JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

Impact Damage Formation on Composite Aircraft Structures

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

JAMS 2015 Technical Review
March 31 – April 1, 2015

Aircraft Airworthiness & Sustainment Conference 2015
Baltimore Marriott Waterfront, Baltimore MD

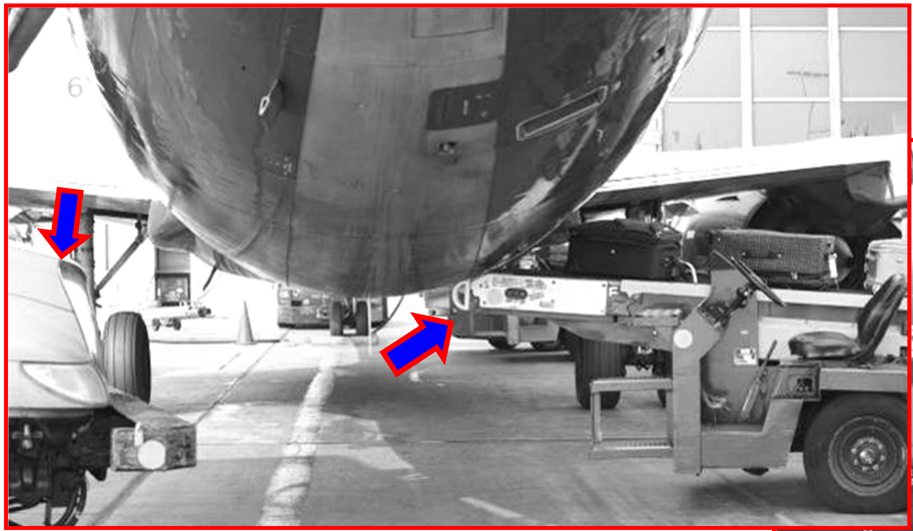
Impact Damage Formation on Composite Aircraft Structures

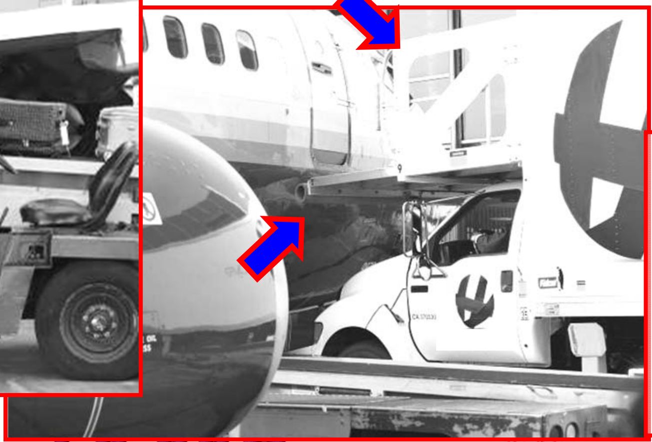
- **Principal Investigators & Researchers**
  - PI: Prof. Hyonny Kim, Professor, UCSD
  - Graduate Students
    - PhD: Zhi Ming Chen, Konstantinos Anagnostopoulos, Moonhee Nam
    - MS: Sean Luong
- **FAA Technical Monitor**
  - Lynn Pham
- **Other FAA Personnel Involved**
  - Curt Davies
  - Larry Ilcewicz
- **Industry Participation**
  - Boeing, Bombardier, Cytec, UAL, Delta, DuPont
  - San Diego Composites, JC Halpin, Avanti Tech
  - Coordination with Bishop GMBH (EASA-funded)

Impact Damage Formation on Composite Aircraft Structures

- **Motivation and Key Issues**
  - impacts are ongoing and major source of aircraft damage
  - high energy *blunt* impact damage (**BID**) of interest
    - involves large contact area
    - damage created can exist with ***little/no exterior visibility***
- **Sources of Interest:** those acting over wide area and/or multiple structural elements, leaving low/no visibility
  - ground service equipment (GSE) rubber bumpers
  - railings, blunt/round corners, FOD of unknown geometry
  - hail ice

Hail Ice Impact
- upward & forward facing surfaces
- low mass, high velocity (25 to 230+ m/s)





Ground Vehicles & Service Equipment
- side & lower facing surfaces
- high mass, low velocity

CECAM JAMS AMTAS

Overall Program Objectives

General Objectives Applicable to Blunt Impact Sources of Interest:

- **Understand blunt impact damage formation and visual detectability**, seeking to:
  - establish how damage is affected by bluntness/contact-area
  - determine key phenomena and parameters controlling both internal and external/visual damage formation
  - identify and predict failure thresholds (useful for design)

- **Develop analysis and testing methodologies**, including:
  - physically-based modeling capabilities validated by tests, and
  - defining how to analytically predict if damage is visually detectable
    - surface crack (failure criteria), residual dent
  - for GSE impact on large-sized structure: defining appropriate boundary conditions between full-scale panels vs. entire aircraft

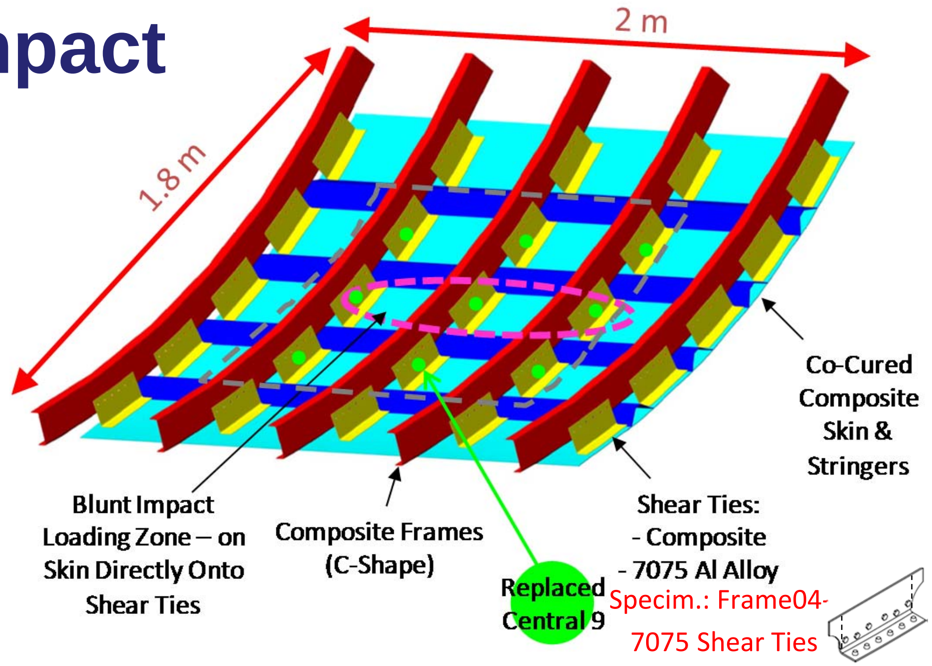
Outline

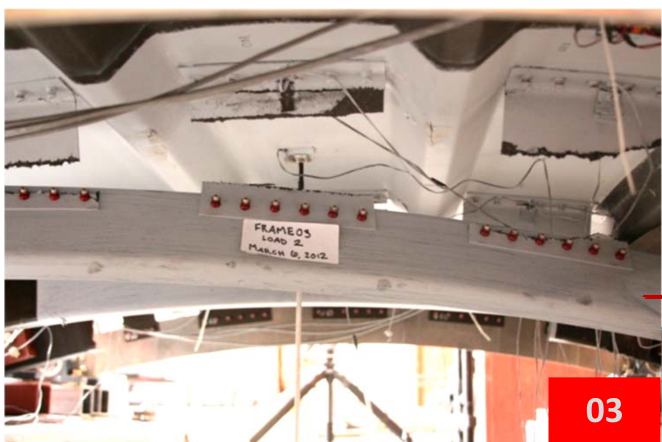
- Ground Service Equipment (GSE) High Energy Blunt Impact
- Blunt Impact Damage to Sandwich Panels
- Conclusions, Benefits to Aviation, and Future Work

