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Impact Damage Formation on Composite Aircraft Structures

2013 Technical Review

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Impact Damage Formation on Composite Aircraft Structures

- **Principal Investigators & Researchers**
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  ** students have graduated*
- **FAA Technical Monitor**
  - Lynn Pham
- **Other FAA Personnel Involved**
  - Curt Davies
  - Larry Ilcewicz
- **Industry Participation**
  - Material support by Cytec, San Diego Composites, Boeing
  - Participation by Bombardier, UAL, Delta, JC Halpin, Avanti Tech
  - Collaborations with Sandia Labs, Bishop GMBH (EASA-funded)

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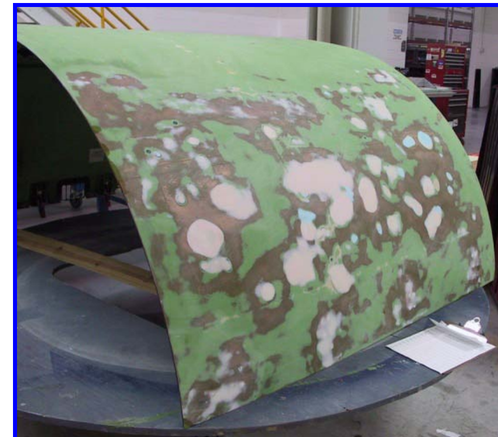
Impact Damage Formation on Composite Aircraft Structures



- **Motivation and Key Issues**
  - impacts are ongoing and major source of (hidden) damage
  - high energy blunt impact damage (**BID**) of key interest
    - involves large contact area, not well understood
    - can possibly exist with ***little or no exterior visibility***
  - **Existing Needs:** (i) establish clear understanding of damage formation from ***blunt*** sources, (ii) prediction capability
- **Focus: sources of concern are <u>blunt impacts</u> affecting <u>wide area</u> and/or <u>multiple structural elements</u>**

<u>Hail Ice Impact</u>

- upward & forward facing surfaces
- low mass, high velocity
- threat: 38-61 mm diam. ice at in-flight speed

Ground Vehicles & <u>Service Equipment</u>

- side & lower facing surfaces
- high mass, low velocity
- wide area contact
- damage at locations away from impact likely
- threats:
  - belt loader ~3,000 kg
  - cargo loader ~15,000 kg

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Impact Damage Formation on Composite Aircraft Structures

- **Objectives**
  - Characterize Blunt Impact threats and locations where damage can occur
  - Understand BID formation and visual detectability
    - determine key failure modes, phenomena and parameters
    - how affected by bluntness/contact-area
    - ID & predict failure thresholds (useful for design)
    - what conditions relate to development of significant internal damage with minimal or no *exterior visual detectability?*
  - Develop analysis & testing methodologies
  - Establish new modeling capabilities validated by tests
- **Approach**
  - Experiments: impact representative structure/specimens
    - » wide area high energy blunt impact – e.g., from ground service equipment
    - » high velocity hail ice impacts – in-flight and ground-hail conditions, internal stiffeners
    - » low velocity impacts – non-deforming impactor, large radius effects
  - Modeling – nonlinear FEA, analytical
  - Communicate results to industry, collaboration on relevant problems/projects via workshops and meetings (visit company, at UCSD, teleconf)

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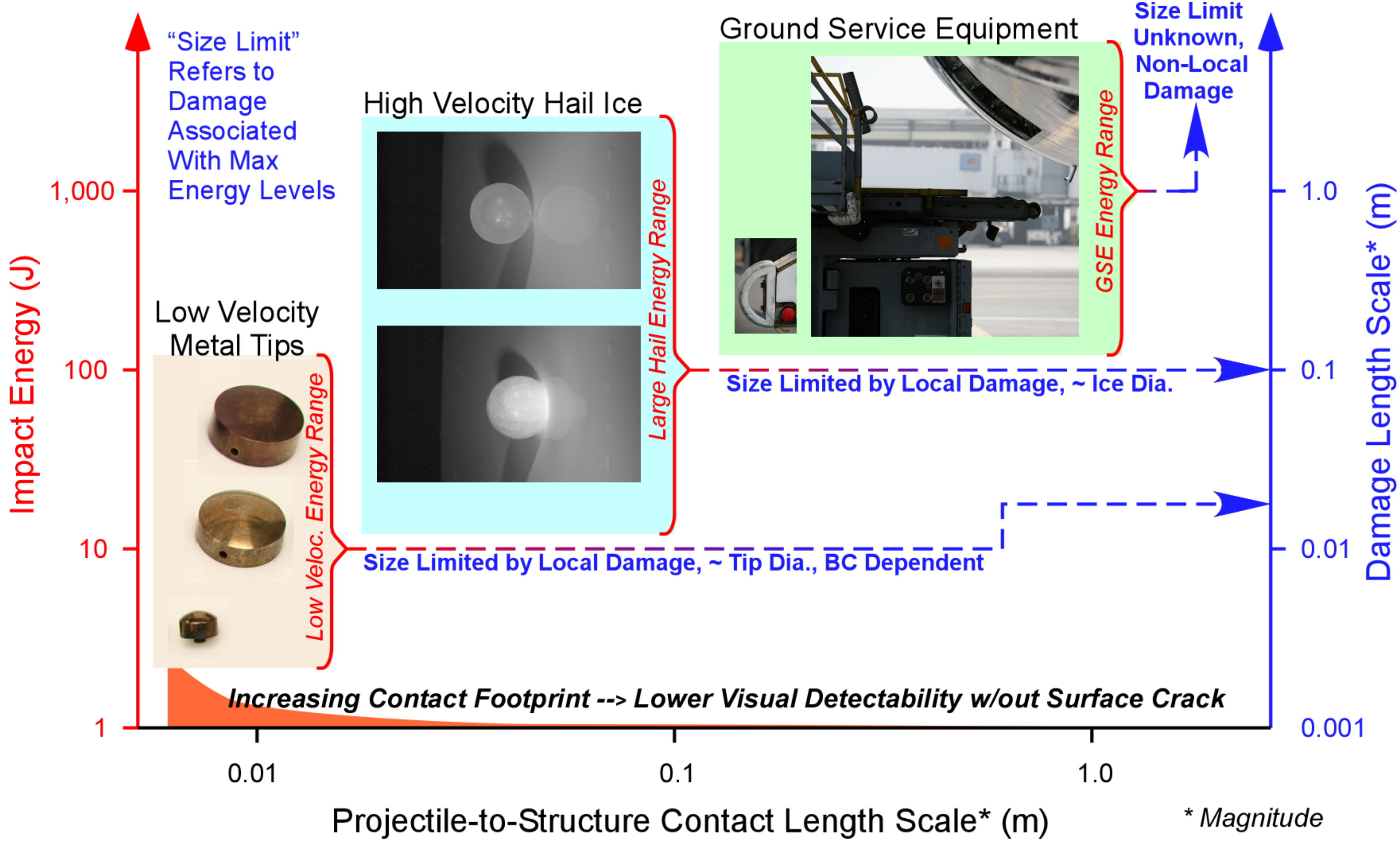
Blunt Impact Energy-Damage Spectrum



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Outline

- Ground Service Equipment (GSE) High Energy Blunt Impact
- Hail Ice High Velocity Impact
- Blunt Metal Tip Low Velocity Impact

Ground Service Equipment High Energy Impact

Recent activity concentrated in two areas:

- Continued Wide Area Blunt Impact Testing
  - 1st large-sized panel (ID: Frame03) tested to large damage state (March 2012 / JAMS 2012)
  - 2nd Large-sized panel (ID: Frame04-1) tested to lower damage state (May 2012)
  - 2nd Large-sized panel (ID: Frame04-2) reconfigured with more substantial 7075 Al Alloy shear ties (thicker, longer) and tested to large damage state (August 2012)
- Model Development – all topics are currently in progress
  - Blunt impact modeling methodology
    - establishing how to model wide area blunt impact events
    - predict damage initiation, growth, and final state – entire process to final failure mode
  - Understand effects of panel configuration – stringer, frame, shear tie geometry, spacing, etc.
  - Failure modeling of coupon-level and element-level test specimens
    - analysis of simpler specimens – damage initiation, growth, final failure
    - prediction capability of key small-scale phenomena → affects large damage prediction
  - Addressing model complexity and computational cost issues
    - cost: (i) model formulation using only shell elements – allows large-sized structure modeling, (ii) geometric simplification of complex features such as bolt lines
    - interlaminar failure modes prediction – cohesive elements, multi-shell layers
  - Establish failure criteria for FEA prediction of damage visibility from "soft" impact

Blunt Impact Tests – Specimen Description and Results Overview

Specimen "Frame03"

- Composite shear ties
- Tested 3/2012 @ 0.5 m/s; 225 mm stroke
- Major damage: (i) 9 shear ties broken, (ii) 3 frames cracked each at 2 locations (between central loading and outer BC)
- No exterior visibility

