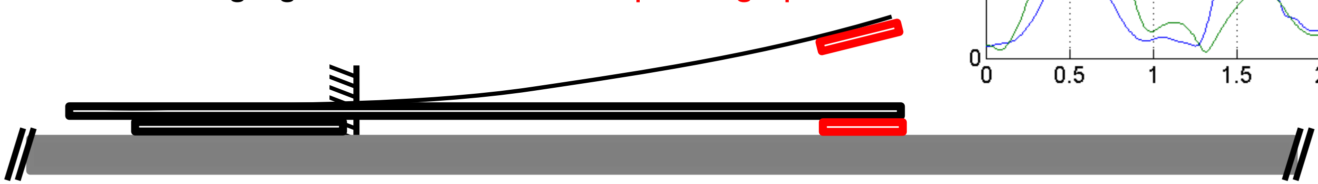
Aluminum Tip – 0.56 mm thick

Uni-directional Carbon/Epoxy $[0]_8$ Layup; 0.56 mm thick



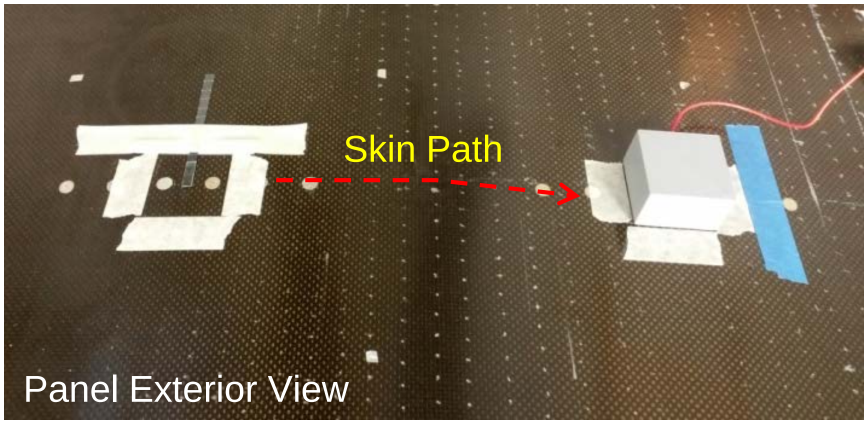
- Flick impactor → generates excitation having frequency in range of interest (30-80 kHz; target 50 kHz)
- Excitation frequency controllable by changing mass/area of the impacting tip.