GSE High Energy Blunt Impact

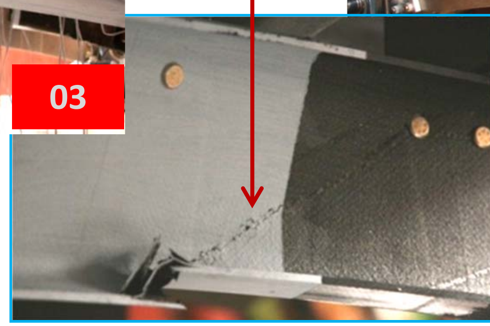
Previous Results Summary I

- 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





Frame Failure Near Outer Shear Ties



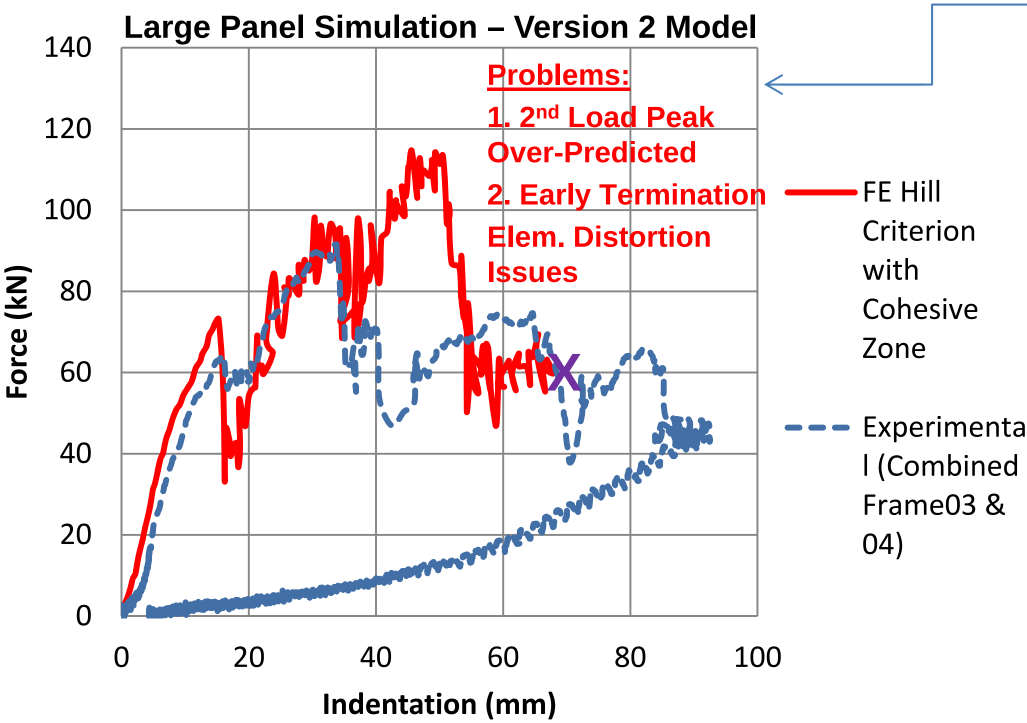
Damage Not Visible from Exterior

GSE High Energy Impact – Previous Results Summary II

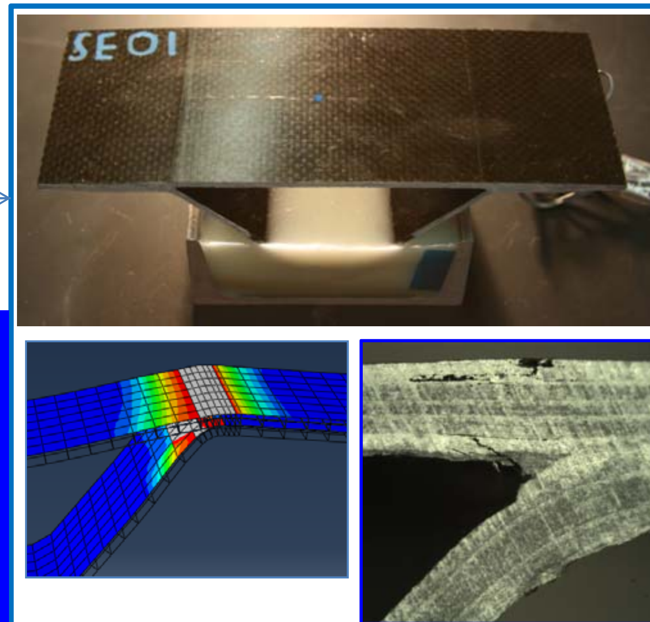
Modeling Results as of March 2014

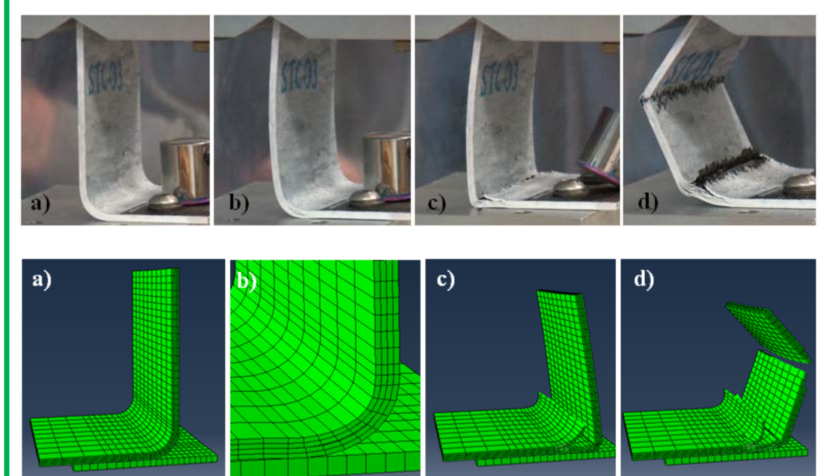
- skin-stringer cracking –visible cracking onset
- shear tie crushing
  - layered continuum shell elements with cohesive surface interactions
  - model properties from: coupon test data, literature
  - validation with element-level test

- **full panel simulation (2014 Version 2)** – early termination due to failed element distortion issues



