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Impact Damage Formation on Composite Aircraft Structures

Hyonny Kim,

Dept. Structural Engineering, UC 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: Zhi Chen, Sara White
    - MS: Monica Chan, Sean Luong
- **FAA Technical Monitor**
  - Lynn Pham
- **Other FAA Personnel Involved**
  - Curt Davies
  - Larry Ilcewicz
- **Industry Participation**
  - Boeing, Bombardier, Cytec, UAL, Delta
  - San Diego Composites, JC Halpin, Avanti Tech
  - Coordination with Bishop GMBH (EASA-funded)

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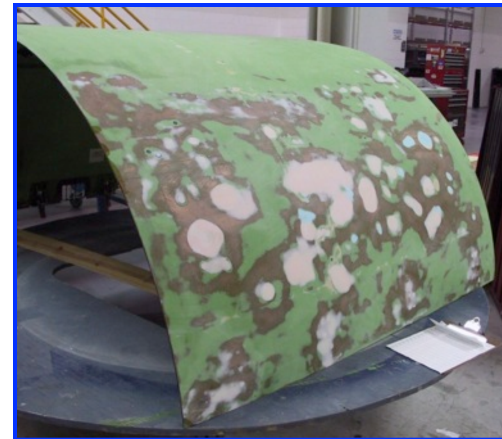
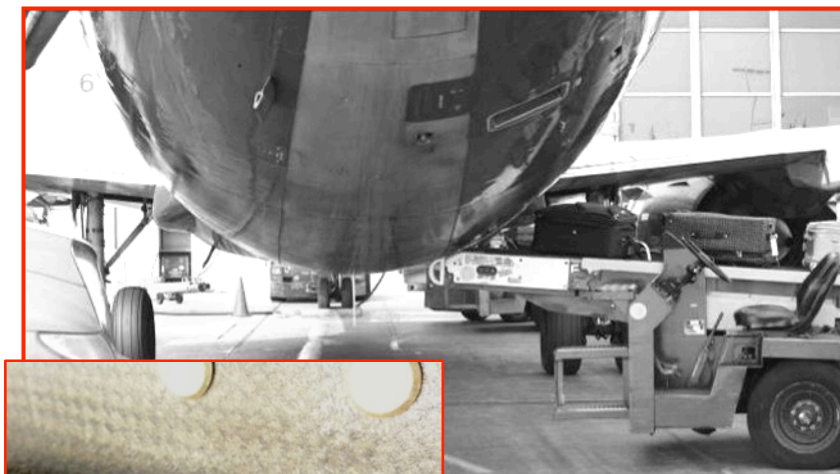
Impact Damage Formation on Composite Aircraft Structures

- **Motivation and Key Issues**
  - impacts are ongoing and major source of creating damage
  - high energy ***blunt*** impact damage (**BID**) of key interest
    - involves large contact area
    - damage created can exist with ***little/no exterior visibility***
- **Sources of Interest:** those that affect wide area or multiple structural elements
- **Needs:** (i) establish clear understanding of damage formation from ***blunt*** sources vs. visibility, (ii) prediction capability



Hail Ice Impact

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



Ground Vehicles & Service Equipment

- 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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Overall Program Objectives

- **Source Identification:** characterize blunt impact threats – relate to operations
- **Damage:** understand BID formation and visual detectability
  - determine key failure modes, driving phenomena, governing parameters
  - how damage and visibility affected by bluntness/contact-area
  - relate visibility to damage severity for various blunt impact sources
  - what conditions relate to development of significant internal damage with minimal or no exterior visual detectability?
  - identify & predict failure thresholds (useful for design)
  - provide guidance on the inspection and detection of BID to internal structural members
- **Test:** develop testing methodologies
  - defining stiffness and inertial BCs to represent complete structure
  - establish data for supporting modeling capability development
- **Prediction:** establish new modeling capabilities validated by tests
  - key failure modes, focusing on those not easily predicted by FEA
  - guidance on predicting damage visibility – dent and/or visible surface crack
- **Dissemination:** communicating results to industry and collaboration on relevant problems/projects via workshops and meetings

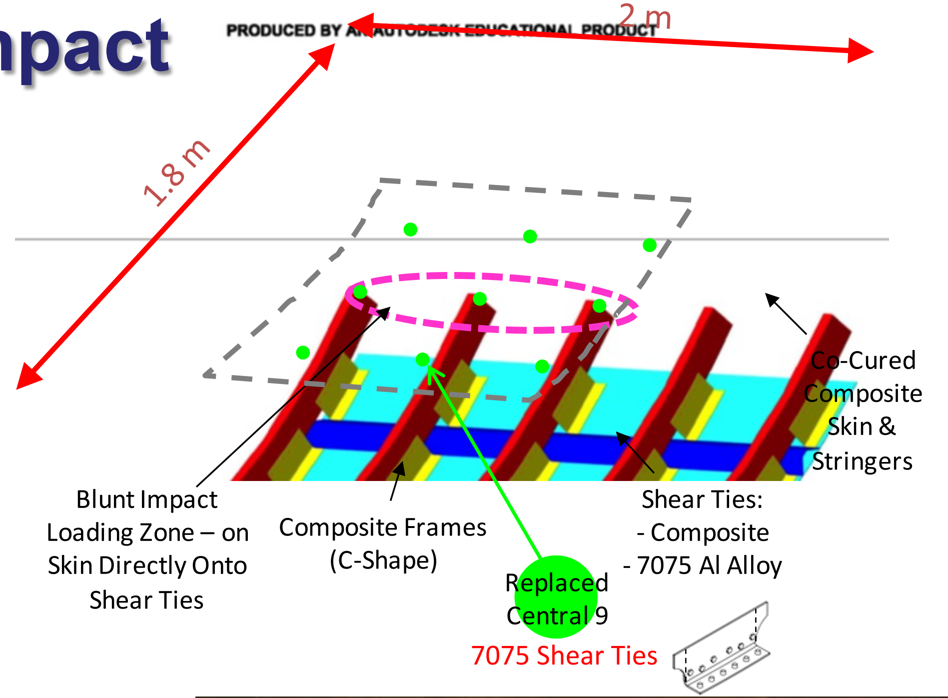
Outline

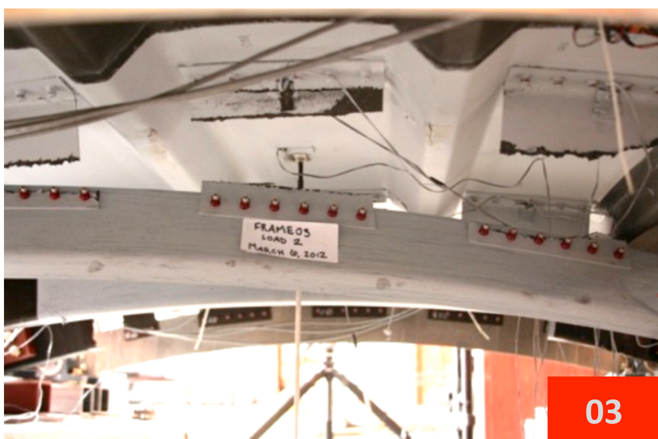
- Ground Service Equipment (GSE) High Energy Blunt Impact
- Blunt Impact Damage to Sandwich Panels
- Conclusions, Benefits to Aviation, and Future Work

GSE High Energy Blunt Impact
Previous Results Summary I

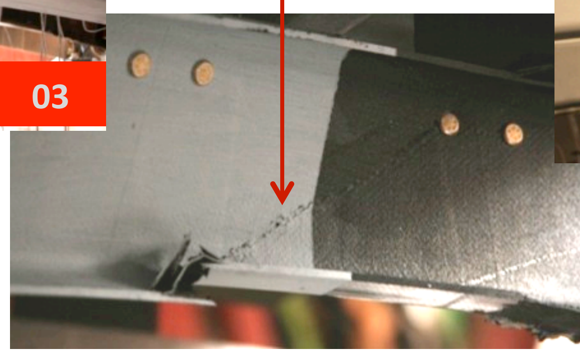
Large Specimen Blunt Impact Tests

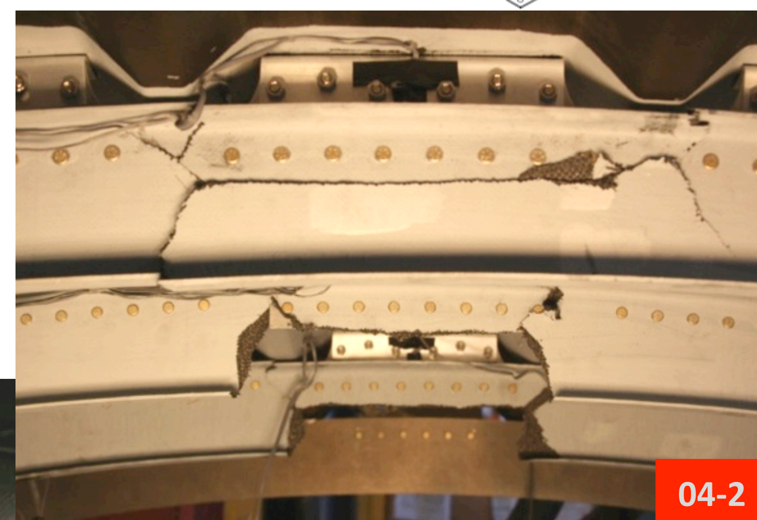
- series of large specimens (ID: Frame03, Frame04-1, Frame04-2) tested
- Frame03 (composite shear ties):
  - internal damage to frames and shear ties
  - no skin cracking / no visibility
- Frame04-2 (7075 Al shear ties):
  - direct shearing of frames at shear ties
  - light skin cracking – due to overdriven test





Frame
Failure
Near BCs





[Frame03 Test Video]