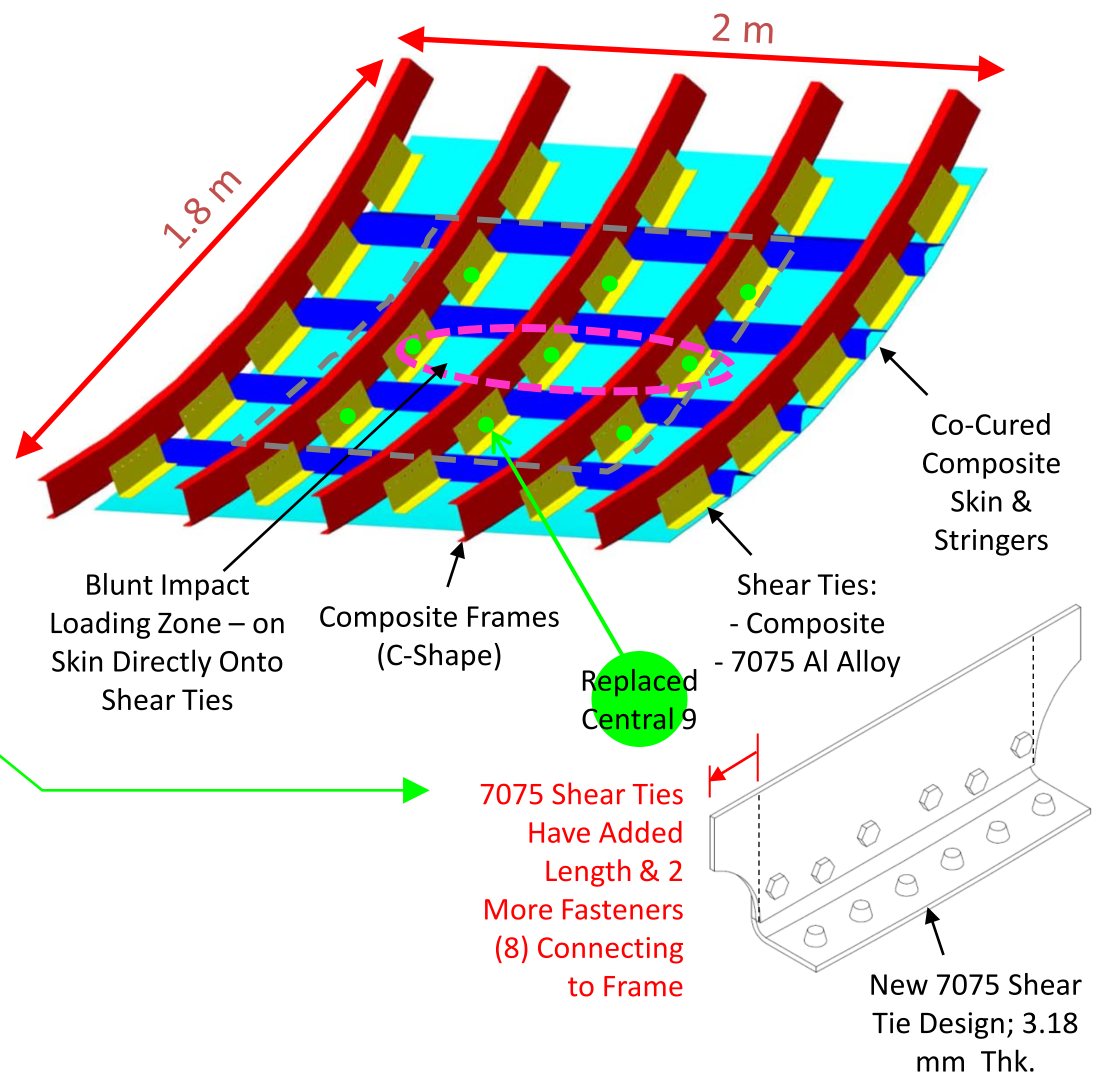
Specimen "Frame04-1"

- Composite shear ties
- Tested 5/2012 @ 0.25 m/s; 180 mm stroke
- Intentionally lower-level stroke to excite low-level damage -> only center 3 shear ties crushed with no other damage
- No exterior visibility

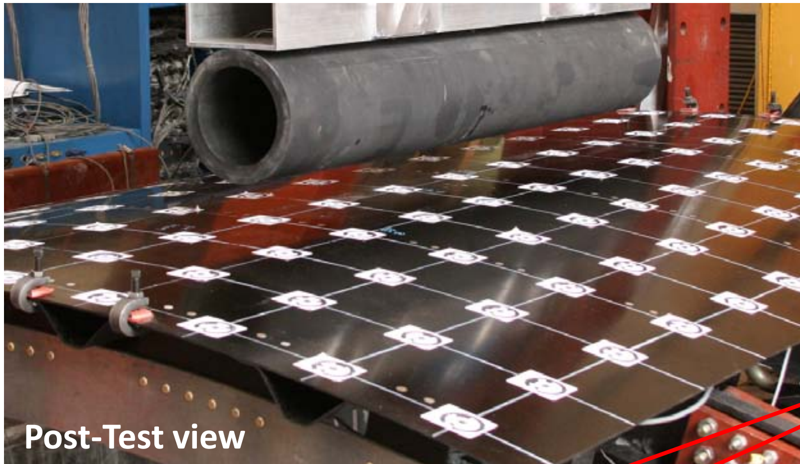
Specimen "Frame04-2"

- Retrofitted Frame04-1 with 7075 Al alloy shear ties – replaced inner 9 shear ties
- Tested 8/2012 @ 0.5 m/s; 225 mm stroke
- Major damage: all 3 frames <u>locally</u> failed at joint with shear tie
- No shear tie failure
- Low level exterior visibility – light skin cracks towards outer (non-loaded) frames

All three specimens have common skin, stringer, and frames.

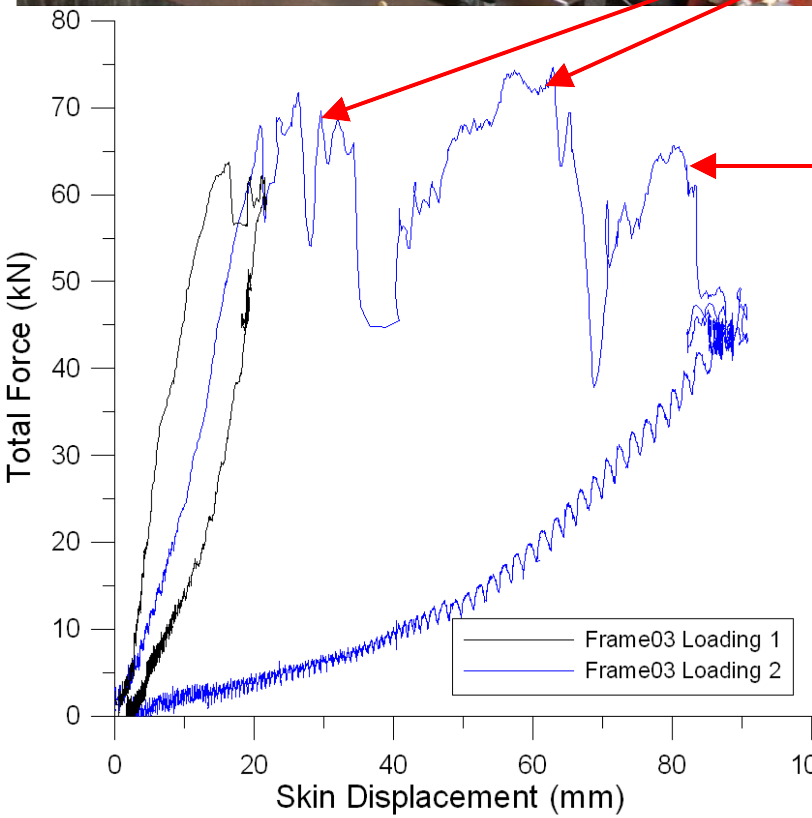


Frame03 Test Summary

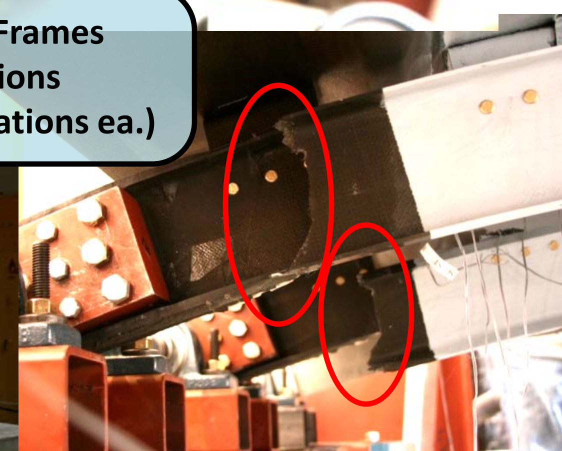


Key Points:
- Major Frame & Shear Tie Damage
- No Exterior Visibility

Broken Shear Ties at 9 Locations (3 Shear Ties per 3 Frames)



Fractured C-Frames at 6 Locations (3 Frames, 2 locations ea.)



Frame04-1 and Frame04-2 Specimens

- Skin & Stringers Identical to Specimen Frame03
- Frame04-1: composite shear ties
- Frame04-2: aluminum alloy shear ties (7075)

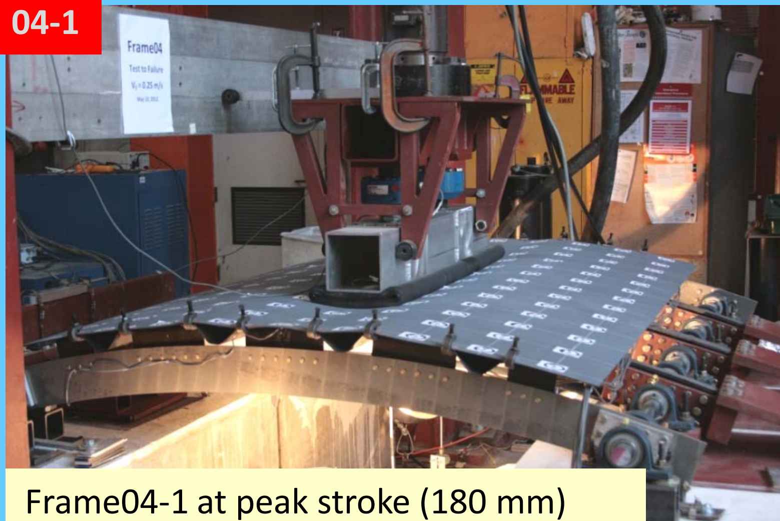
Thickness increased by ~25%
and added two more fasteners
in connection to frame.

Frame04-1 – Composite Shear Ties

Frame04-2 – Aluminum Alloy (7075) Shear Ties

Frame04-1 and Frame04-2 Results

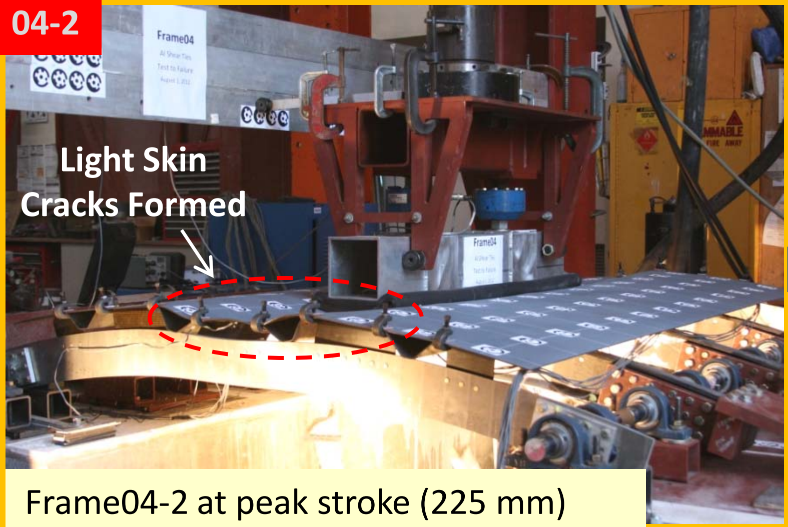
04-1



Frame04-1 at peak stroke (180 mm)

Local shear tie failure. No other damage.