Element-Level Test + Model Development





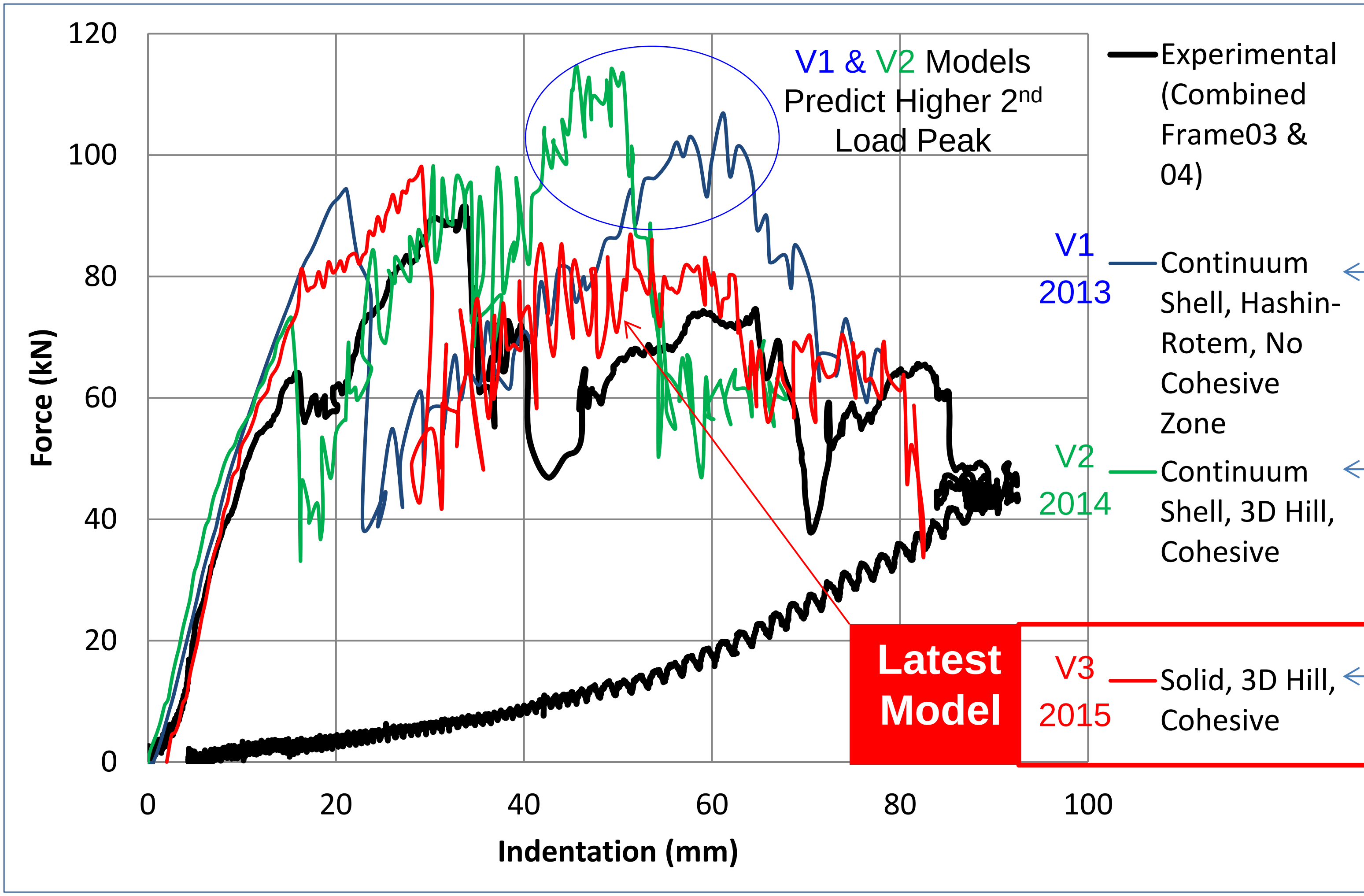
Continuum shell with cohesive interfaces

Large Panel Simulation

Results as of March 2015 - Version 3 Model

- refinement to shear tie modeling → apply to large panel
- 2015 V3 model predicts all failure modes
- final frame fracture failure mode predicted – model runs to completion (no crash)