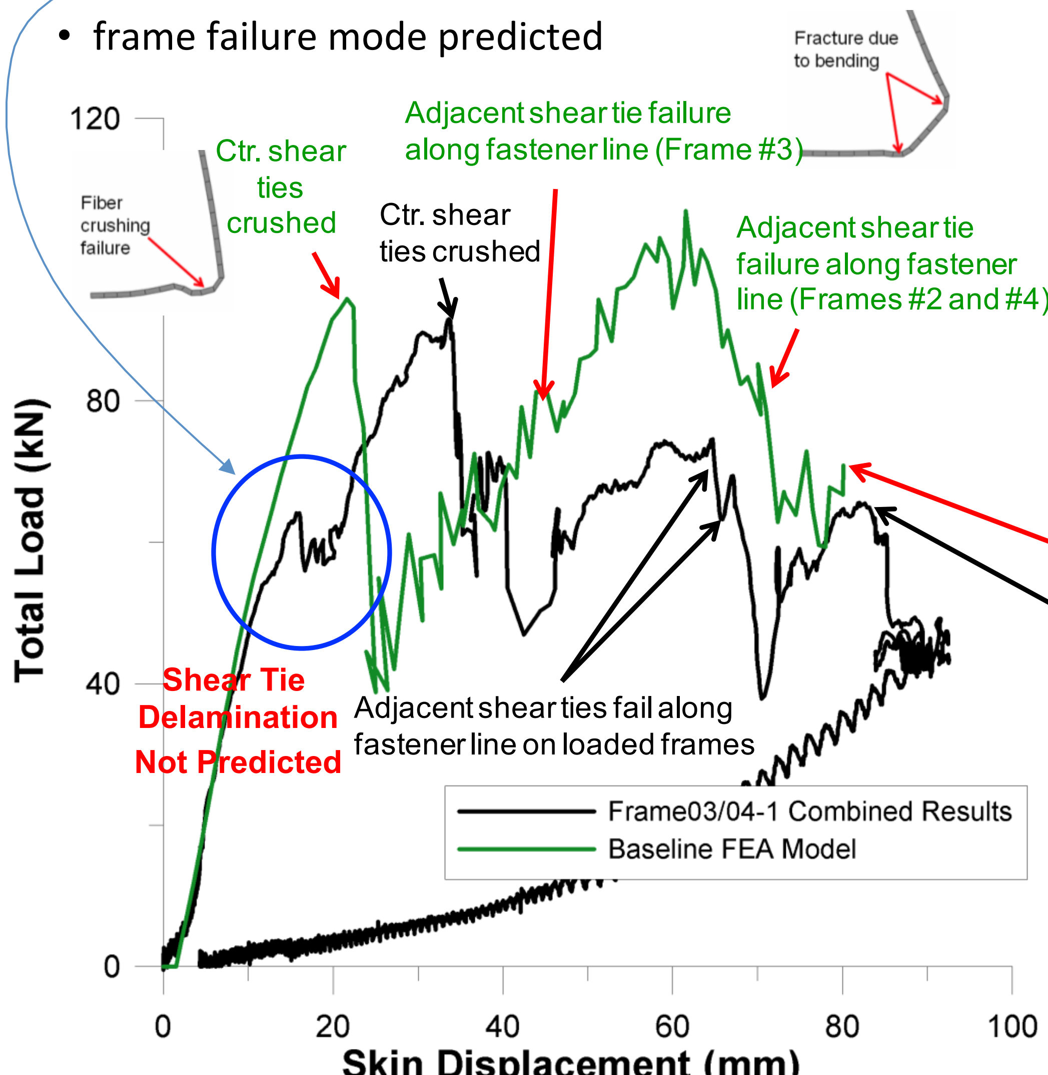
Post-Test View of Specimen Frame03
- No Exterior-Visible Damage

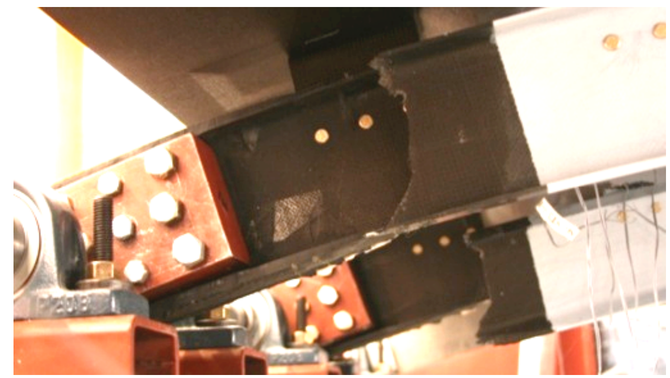
GSE High Energy Impact – Previous Results Summary II

Modeling Results as of March 2013

- predicts failure modes from in-plane (ply) stresses, but not interlaminar failures
  - initial mode: shear tie delamination occurs 1st – affects subsequent history
- frame failure mode predicted

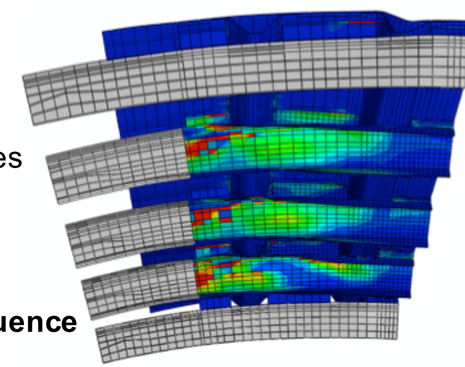
For 2013-2014: interlaminar failure prediction capability





Frame failure near boundaries

Frame failure near boundaries

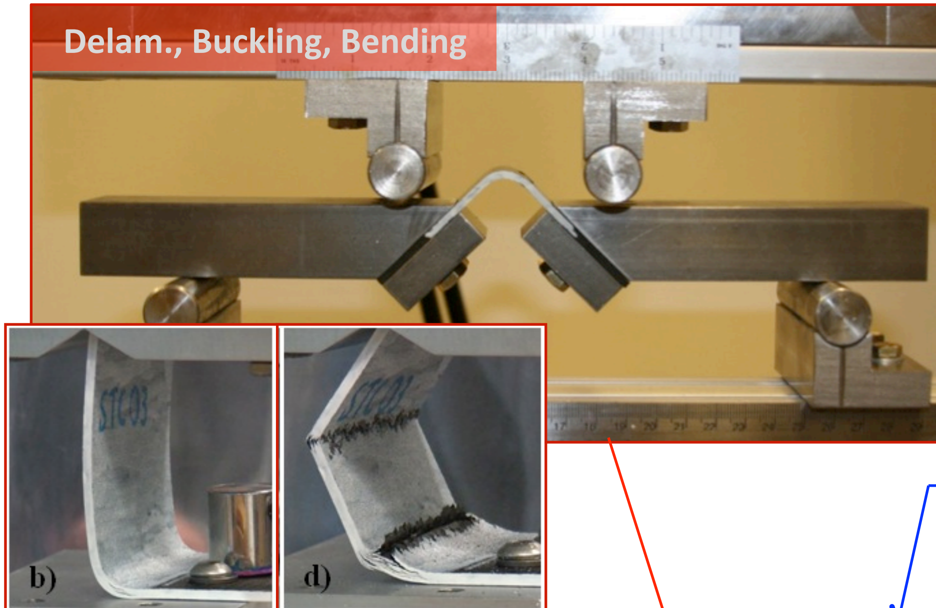


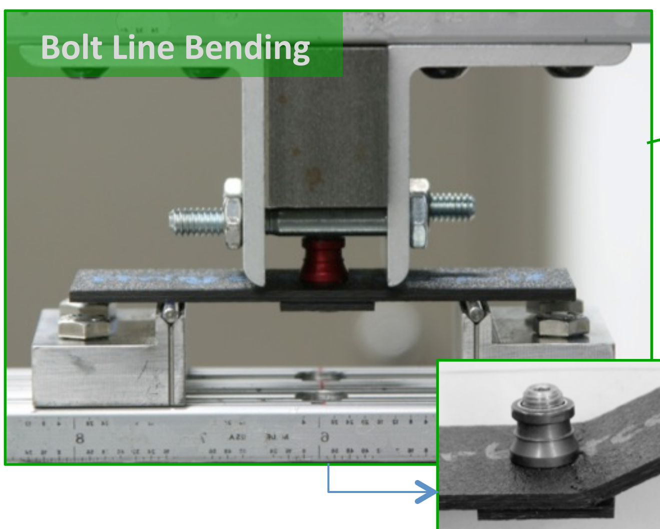
Good correlation
- **initial load drop**
- **failure mode sequence**
- **final failure**

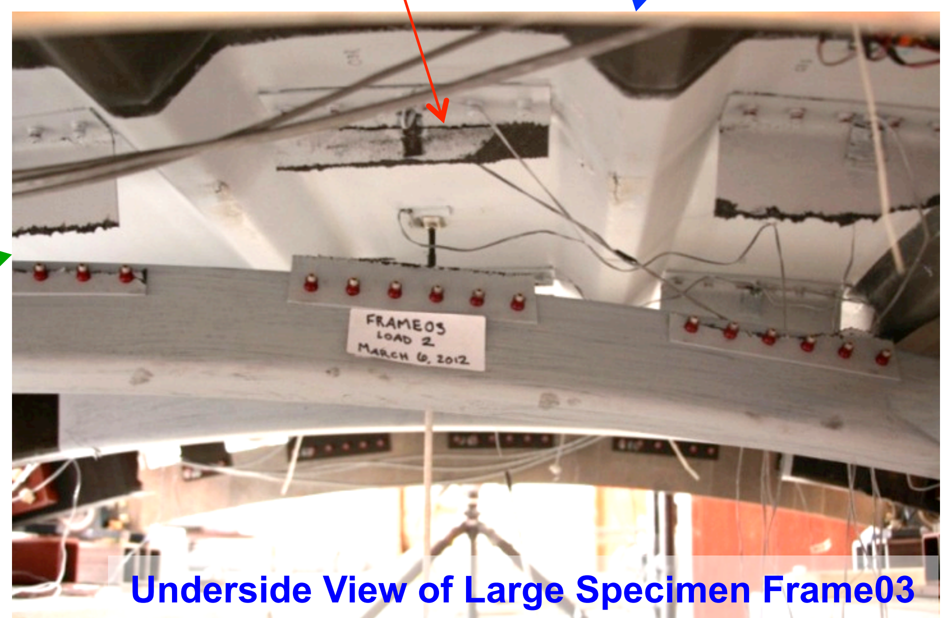
Issues with
- **initial & intermediate failure displacements**

Building Modeling Capability: Element-Level Tests

- small-scale failures affect large-scale overall behavior
- element-level tests conducted to support accurate model development
  - key failure modes
  - initiation & growth
  - final failure
- no “tuning” of material properties







Underside View of Large Specimen Frame03

Also:
- Frame Bending
- Frame Torsion
- Stringer Penetrate by Frame Indentation
- Stringer Delam.