04-2



Frame04-2 at peak stroke (225 mm)

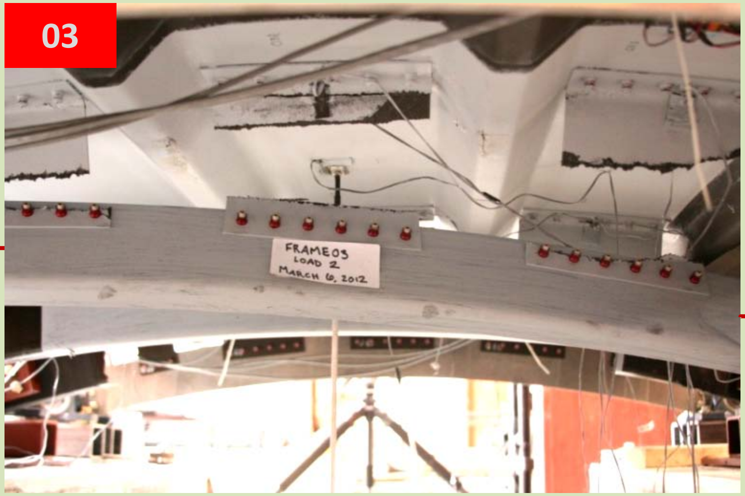
Local frame failure – no shear tie damage.

Comparison Frame03 and Frame04-2

Both loaded with 225 mm actuator stroke

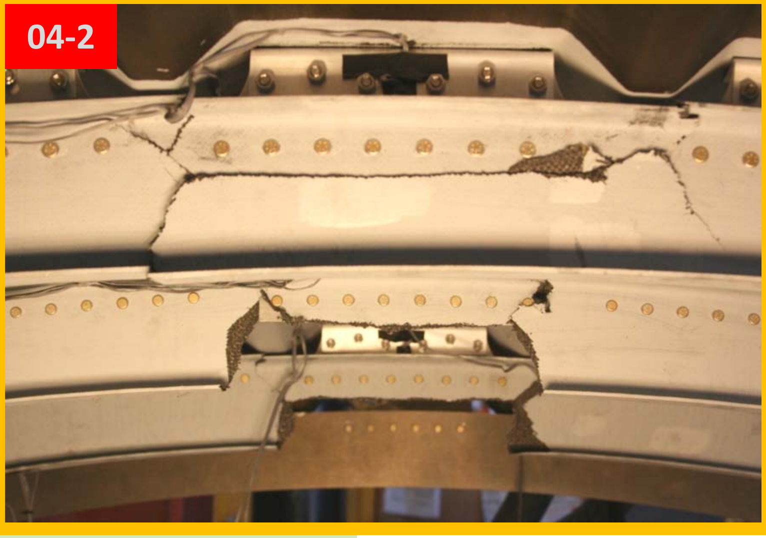
Frame03 – Non-local failure of frame away from center due to load transfer between stringer-frame contact & frame rotation. No visible cracks or dent.

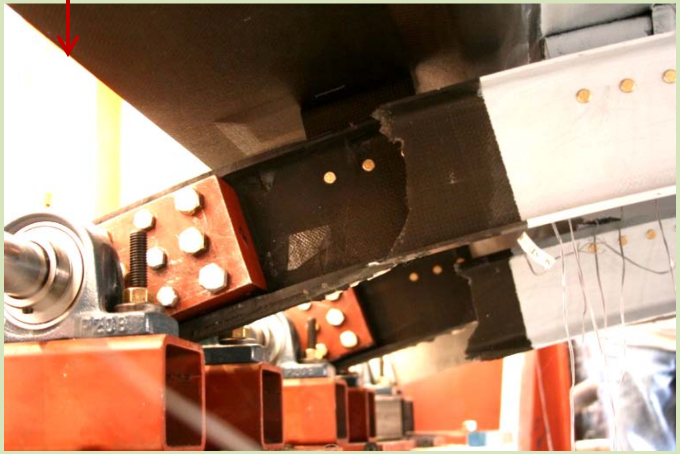
Frame04-2 – Local failure of frame @ center. No shear tie failure, thus no major frame rotation. Minor skin cracks visible away from impact site.

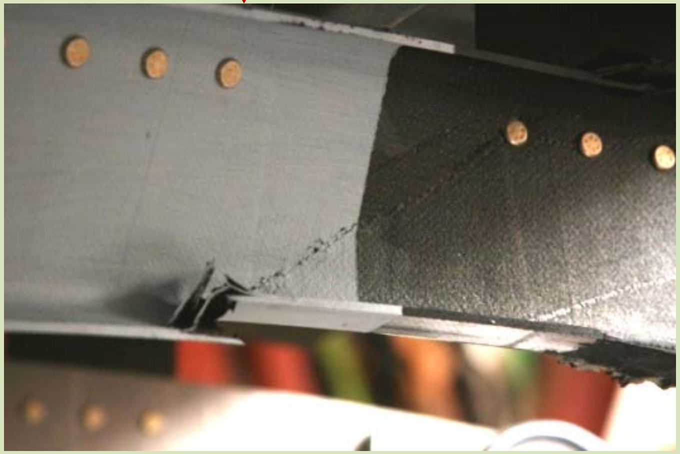


Near BCs

Near BCs



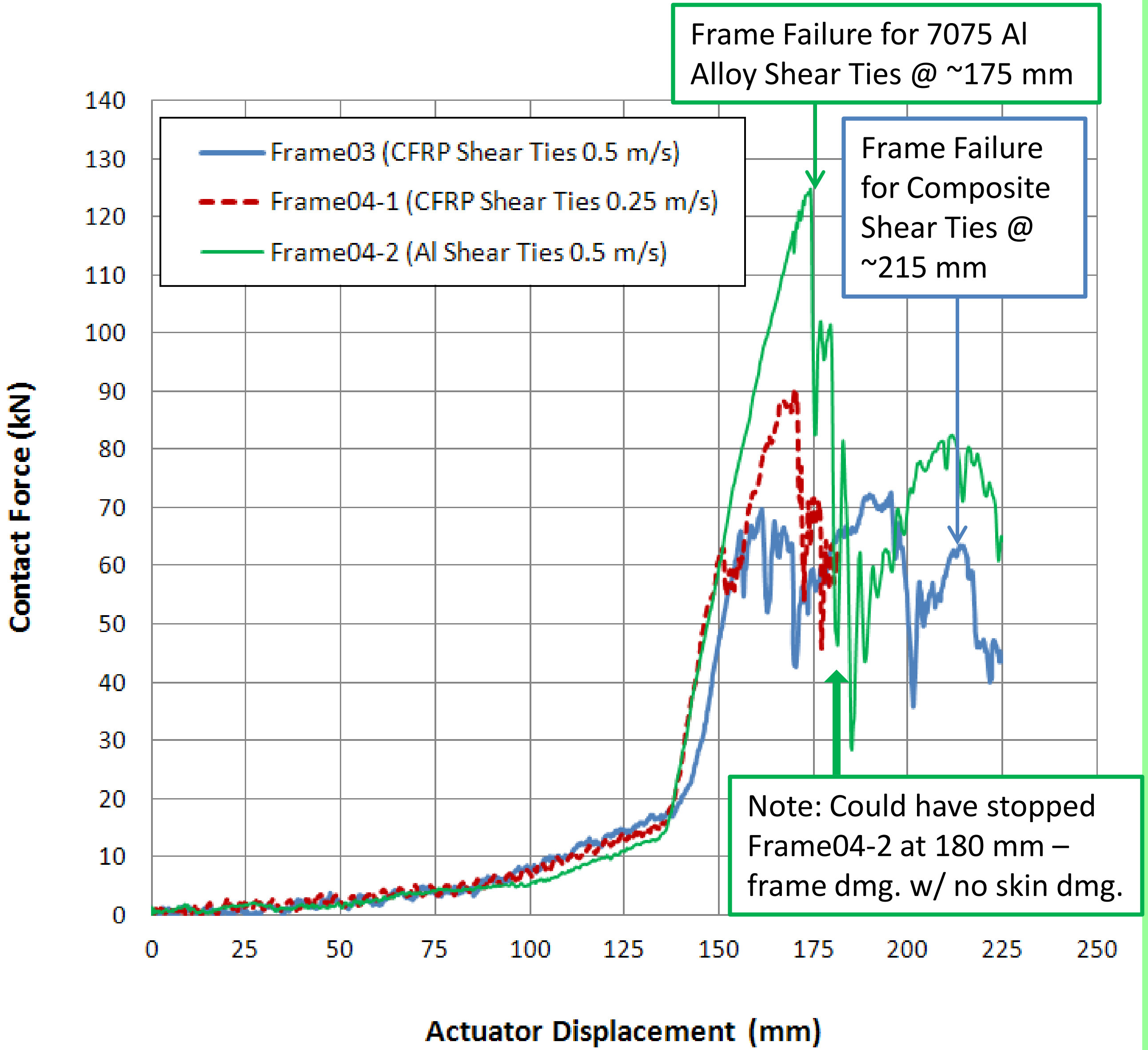




[Frame03 Test Video]

[Frame04-2 Test Video]