VIDEO
Full Panel
Simulation Solid
Shear Ties

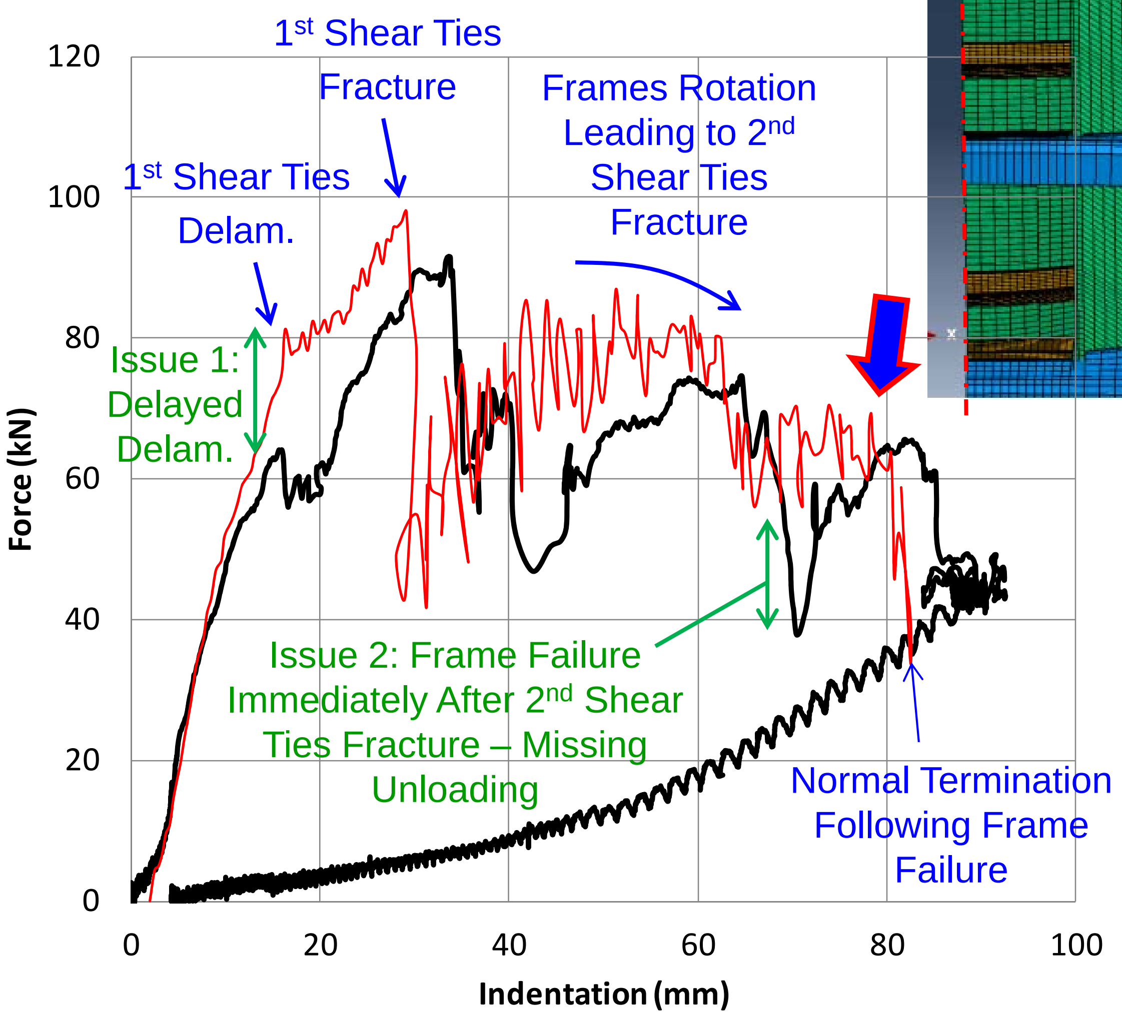


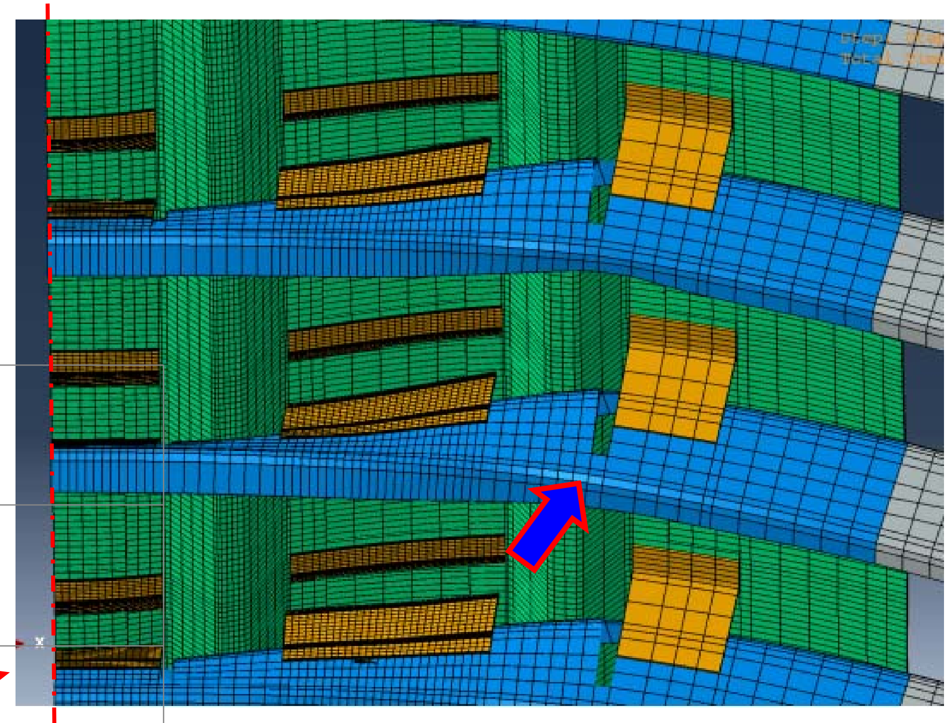
← No delam., 2nd load peak off.

← Shear ties delam., 2nd load peak off, early termination.

← Shear ties delam., 2nd load peak match, frame failure, model runs to completion.

Large Panel Simulation
Version 3 Model Details





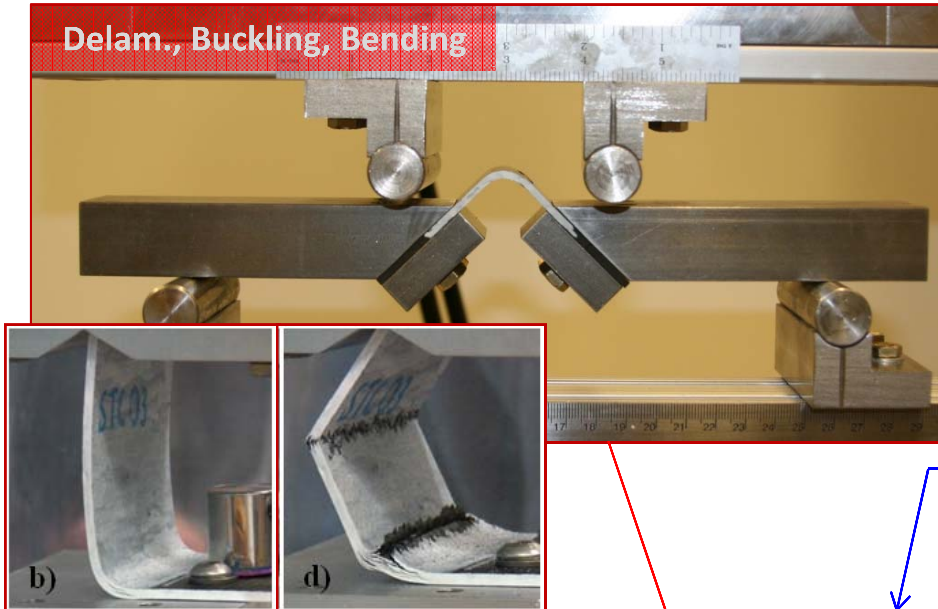
Shear Tie Modeling Details:

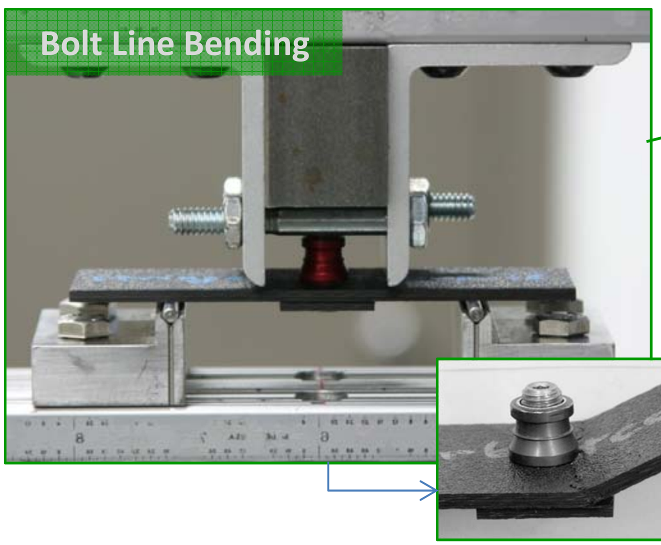
- continuum solid elements; 12 layers through the thickness
- section control enabled for stability
- cohesive surface interaction applied between elements
- 3D Hill failure criteria

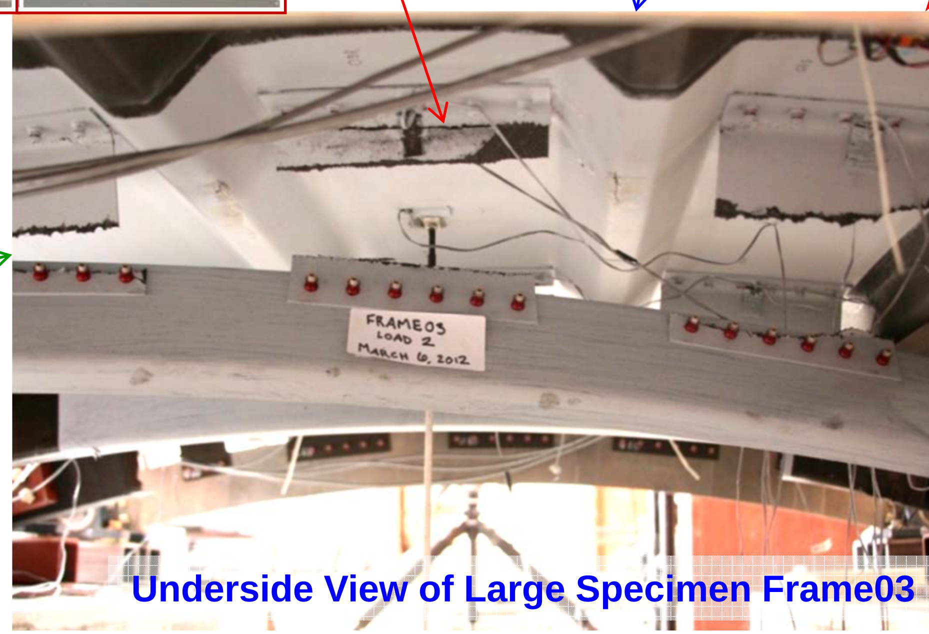
Improvements still needed , including accurate frame failure prediction.