Shear Tie Coupon Compression

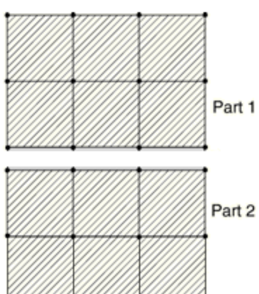
Shear tie coupon cut from full shear tie and loaded under compression.

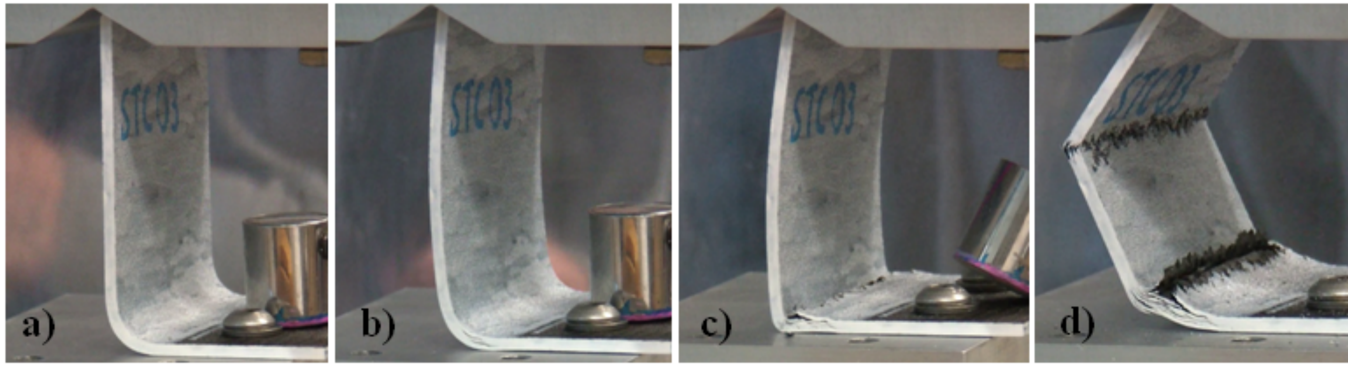
- bolted to base (skin side), simple V-groove at top BC

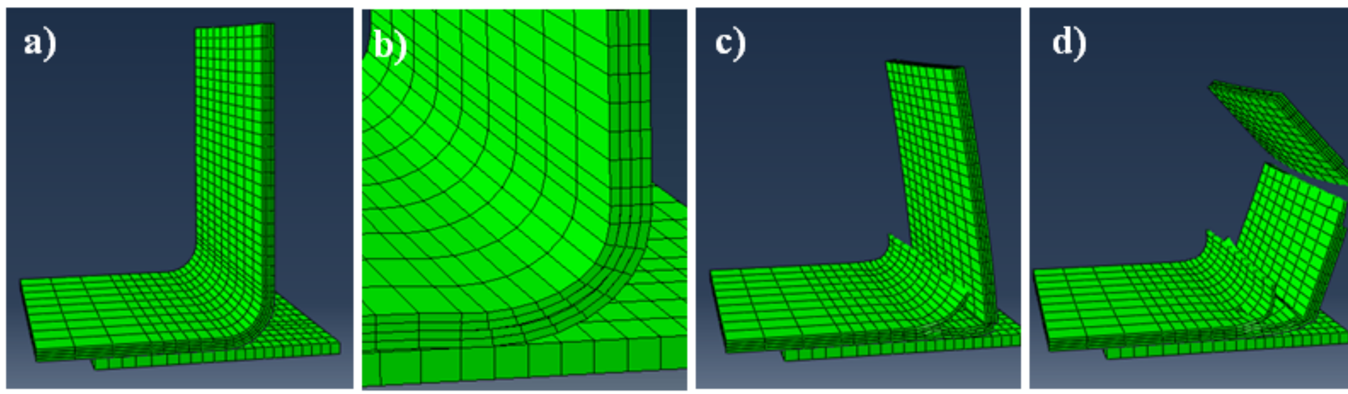
Curved geometry delaminates due to interlaminar tension under opening moment.

Shear tie coupon modeled via

- 4-6 layers of continuum shell elements (SC8R)
- cohesive surface interactions applied between layers
- Hill criterion for 3D failure (intraply fiber under σ_{13} & σ_{23})







