High Energy Wide Area Blunt Impact Session

UCSD FAA Research

Supported by FAA Joint Advanced Materials and Structures (JAMS) Center of Excellence

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2015 FAA/Bombardier/TCCA/EASA/Industry Composite Transport Damage Tolerance and Maintenance Workshop

15-17 September 2015, Montreal, Canada

Introduction

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- Motivation and Key Issues
  - impacts are ongoing and major source of aircraft damage
  - <u>high energy wide area blunt impact</u> (HEWABI) is of particular interest
    - involves large contact area, multiple elements
    - damage can exist with *little/no exterior visibility*
- Sources of Interest:
  - **ground service equipment (GSE)** rubber bumpers
  - railings, blunt/round corners

Recent GSE Collision Examples

Image credit: “Service vehicle hits plane's belly, flight grounded”, The Sun Daily, Posted on 15 May 2014 - 05:45pm, *Last updated on 15 May 2014 - 11:37pm* Charles Ramendran.
http://www.thesundaily.my/news/1047024

Image Credit: Aircraft Rescue and Fire Fighting (ARFF) Working Group, Sep 8, 2015.
http://arffwg.org/58222/

Recent GSE Collision Examples

Image credit: “Baggage vehicle hits plane at SeaTac; no injuries” Posted 1:23 PM, February 8, 2015, by Q13 FOX News Staff, Updated at 01:41pm, February 8, 2015. http://q13fox.com/2015/02/08/baggage-vehicle-hits-plane-at-seatac-no-injuries/

Image credit: “1.5 year old Airbus A330 may be a total loss after service truck hits the nose (pics) (edited)” Last edited Thu Jan 15, 2015, 02:38 PM. http://www.democraticunderground.com/10026087459

Recent GSE Collision Examples

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- **Youtube video published May 1, 2014 “Lorry hits plane. Truck crashes into plane” showing truck driving into side of aircraft, then vehicle backed up and driven away.**
- **https://www.youtube.com/watch?v=788mOucDELU**

Play Video Here

UCSD Blunt Impact Research Objectives

- Understand what damage forms under blunt impact conditions
  - determine key damage modes and phenomena/parameters controlling these
  - what factors affect visual detectability
  - identify and predict failure thresholds
- Develop analysis and testing methodologies, including:
  - physically-based modeling capabilities validated by tests
  - progressive damage analysis capturing initial through final failure modes
  - defining how to analytically predict if damage is visually detectable
    - surface crack (failure criteria)
    - residual dent
- Establish Non-Destructive “quick” detection method
  - find *major* damage to internal structure: severely cracked frames, damaged shear ties
  - detection performed only from exterior skin-side
  - system must be “ramp friendly”
  - relate NDE-measurements with damage location, mode, and size/severity

Approach

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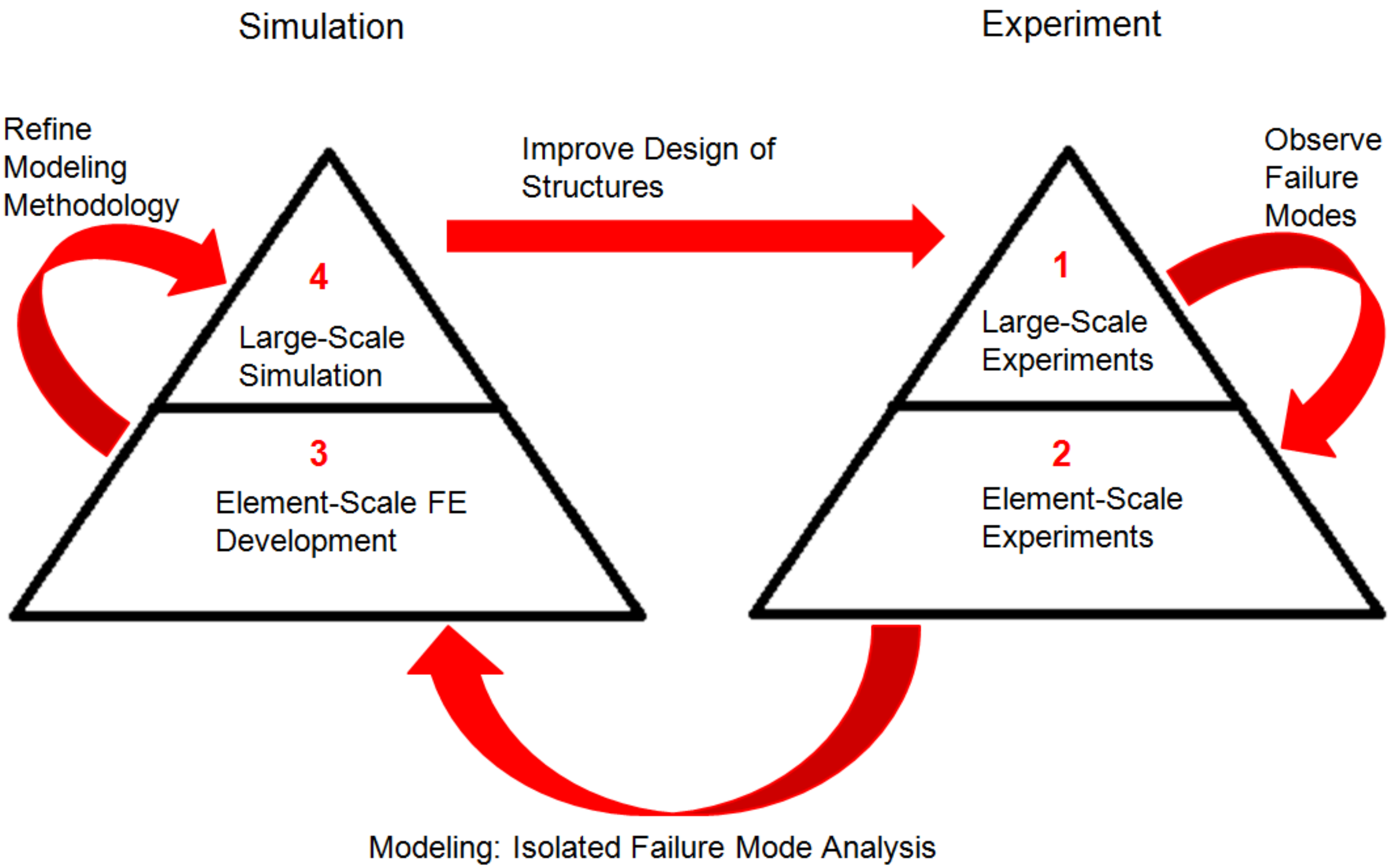
- identify key failure modes from large-scale tests
- focused study of failure modes via simple element tests → modeling capability
- transfer modeling capability to predict large-scale structural behavior



Topic I:
Summary of Large Scale Experiments

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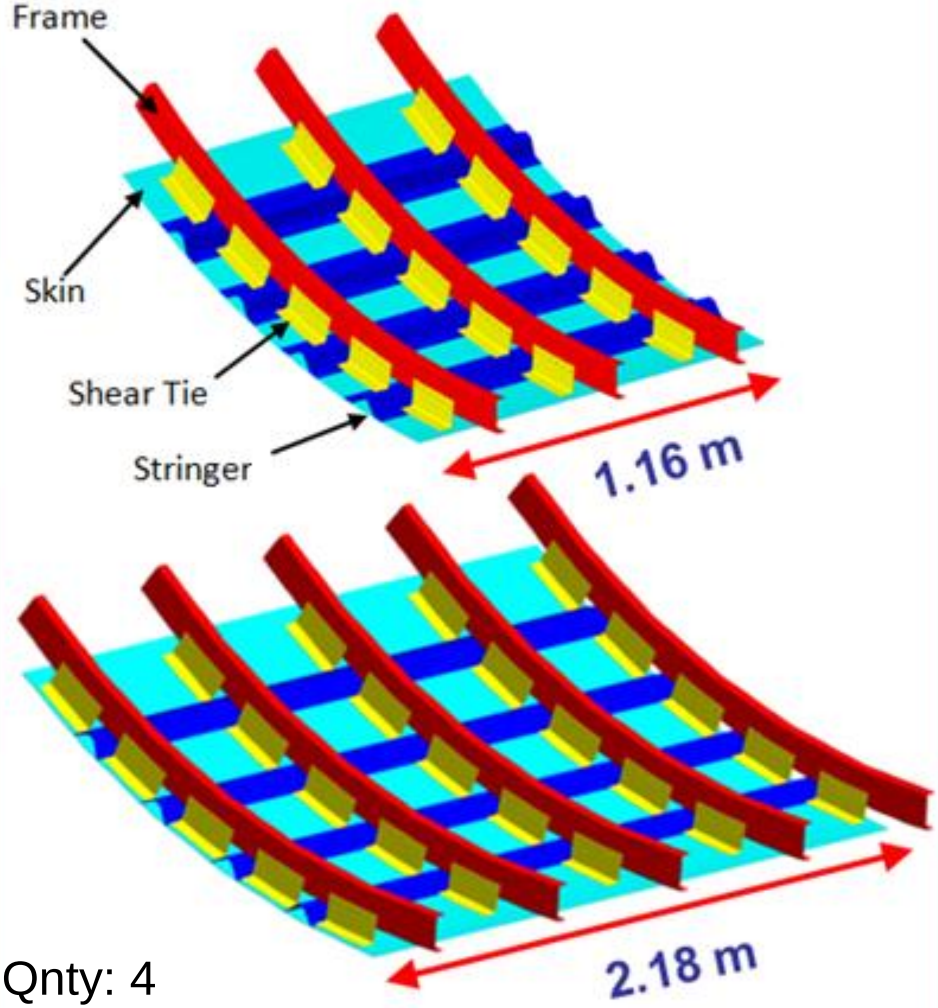
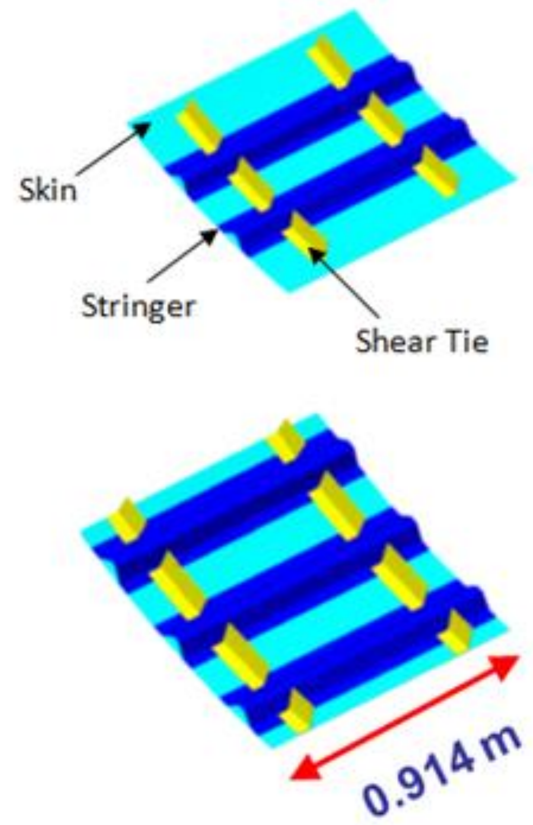
FrameXX Series Specimens
Stringer and C-Frame Reinforced Skin Specimens



Qnty: 4

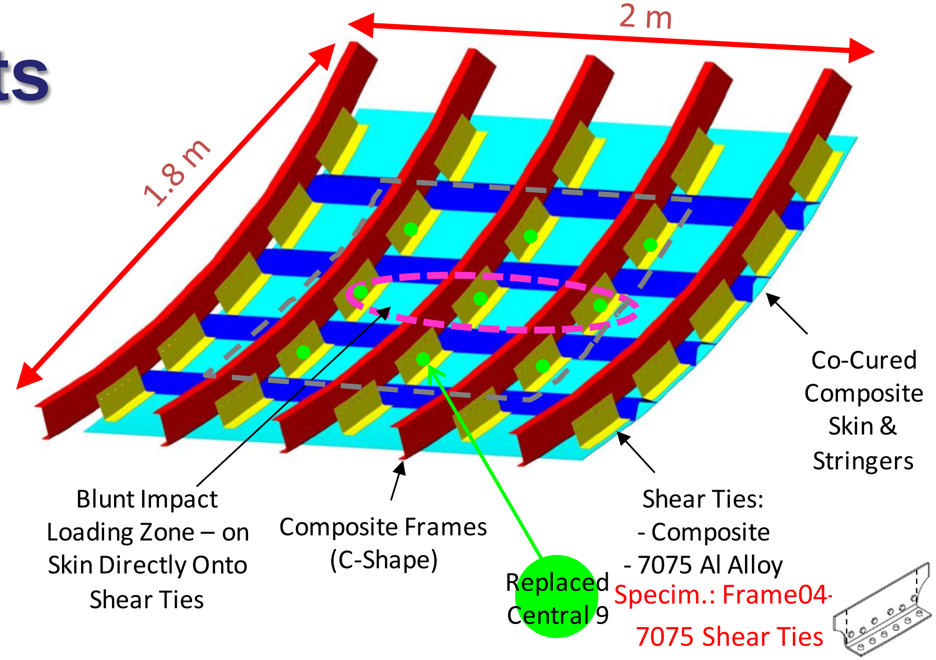
StringerXX Specimens Stringer-Reinforced Skin Specimens



Qnty: 7

Large Panel Dynamic Tests

- series of large specimens (ID: Frame03, Frame04-1, Frame04-2) tested
  - internal damage to frames and shear ties
  - no skin cracking / no visibility
  - specimen with strong shear ties exhibited direct shearing of frames at shear ties



Damage Not Visible from Exterior

Frame03 and 04 Damage Progression

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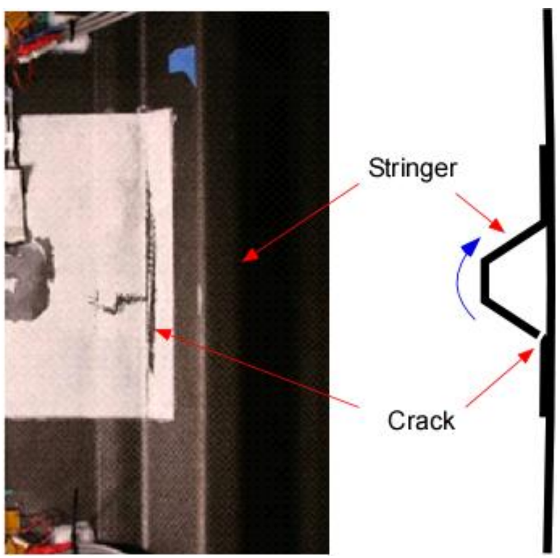
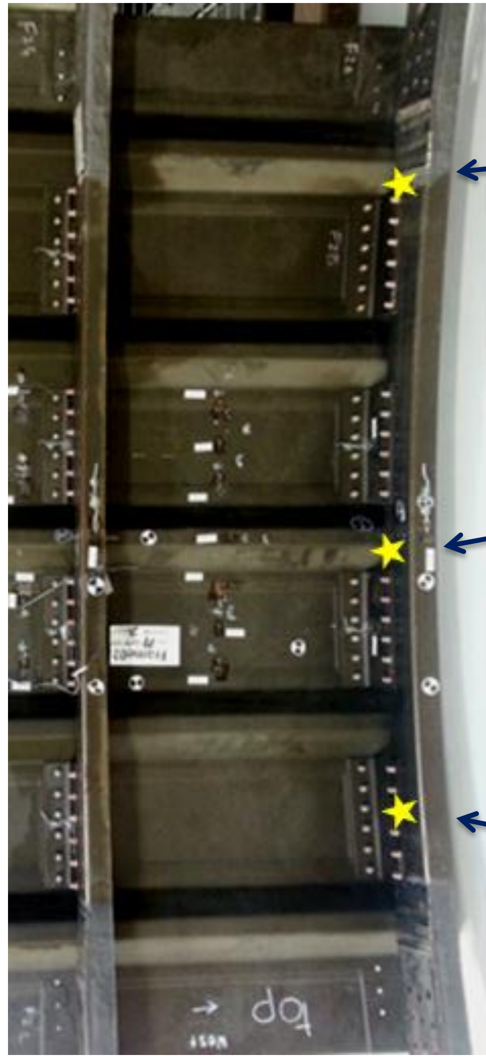
Damage Modes Summary