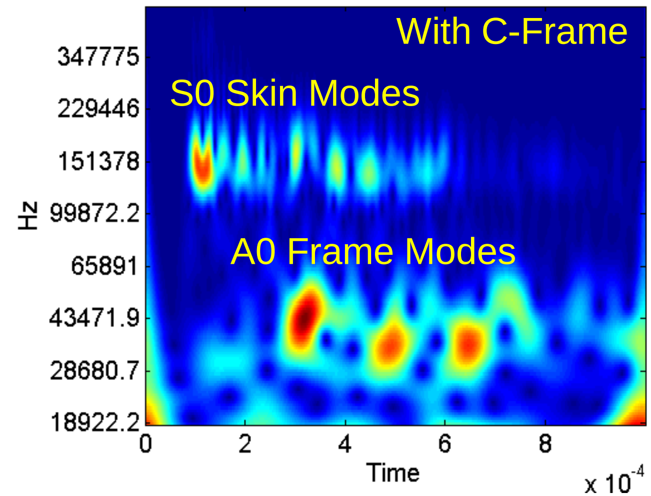


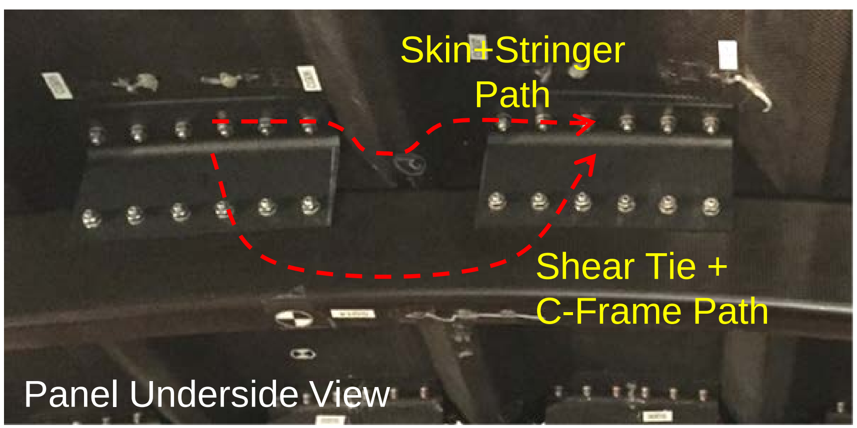


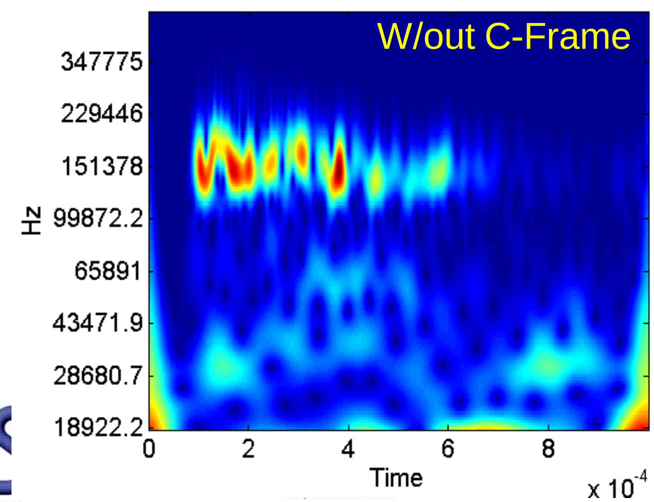
Mini Impactor on Composite Panel

- Excitation and measurement (R15 contact transducer) on exterior skin-side
- S0 waves through skin path move faster (~150 kHz content); arrives first
- A0 waves through C-frame path move slower (~50 kHz content); arrives 0.2 ms later
- Specimen with C-frame removed has only skin modes content









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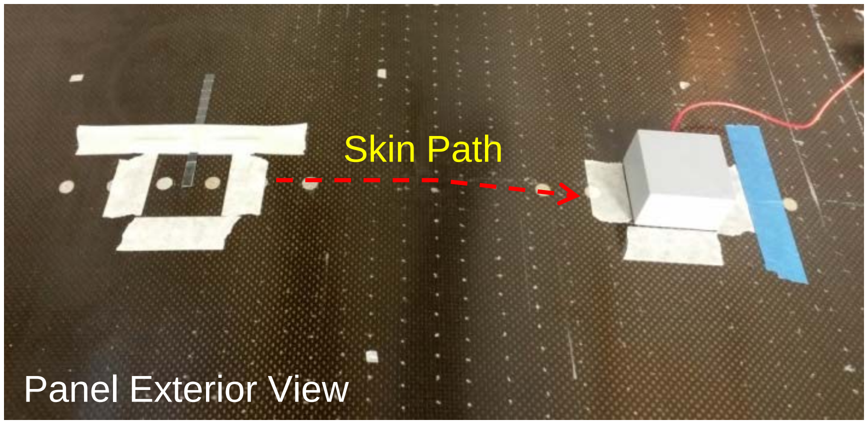
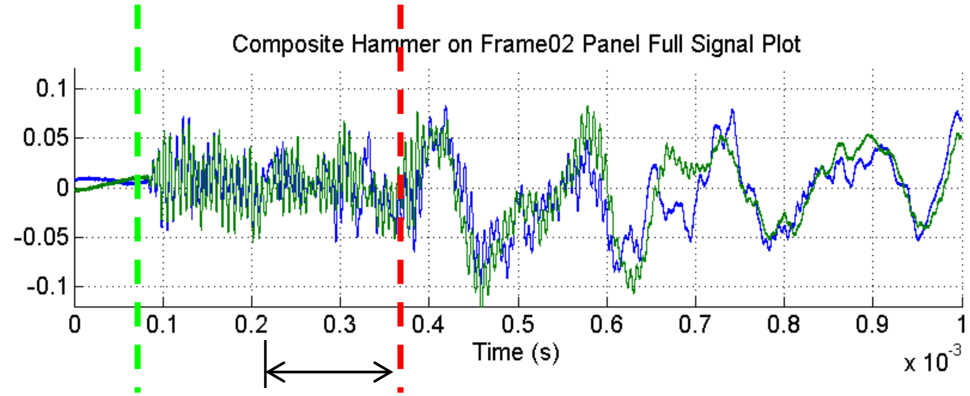
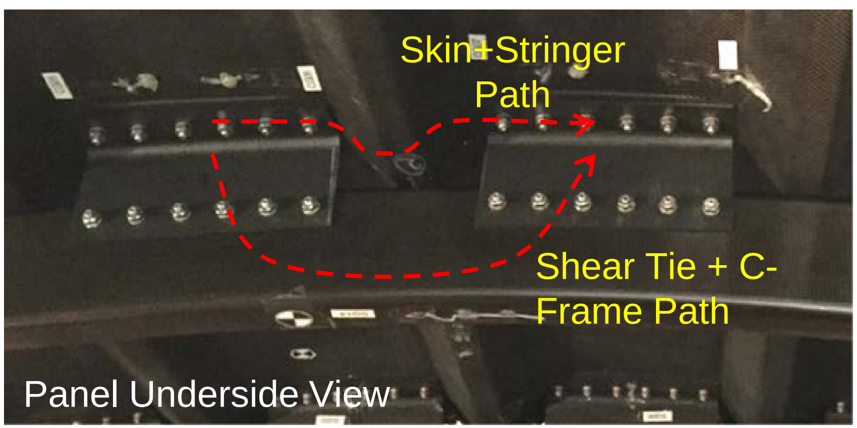
Mini Impactor on Composite Panel