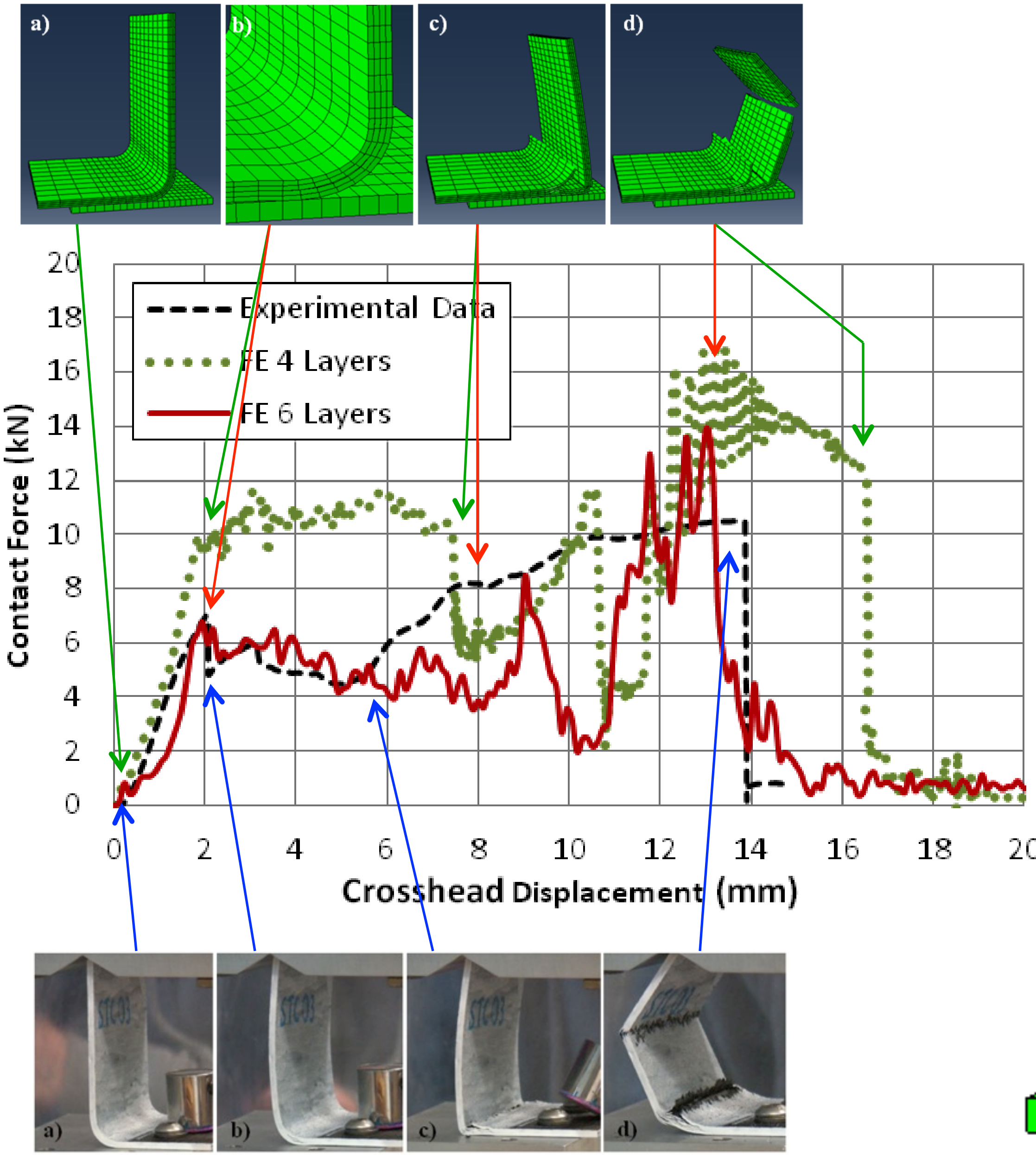
Initial Geometry Before Loading

Delamination Due to Opening Moment

Corner Failure – Shear Tie Straightens

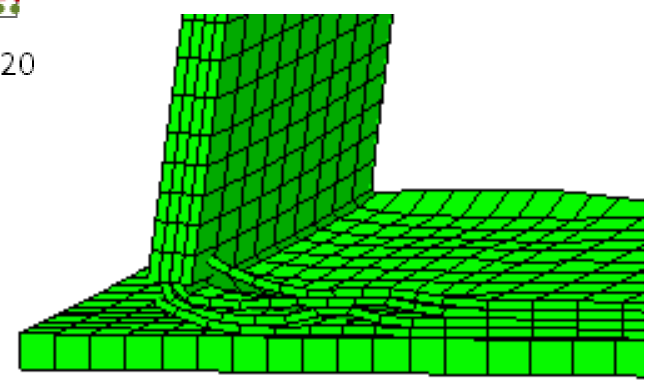
Bending Failure Following Buckling

Shear Tie Coupon Compression Results



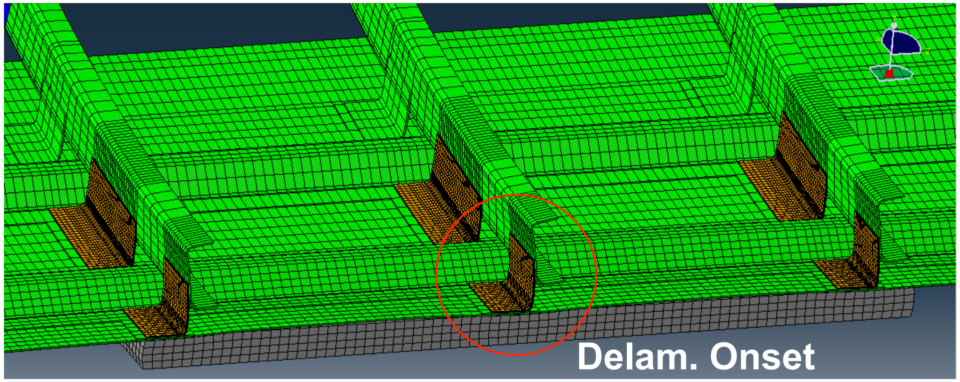
4-Layer Model Animation

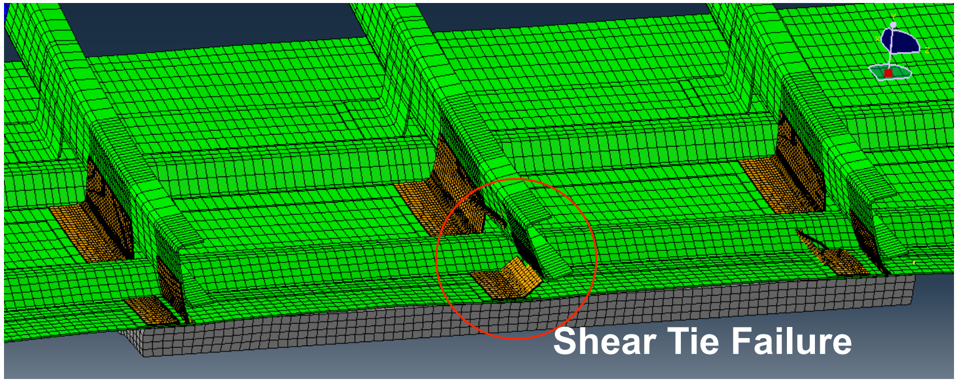
- more accuracy with increasing number of continuum shells through thickness
  - 4 layers: 3 plies/group
  - 6 layers: 2 plies/group – predicts initial delam. onset & final failure well
- higher cost – more elements and more cohesive surface layers

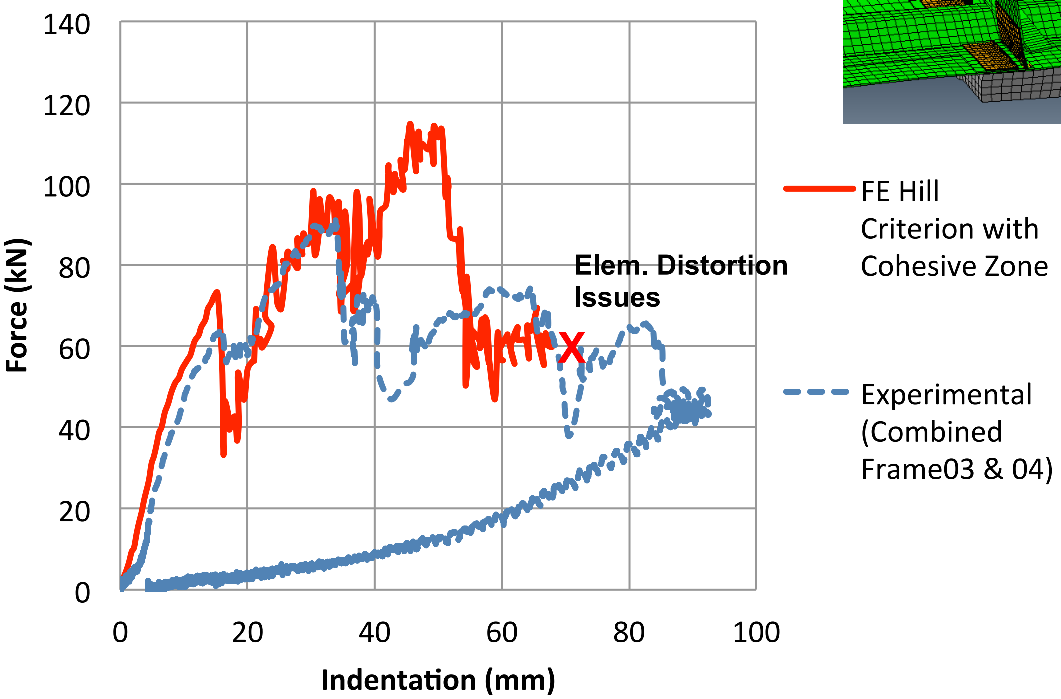


Large Panel Modeling

- accurate modeling capability established via element-level test
- modeling approach applied to large panel
- results capture initial response of shear ties (delam.) well
- final failure not yet reached due to stability/cost issues (work in progress)



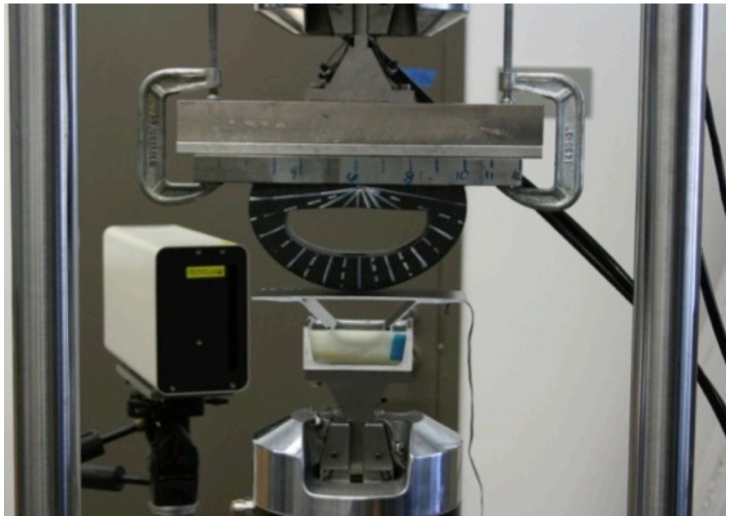


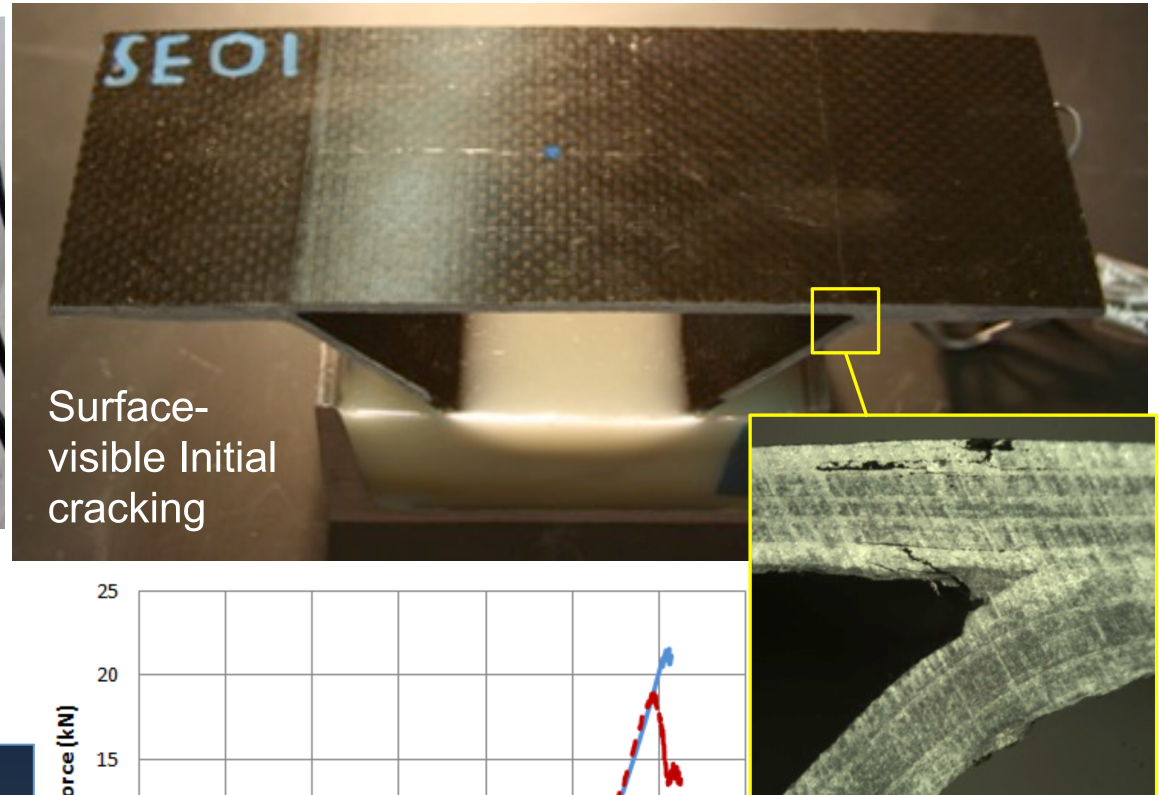


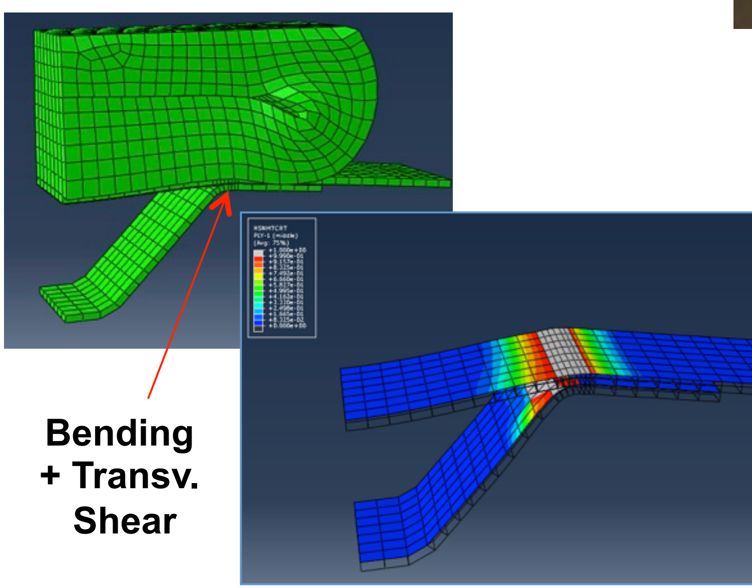
Full Panel Simulation Layered Shear Ties - View 1