- **partially-cracked frame** – damage away from impact site
- **shear ties delamination**
- **cracked/crushed shear ties** in all specimens
- **stringer-skin disbond**
- **stringer heel crack**



Partially-cracked frames – from specimen Frame02



Low visibility of C-frame cracks located away from impact

Topic II: Small-Scale Studies – Experiments & FE Development

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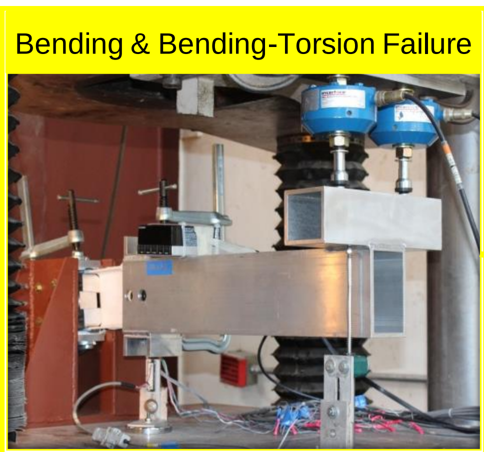
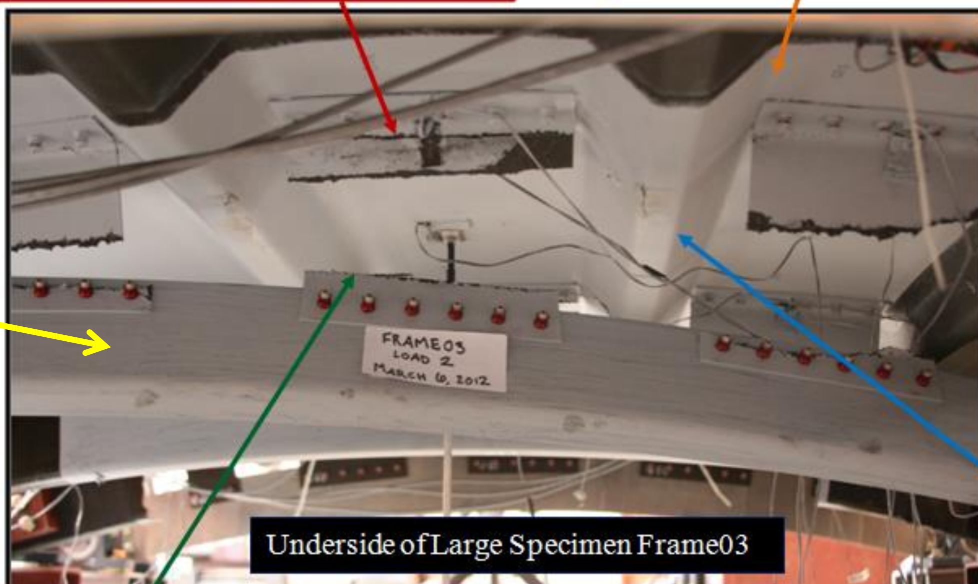
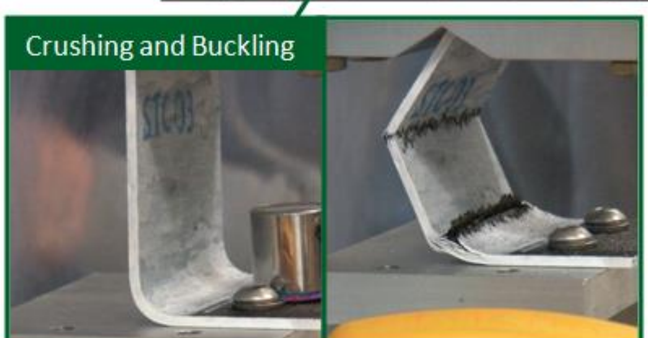
Model Capability Development at Small Scale → Transfer to Large Scale







Stringer Element Compression

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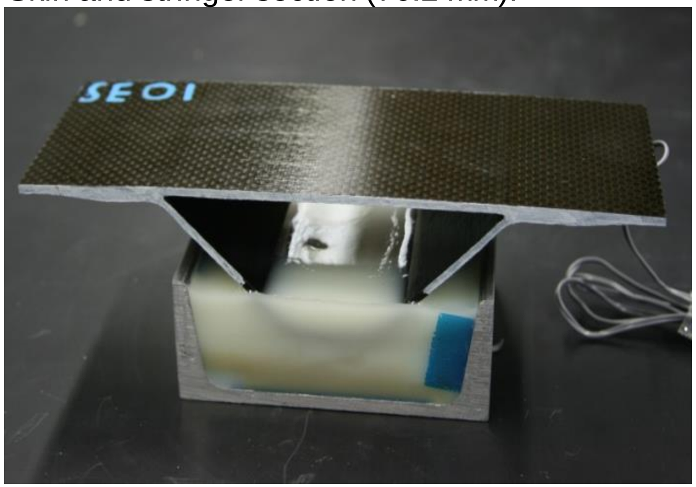
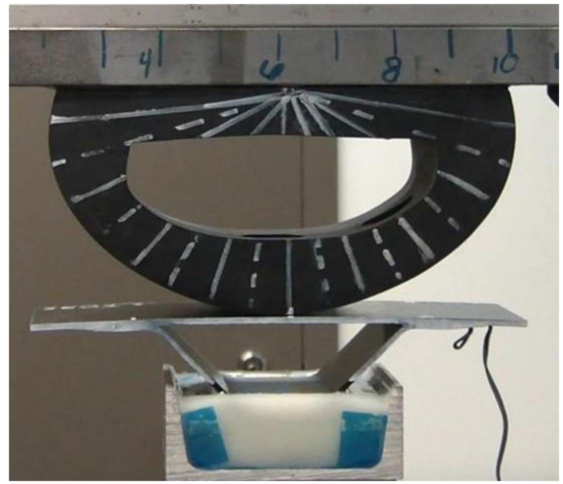
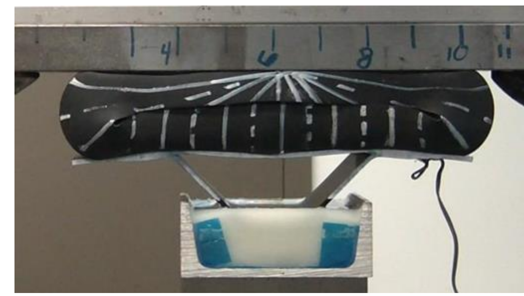
Focus: to examine externally-visible skin failures caused by bumper indentation

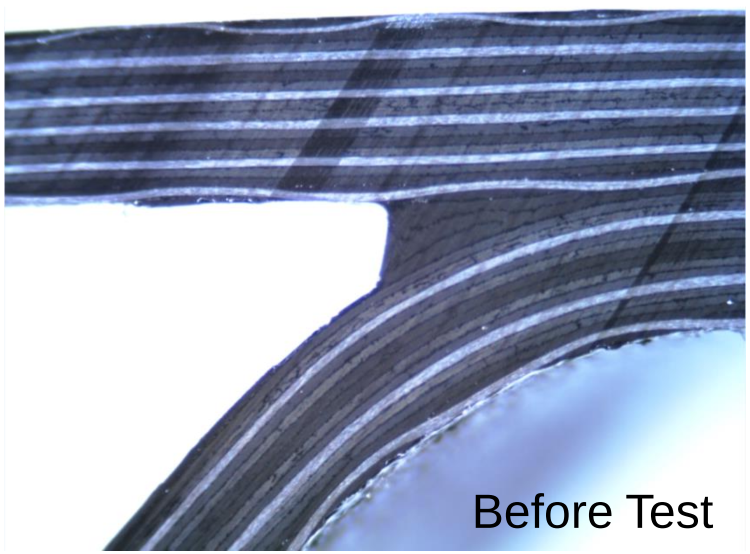
Skin and stringer section (76.2 mm):



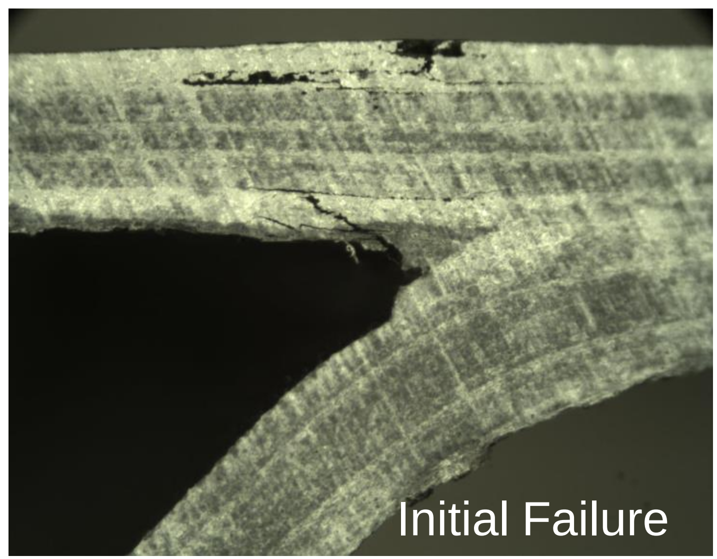


Tested by compression against the bumper





Before Test



Initial Failure

18-ply skin layup $[0/45/90/-45]_{2S}$

- Tension cracks on top 2 plies
- Compression and shear cracks at bottom 3 plies

Stringer Element Compression Modeling

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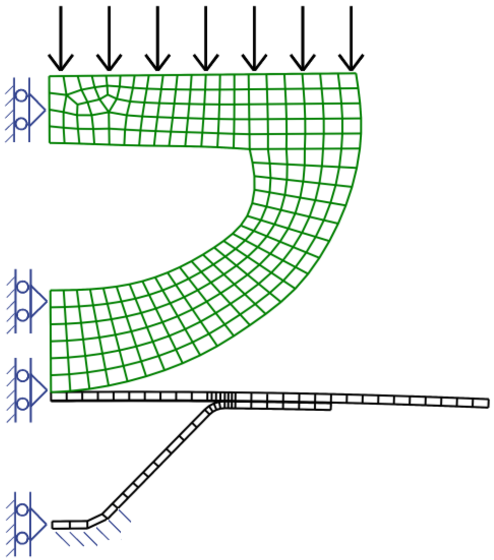
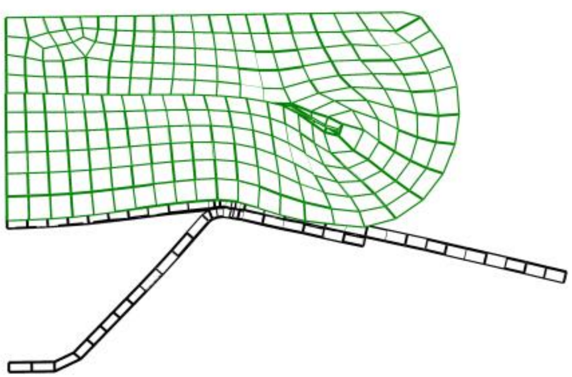
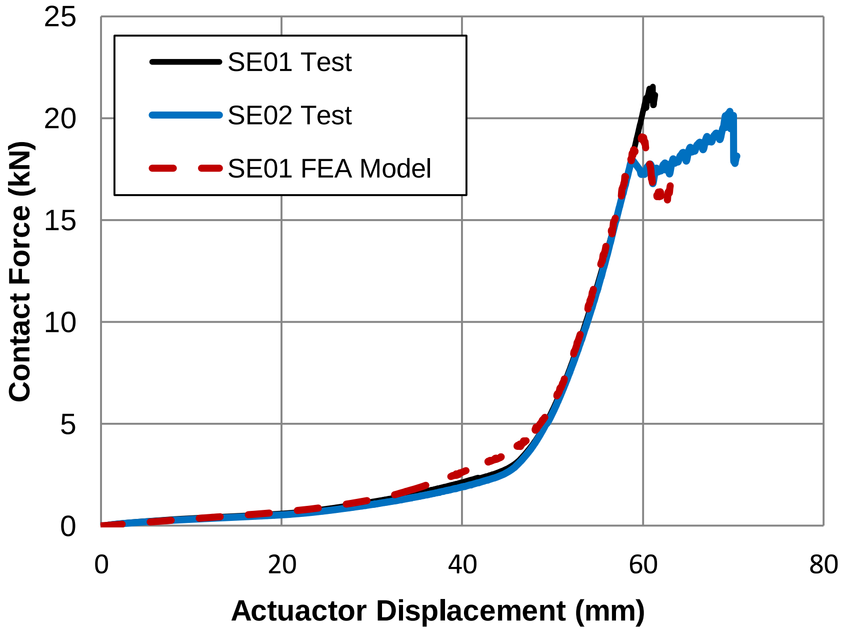


- Half model with symmetry B.C.
- Stringer element fixed at top of stringer
- Bumper model imported from previous section
- 2 layers of shell elements (SC8R) for skin and stringer
- Hashin-Rotem failure criteria
- No cohesive zone modeling, tie displacement at contacting nodes between skin and stringer

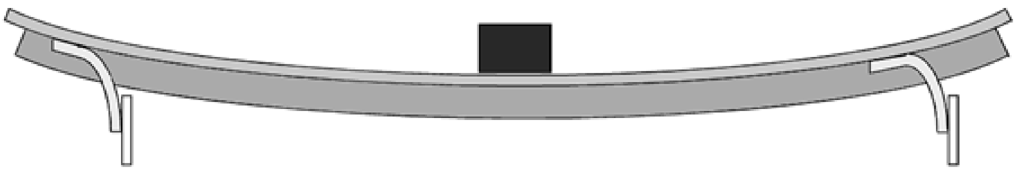


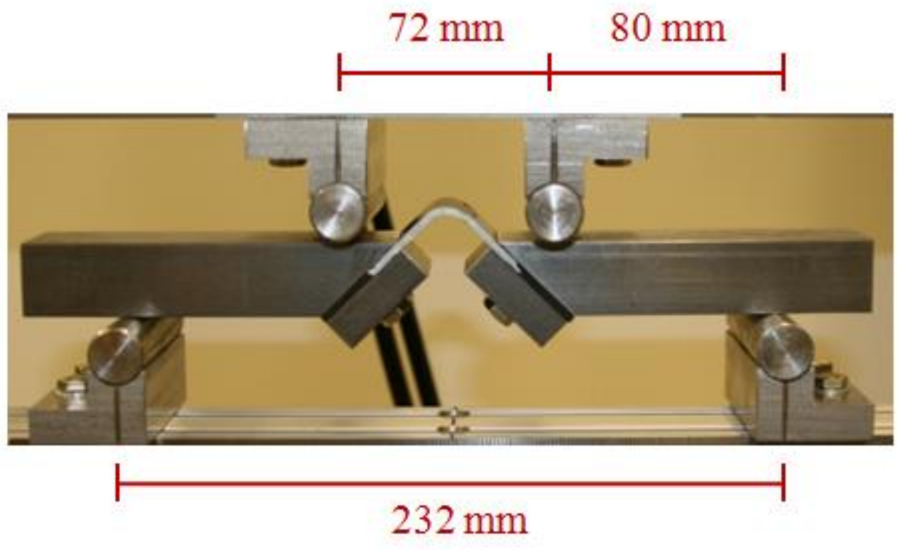
At full compression, the skin bent at the edge of the joint.