Loading Comparison

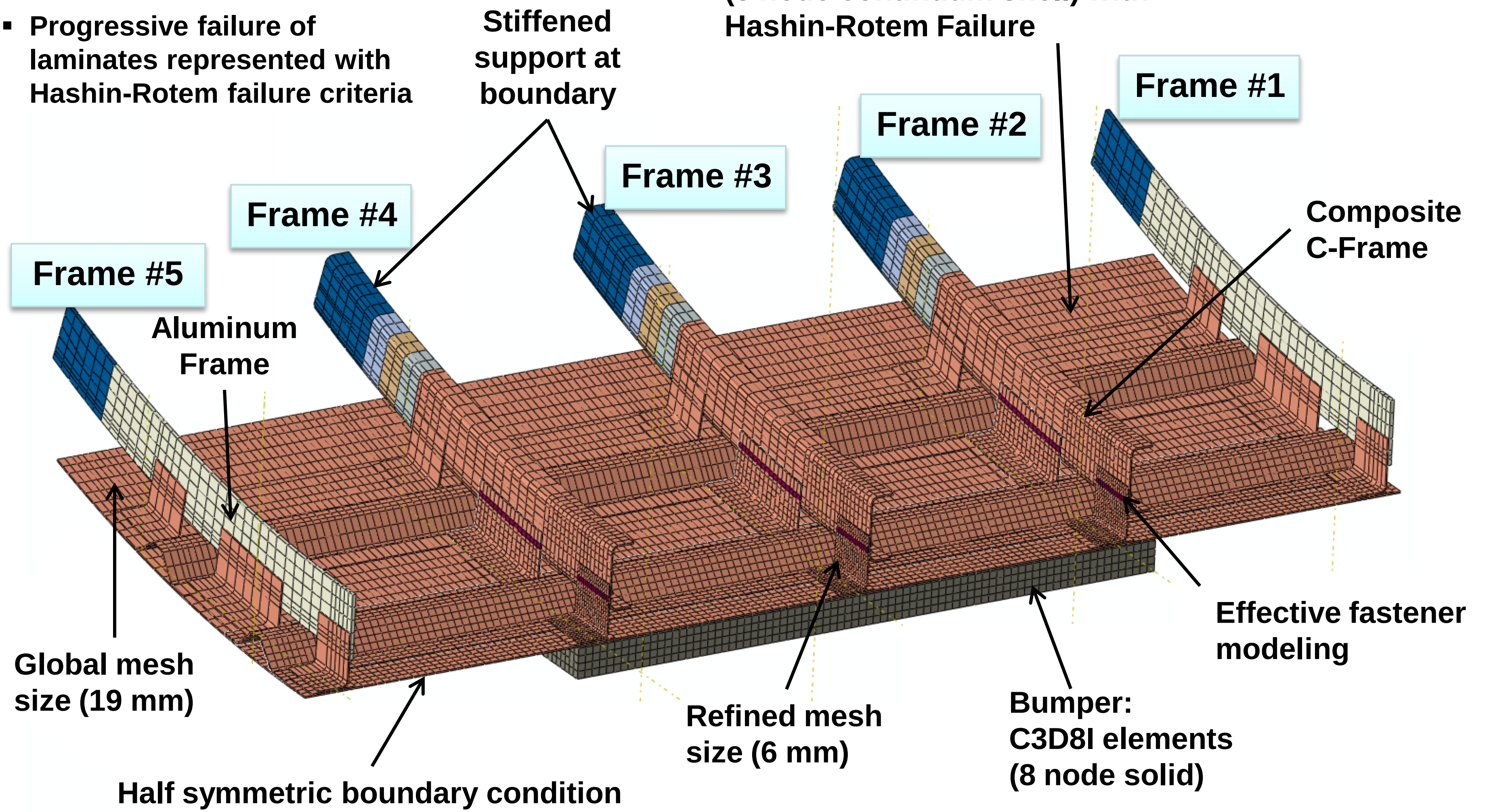


Key Observations:

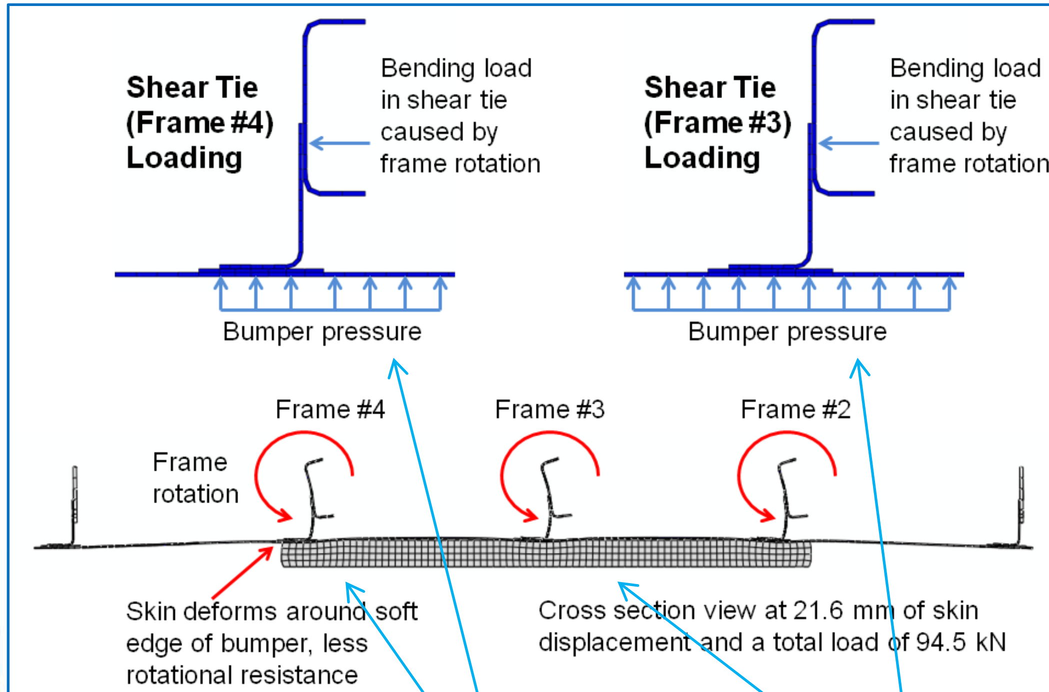
- Weak shear ties
  - shear tie crushing & progressive failure
  - stringer-to-frame contact & large frame rotation
  - non-local frame failure *away* from loading location
- For strong shear ties not failing
  - higher forces develop before initial failure
  - frame failure is initial mode w/ no large frame rotation & stringer-frame contact prior
  - frame failure is local, near loading location
- Failure thresholds and energy absorption
  - dependent on specifics of internal components
  - possible tuning of damage modes (e.g., only shear tie failure) can be achieved by design of components

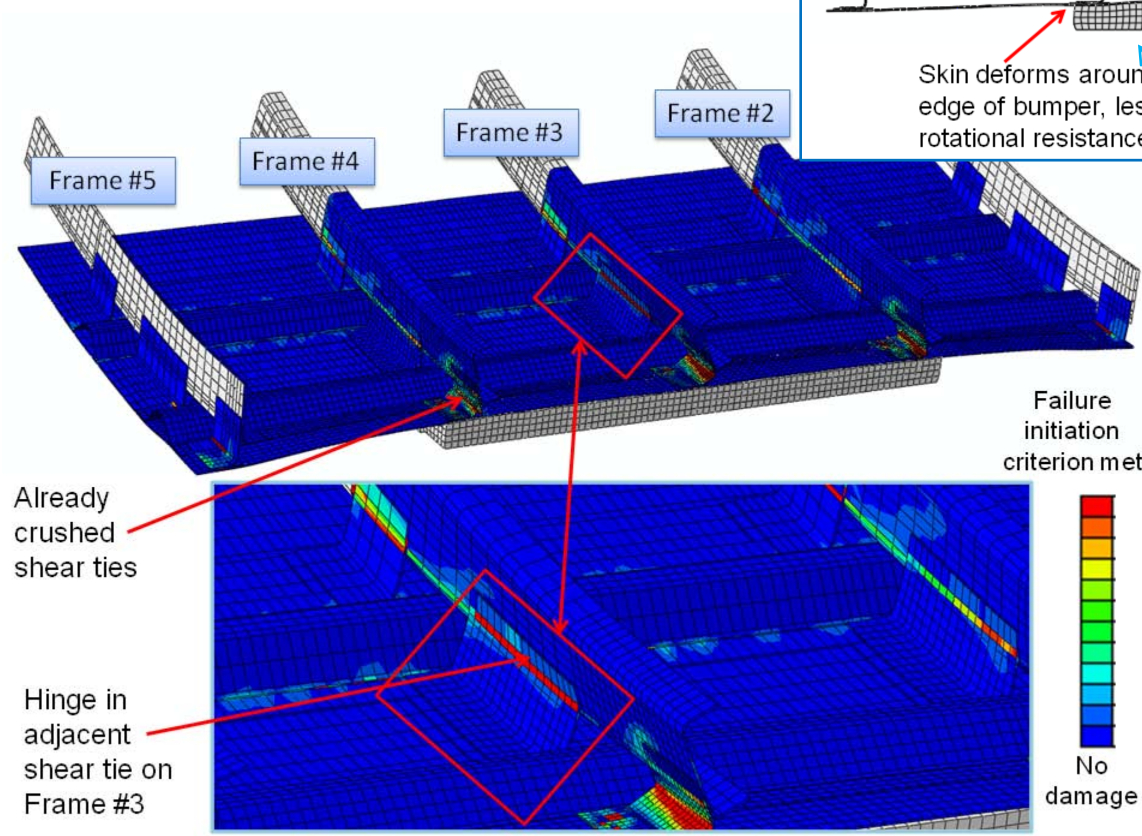
FEA Model Development

- **Continuum shell elements used for lower computation cost (compared to ply-by-ply solid element representation)**
- **Progressive failure of laminates represented with Hashin-Rotem failure criteria**