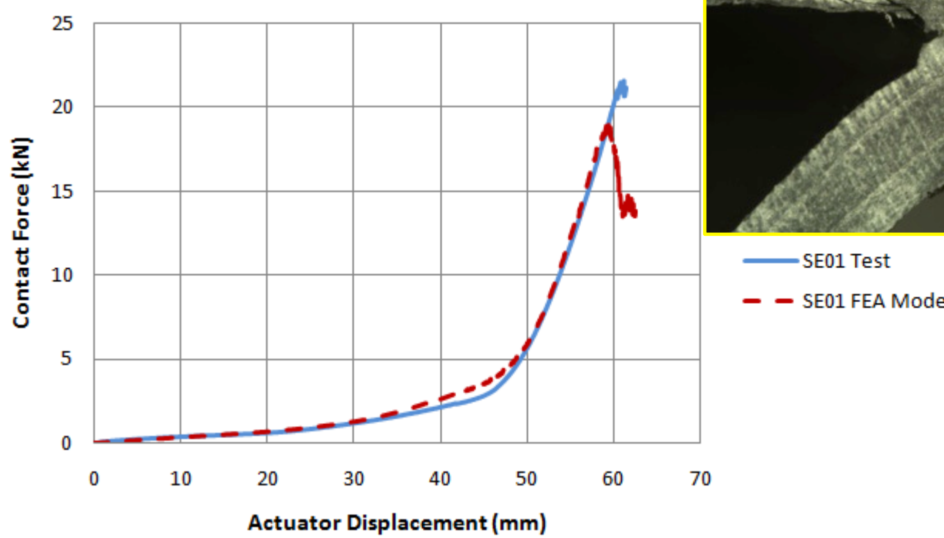
Skin Cracking Under Bumper Contact Zone

- stringer element tests to excite just-visible failure modes by bumper indentation
- define FEA criteria indicating visibility – for fabric outer layer, vs. unidirectional





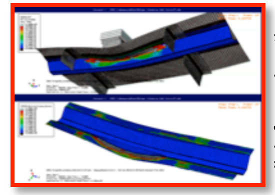




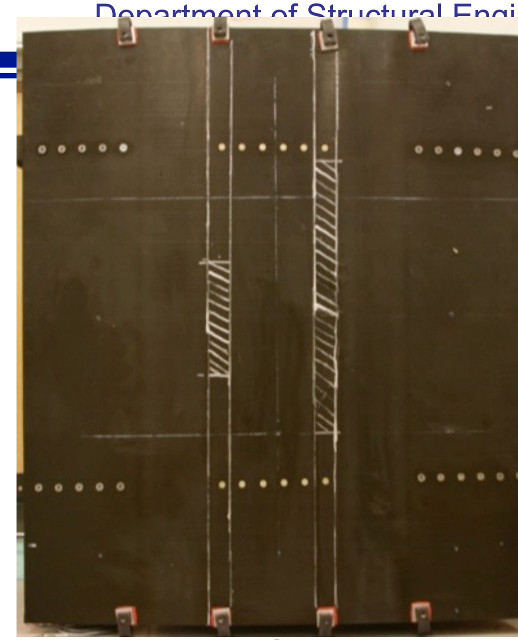
Small Panel Modeling

Test and Model Comparison

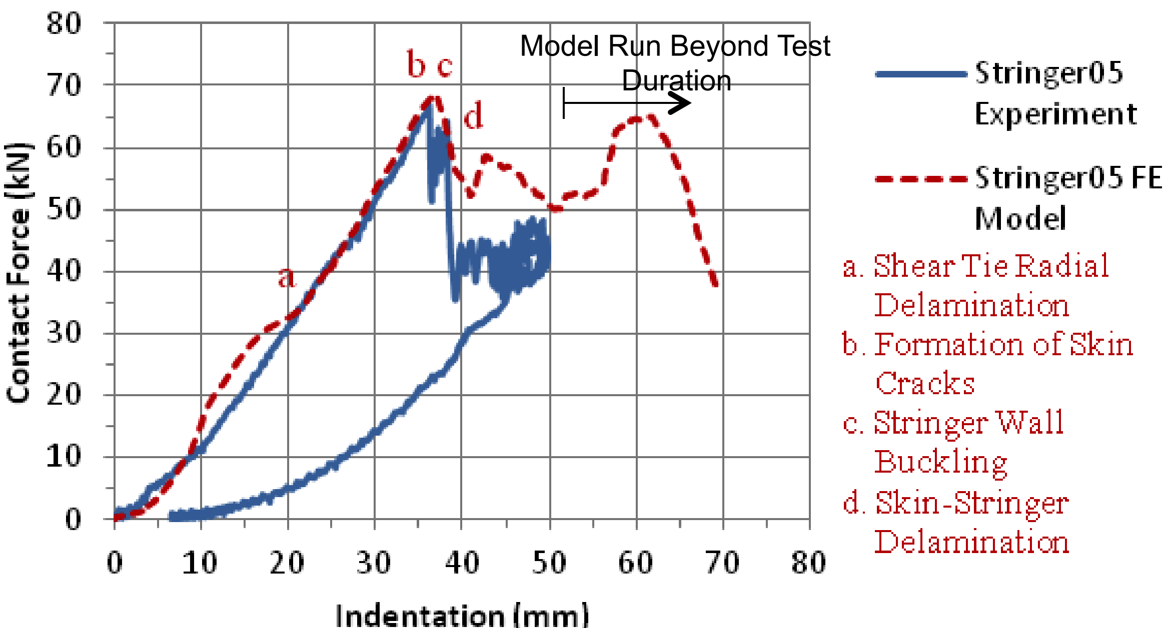
- **stringer-skin delamination predicted between shear ties**
- **grows from loading location outwards**
- **FEA model successfully matches:**
    - **Initial stiffness and failure initiation loads**
    - **failure modes and final damage state**

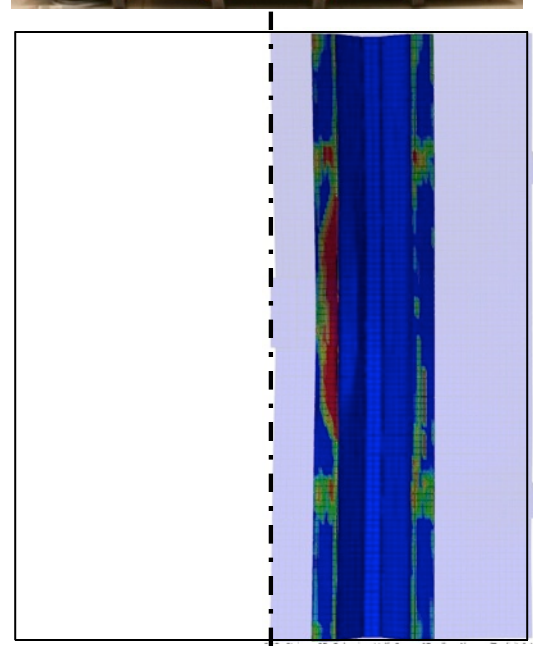


click for animation



Post-test damage state (hatched zones show skin-to-stringer delamination)

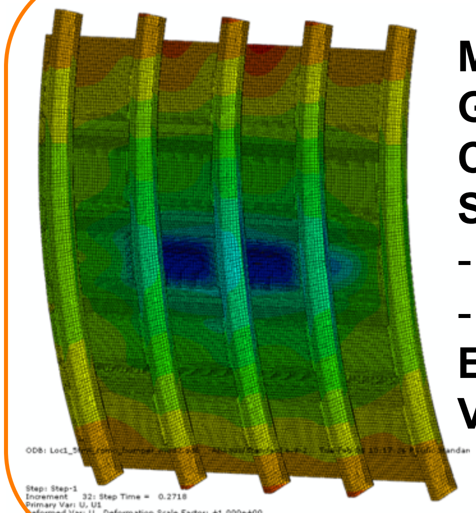




FEA model predicted delamination

Modeling Capabilities Plan

UCSD
Department of Structural Engineering



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

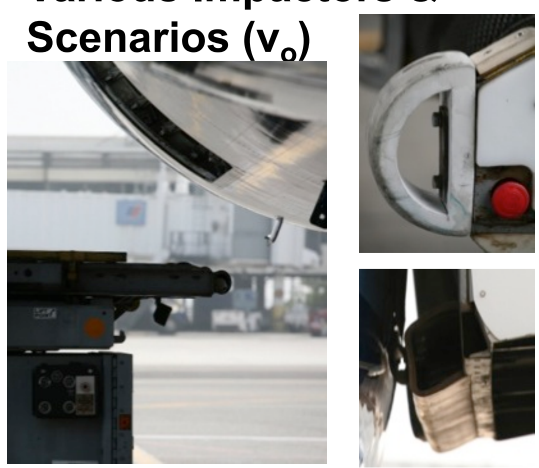
Dynamic Effects

Externally Visibility

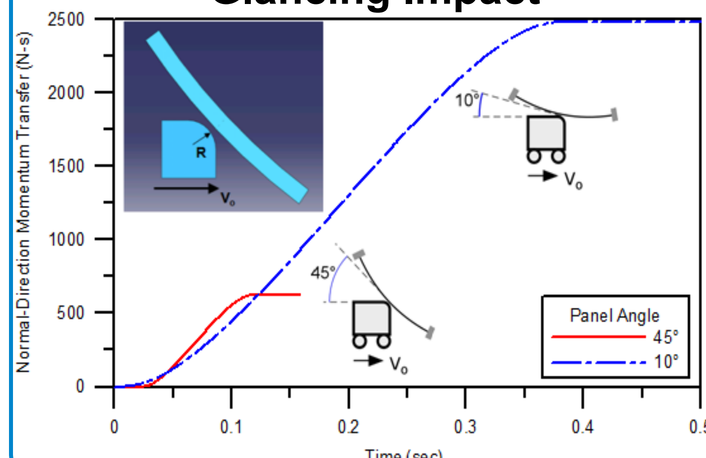
Apply to study and predict response for:

Size, Complex Internal Structure, Geom., Joints

Various Impactors & Scenarios (v_o)