Full Panel Modeling Success Foundation:
Establish Modeling Capability Via 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

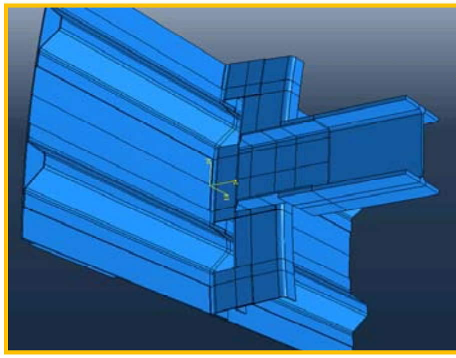


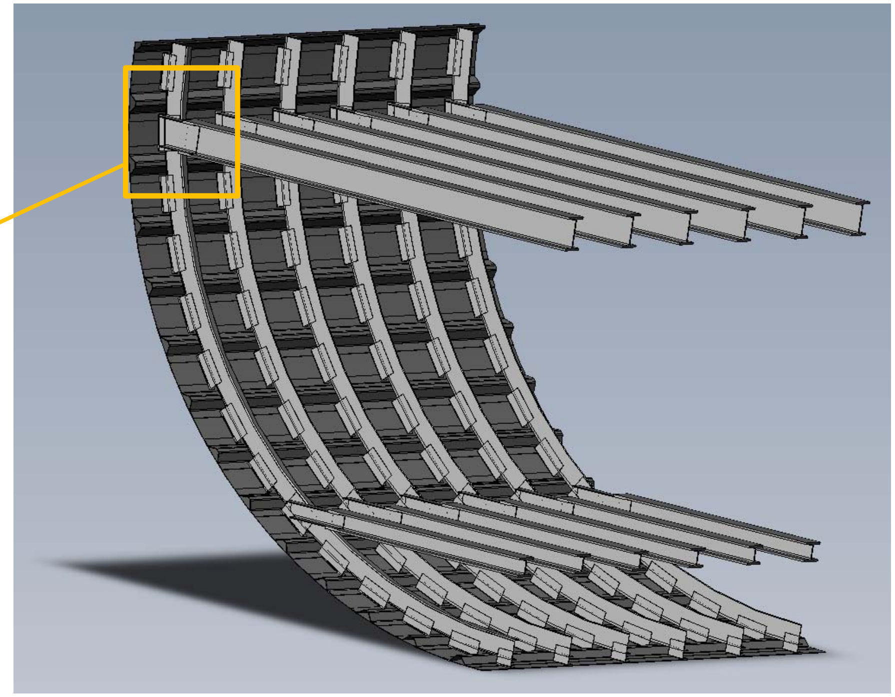




Need to Add:
- Frame Bending
- Frame Torsion
- Stringer Penetrate by Frame Indentation
- Stringer Delam.

Frame-to-Floor Structure Interaction



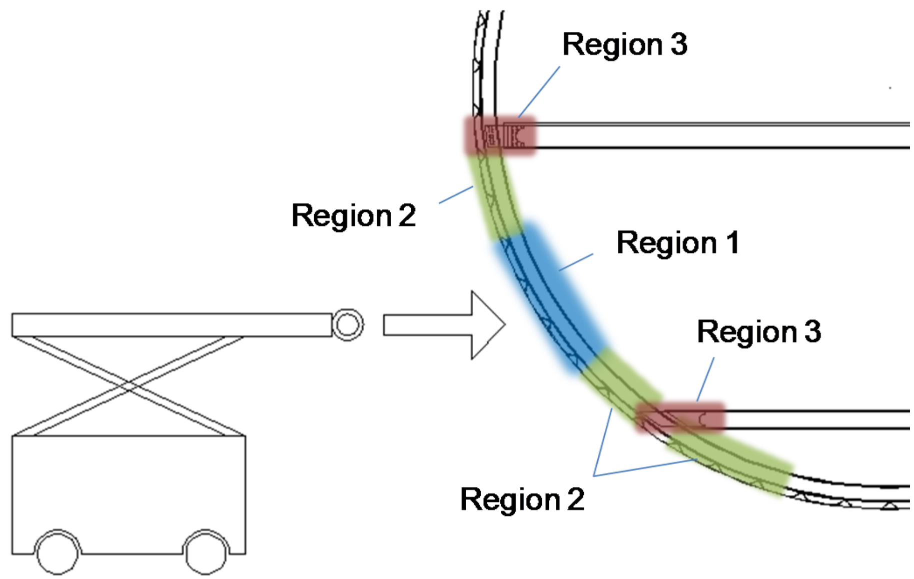


Focus:

- C-frame failure due to GSE impacts close to floor structure
  - **Region 1**: bending dominated
  - **Region 2**: more stiff – high beam shear
  - **Region 3**: most stiff – frame & joint crush
- frame-to-floor joint failure & stiffness/BC effect
- prediction-capability → explore various configurations & scenarios