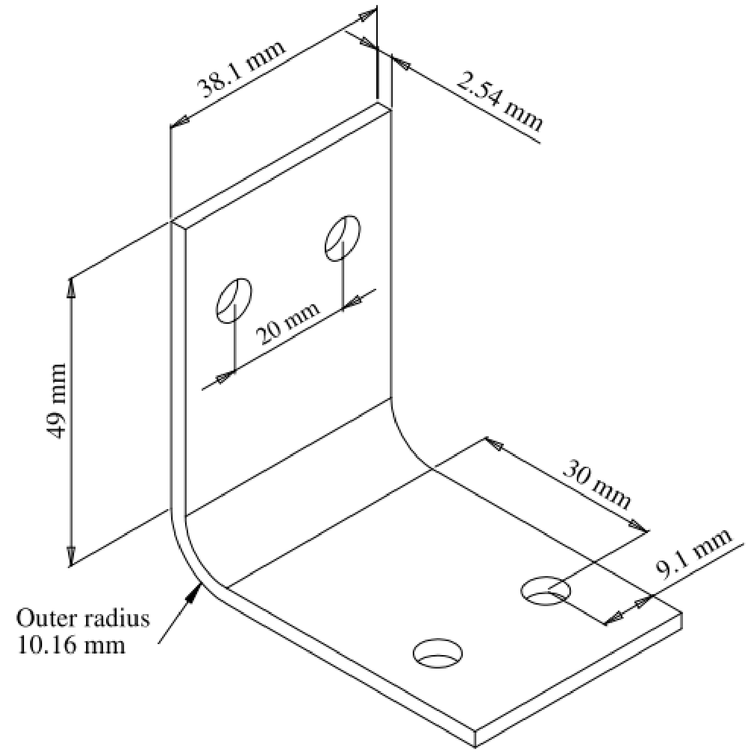


Radial Delamination – Curved Beam Opening

Focus: investigate the shear tie radial delamination due to opening moment







- X840 Z60 6K fabric carbon/epoxy
- 12 plies layup $[\pm45/0]_{3S}$
- Pure opening moment
- Radial tension stress induced delamination

Radial Delamination – Curved Beam Opening Model

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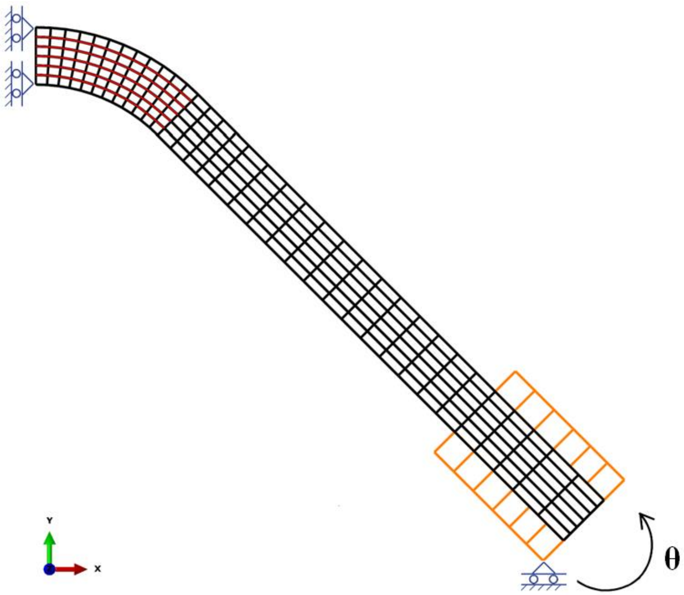
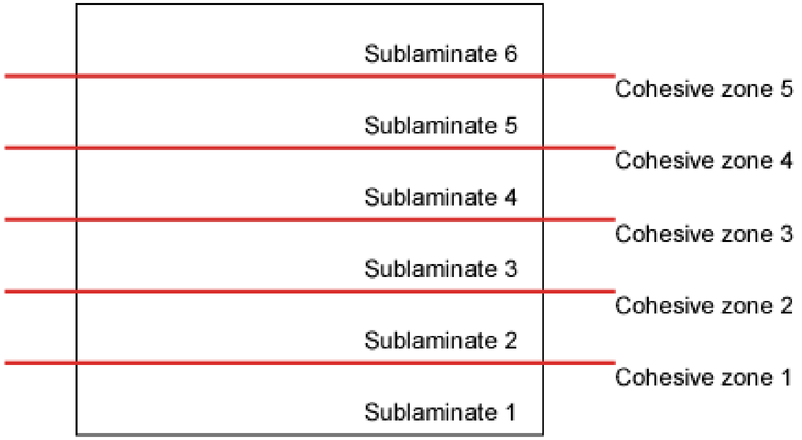


- Half model with symmetry B.C.
- Rollers and rotation B.C. at the flange
- Composite layup partitioned into sublaminates and represented with continuum shell element (SC8R) layers
- Cohesive surface interactions simulate delamination
- 0.66 mm mesh size at curved corner
- Fiber failure not modeled

Ply 12	45°
Ply 11	0°
Ply 10	45°
Ply 9	0°
Ply 8	45°
Ply 7	0°
Ply 6	0°
Ply 5	45°
Ply 4	0°
Ply 3	45°
Ply 2	0°
Ply 1	45°



Radial Delamination – Curved Beam Opening Model

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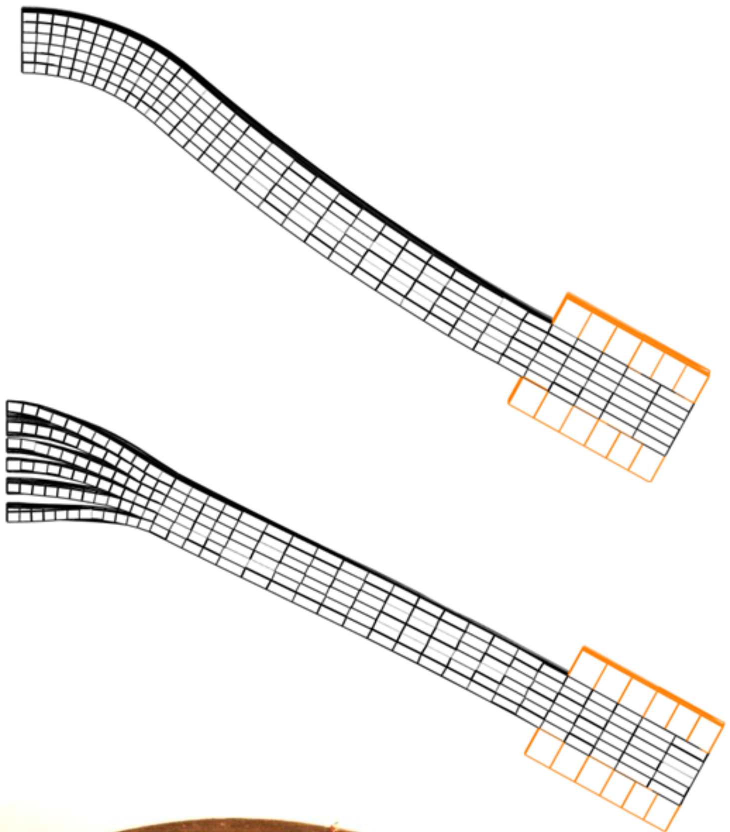

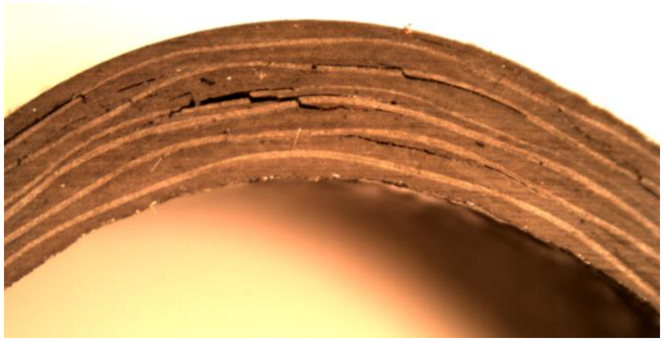

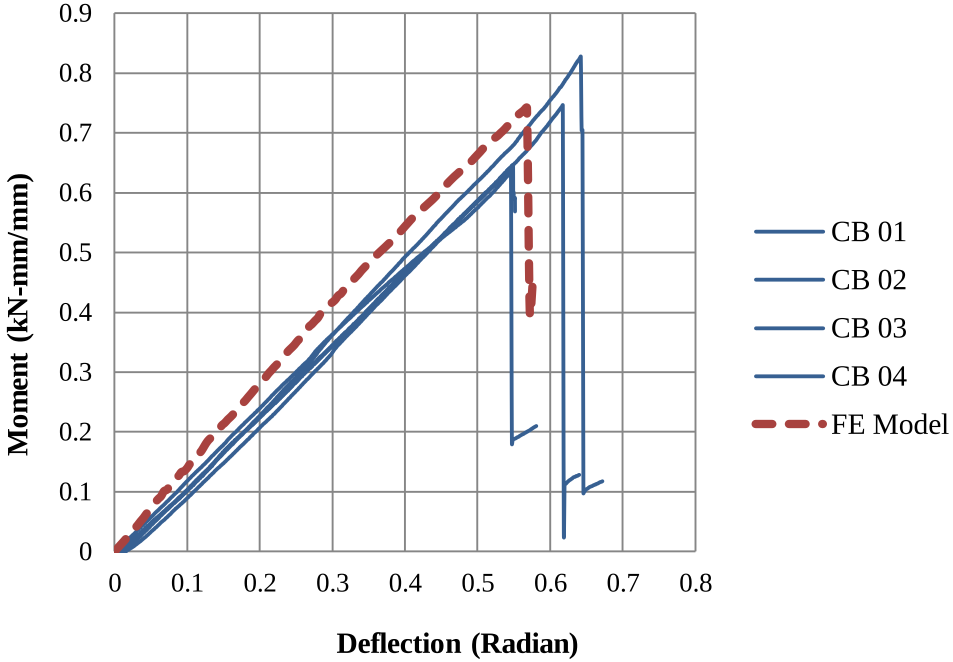

- Model captured the sudden delamination formation
- Failure was more widespread, possibly due to speed increase and reduced number of cohesive layers

Shear Tie Element - Compression and Buckling

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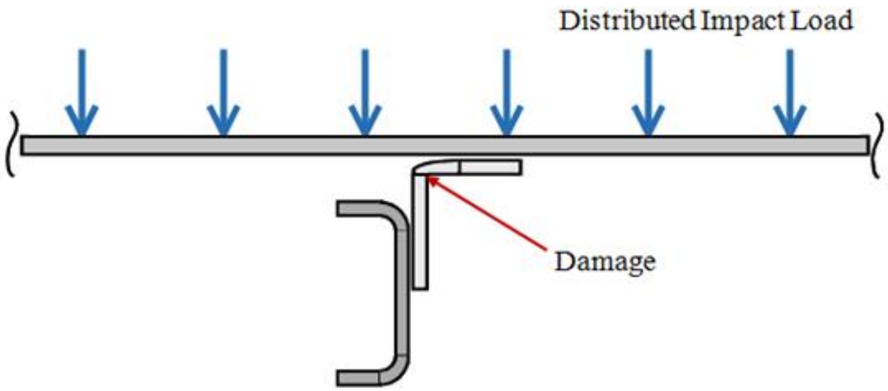
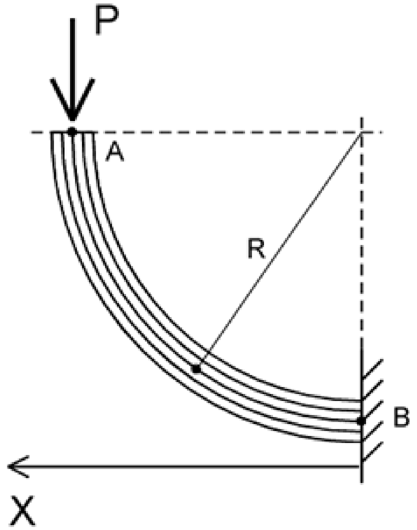
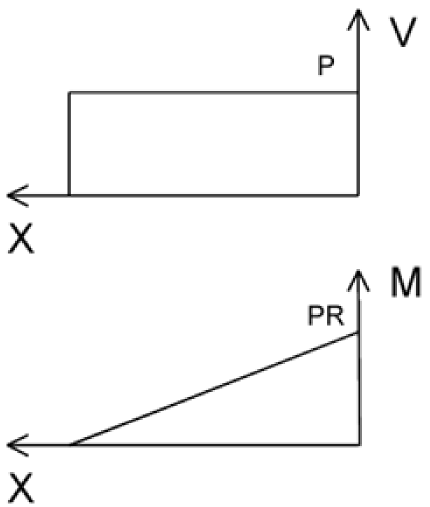
Focus: study shear tie radial delamination and crushing due to compression loading



Pivot on top

Bolted at the bottom





Delamination and fiber crushing expected at point B:

- Constant shear force
- Peak interlaminar shear at B
- Linearly varying moment
- Peak interlaminar tension at B

Shear Tie Element Damage Progression - Compression and Buckling

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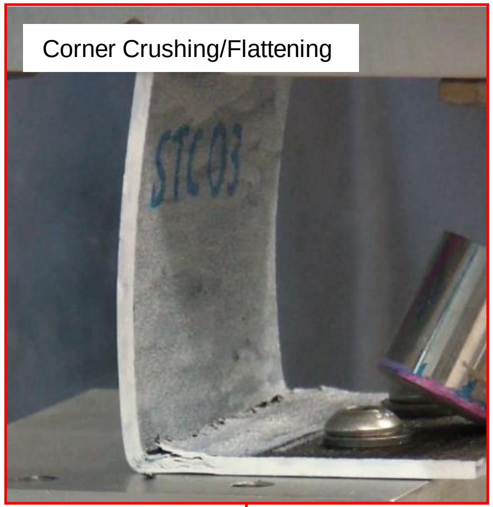