Glancing Impact



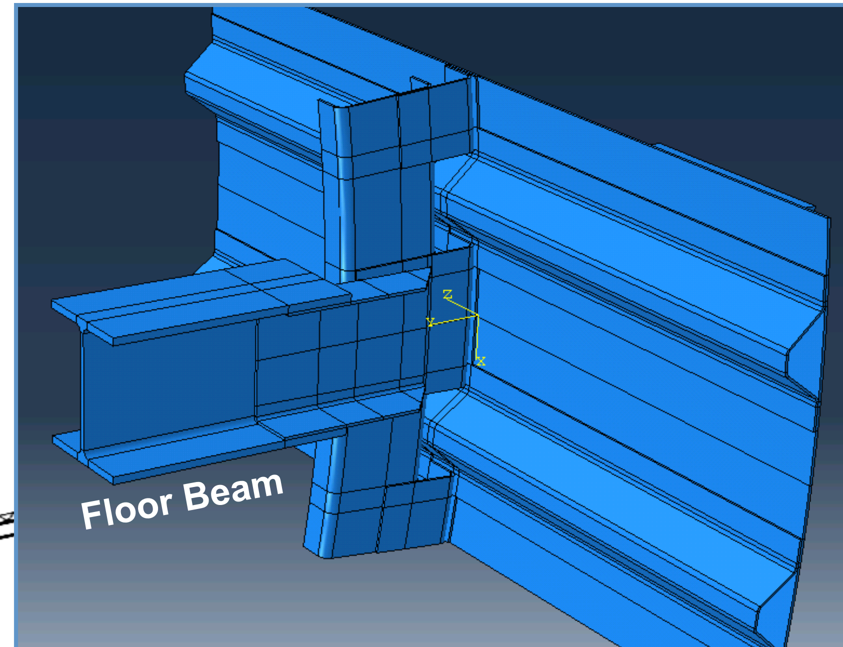
Floor Structure Interaction

Focus:

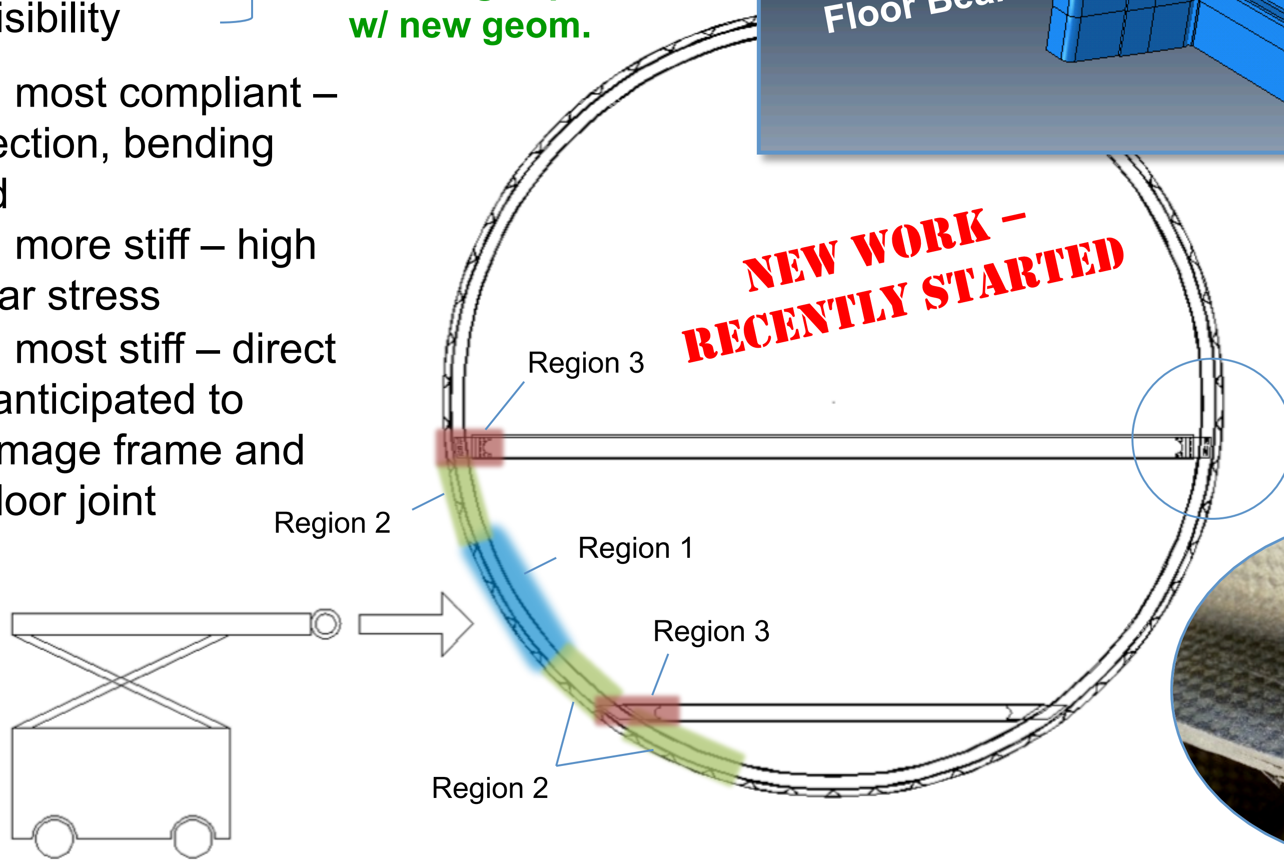
- frame-to-floor joint failure & stiffness/BC effect
- glancing Impact
- damage locations vs. contact location vs. external visibility

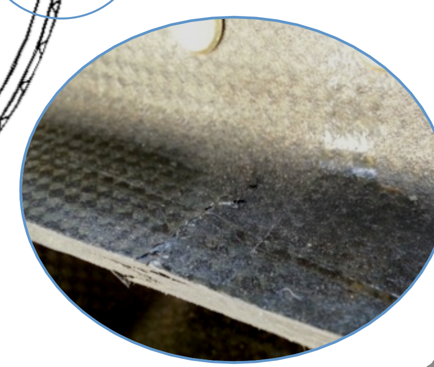
A. explore via modeling how affected by various structural configurations – e.g., shear tie geom., stringer spacing, etc.

B. test large specimen w/ new geom.



- **Region 1**: most compliant – large deflection, bending dominated
- **Region 2**: more stiff – high beam shear stress
- **Region 3**: most stiff – direct GSE hits anticipated to readily damage frame and frame-to-floor joint





Outline

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

Blunt Impact Damage to Sandwich Panels

- Investigate internal damage morphology of impacts on sandwich panels using blunt impact sources
  - metal tips of varying tip radii: R12.7 to R76.2 mm (low vel.)
  - 50.8 mm ice spheres at glancing angles 10 to 40 deg. (high vel.)
  - special focus on levels just barely visible damage
    - understand impact conditions resulting in subsurface damage formation (barely visible dents)
    - focus on core damage with no facesheet cracking
    - relate core damage severity vs. dent depth / span

Currently Ongoing

- Determine the reduction in core strength / fracture properties as function of (i) damage severity and (ii) dent visibility
  - direct measurement
  - modeling (including prediction of impact-induced damage)
- Investigate heavier-core sandwich panels with thicker facesheets
  - varying core density, varying facesheet config.

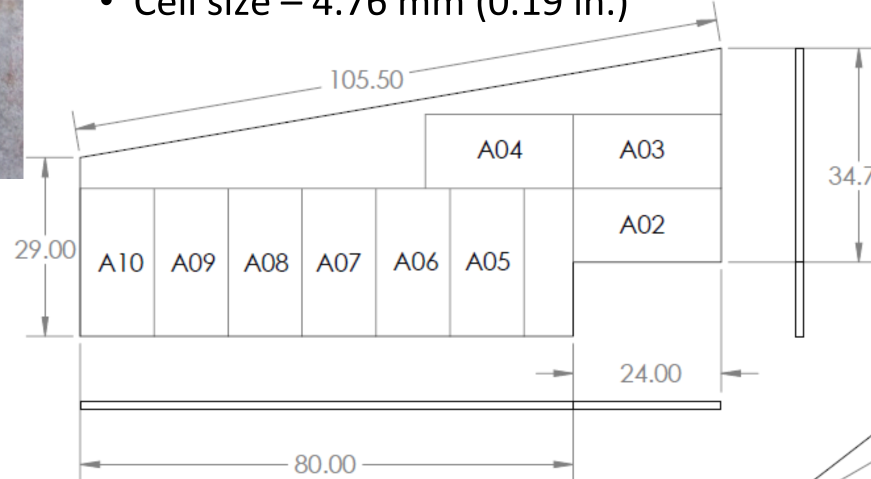
Future Direction

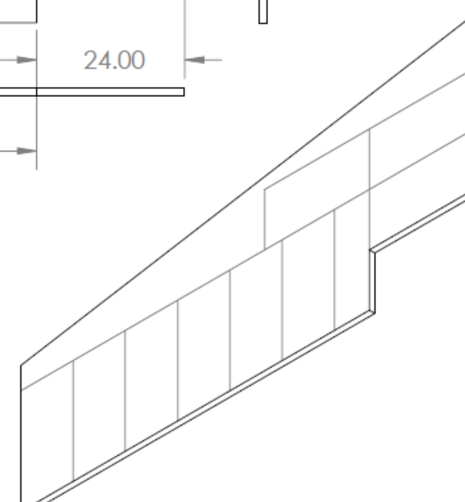
Sandwich Panel Specimens

Tip-damaged A320 rudder - received from Delta Airlines (P/N D554 71004 0000)