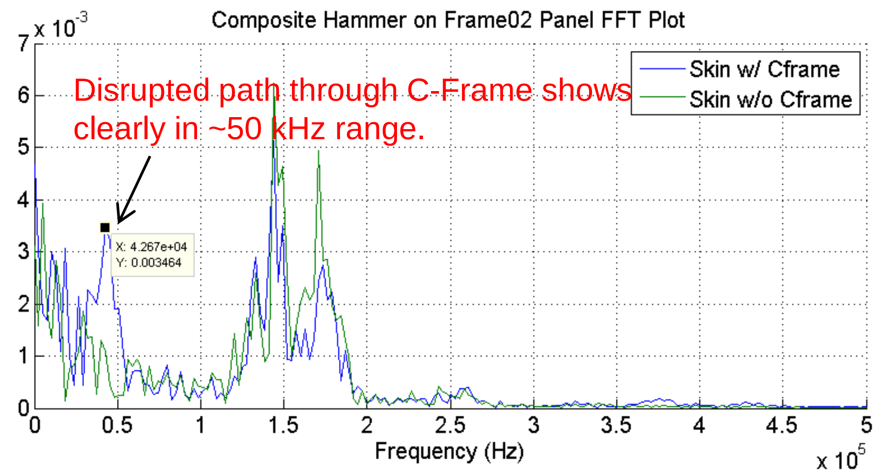
- Gating of time signal important for capturing different modes of interest – specifically those passing through frame.
- FFT shows clear sensitivity to disrupted path (C-frame detached at bolts to represent being fully cut)





Includes A0 modes through C-Frame path





Outline

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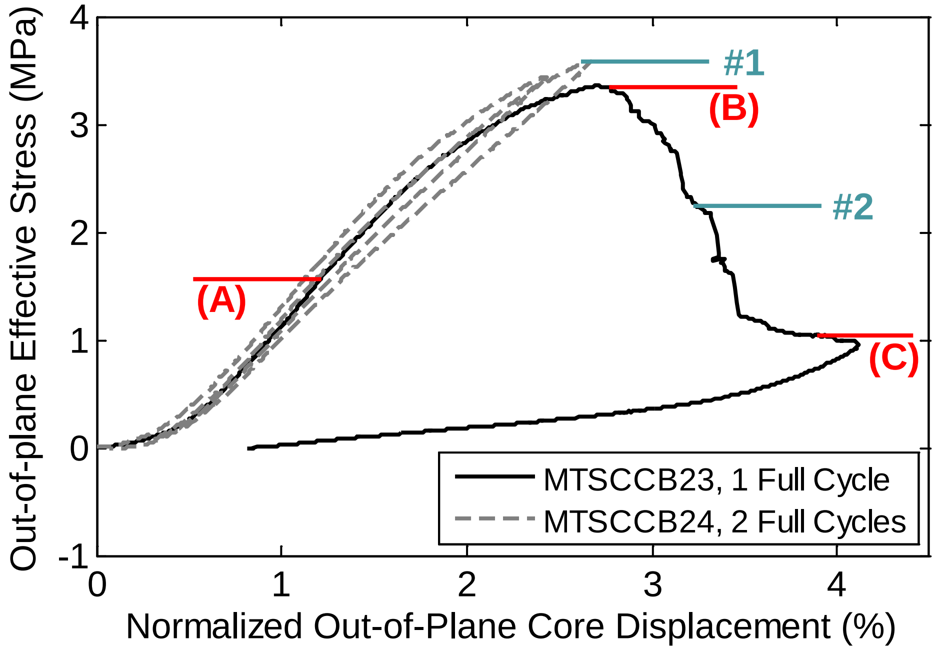
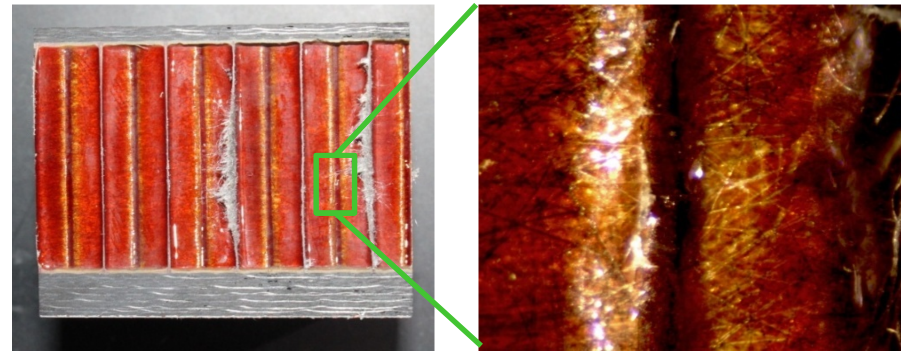
Damage on Nomex® Cores (Flatwise Compression)