Frame Relative Loading – Center of Bumper of Near Ends





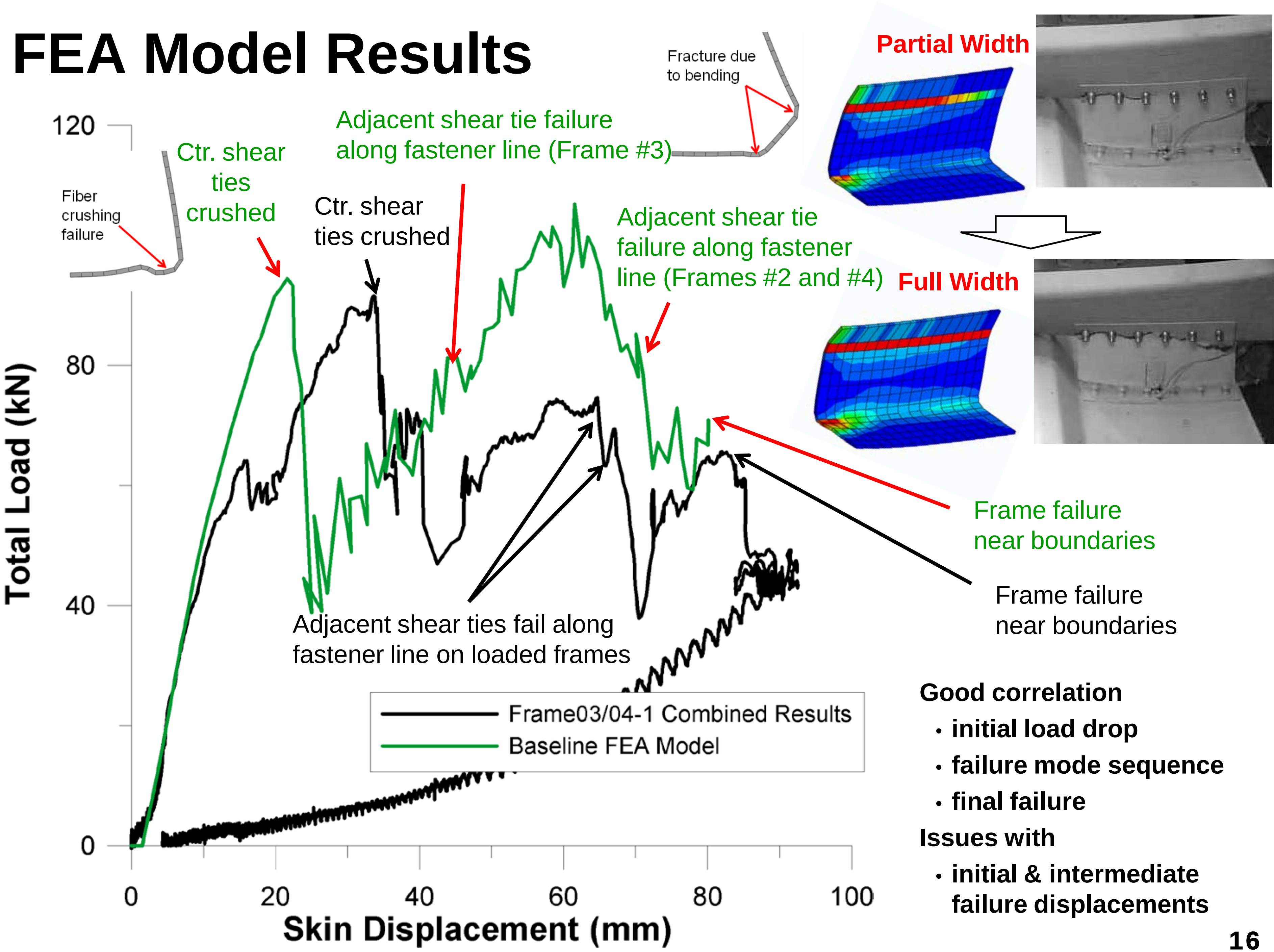
Outer frames carry less load

Inner frames carry more load

Shear ties at inner frames fail first

- **directly-loaded set**
- **adjacent set**

FEA Model Results



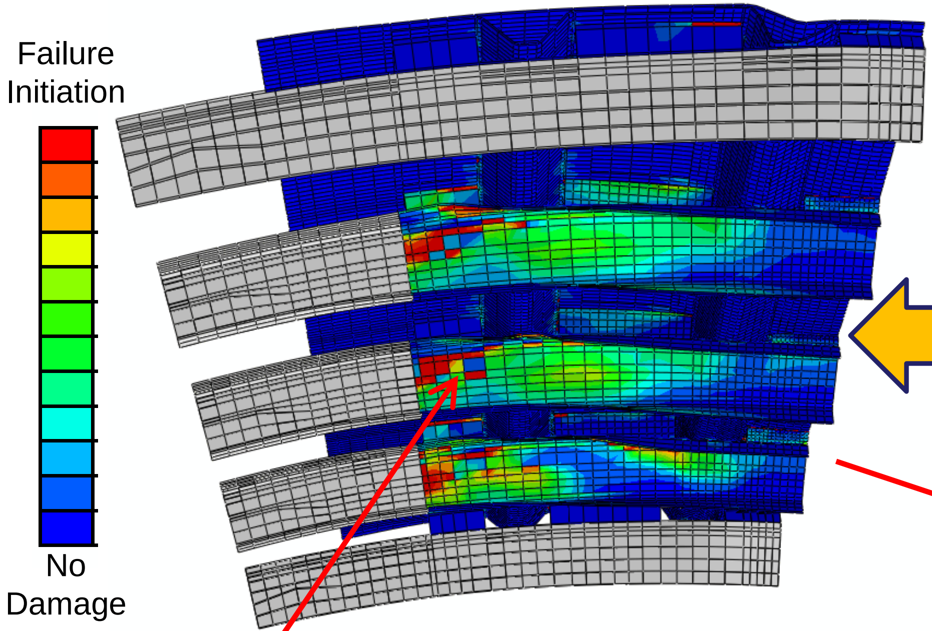
Good correlation

- **initial load drop**
- **failure mode sequence**
- **final failure**

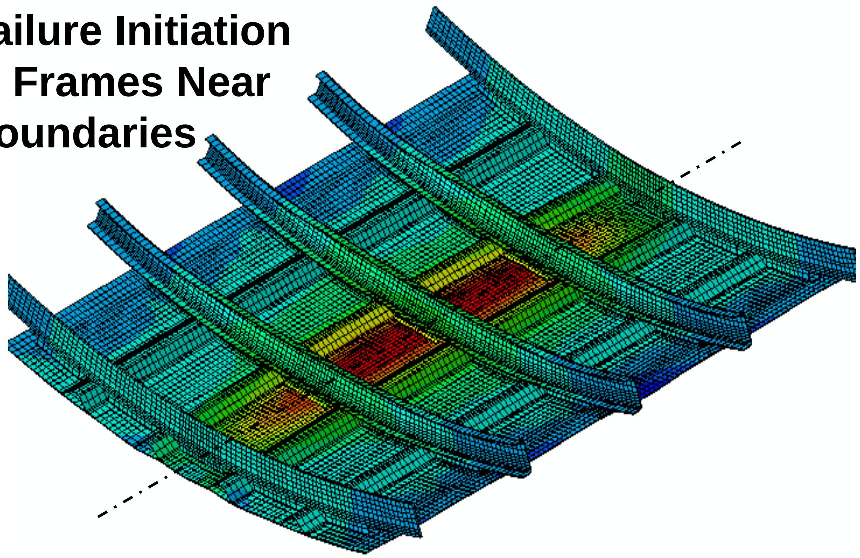
Issues with

- **initial & intermediate failure displacements**

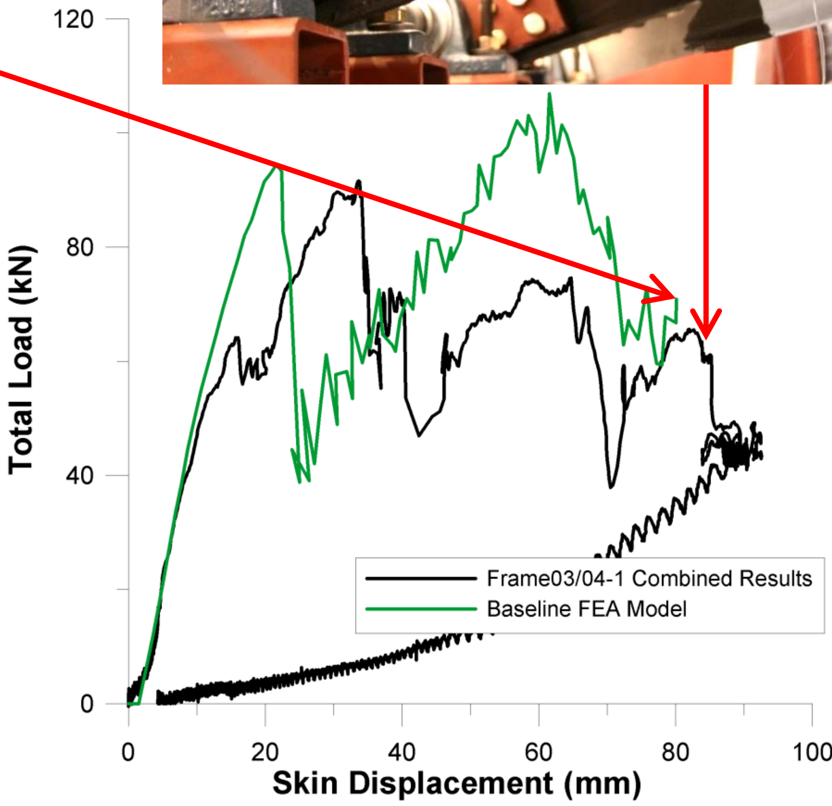
Final Frame Failure Prediction



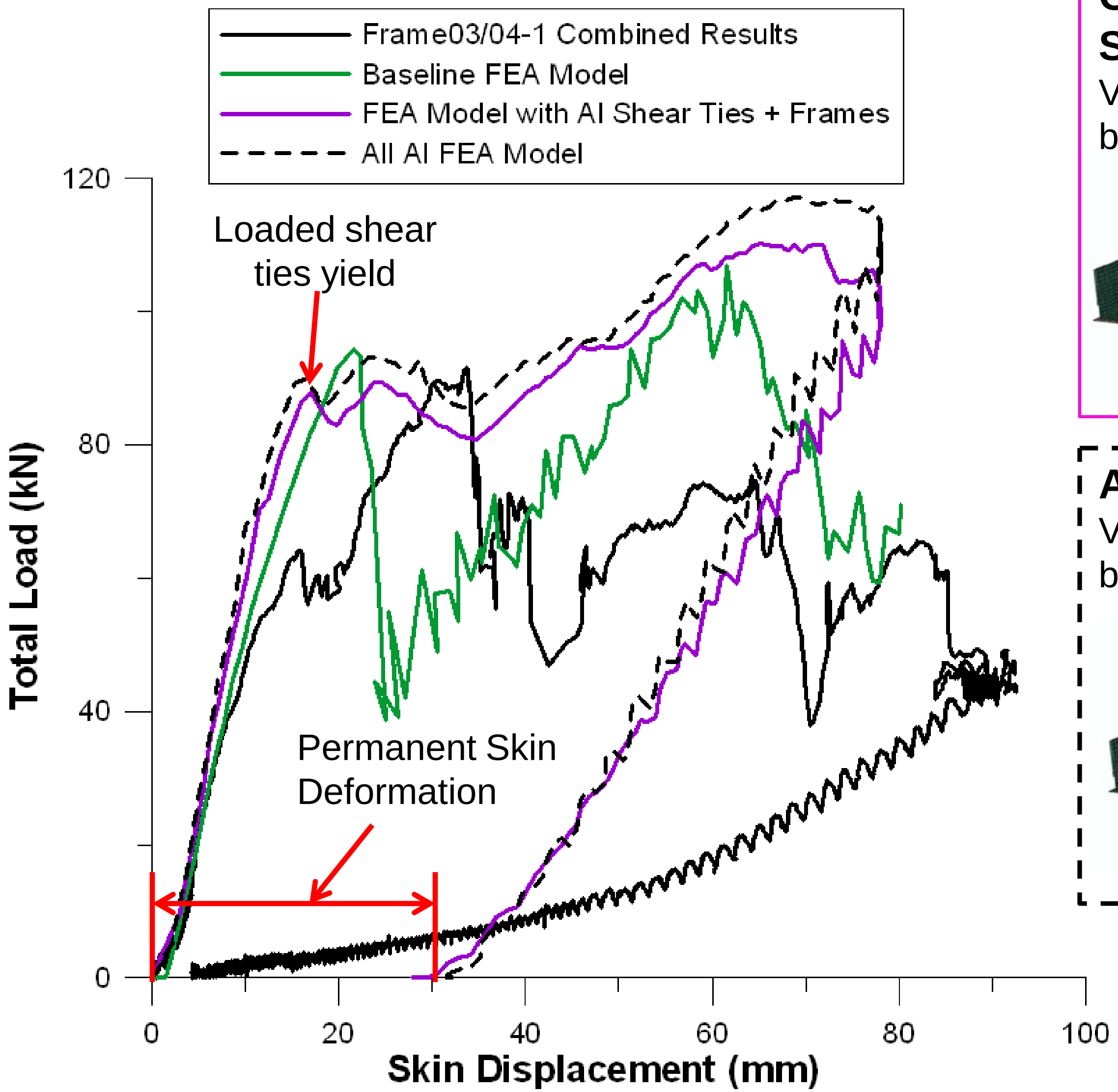
Failure Initiation in Frames Near Boundaries



Frame03 failure away from impact area



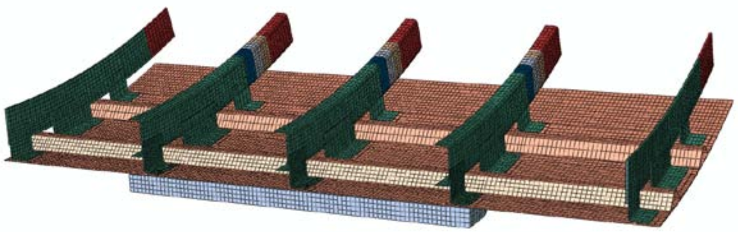
Component Material Study



Aluminum frames and shear ties influence the visual detectability and loading response.