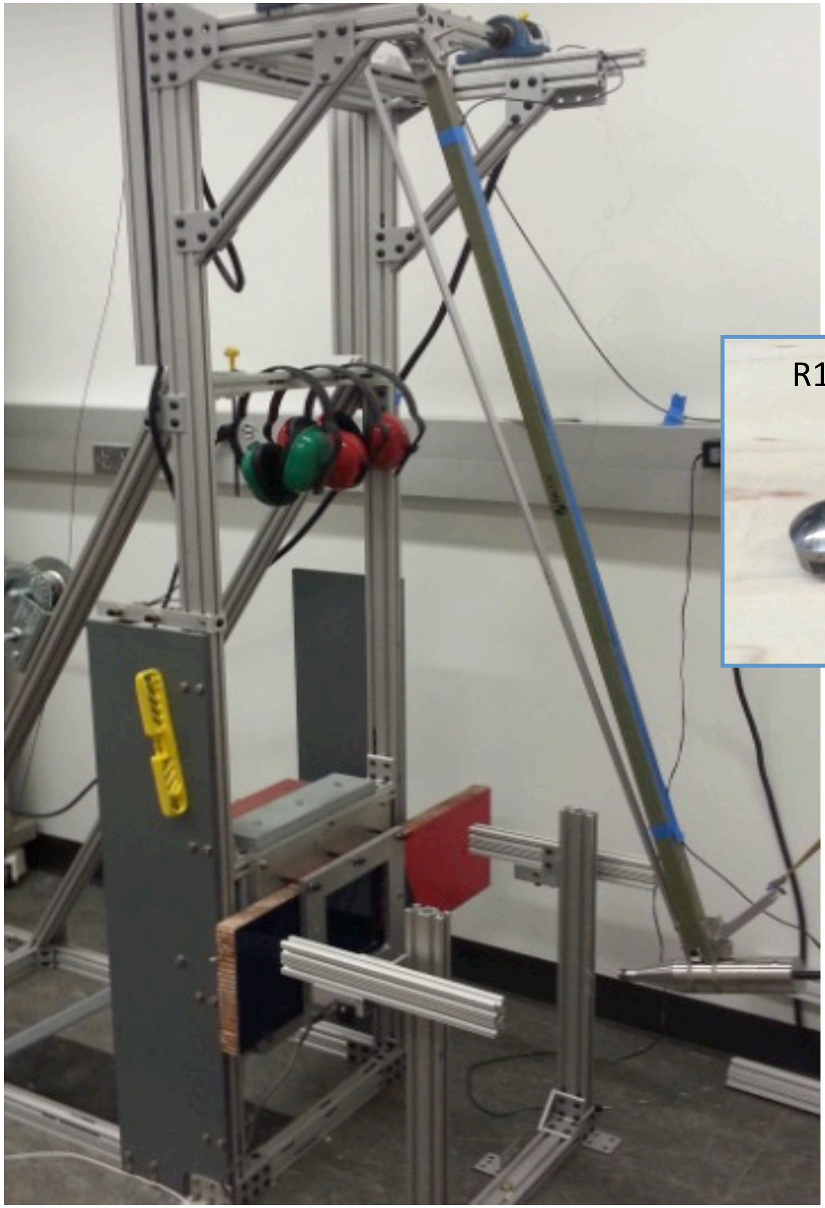
Test specimens details

- Outer facesheet thickness – 1.19 mm (0.047 in.)
- Inner facesheet thickness – 0.64 mm (0.025 in.)
- Core thickness – 29.4 mm (1.16 in.)
- Core density – 32 kg/m^3 (2 lb/ft^3)
- Cell size – 4.76 mm (0.19 in.)

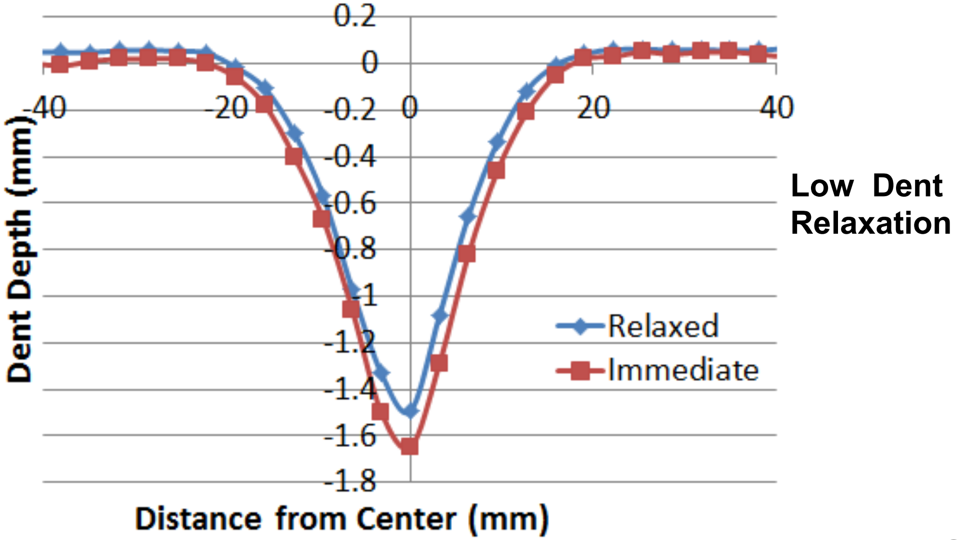




Low Velocity Blunt Impact

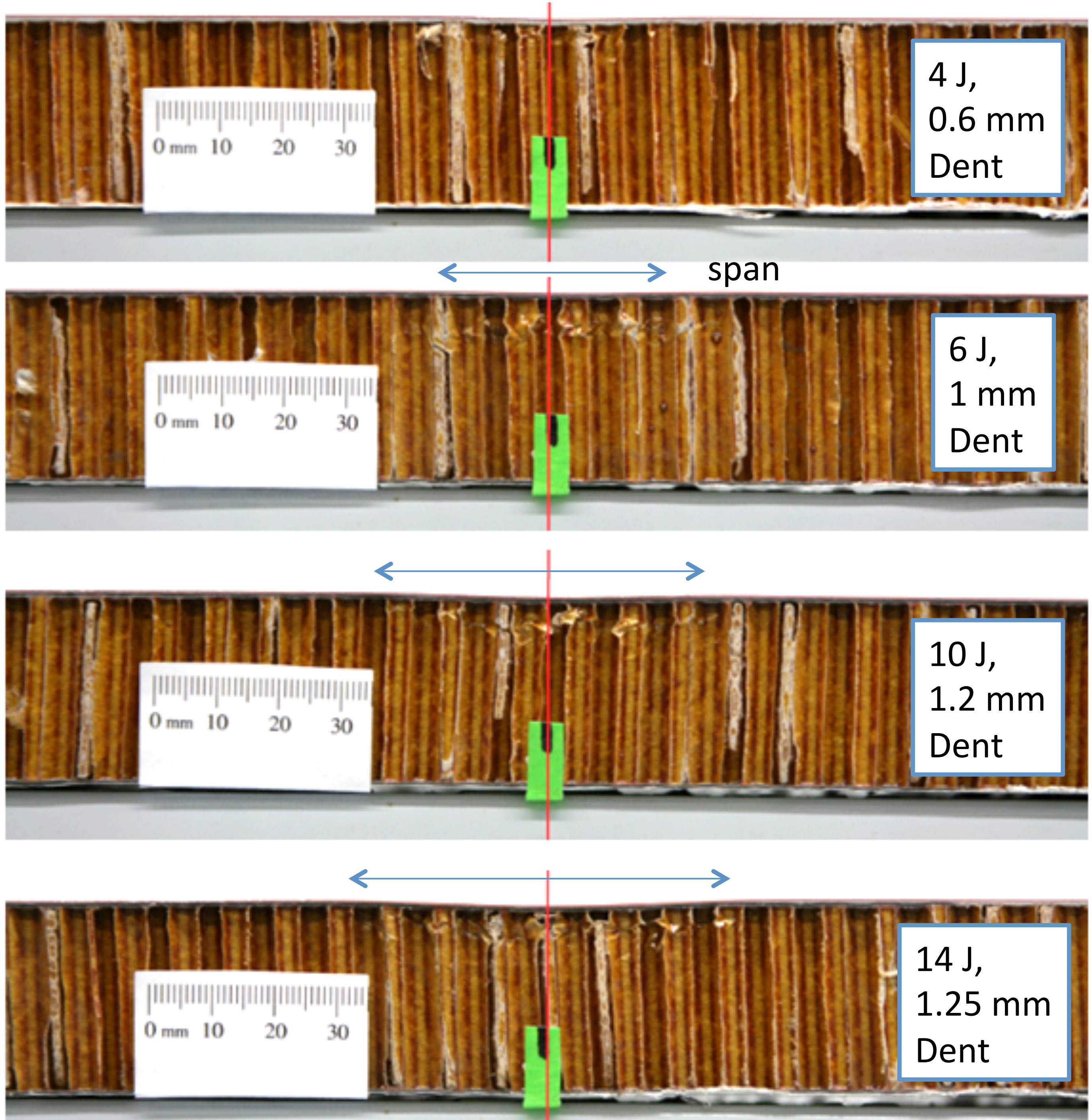


- Pendulum Impactor with 1.4 m arm
- Panel held in a 165 mm (6.5 in) square opening window
- 12.7 to 76.2 mm radius tips represent generic low velocity sources