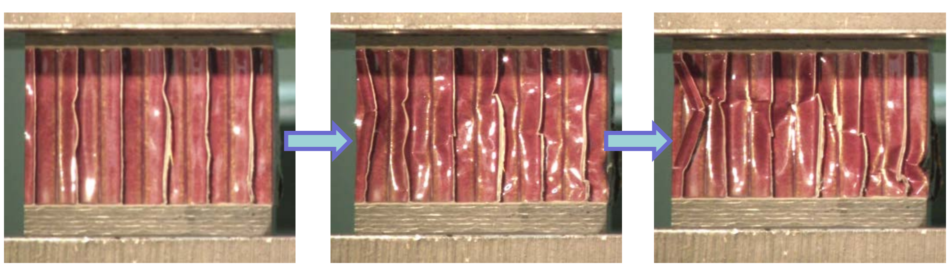




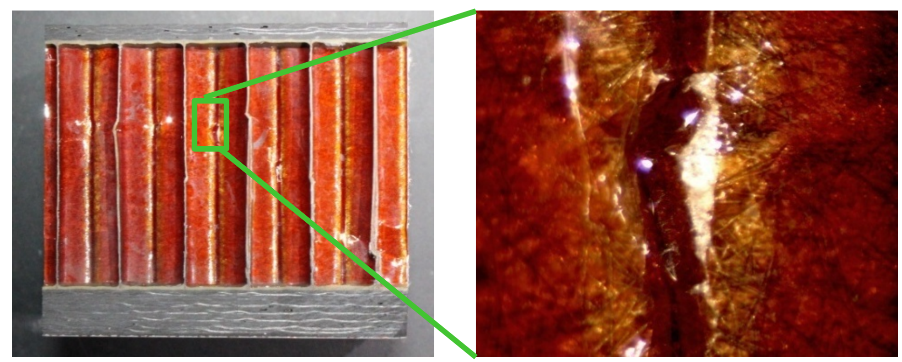
Unloading at peak stress (point #1):

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

Sequence of failure events



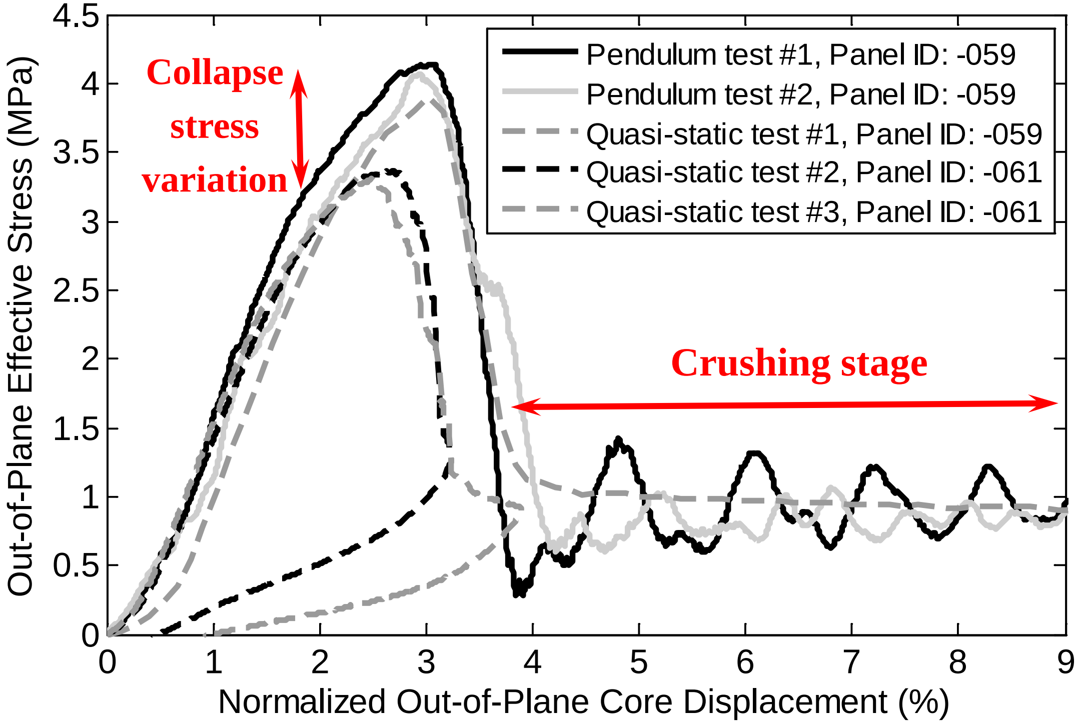
(A): Onset of post-buckling | **(B): Onset of resin fracture** | **(C): Core crushing plateau**