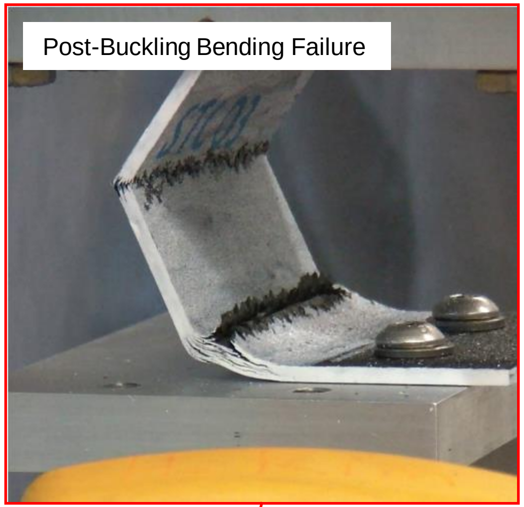

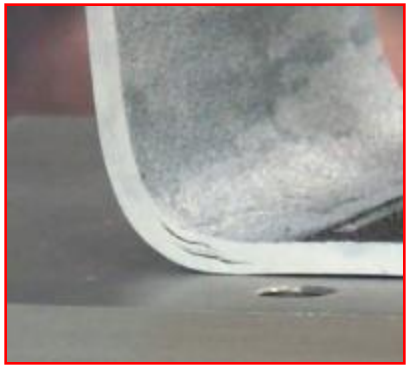

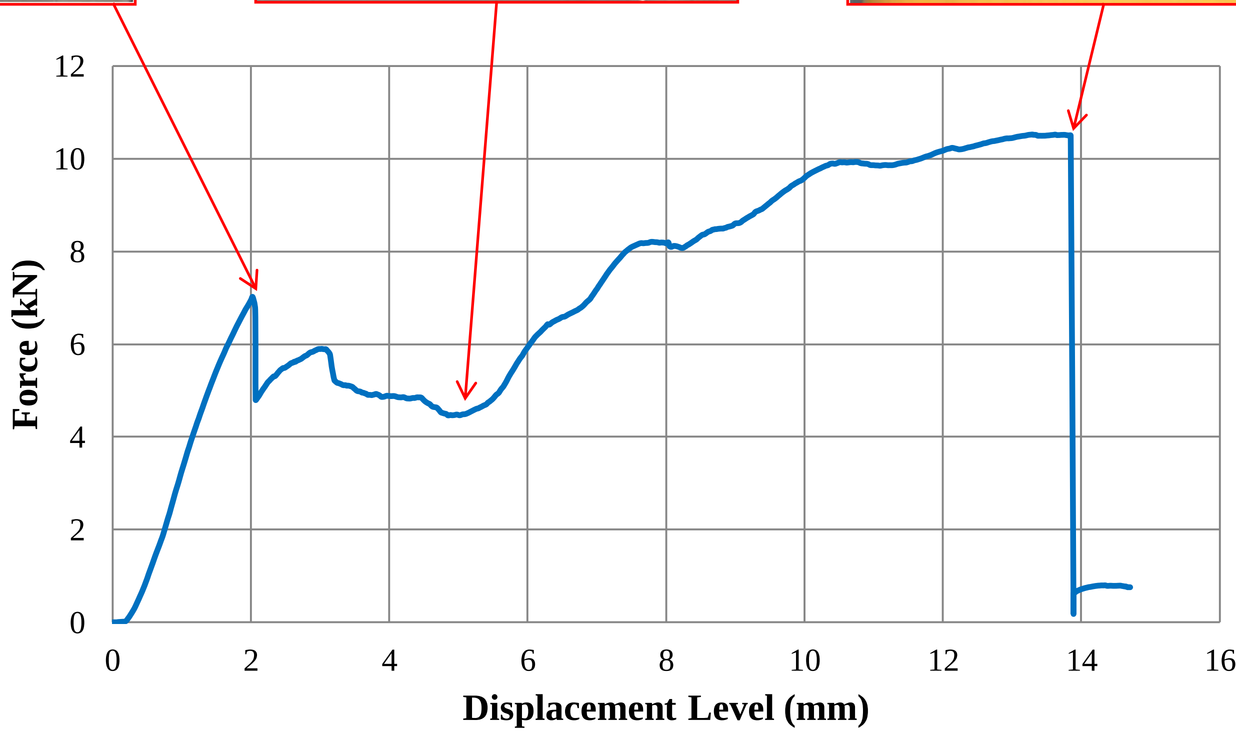

Shear Tie Element - Compression and Buckling Model

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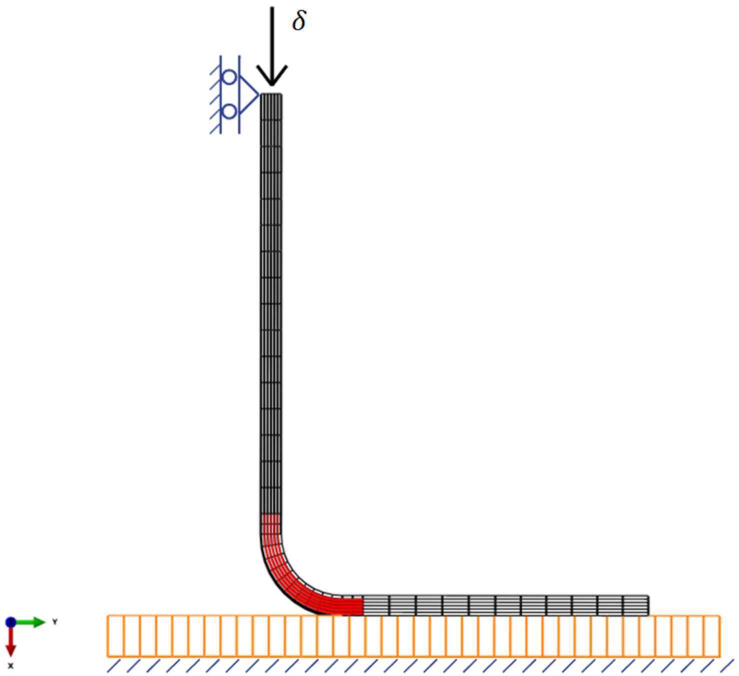

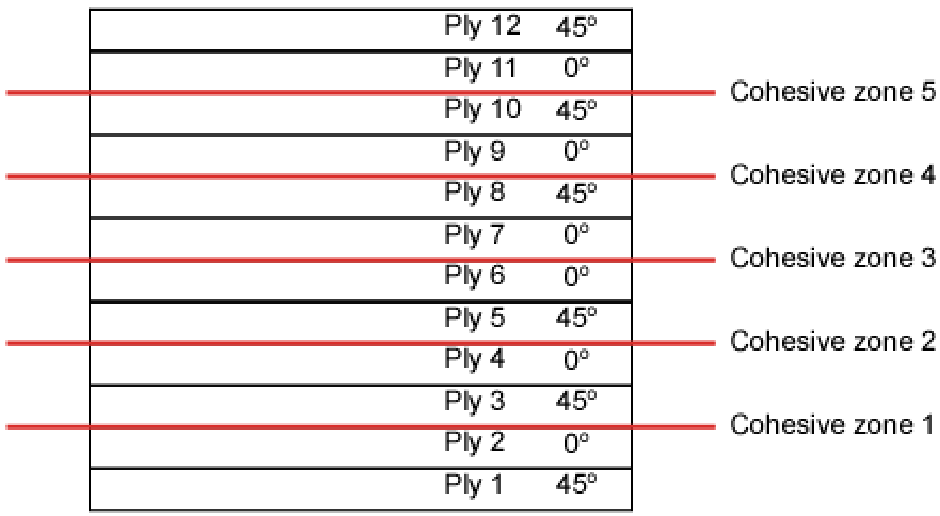

- Fixed at aluminum plate, roller and applied displacement at flange
- Penalty contact constraint
- 1.27 mm mesh in curved corner, 3.3 mm elsewhere
- Solid (C3D8R) elements

- 12 element layers through the thickness
- Cohesive surface interaction at curved corner to simulate delamination
- Hill's 3D failure criteria for ply failure

$$I_F = \frac{{\sigma_{11}}^2}{X^2} + \frac{{\sigma_{22}}^2}{Y^2} + \frac{{\sigma_{33}}^2}{Z^2} - \frac{\sigma_{11}\sigma_{22}}{X^2} - \frac{\sigma_{22}\sigma_{33}}{Y^2} - \frac{\sigma_{11}\sigma_{33}}{Z^2} + \frac{{\sigma_{12}}^2}{{S_{12}}^2} + \frac{{\sigma_{23}}^2}{{S_{23}}^2} + \frac{{\sigma_{13}}^2}{{S_{13}}^2} = 1$$

Shear Tie Element - Compression and Buckling Model

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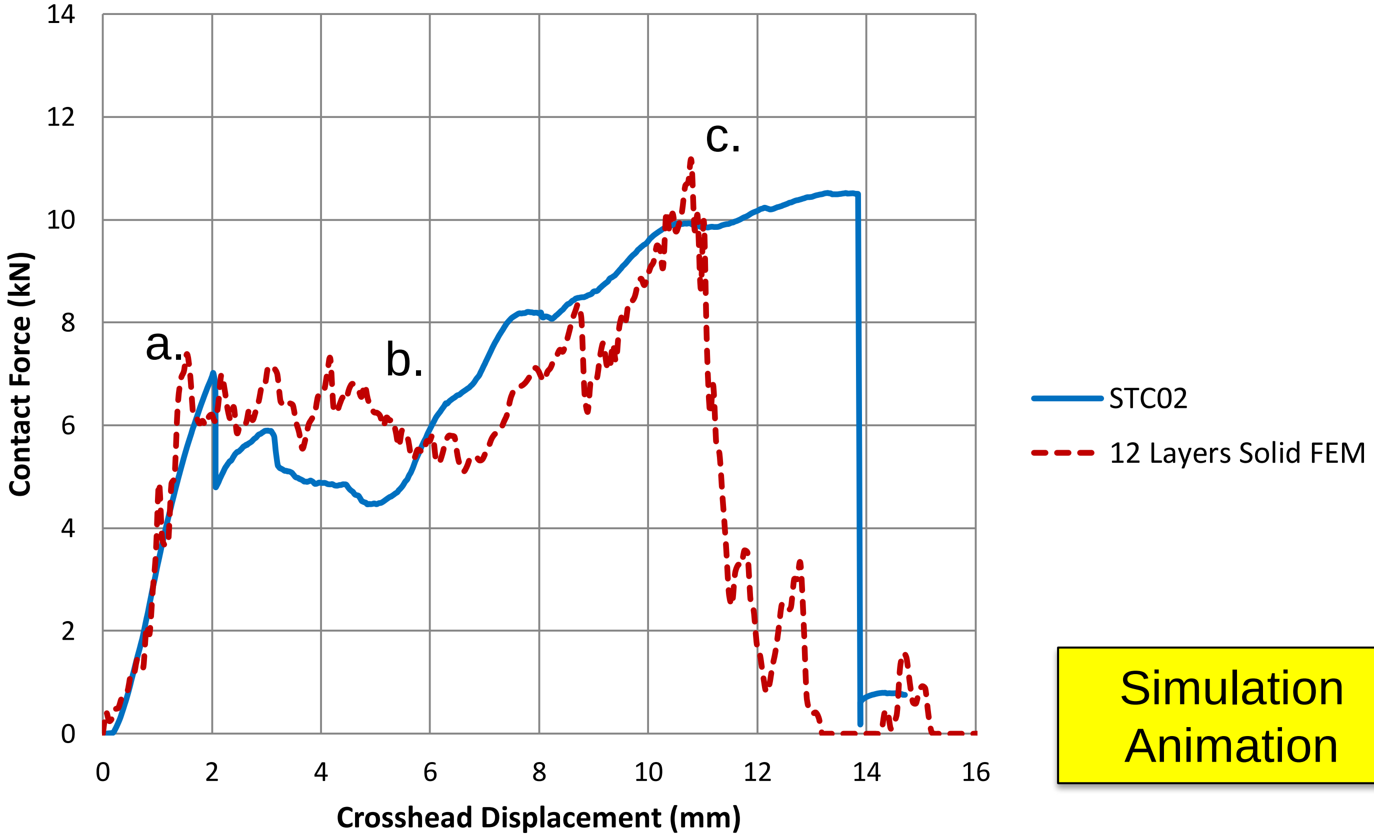
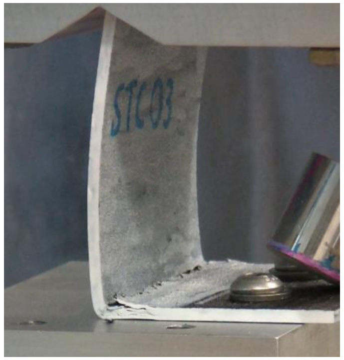
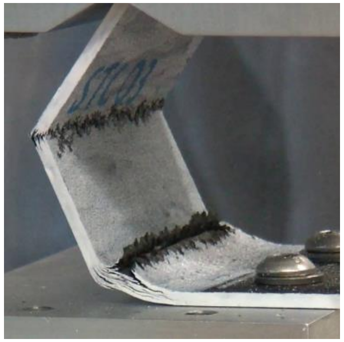
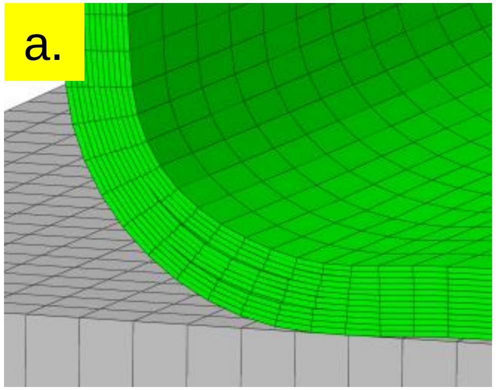
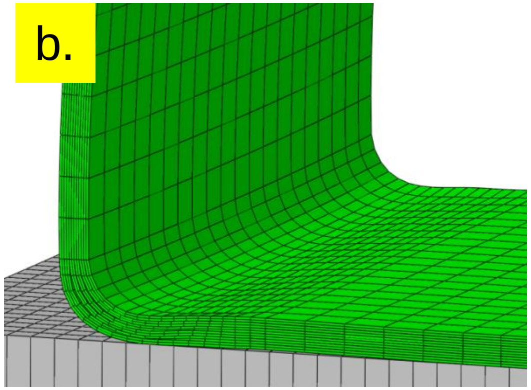