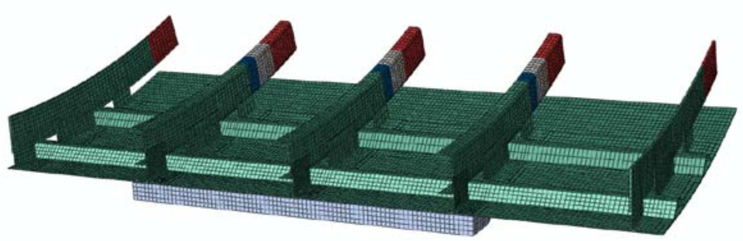
Composite Panel with Aluminum Shear Ties & Frames

Very visible dent after unloading – caused by yielding of the shear ties



All-Aluminum 2024 Panel

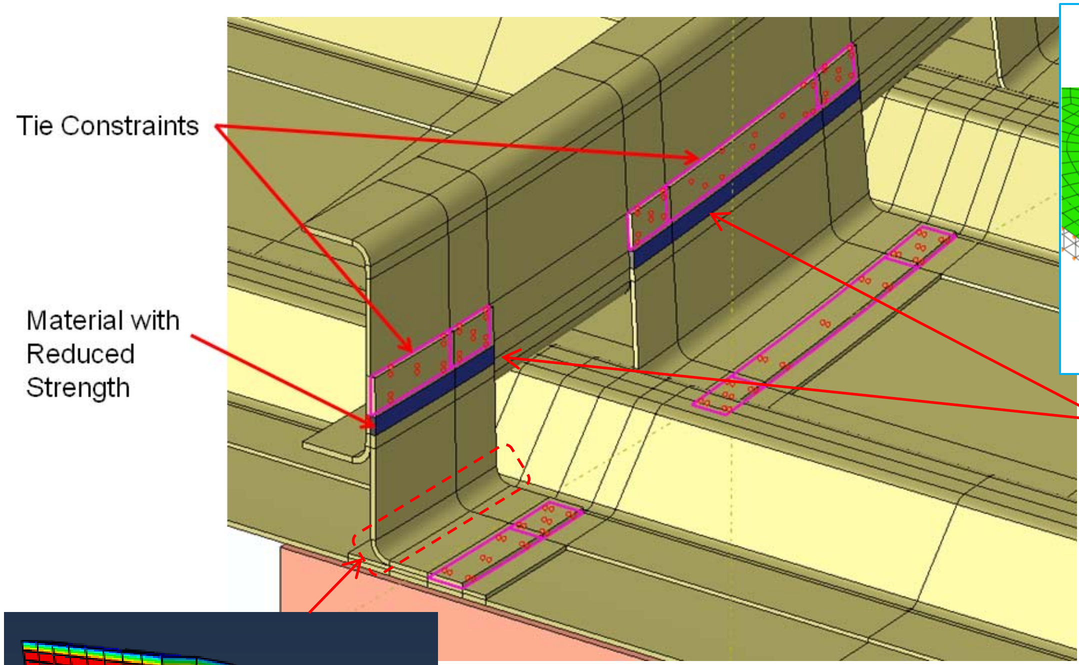
Very visible dent after unloading – caused by yielding of the shear ties

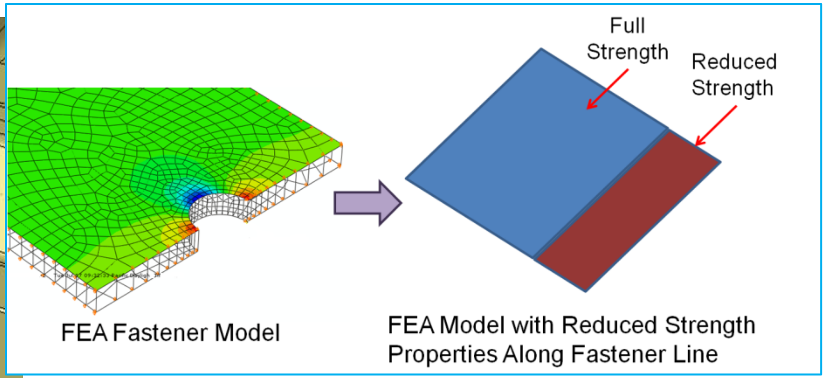


Also Analyzed (not shown): Aluminum Skin with Composite Shear Ties & Frames – similar loading response as all-composite **Baseline** model; local yielding at shear ties likely resulting in visible surface dents

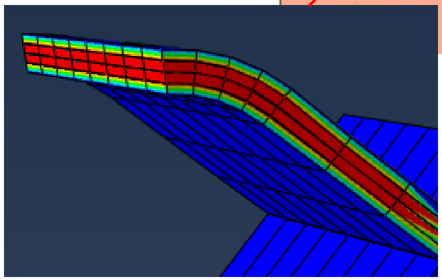
Model Development – Small Scale Processes

- Hierarchical model development: models of element level specimens used to accurately predict small-scale failure processes → these lead up to and affect large-scale failure
- Areas of focus – predict progressive failure process and energy absorption:
  - bolted joint rows – stress concentration effective representation
  - skin-to-stringer delamination
  - skin cracking at stringer to skin junction (high local bending – leads to exteriorly visible cracks)
  - shear tie curved radius region – interlaminar tension failure





Bending failure along fastener line: reduced failure properties in select plies within simple strip – avoid explicitly modeling hole geometry (costly)



Interlaminar tension failure of curved section: modeled via continuum shell elements layers and cohesive zone surfaces

Also (not shown), stinger-to skin delamination and local bending failure of skin surface (visible cracks): establish damage visibility criterion

Outline

- Ground Service Equipment (GSE) High Energy Blunt Impact
- Hail Ice High Velocity Impact
- Blunt Metal Tip Low Velocity Impact

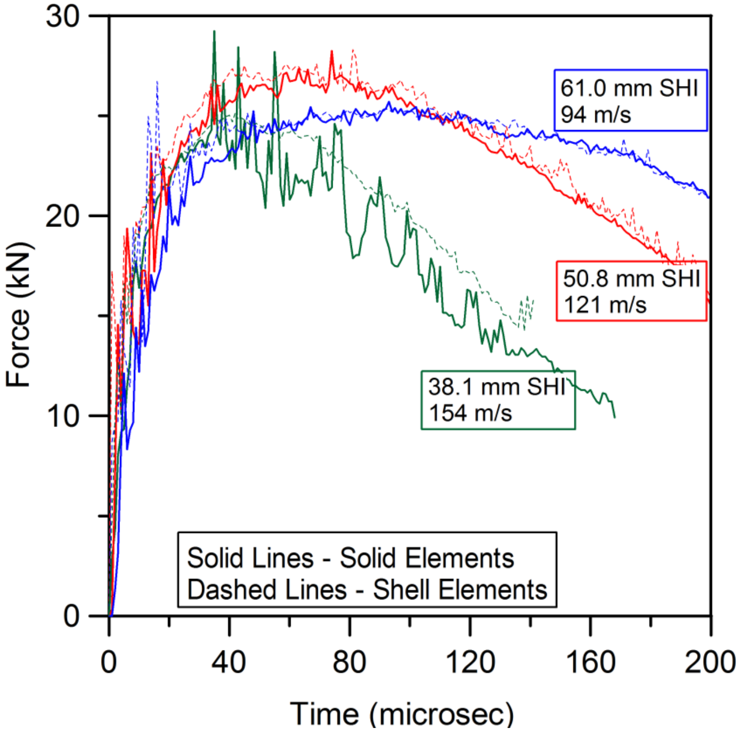
Hail Ice Impact – Critical Force Initiation Criterion

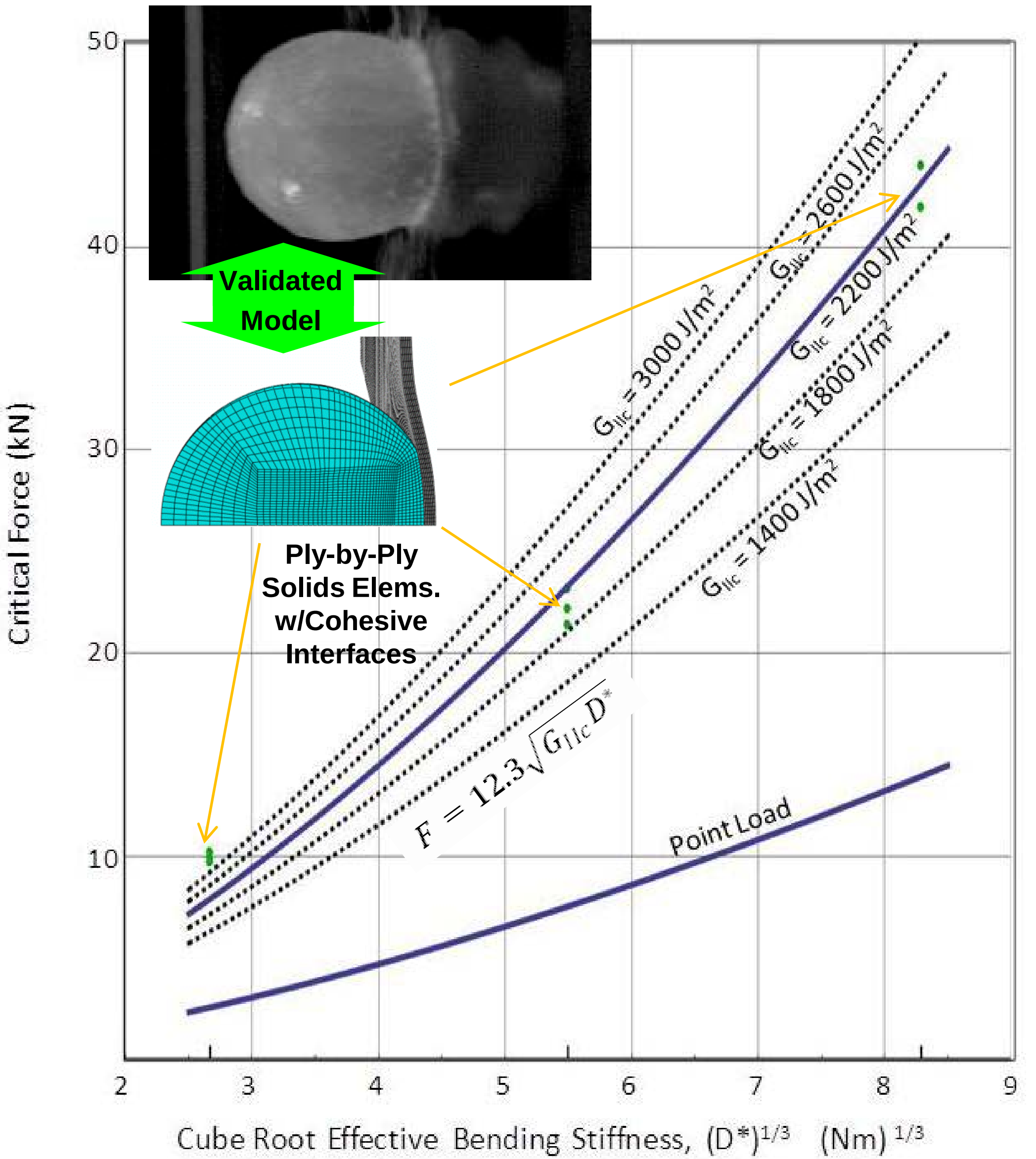
- FEA-prediction of ***delamination onset*** established – predictive model w/ no property tuning
- Failure threshold force – critical force