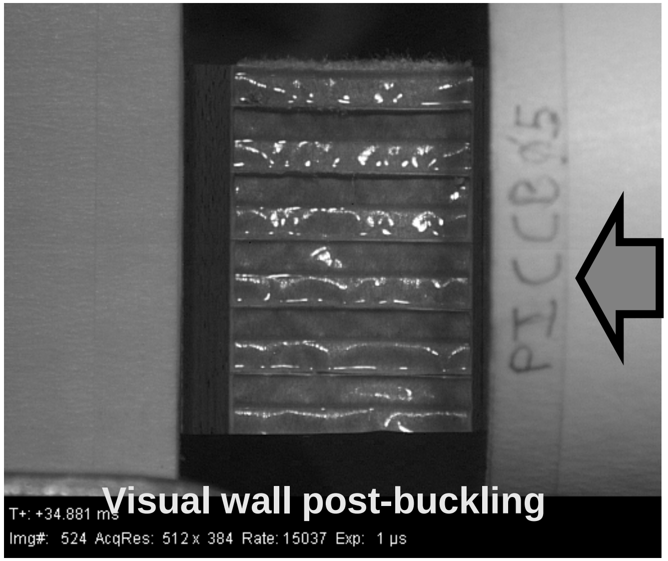
Unloading at unstable region (point #2):

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

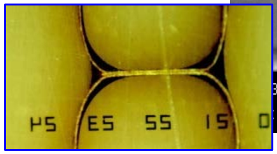
Overview of Flatwise Compression Tests



Pendulum Dynamic Loading

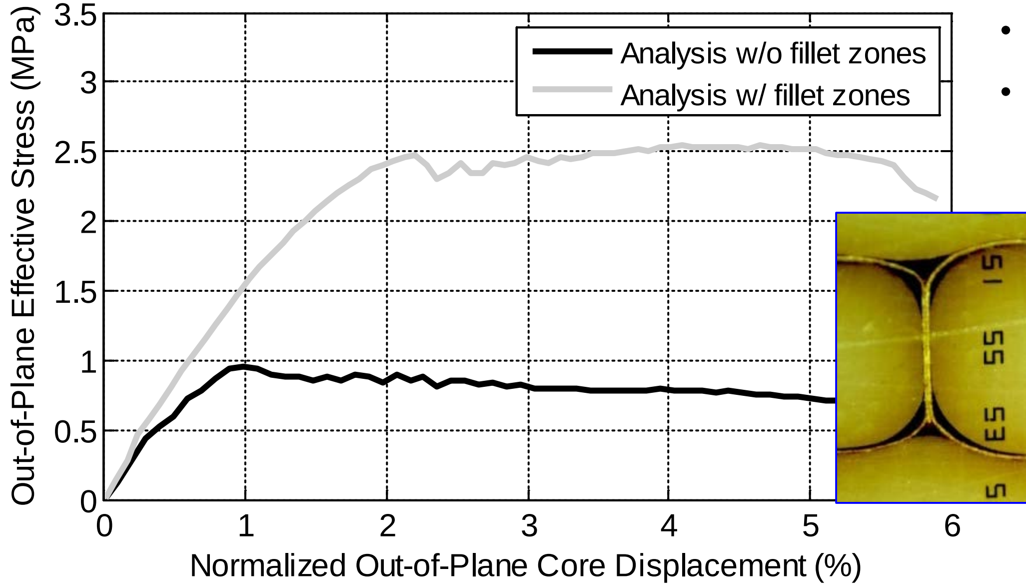


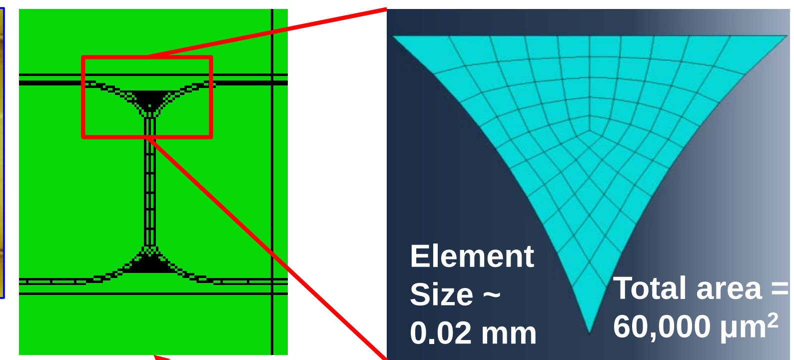
- Collapse stress scatter likely affected by manufacturing process and sandwich curing cycle
- No significant strain rate effects (up to 90 s^{-1}) observed – same effective stress/displacement response and similar failure mechanisms