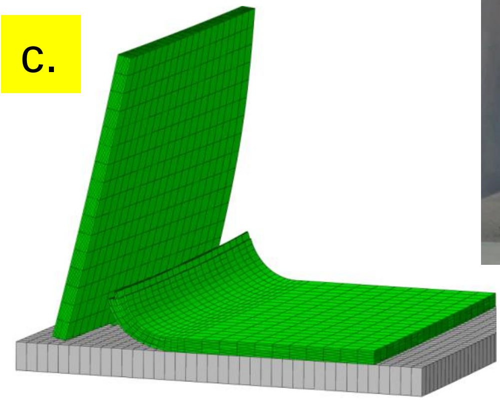




Simulation Animation

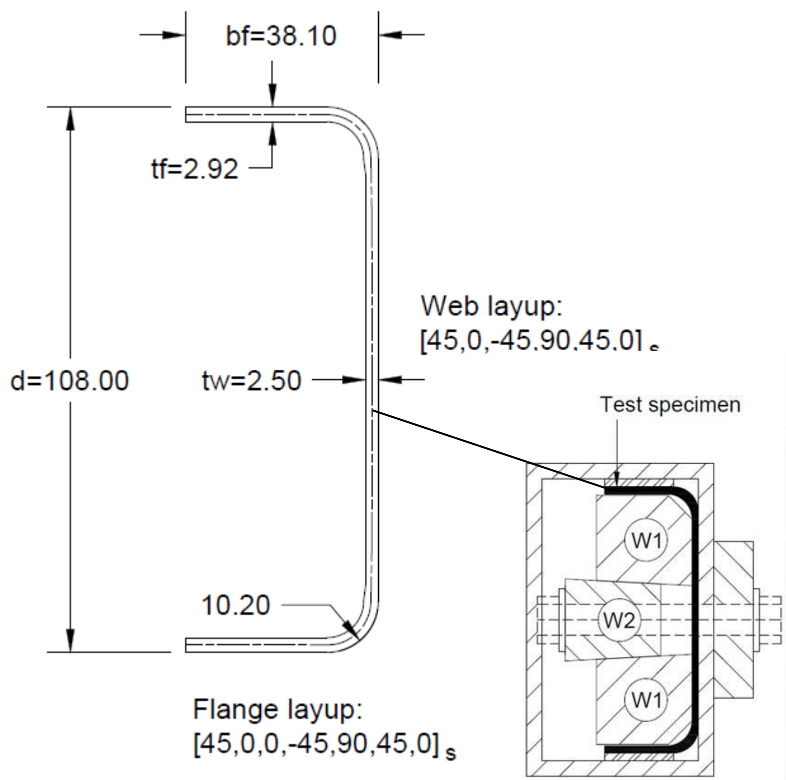


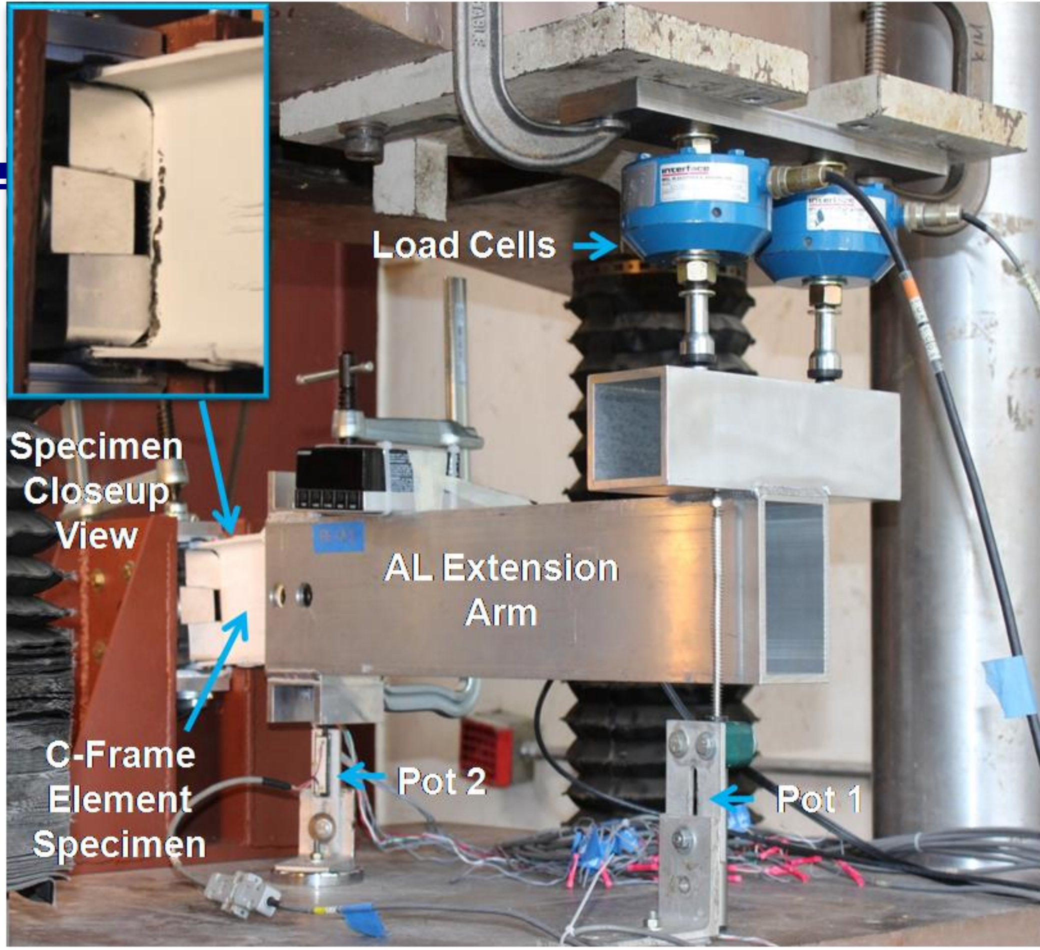


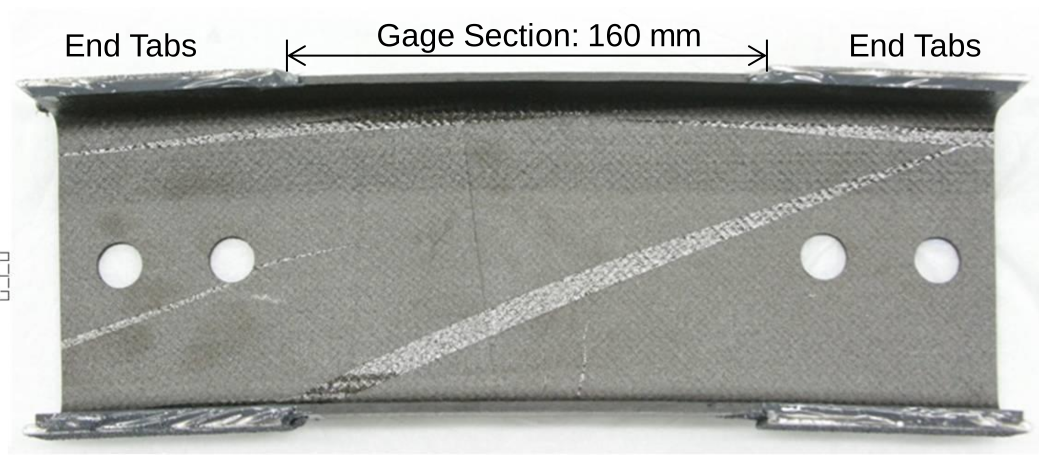


C-Frame Element
Bending & Bending-Torsion

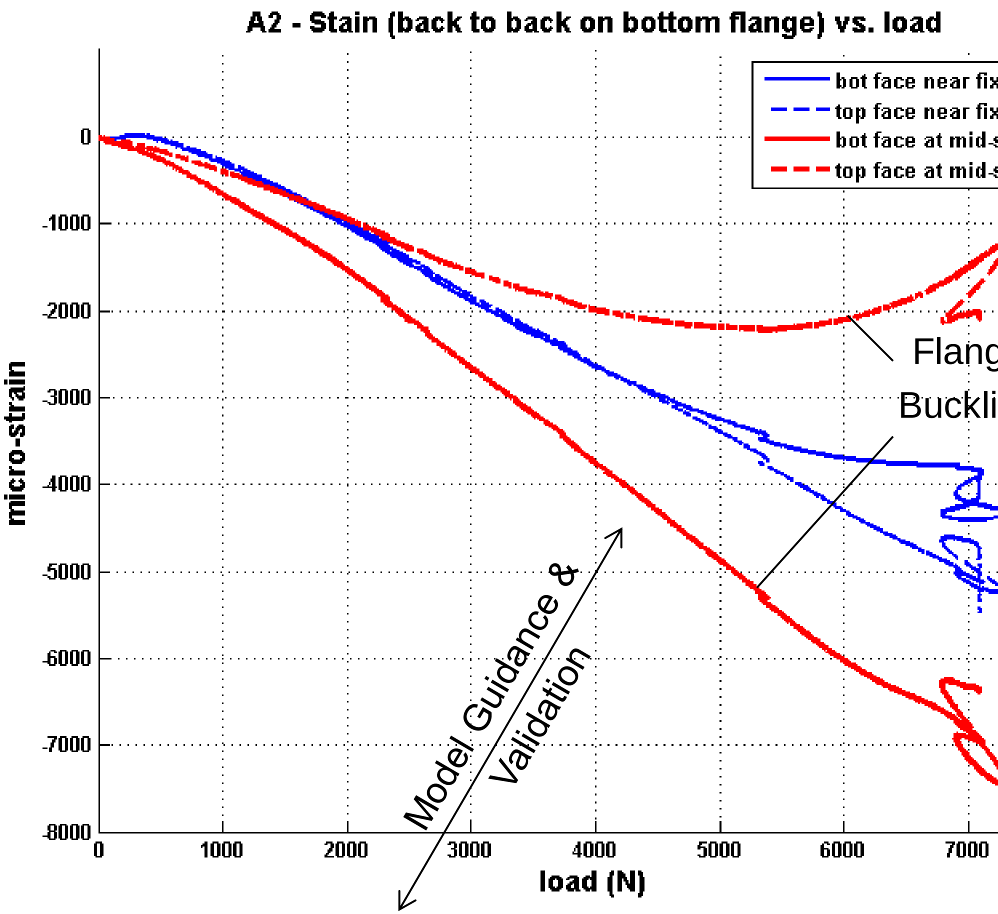
- C-frame test specimen
  - short section w/ extension arm
- fixed end boundary condition
- loaded end:
  - 2 point connection → bending
  - 1 point → bending + torsion



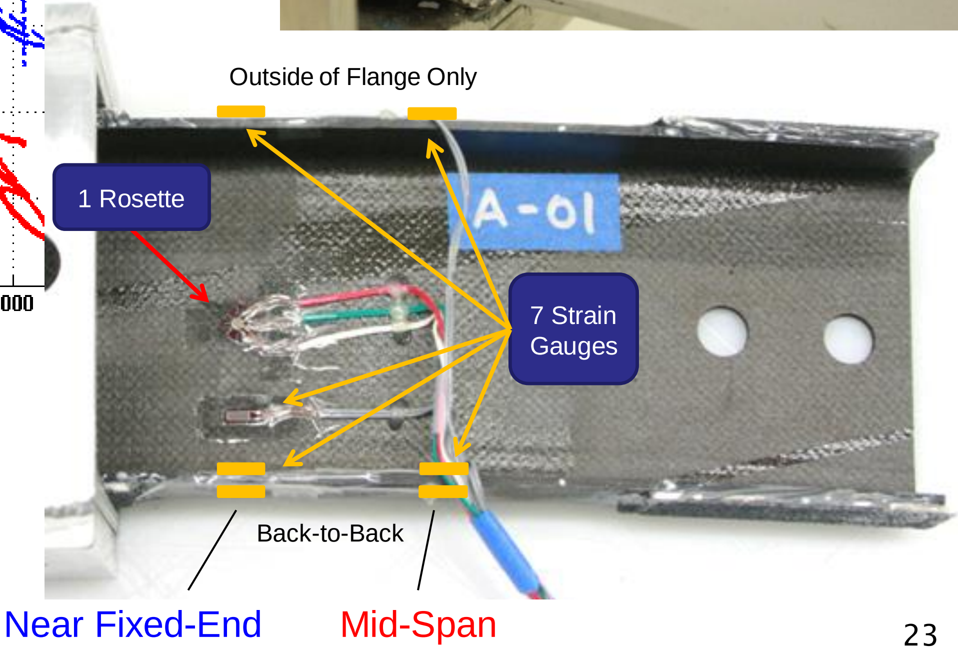


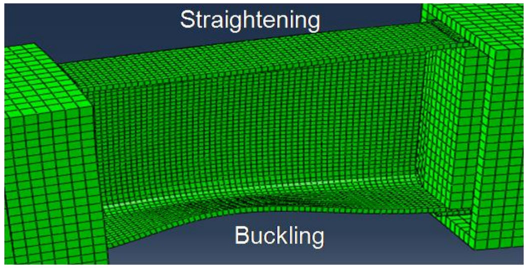


C-Frame Element Bending Test Results (A2)



Comp. Bending Failure (A2)





Modeling Work Ongoing

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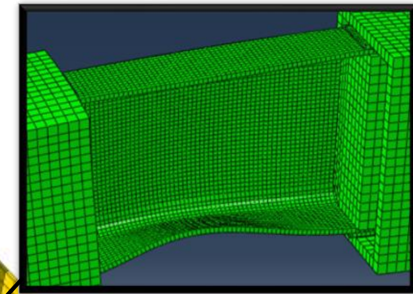
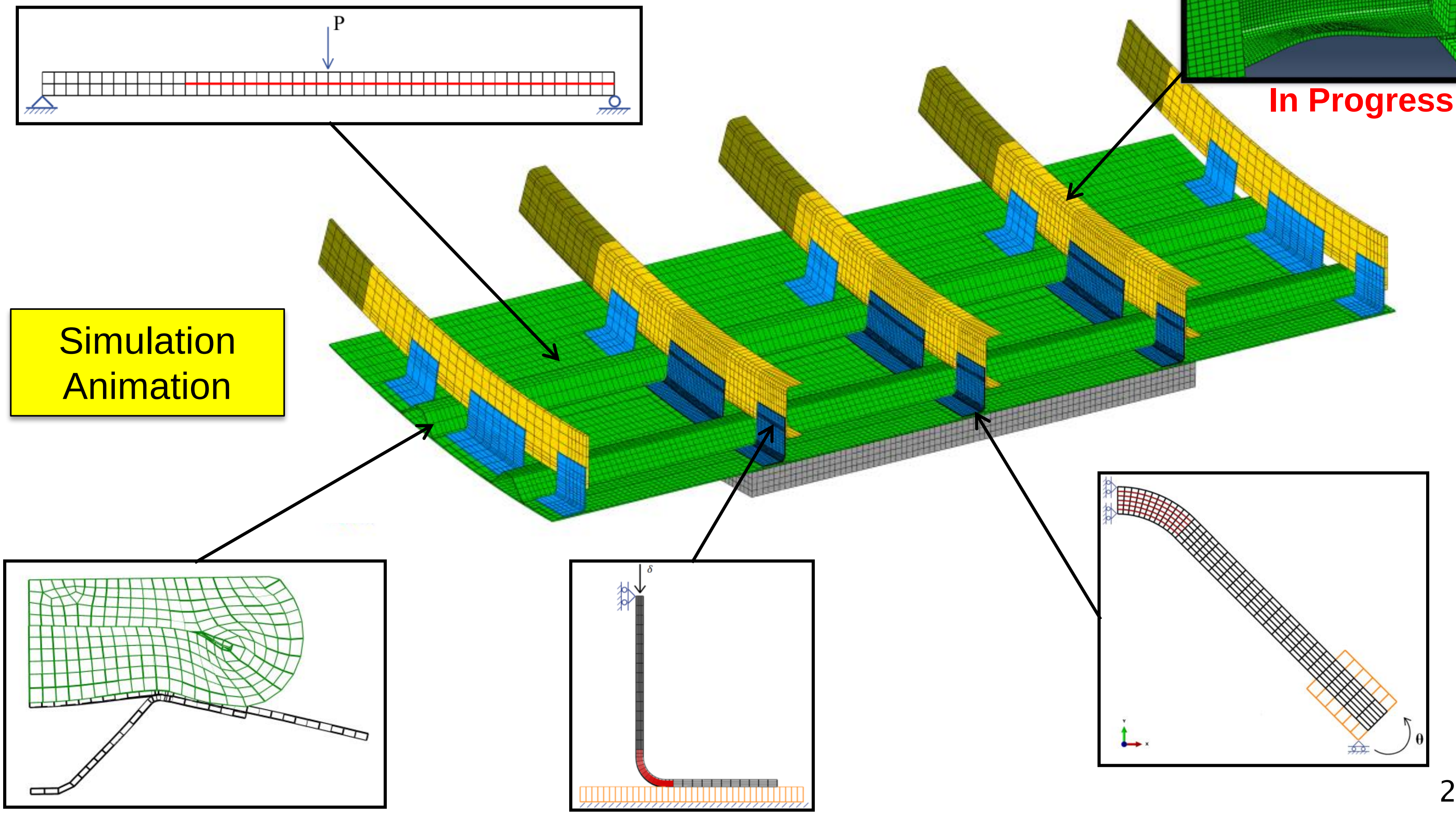
Modeling definitions for element-level small scale studies exported into large-scale models