$$F = 12.3\sqrt{G_{IIc}D^*}$$

Applicable to many composites via effective bending stiffness D* and Mode II SERR G_{IIC}

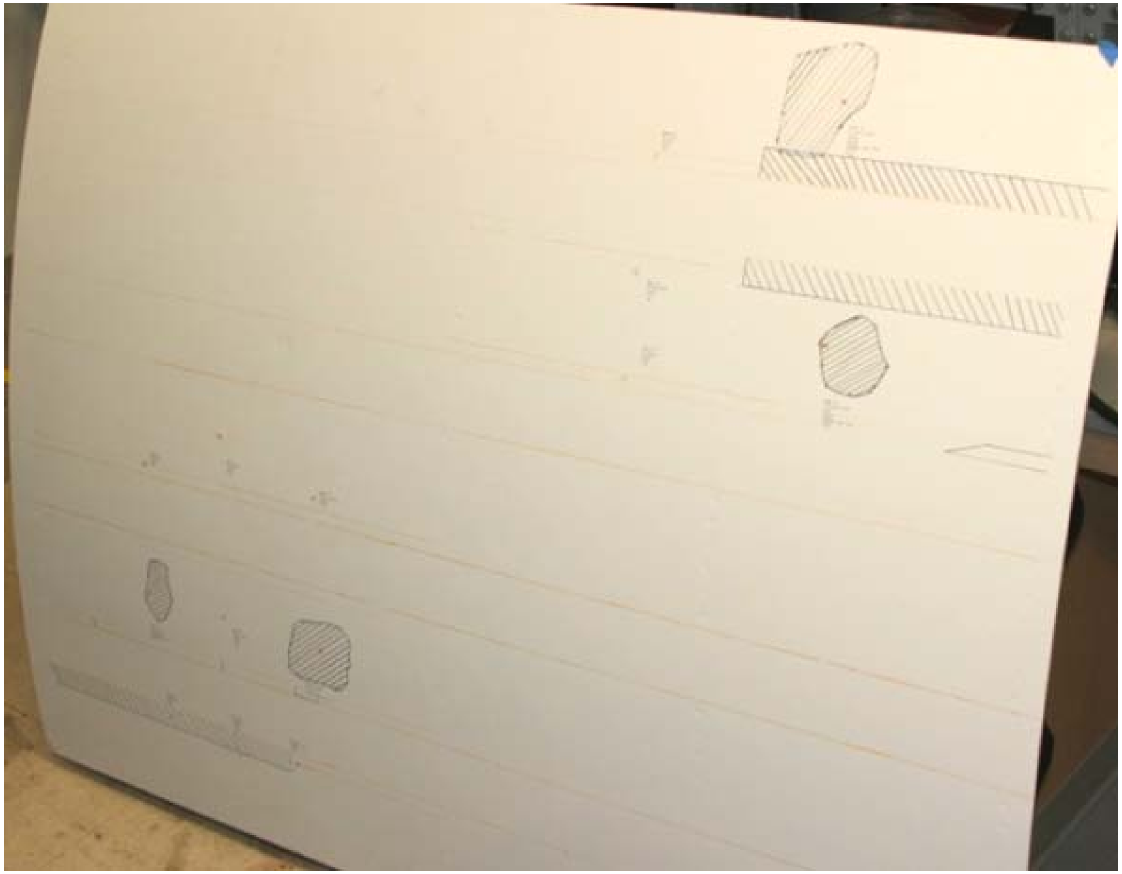
For low-cost model w/ shell elements: Critical Force can be used as failure criterion with shell elements to predict damage initiation



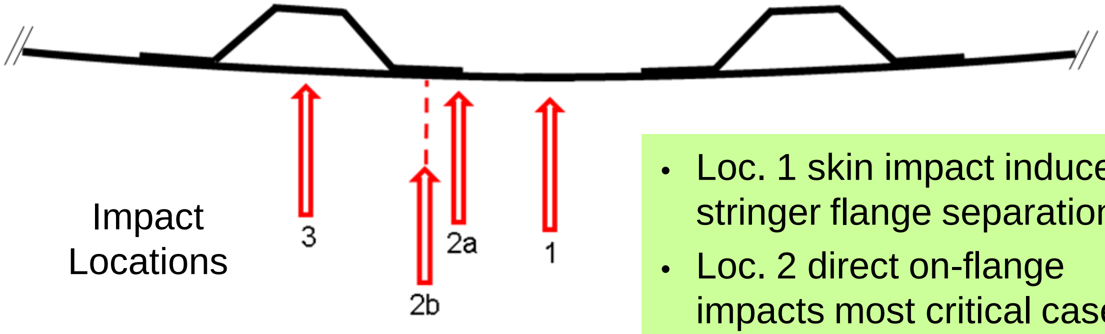


Hail Ice Impact – Stringer Stiffened Panels

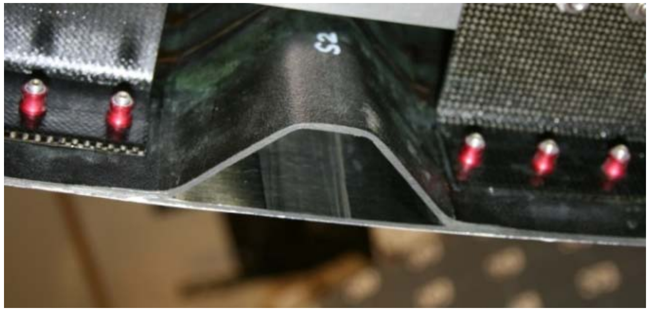
- Determine effect of hat stringer on
  - (i) damage initiation
  - (ii) damage modes
- Comparison to 305 x 305 mm 16 ply flat panel impact data: FTE = 489 J
- Test details:
  - 61 mm ice spheres
  - two 4-stringer panels – curved 16 ply T800/3900-2 with bolted shear ties



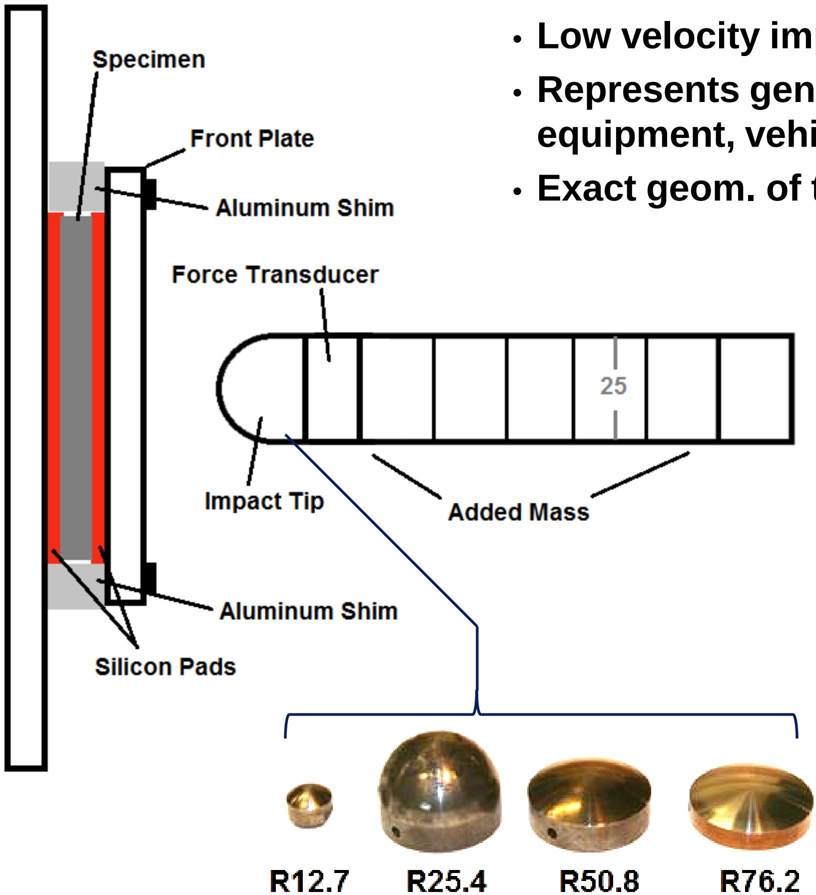
Impact Location	FTE (J)	Knockdown Factor
1 – Middle of bay	227 - 567	0.51 - 1.3
2a – End of stringer Flange	N/A	N/A
2b- Middle of stringer Flange	183	0.41
3 – Middle of Stringer	357	0.80
4 – Directly over Shear Tie	N/A	N/A



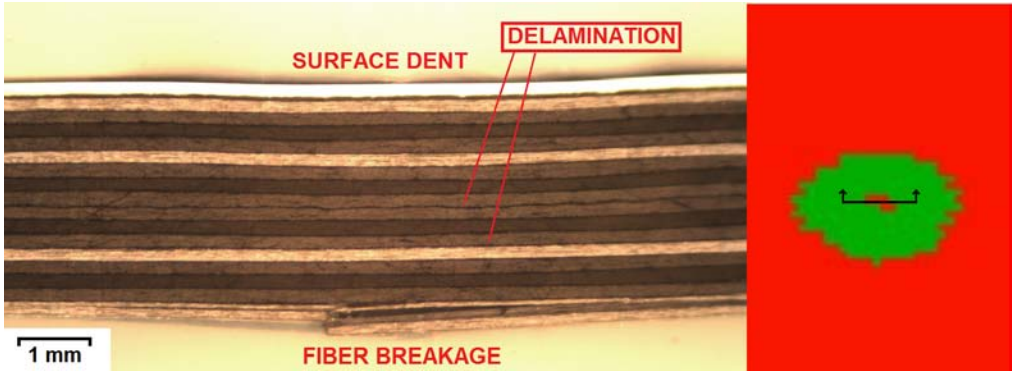
- Loc. 1 skin impact induces stringer flange separation
- Loc. 2 direct on-flange impacts most critical case.