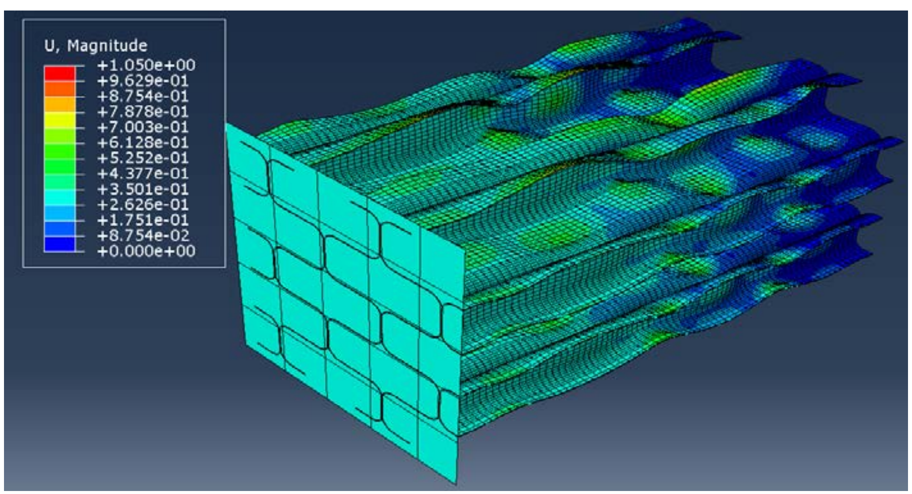


Detailed Modeling of Nomex® Cores

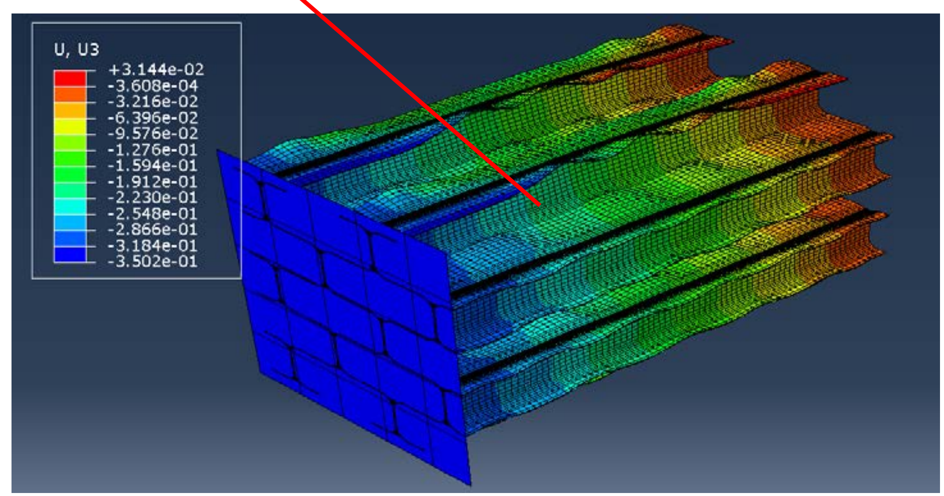
- Resin fillets enhance stability of core cells
- Issue: limited data on Nomex® paper and phenolic resin – need to measure







Collapse for non-filleted core



Collapse for filleted core

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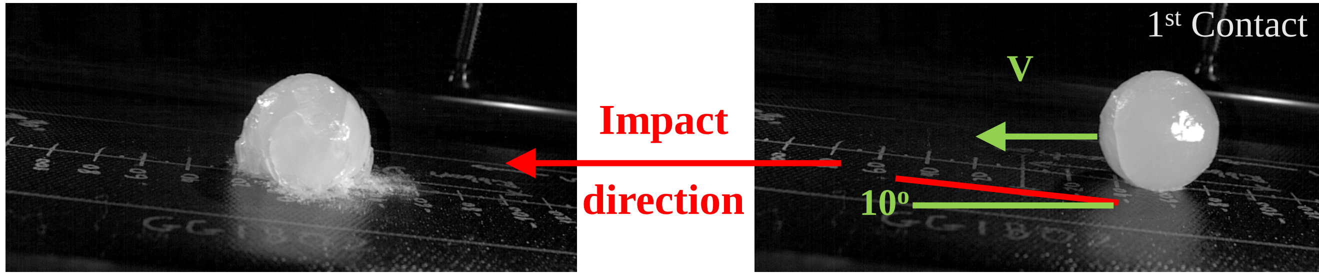
Hail Impact: Low Glancing Angle Tests

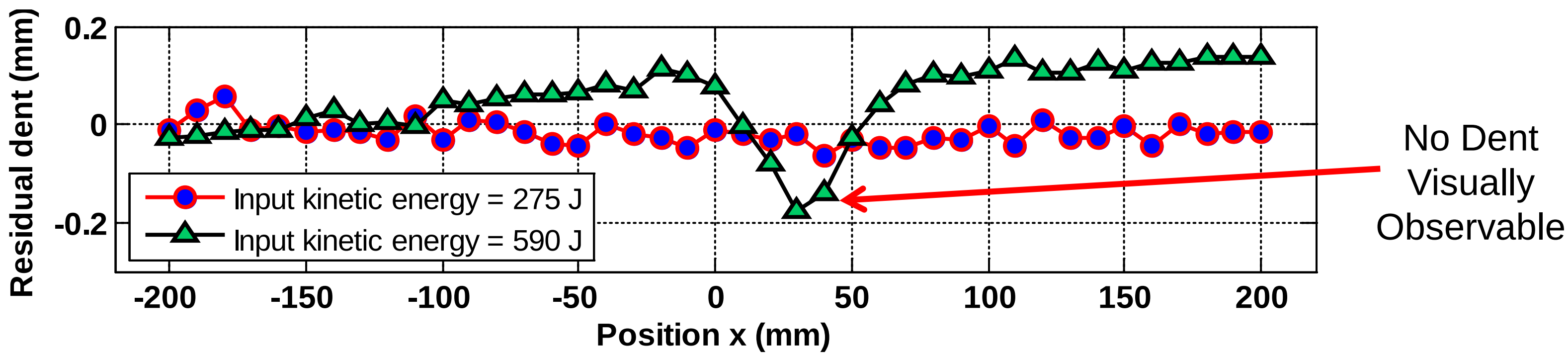
- 10° glancing angle, 80 - 160 m/s velocity; 275 - 800 J kinetic energy