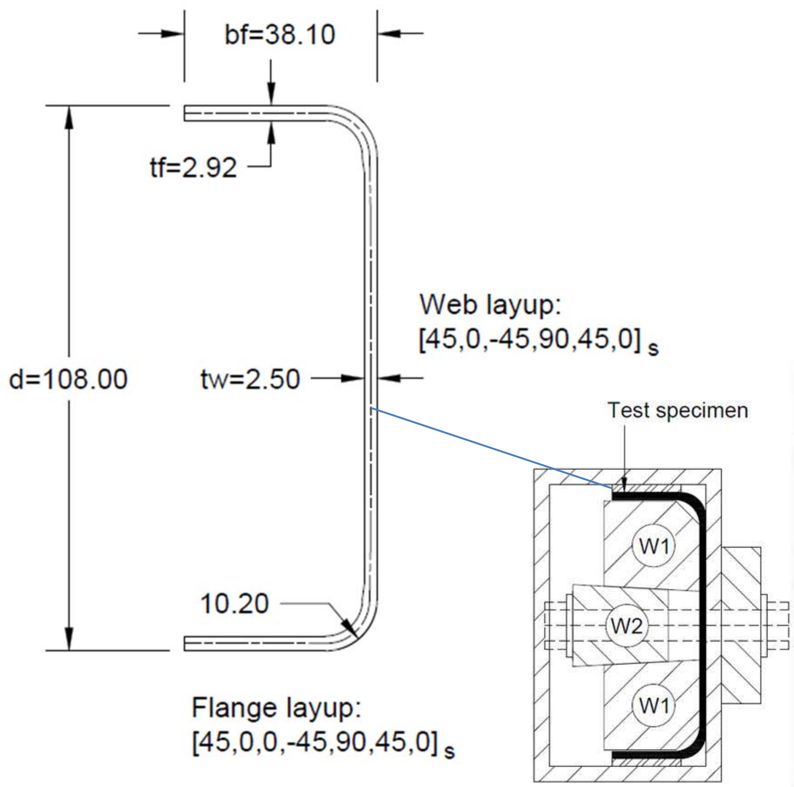
Need: element-level C-frame tests

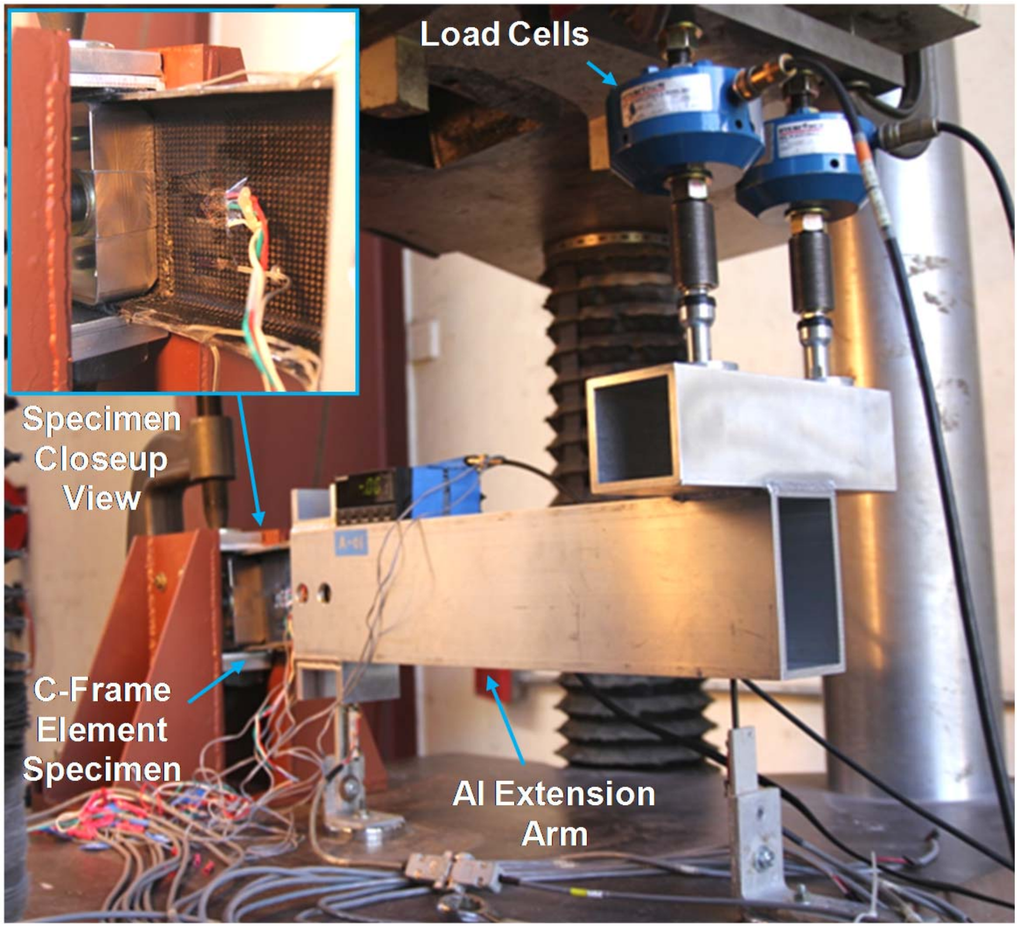
- bending
- combined bending + torsion



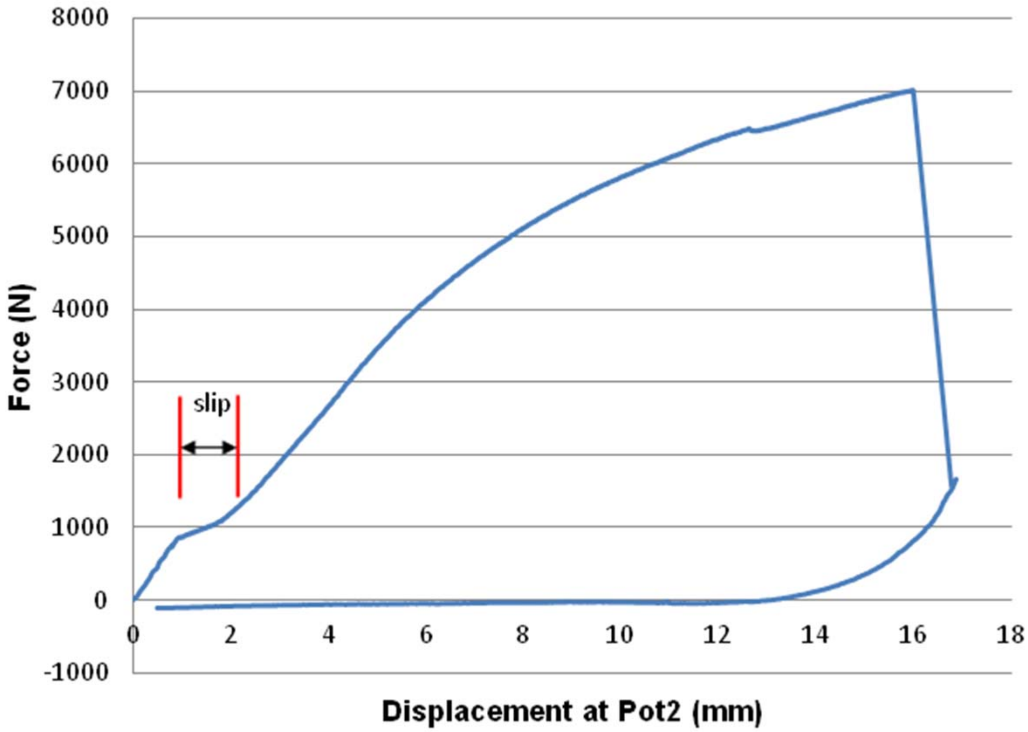
C-Frame Element Test Specimen

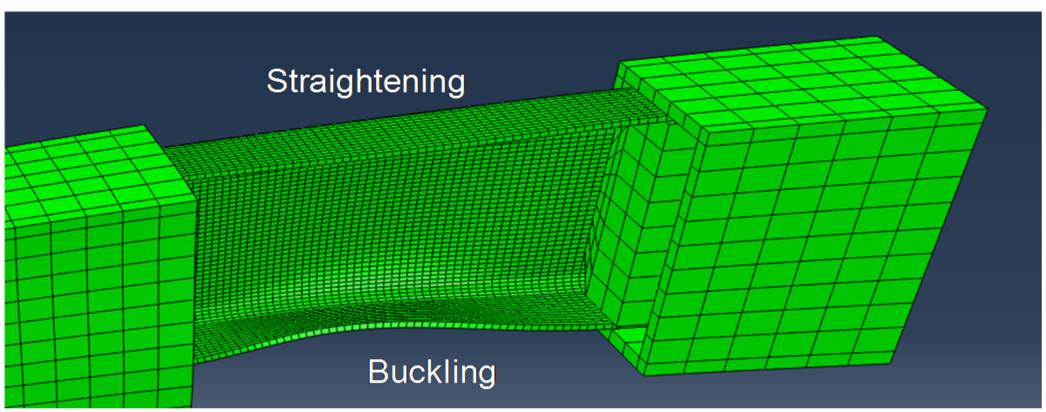
- C-frame test specimen
  - short section w/ extension arm
- fixed end boundary condition
- loaded end:
  - 2 point connection → bending
  - 1 point → bending + torsion