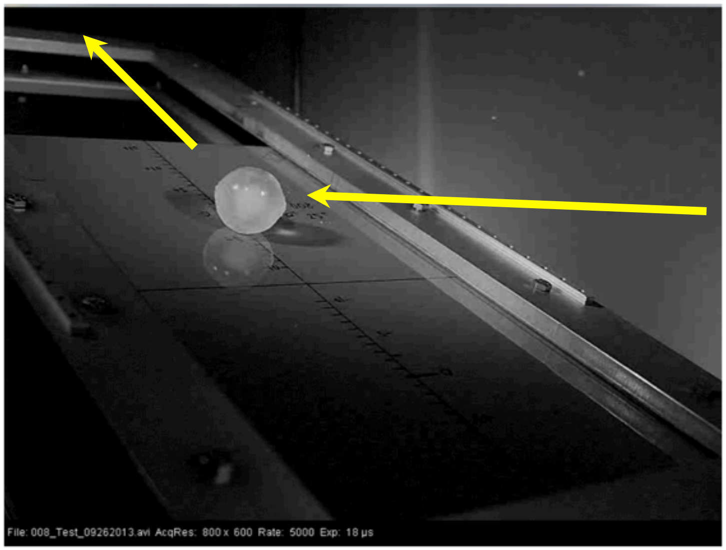


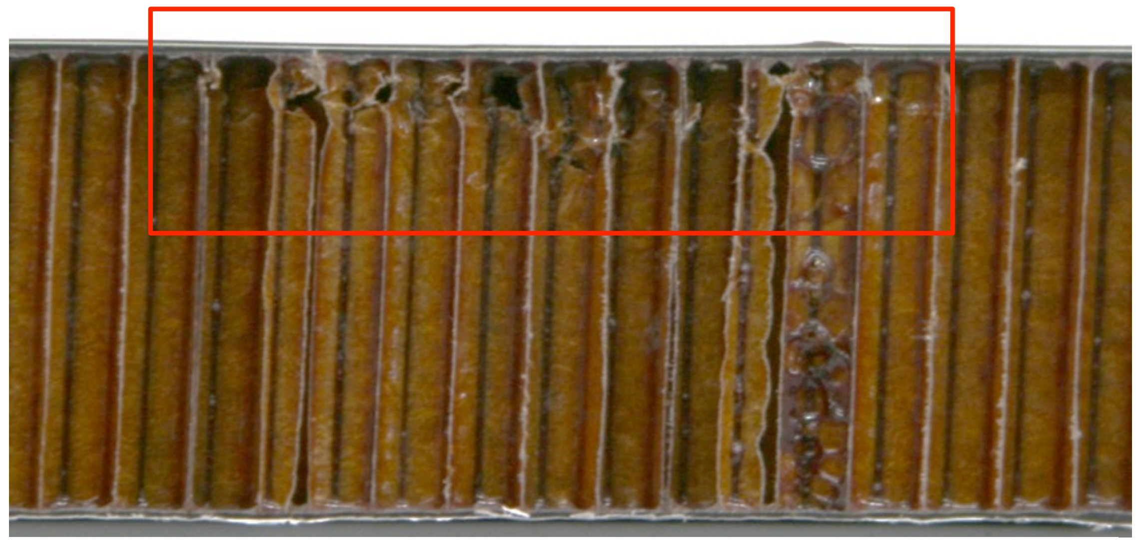
Low Velocity Impact Damage Progression

- R50.8 tips impacts from 4 to 14 J energy
- For increasing energy:
  - depth of core damage does not strongly increase
  - span of crushed zone widens
  - severity of core wall fracture increases

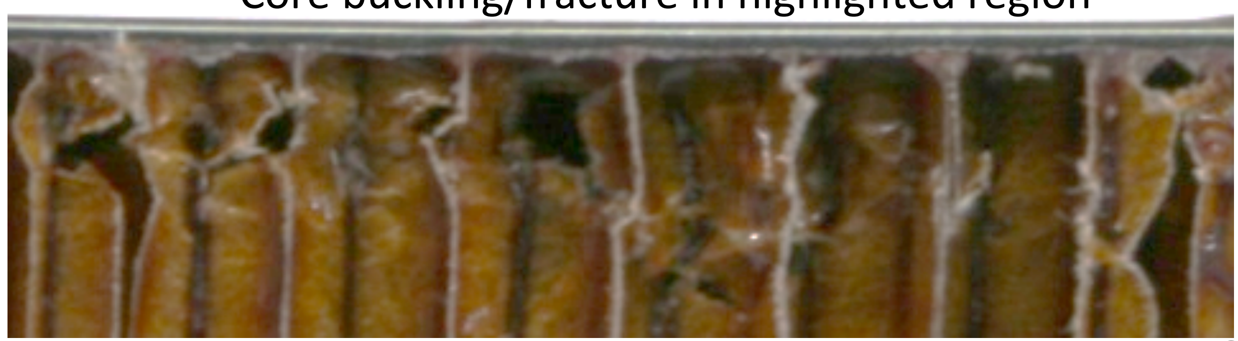


High Velocity Ice Impact – Example Results





Core buckling/fracture in highlighted region



Test Details:
Impact Angle: 25 degrees
Hail Diameter: 50.8 mm
Velocity: 43.3 m/s
Peak Dent Depth: 0.40 mm

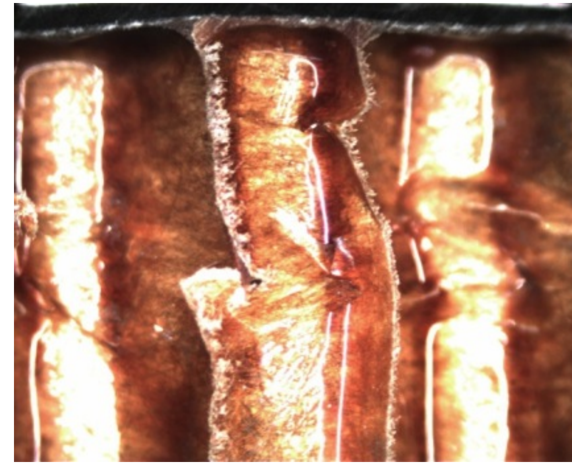
Summary: Core Blunt Impact Damage Modes

- **Mode A:** slight wrinkling of cell walls (not easily visible)
- **Mode B:** clearly visible wrinkling of cell walls
- **Mode C:** buckling of cell walls; folded
- **Mode D:** fracture/ bursting of cell walls

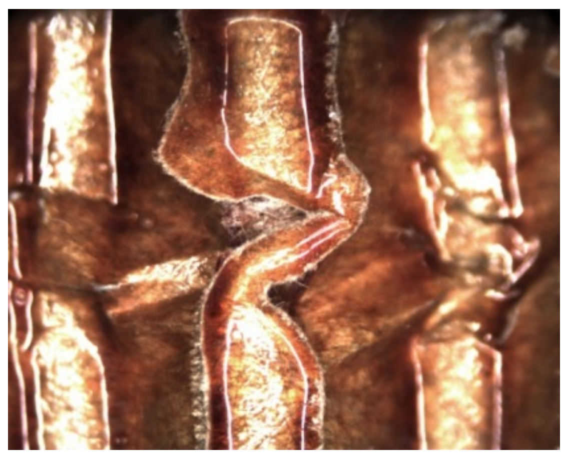
Need to:

- understand physics of core damage formation
- predict core damage via FEA
- relate core damage to reduction in core strength
- define models accurately predicting core damage propagation

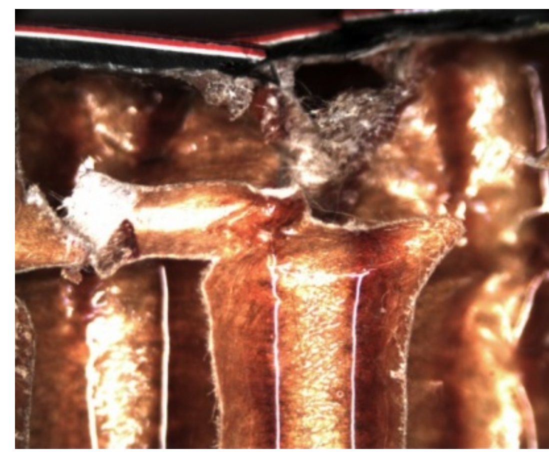
(a) Mode A



(b) Mode B



(c) Mode C



(d) Mode D

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Conclusions

Ground Service Equipment (GSE) High Energy Blunt Impact

- accurate large structure modeling requires development of modeling capability based on simple structural element specimen tests
- layered modeling approach using continuum shells and cohesive surface interactions shown to be capable of predicting delamination and failure under high transverse shear
- within-ply failure under high out-of-plane shear requires 3D criterion – Hill used successfully, but need to implement user-material definition (3D Hashin)

Blunt Impact Damage to Sandwich Panels

- significant internal core damage possible with very low dent levels
  - any surface-visible denting = significant internal core damage
- fracture of core walls found to be approx. planar and at fixed depth below facesheet/core interface (roughly 1X to 2X cell size)
- blunter impacts (larger radius) produce more shallow dents that exhibit more relaxation over time

Benefits to Aviation

Ground Service Equipment (GSE) High Energy Blunt Impact

- Understanding of prospective damage produced from wide-area GSE impact events
  - awareness of phenomena and possible internal failure modes
  - provides key information on mode and extent of seeded damage, particularly non-visible impact damage (NVID) from blunt impact threats – for Damage Tol. scenarios
  - threat conditions causing significant damage – range of energy level needed
- Establish FEA modeling capability that can predict:
  - onset and growth of cracks that lead to large-scale damage and degradation
  - damage locations – could be away from location of impact
  - if GSE impact damage is visible from exterior
  - response of different configuration of interest
- Identify how to detect/monitor occurrence of damaging events
  - key measurable quantities signifying major damage creation – e.g., acoustic waves
  - what inspection technique should be used? where?

Blunt Impact Damage to Sandwich Panels

- Increase understanding of: blunt impact damage modes, governing mechanisms
- Insight into properly seeding damage for damage tolerance assessment
- Assessment of internal core damage state based on external damage visibility

Looking Forward 1/2

Ground Service Equipment (GSE) High Energy Blunt Impact

- Include effects of floor joints and floor beams to better represent fuselage structure
- Systematically investigate effect of geometry of components on blunt impact damage – e.g., geom. and position of stringers, shear ties, frames
- Quarter-barrel or half-barrel fuselage tests
  - needs to include internal floors, joints, and other structure
  - impact with actual GSE vehicle (or rolling-mass representative)
  - glancing impact effects
- Blunt Impact on Other Structure Types
  - metal-composite hybrid , all-metal construction, aged metal structures (WFD interest)
  - sandwich construction
  - non-fuselage locations – e.g., lower wing and empennage surfaces
- Continued developments to establish high fidelity FEA modeling capability
  - accurately predict damage initiation, progressive failure process, damage extent, energy absorption, accounting for interlaminar failures
- Define generally-applicable visibility metrics and failure criterion compatible with FEA
- NDE methods for finding major damage to internal structure, including frame cracks and shear tie failures
- Education/Training: dissemination of results, host workshops

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Looking Forward 2/2

Blunt Impact Damage to Sandwich Panels

- Relate observations of internal core damage depth and span to external visibility
- Compression after impact testing of the panels tested – relate residual strength to types of damage
- Establish capability within explicit FEA simulation to predict:
  - blunt impact induced damage modes, size, and severity
  - post-impact residual strength reduction – damage propagation under peel and transverse shear
- Conduct post-impact facesheet peel/fracture tests
  - focus on sub-visible core damage effects
  - damage modes and morphology relationship to core, facesheet, and adhesive attributes
  - correlate results with FEA predictions
- Investigate effect of multi-hit and impact adjacency
- Determine how core/facesheet/fillets interact with each other as related to impact damage formation, location, and subsequent disbond growth
- Explore efficient and effective NDE methods to assess core damage

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