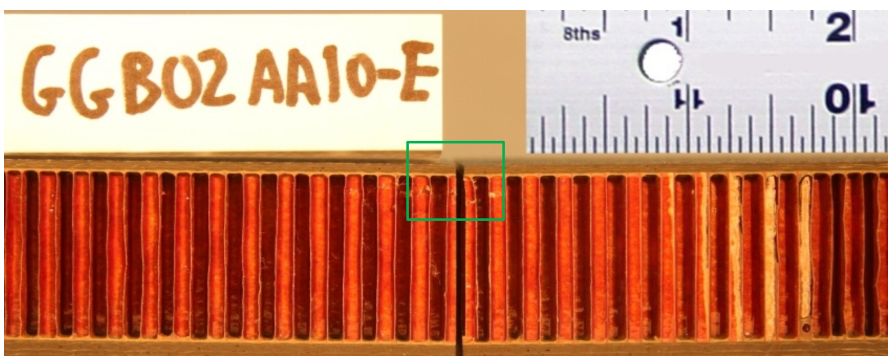
50.8 mm ice ball in foam sabot



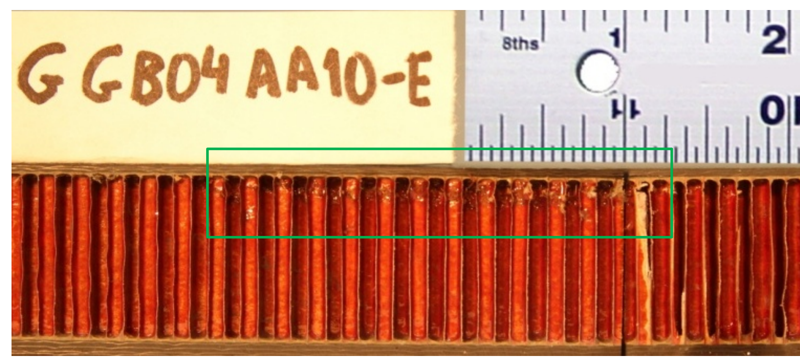
t = 4.14 ms from trigger

t = 3.64 ms from trigger





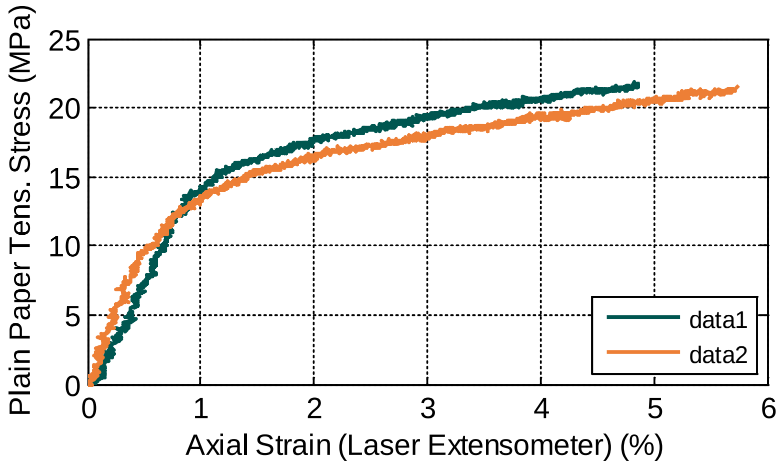
Threshold energy for core damage onset = 275J



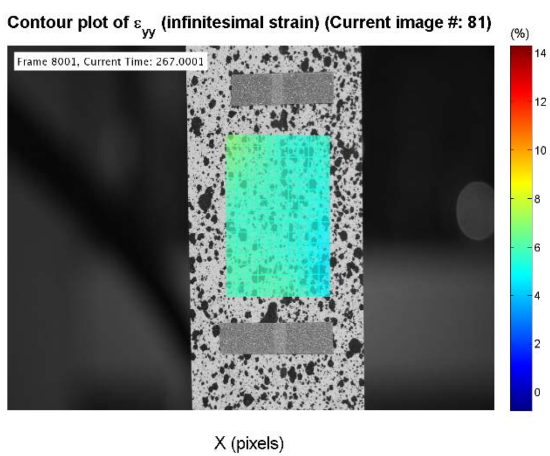
Core crushing span for 600 J energy: ~76 mm

Ongoing Activities

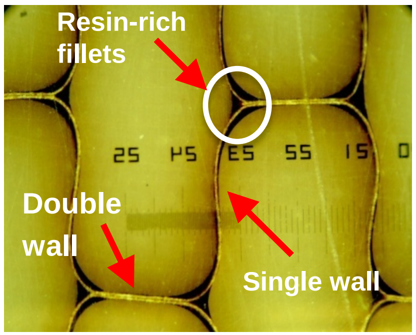
- Mechanical characterization of Nomex® paper and phenolic resin