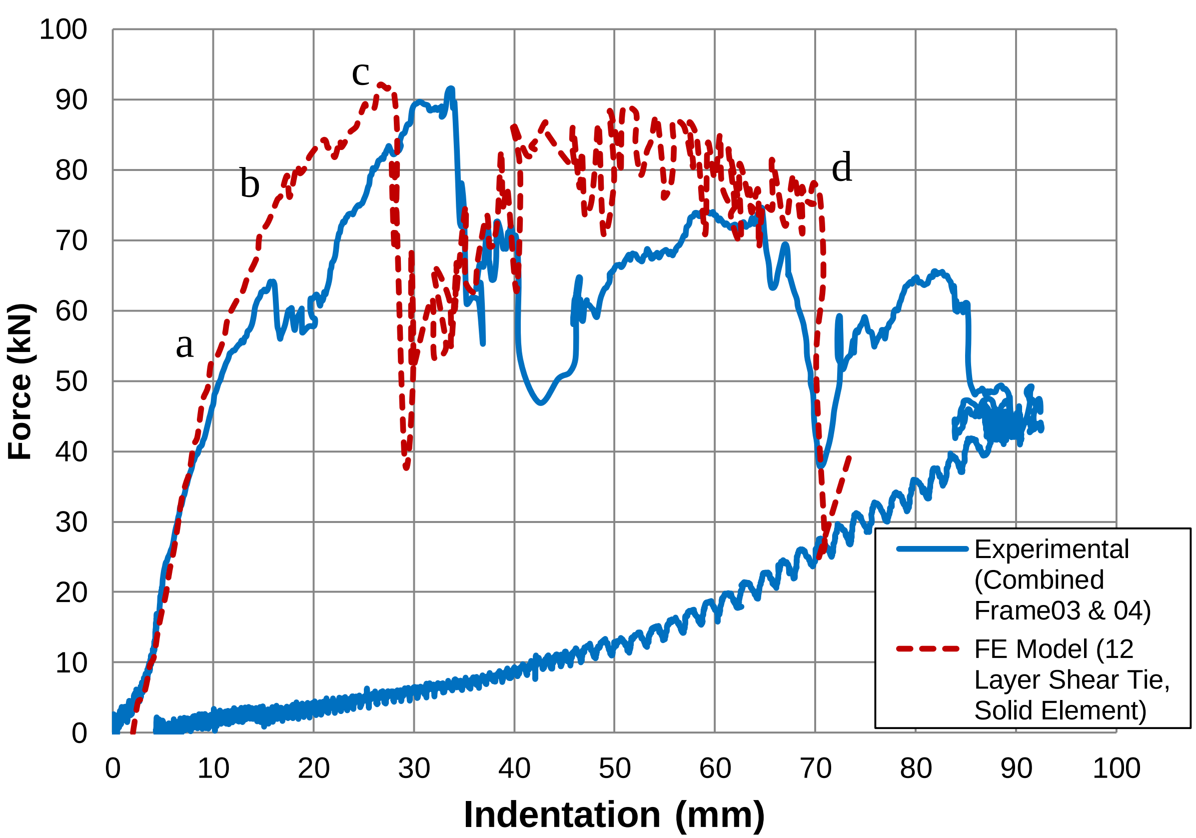


In Progress



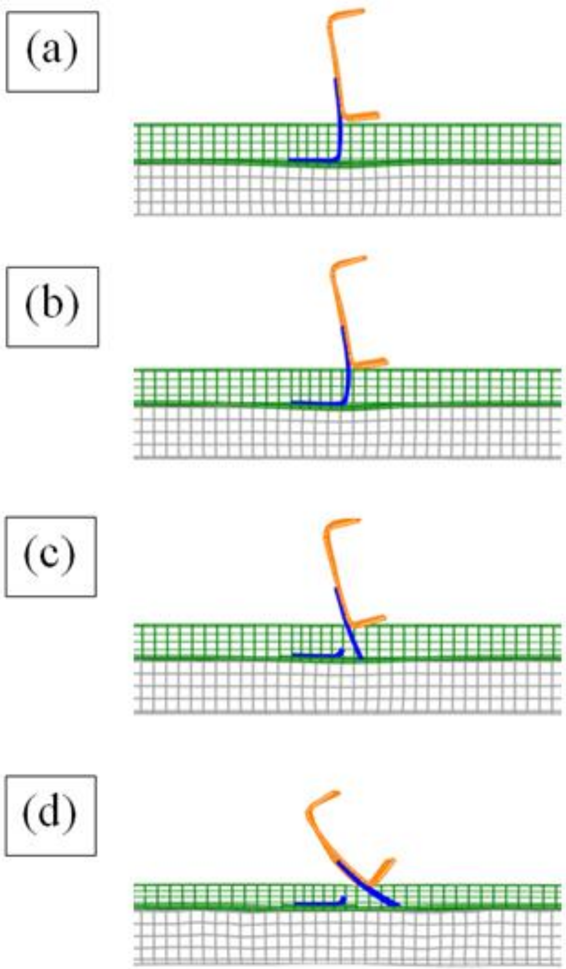
Simulation Animation

Frame03 Model – Key Failure events



Failure events in the model:

a. Impacted shear tie radial delamination
b. Impacted shear tie corner crushing
c. Impacted shear tie fracture
d. Adjacent shear tie and C-frame fracture



Cross-section view through C-frame

Modeling Capabilities Plan

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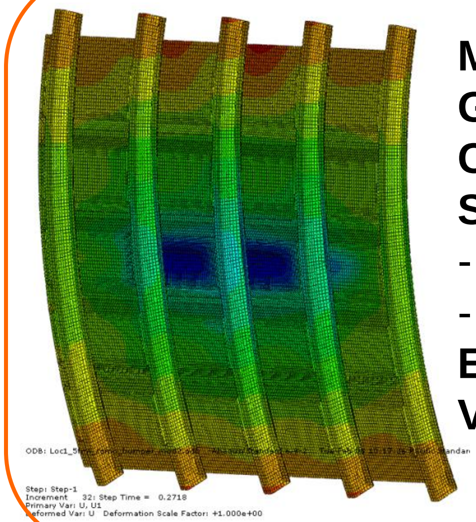


Models of Generic Curved Panel Specimens
- Static
- Dynamic

Experimental Validation

Establish Capabilities

Define Methodologies With Element Level Tests

Capture Key Failure Modes (Major Damage)

Damage Initiation Criteria

Damage Progression

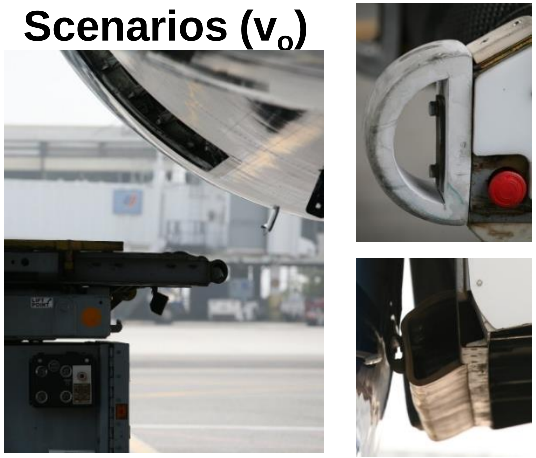
Dynamic Effects

Externally Visibility

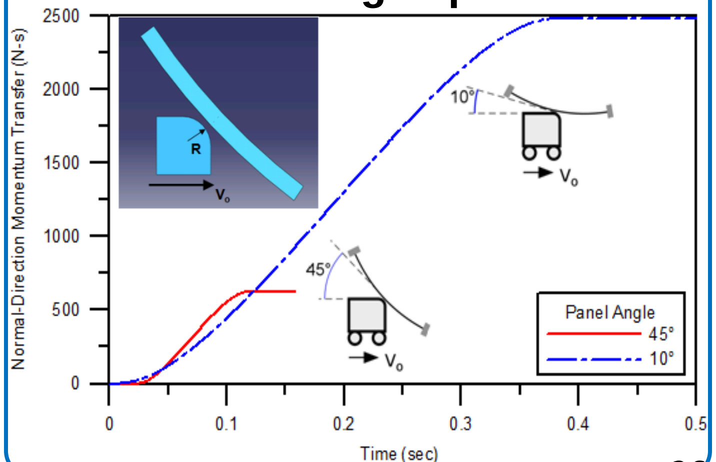
Apply to study and predict response for:

Size, Complex Internal Structure, Geom., Joints

Various Impactors & Scenarios (v_o)



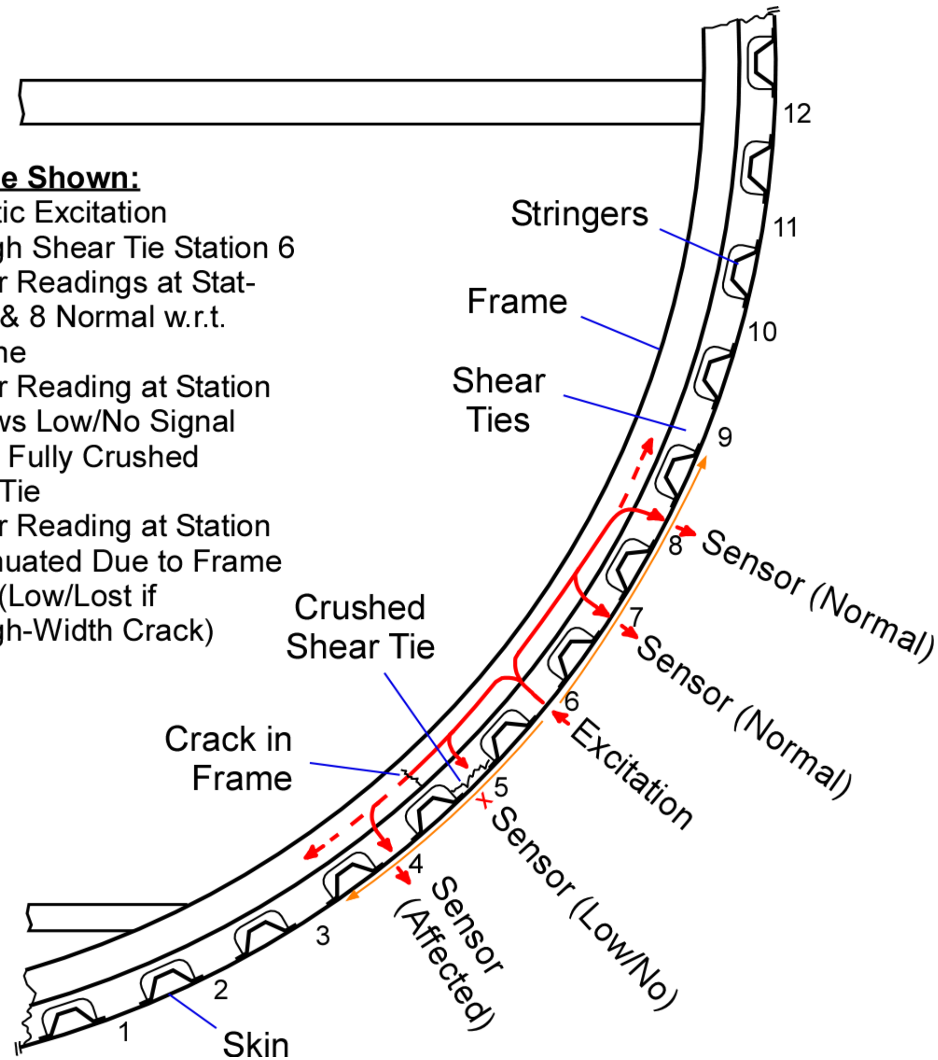
Glancing Impact



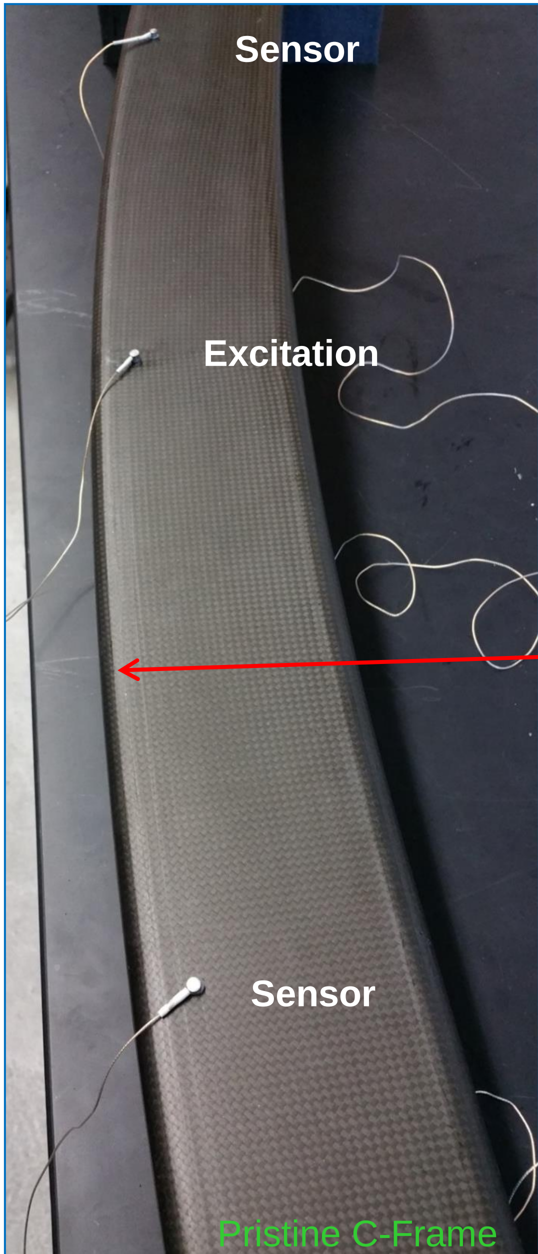
NDE Methods for Detecting Major Damage in Internal Composite Structural Components

- pitch-catch guided ultrasonic wave (GUW) approach
- C-frame is like 1D waveguide
  - wave transmission along length affected by damage
  - broken shear tie and frame will attenuate/modify signal
- key issues:
  - find dominant frequencies associated with those waves/modes sensitive to damage
  - complex geometry, many interfaces
  - parallel wave path through skin

Example Shown:
- Acoustic Excitation Through Shear Tie Station 6
- Sensor Readings at Stations 7 & 8 Normal w.r.t. Baseline
- Sensor Reading at Station 5 Shows Low/No Signal Due to Fully Crushed Shear Tie
- Sensor Reading at Station 4 Attenuated Due to Frame Crack (Low/Lost if Through-Width Crack)



GUW Tests on Damaged C-Frame



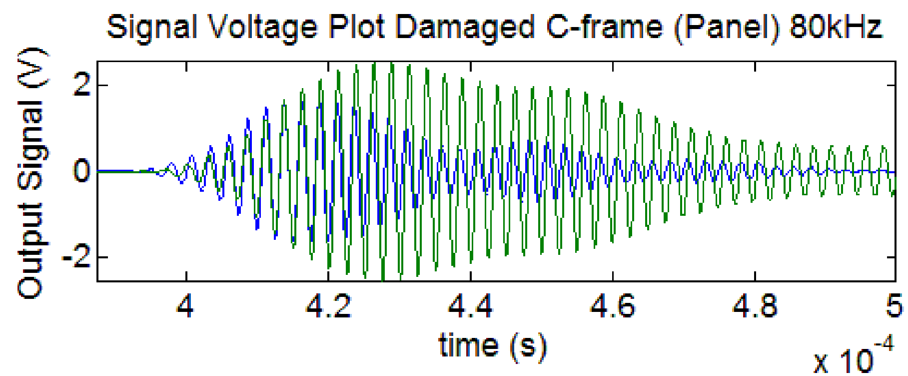
Partial Crack

Frequency sweep conducted to find dominant frequencies (80 kHz shown below).

Expect: presence of damage → attenuation of signal.

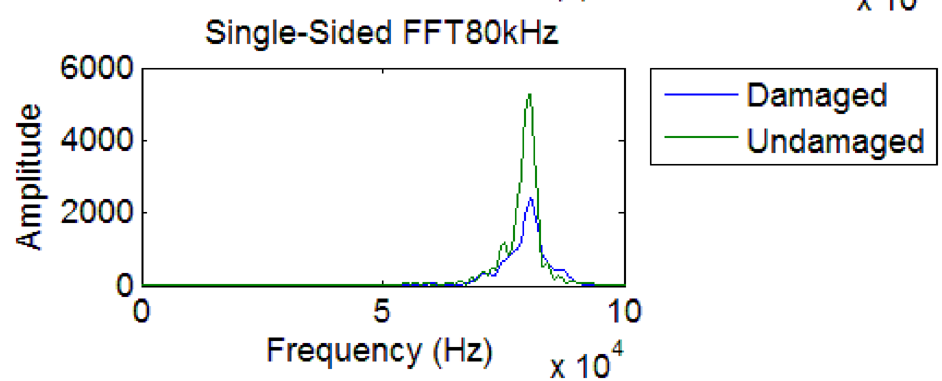
Damaged C-frame installed in panel:

- significant attenuation (55%) through damaged path
- ***crack in C-frame flange detectable*** for sensors directly mounted to frame – next: test sensing through skin



Sensors located 305 mm (12 in.) from Excitation.