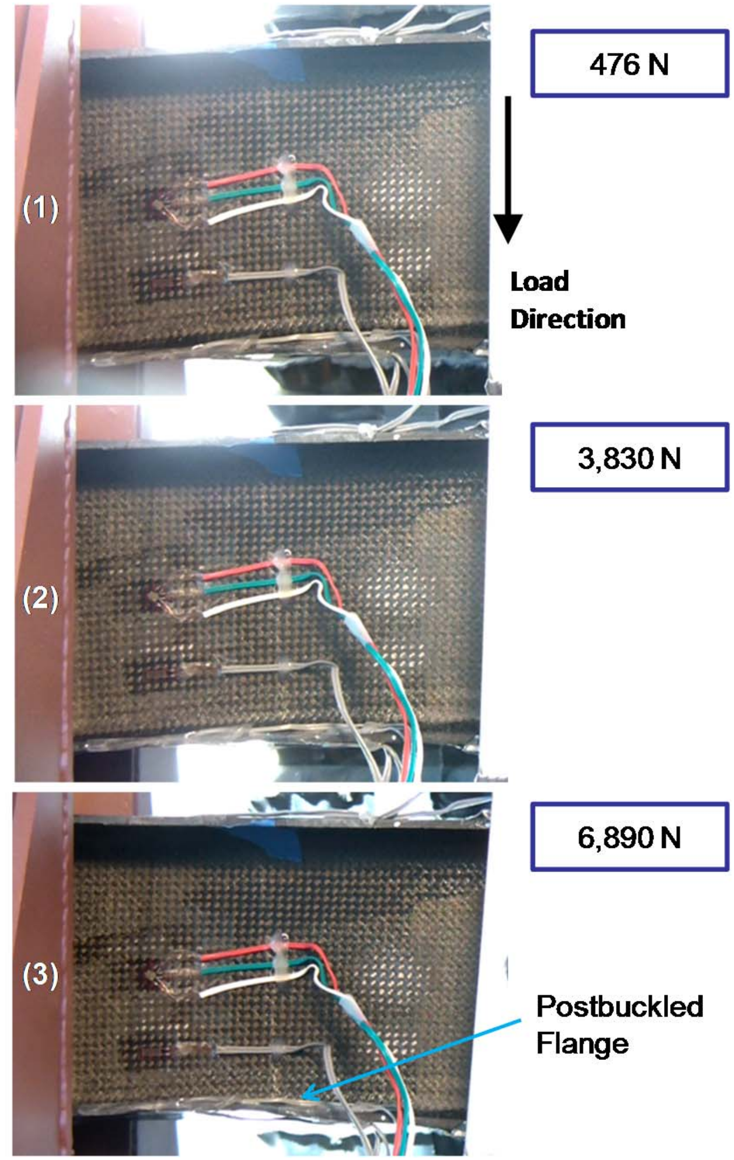




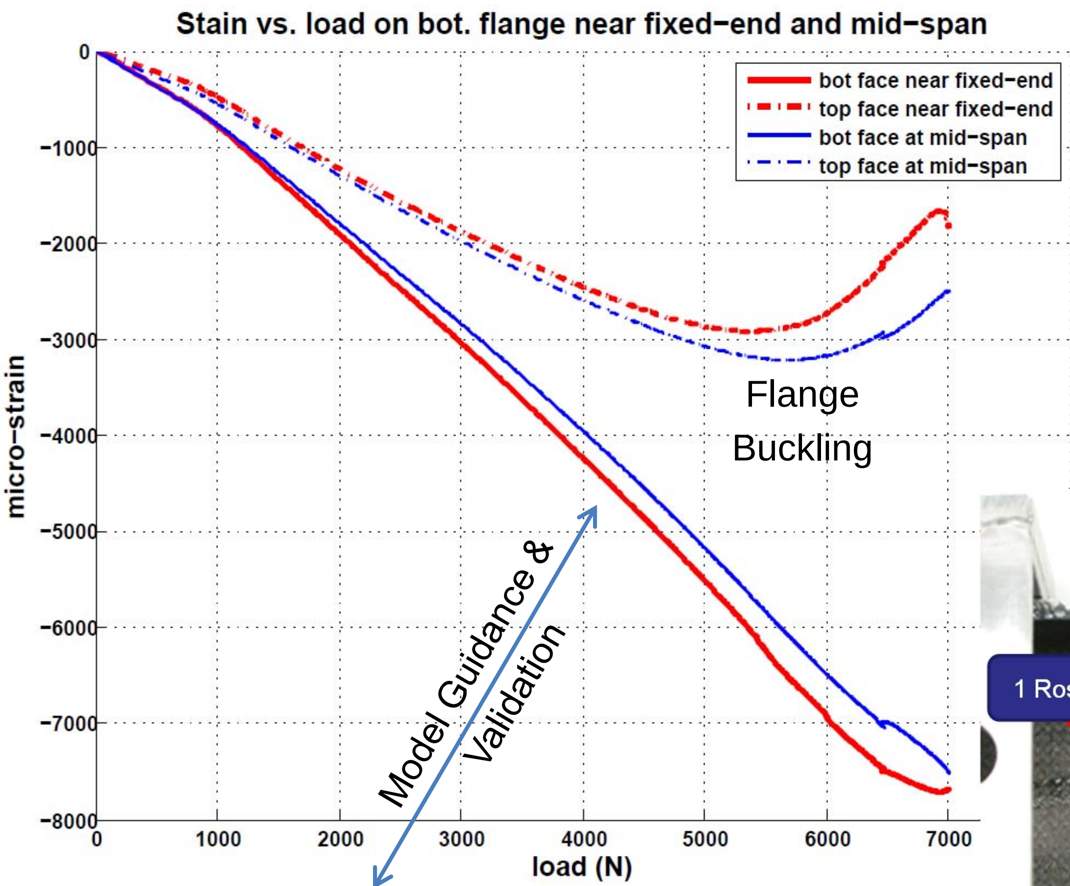
C-Frame Element Bending Test Results

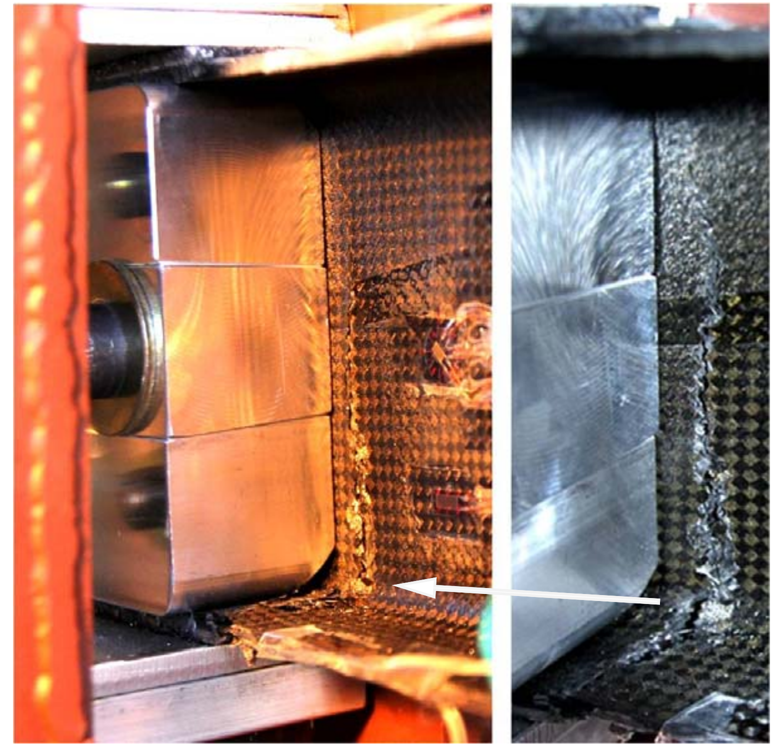


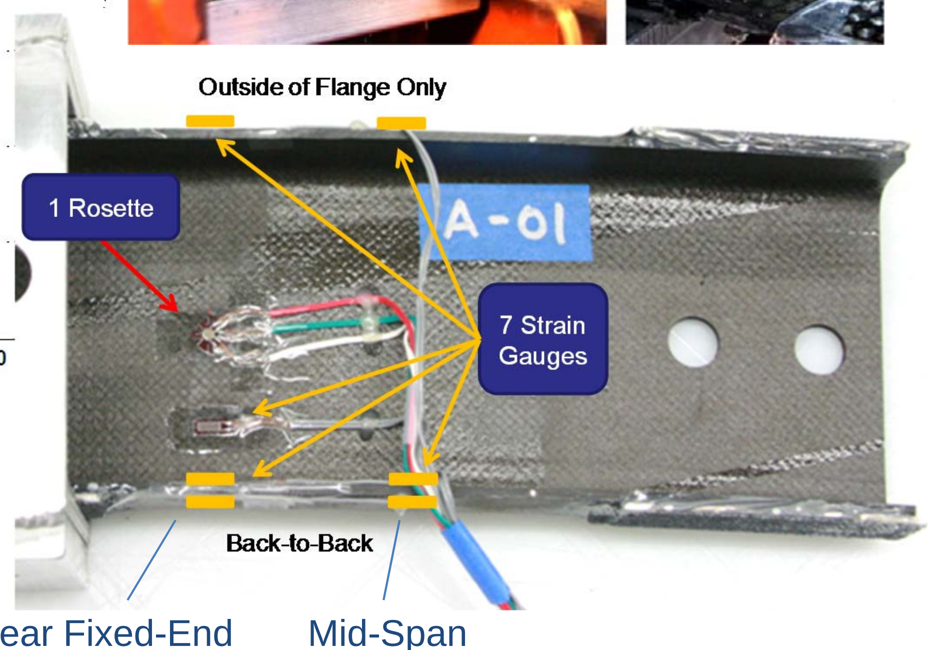


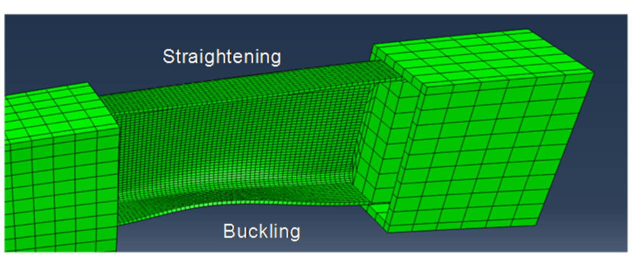


C-Frame Element Bending Test Results





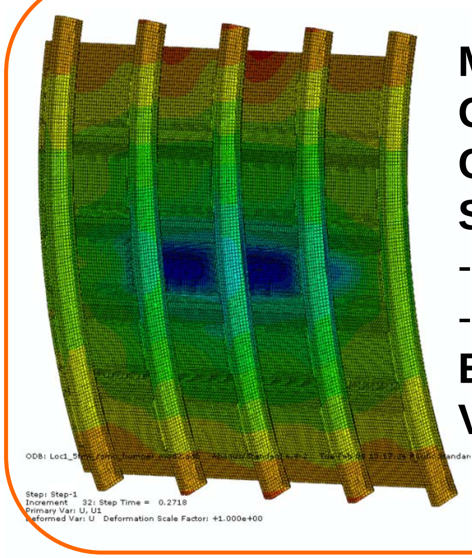




Modeling Work Ongoing

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

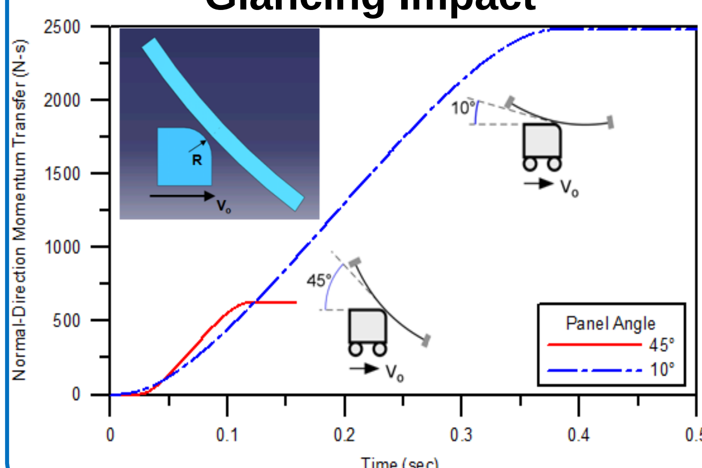
Apply to study and predict response for:

Size, Complex Internal Structure, Geom., Joints

flightglobal.com/FlightBlogger

Various Impactors & Scenarios (v_o)

Glancing Impact



Outline

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

Overview and Previous Work Summary