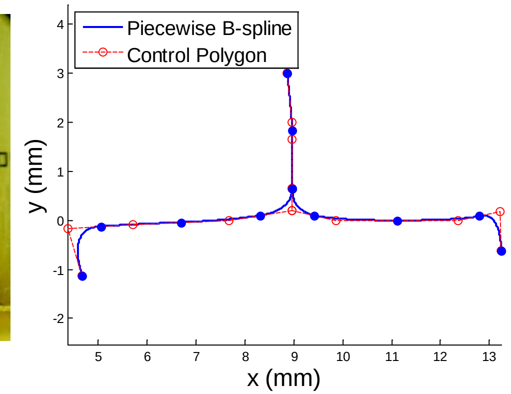


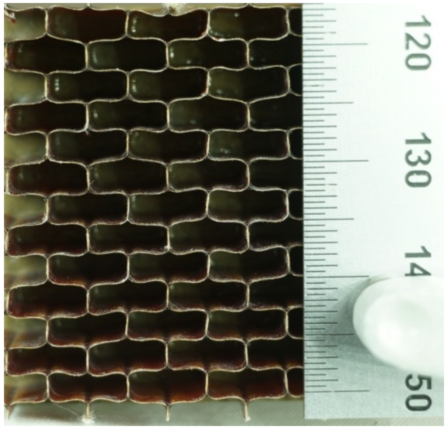
- Digital image correlation method for strains
  - Validation of DIC with office paper coupons
  - Extend to Nomex Paper
  - Obtain properties through tension

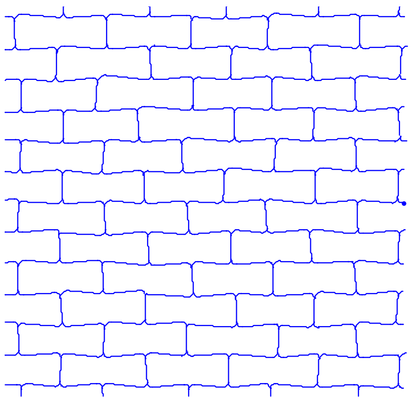


- Generate imperfect geometry using B-spline theory to account for defects









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Outline

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

Summary/Conclusions

Ground Service Equipment (GSE) High Energy Blunt Impact

- 2nd generation large panel specimen was designed and updated – includes frame-to-floor interaction.
- Reduced-sized truncated specimen shown to exhibit equivalent response with full quarter-barrel specimen.
- Tooling fabricated and materials ordered/received.

Blunt Impact Damage to Sandwich Panels

- Significant core damage has been experimentally documented through ongoing gas gun tests at low angles of attack; no dent visible.
- "Inverted" building block approach being followed to 1) quantify core damage extent through panel impact tests, 2) assess main core damage mechanism based on simplified tests (e.g. flatwise tests), 3) establish damage contribution of the constituents of the composite Nomex® paper/phenolic resin system through computational and experimental work at meso-structure scale.

NDE of Major Internal Damage

- Non-contact approach system demonstrated successfully
    - less effort and faster
    - yields more stable signals due to absence of coupling and operator variations
- Mini-Impactor generates frequency excitation suitable for both skin and internal damage detection; large amplitude and does not require high power amplifiers.

Benefits to Aviation

Ground Service Equipment (GSE) High Energy Blunt Impact

- Understanding of key physical phenomena through experiments; HEWABI damage near joints and stiffness transitions.
- Improved FE modeling methodology of blunt impact damage

Blunt Impact Damage to Sandwich Panels

- Establish core damage metrics for a set of conditions (size of projectile, projectile angle of attack, skin stiffness, core configuration).
- Quantify effects of the manufacturing defects (imperfections) or manufacturing induced geometric factors (coating thickness, resin fillets) on the widely scattered mechanical properties of Nomex® cores.

NDE of Major Internal Damage

- System developed has large area scan ability, and is field portable.
- Better detection of major damage – e.g., stringer heel cracks, disbonded stringer.
  - higher performance Probability False Alarm vs Probability Of Detection
  - more robust
  - doesn't require differential mode

Looking Forward

Ground Service Equipment (GSE) High Energy Blunt Impact

- Continued development of high fidelity FEA modeling capability – validated at element level.
- Large specimen: boundary fixture design and manufacture, specimen fabrication (layup, assembly), conduct experiments.
- Continued study of failure in frame from bending and combined bending-torsion; allows improved FE damage progression models.
- Discrete multiple fasteners modeling/representation within progressive failure analysis.

Blunt Impact Damage to Sandwich Panels

- Experimental work on phenolic resin specimens as well as composite phenolic resin/Nomex® paper laminates → obtain material properties needed for detailed Nomex® paper computational models.

NDE of Major Internal Damage

- Further investigation on internal structural wave penetration with mini-impactor.
- Correlate the damage index features with damage location and type.
- Live demo to industry partners.

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