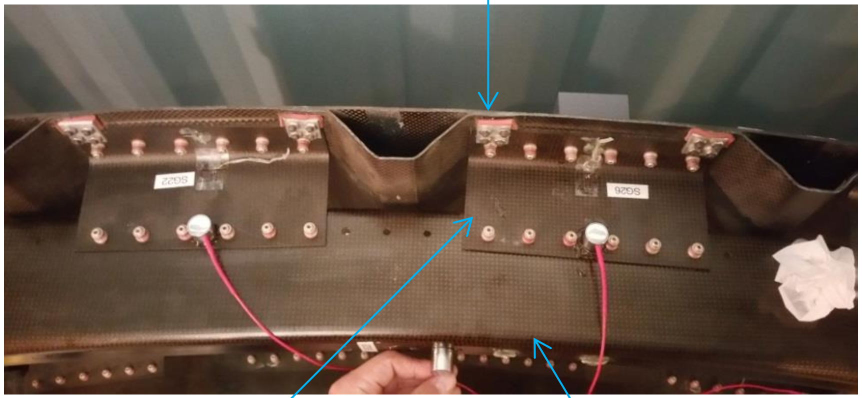
Excitation: 5-cycle sinusoidal burst sent at various frequencies.



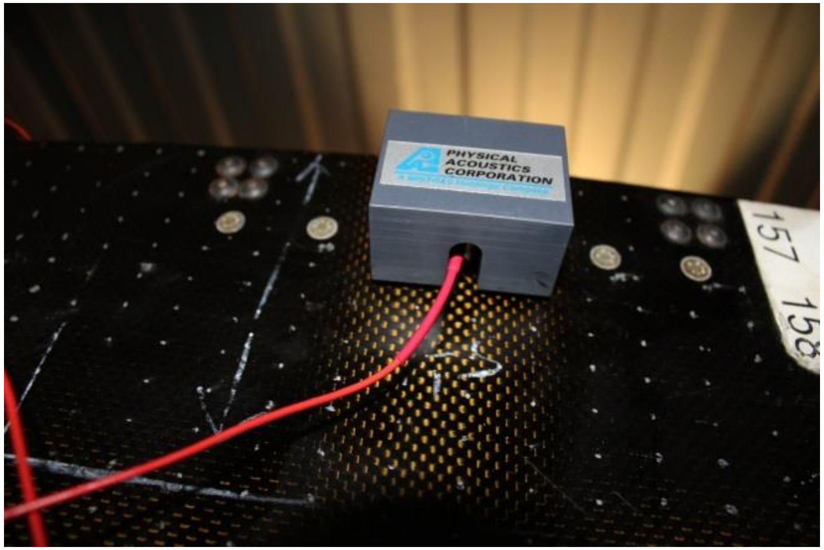
GUW Tests Through Shear Ties

Excite on Skin at Shear Ties → Measure in Frame

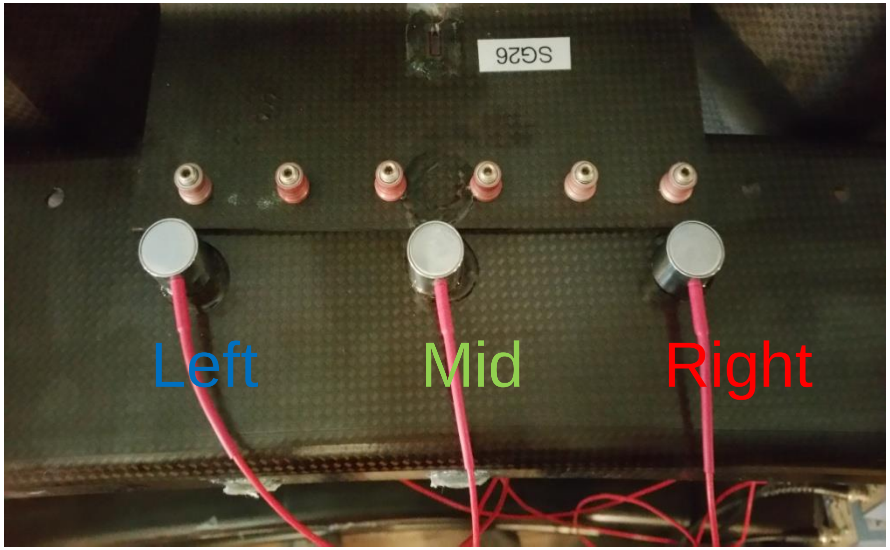
- observe how waves propagate through interfaces and bolt lines
- observe capability of GUW method to detecting damaged shear ties



Excitation on Skin

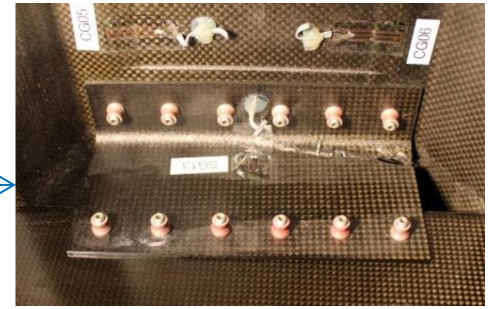


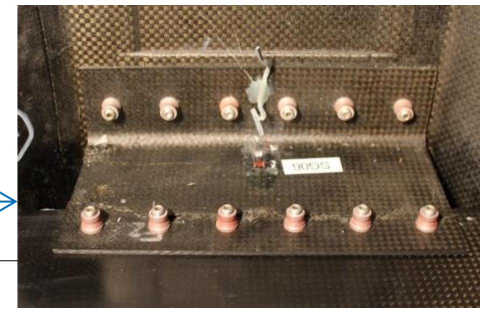
Sensing on Frame

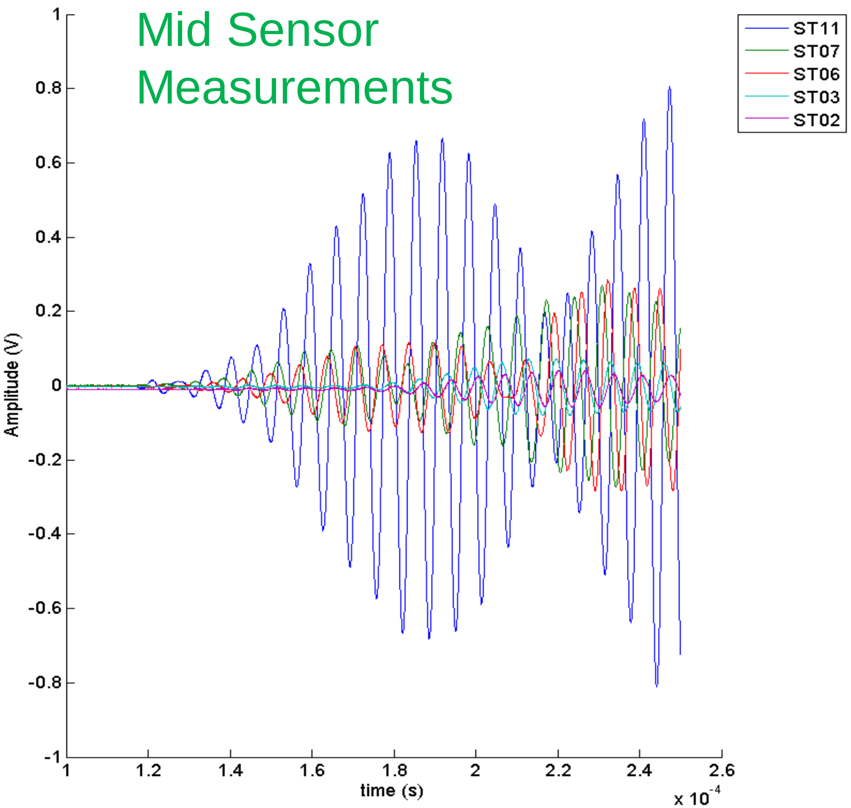


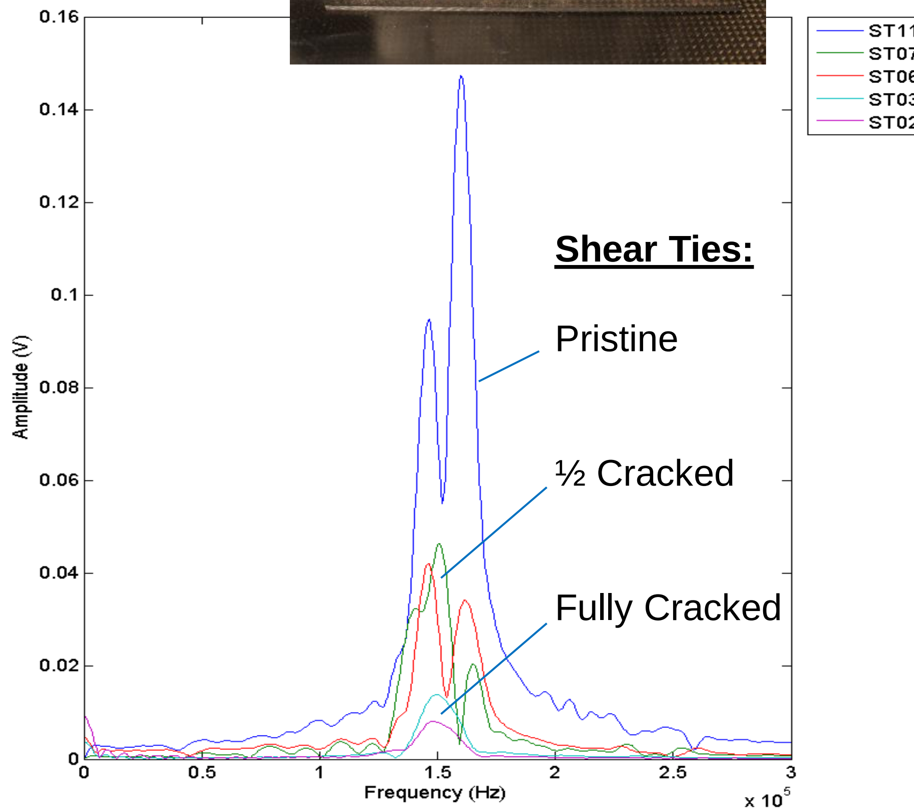
Comparison

- GUW Test: Skin to Frame
  - Shear Tie 11 (Pristine)
  - Shear Ties 07 and 06 are partially cracked at the corner
  - Shear Ties 03 and 02 are fully cracked along the bolt lines





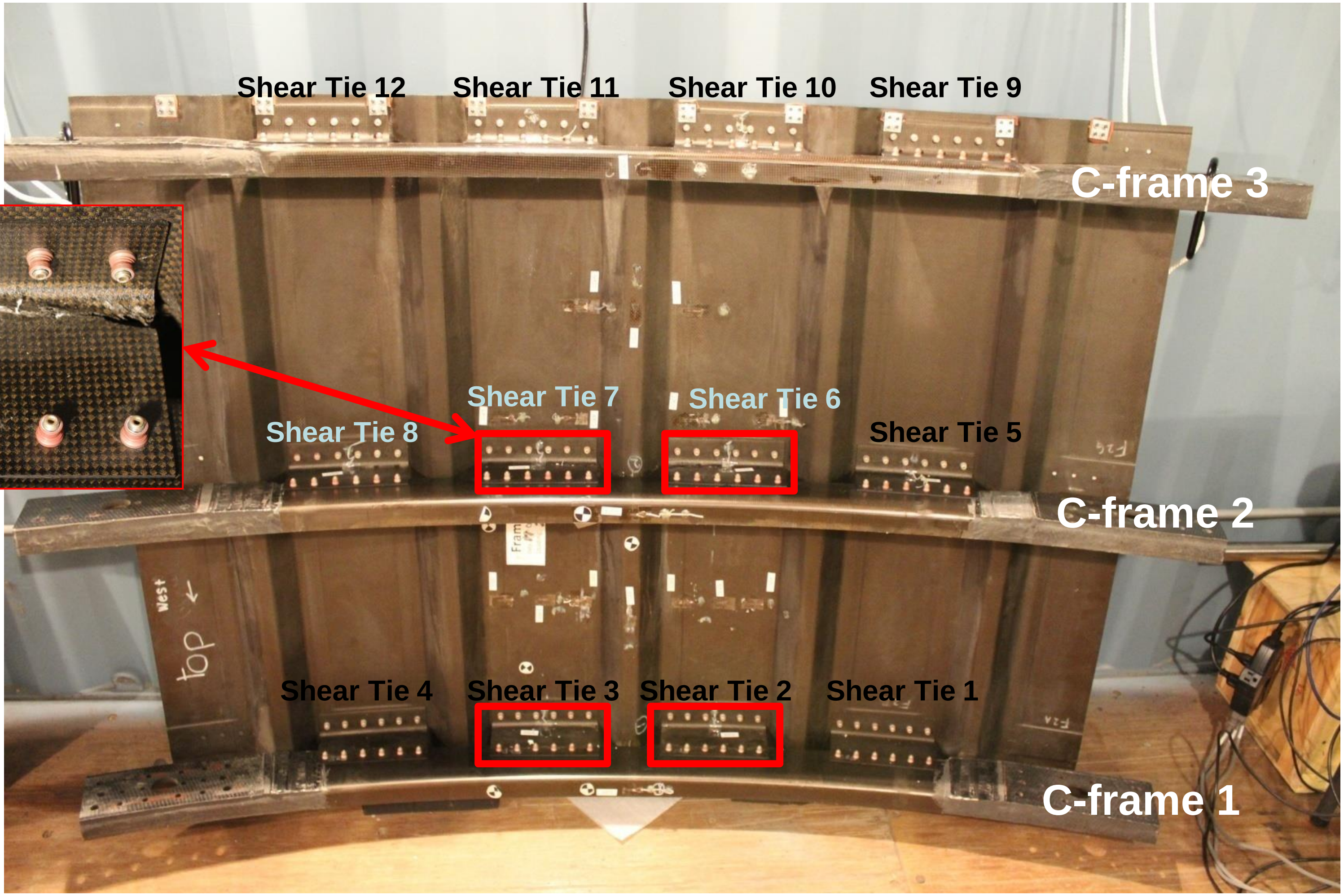




Exterior-Only GUW Tests (Skin-to-Skin)

- Frame 02 Panel With Damaged Shear Ties (2, 3, 6, and 7)
- Excitation and Sensing from Outer Skin Surface at Shear Ties