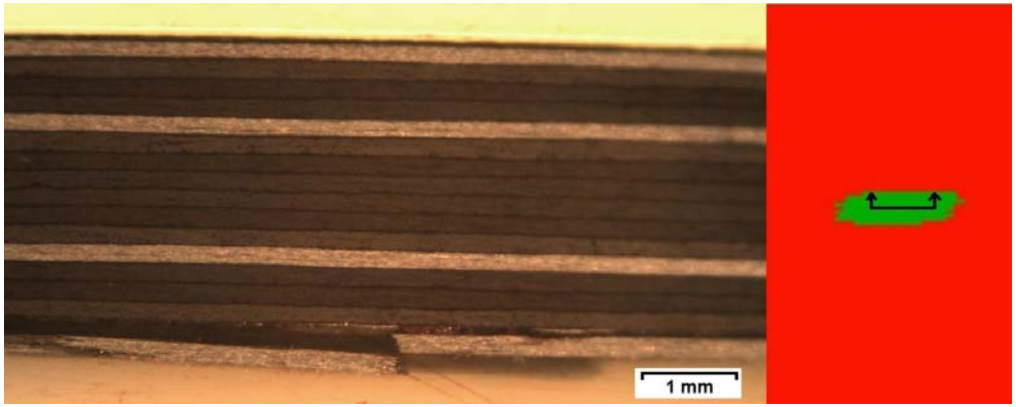


Blunt Metal Tip Low Velocity Impacts



- Low velocity impacts – instrumented pendulum
- Represents generic impacts by various sources such as: dropped equipment, vehicle corners, railings, and other protruding features
- Exact geom. of these items often not well known or not easy to measure





Panel Type	Thickn. (mm)	FTF (kN) for Tip Radius (mm):			
		R12.7	R25.4	R50.8	R76.2
8 Plies	1.7	4.4	5.2	9.7	19.6
16 Plies	3.3	6.3	8.5	12.3	17.6
24 Plies	4.9	8.9	12	14.3	19.8

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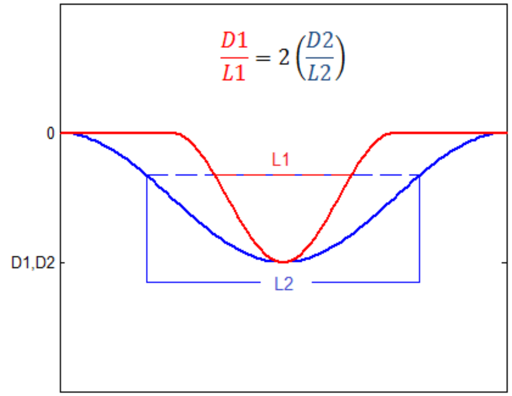
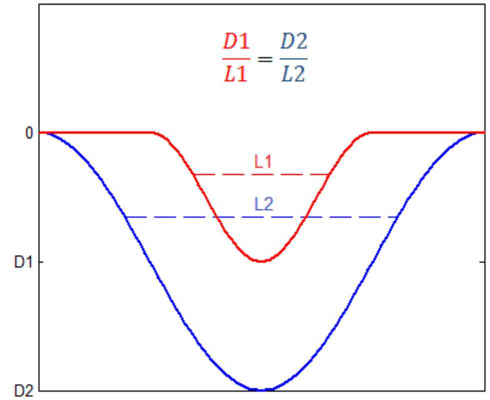
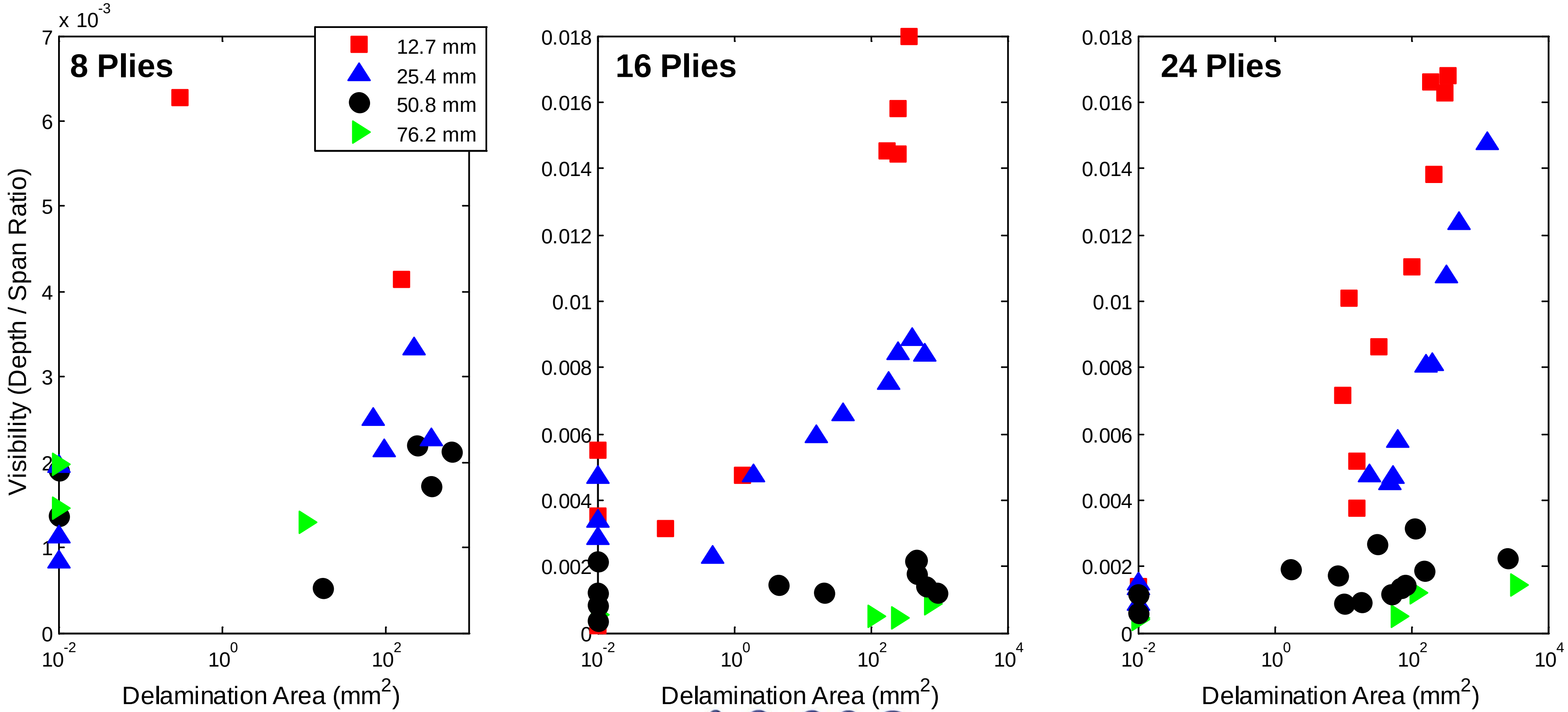
Dent Visibility

- Dent Visibility parameter defined (depth D over span L) of dent
- Strong relationship between visibility and delam. area for R12.7 and R25.4 mm tips
- Wide range of delam. area for R50.8 and R76.2 mm tips at same visibility level







Benefit to Aviation 1/2

GSE Wide Area Blunt Impact

- Understanding of prospective damage produced from wide-area GSE impact events
  - awareness of phenomena and possible internal failure modes – for Damage Tolerance considerations
  - provides key information on mode and extent of seeded damage, particularly non-visible impact damage (NVID) from blunt impact threats
  - threat conditions causing significant damage – range of energy level needed
- Establish FEA models that provide the capability to predict:
  - full detailed failure process – large deformations, failure initiation, growth, key failure modes
  - visibility of the damage produced – failure criteria for impact damage visibility
  - small scale onset of cracks and delamination → leads to greater damage and degradation of structural integrity
- Establish methodologies to analyze whole composite aircraft vs. substructures
  - GSE impacts inducing whole-aircraft motion
  - surrounding GSE secondary impact
- Identify how to detect/monitor occurrence of damaging events
  - what inspection technique should be used? where?
  - e.g., video cameras and sensors that can help to determine impact energy

Benefit to Aviation 2/2

High Velocity Ice Impact

- Critical force (threshold) based failure criterion useful for skin sizing to be damage resistant to hail ice impacts
  - applicable to wide range of composite materials and configurations – accounts for different G_{IIC}
- Impacts to stringer-stiffened panels give insight into
  - resulting damage modes (change in modes)
  - knockdown in failure thresholds relative to skin-only impacts

Blunt Metal Tip Low Velocity Impact

- Insight on effect of tip radius on impact damage
  - specifically delamination area vs. dent depth vs. impactor tip radius
- Dent visibility metric provides metric for damage visual detection accounting for dent depth and span (overall size or area)
- Awareness – e.g., very large radius tips (radius $\geq$ 50 mm) can produce wide range of delamination area for same low-visibility dent depth

Looking Forward

High Energy GSE Impact

- Understanding of glancing impact and boundary condition effects – consider larger sized structure: ½ or ¼ barrel
  - internal joints affecting load paths – e.g., proximity of impact to passenger and cargo floor or locations of high stiffness transition
- Impact on other structure types, metal-composite hybrid, wing structures
- Continued modeling capability development
  - predict full damage process – use to estimate energy absorption
  - accounting for interlaminar failures using shell element based modeling framework
  - define visibility metrics and failure criterion compatible with FEA – focus on when crack formation is visible
  - reduced-order model development – for extension of experimental results to ground operations

Ice Impact

- Establish prediction capability for impacts onto stiffened skins – both by FEA simulation and empirical/analytical relationships
- Hail ice damage resistance and damage modes for sandwich construction
- Investigate effect of multi-hit and impact adjacency

Large Radius Metal Tip

- Residual strength evaluation of already-tested panels – correlation with visibility
- Impact onto stiffened skin panels and sandwich

End of Presentation.

Thank you.

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