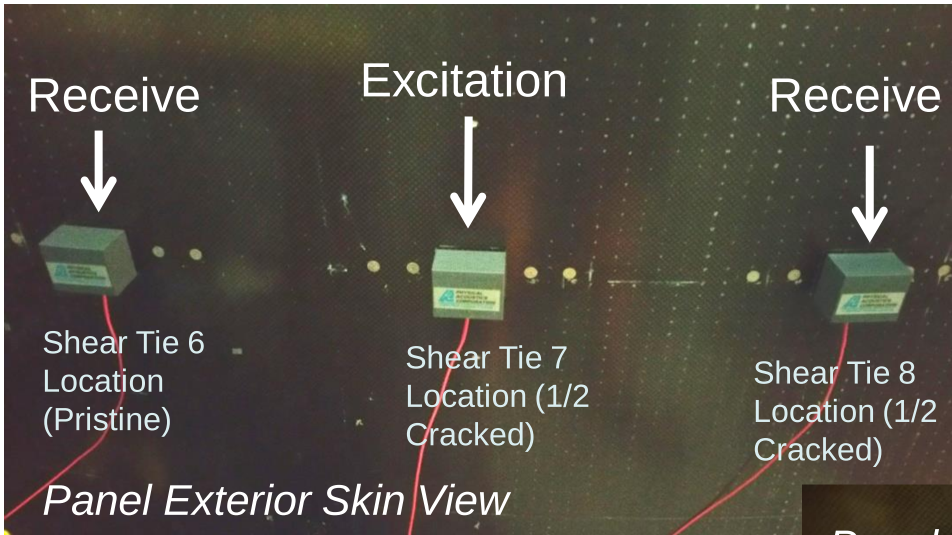
Shear Tie 7



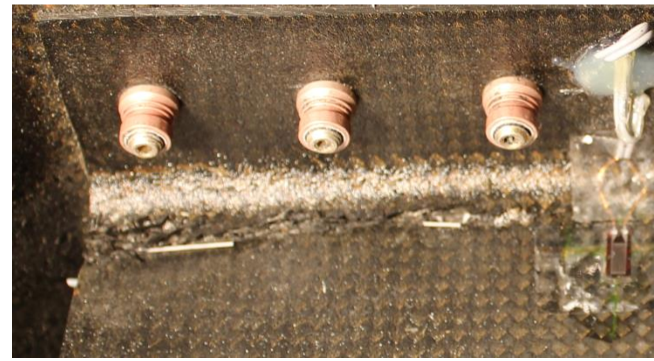
Panel Inside View

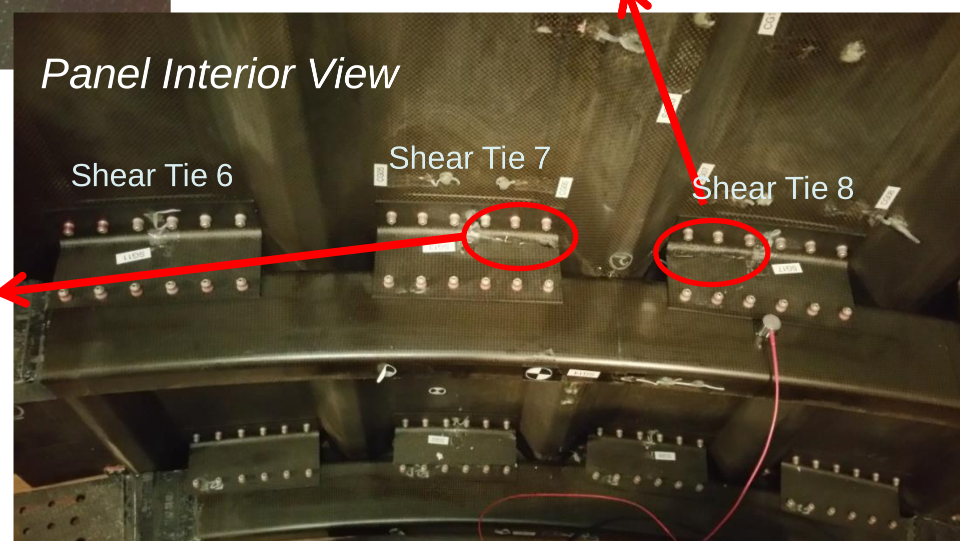
Exterior-Only GUW Test Setup

- GUW test from Skin to Skin (Damaged vs. Undamaged)



Shear Tie 8

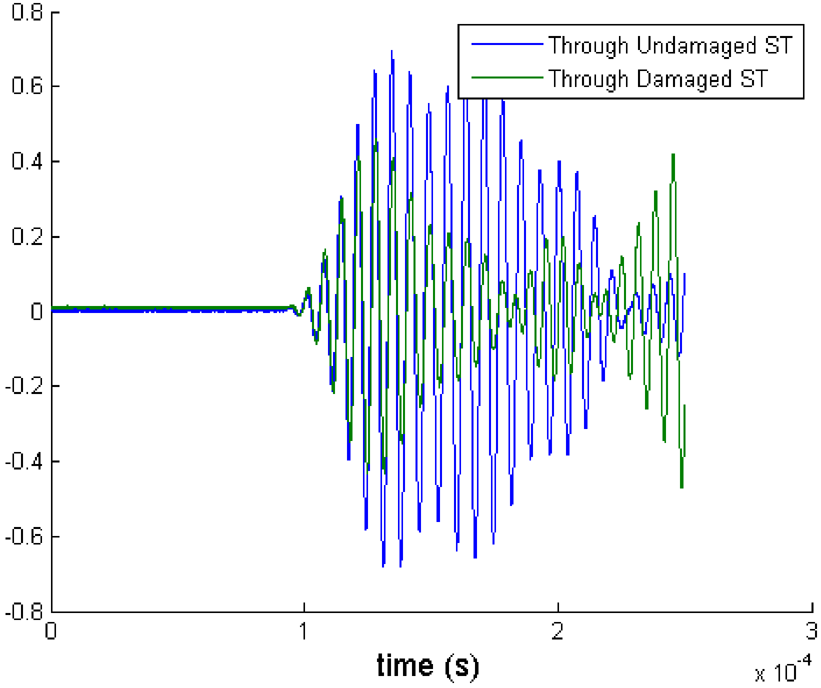


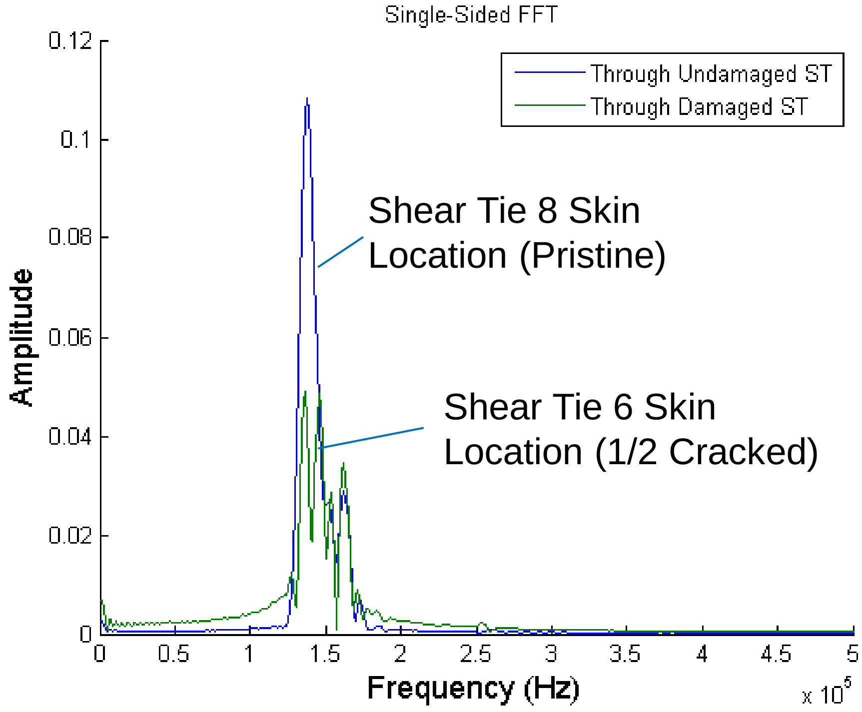


Shear Tie 7

Exterior-Only GUW Test Results

- Excitation at Shear Tie 7
- Receive at Shear Tie 8 (1/2 Cracked) and Shear Tie 6 (Pristine)
- Significant signal strength reduction for path through damaged shear tie





Summary: Blunt Impact Damage

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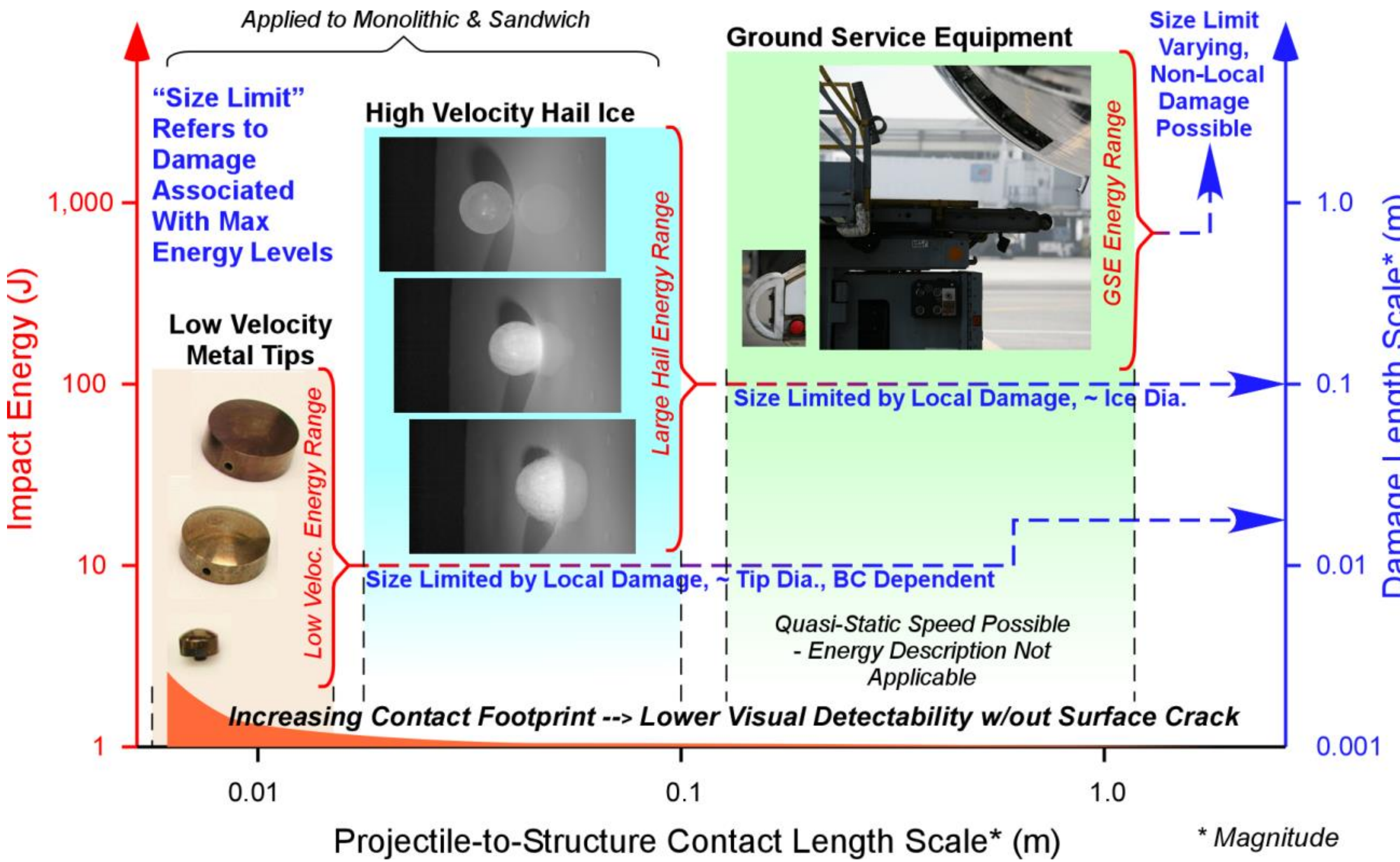
- **Wide contact area allows high contact forces to develop without surface-visible damage**
- **Damage size highly dependent on contact footprint**
- **Damage could be located away from impact site – must inspect along load path**



Summary: Prediction & Detection

UCSD
Department of Structural Engineering

- HEWABI Damage Prediction
  - detailed FE prediction possible
    - » focused element-level experiments enabled accurate analysis procedure development
      - – due to their simplified geometries, loading conditions, and isolated failure modes
    - » models capturing correct physical phenomena can be transferred to accurately predict large-scale structure response
  - must account for early failure modes to capture subsequent history and final failure mode
    - » e.g., shear ties in large panel tests

- Damage Detection
  - guided ultrasonic wave (GUW) methods have demonstrated proof of concept (much work to do still)
    - » significant GUW attenuation through cracked frames and shear ties
    - » exterior-only measurements show sensitivity

Future Plans:
Frame to Floor Structure Interaction

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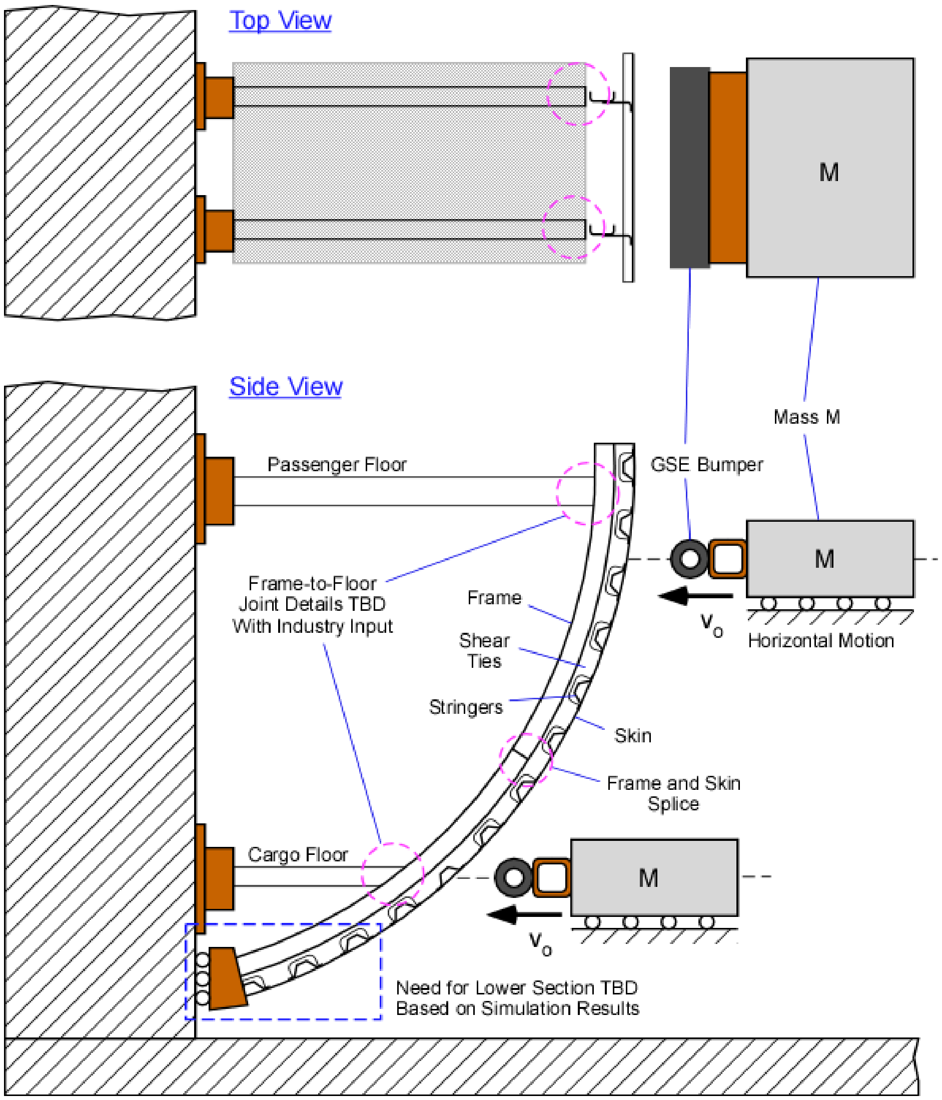

Impact near floor structures

- **Quarter-barrel panel including floor structures will be designed to reflect more actual aircraft fuselage**
  - **frame-to-floor joint**
  - **proper frame-end torsional stiffness BC**
  - **more substantial, continuous shear ties**
- **Main focus will be Frame to Floor Interaction - How damage development will be affected according to new BCs and stress concentration factor.**
  - **impact locations near the floor structures**