- Investigate internal damage morphology of impacts on sandwich panels using blunt/soft impact sources
  - 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
  - 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.)
- Establish impact core crush and dent depth prediction model
- Determine 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 varying core density, varying facesheet config.

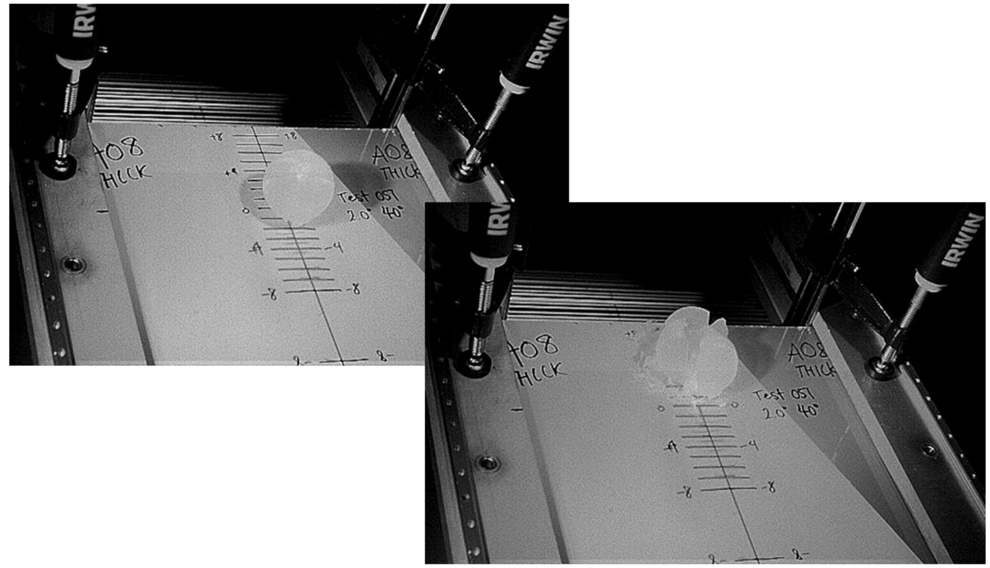
Previous Work

Current/Future Direction

Sandwich Panel Ice Impact Example

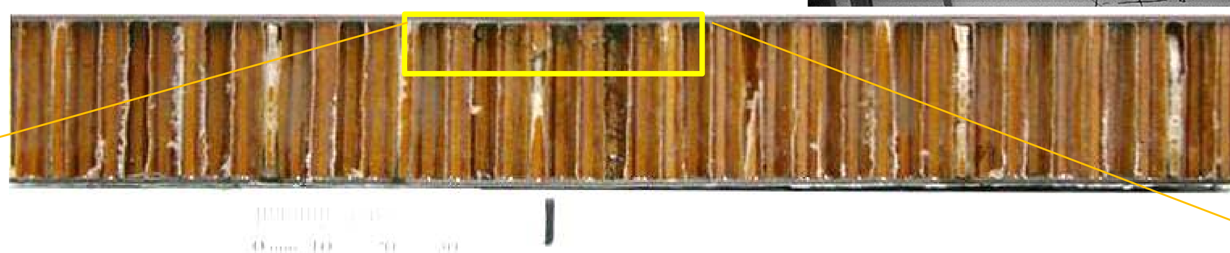
UCSD
Department of Structural Engineering

Panel:
Nomex core 32 kg/m^3,
29 mm depth
Facesheet 1.2 mm thick
woven carbon/epoxy

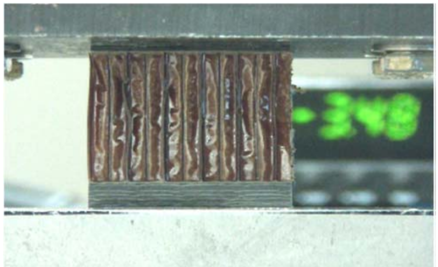


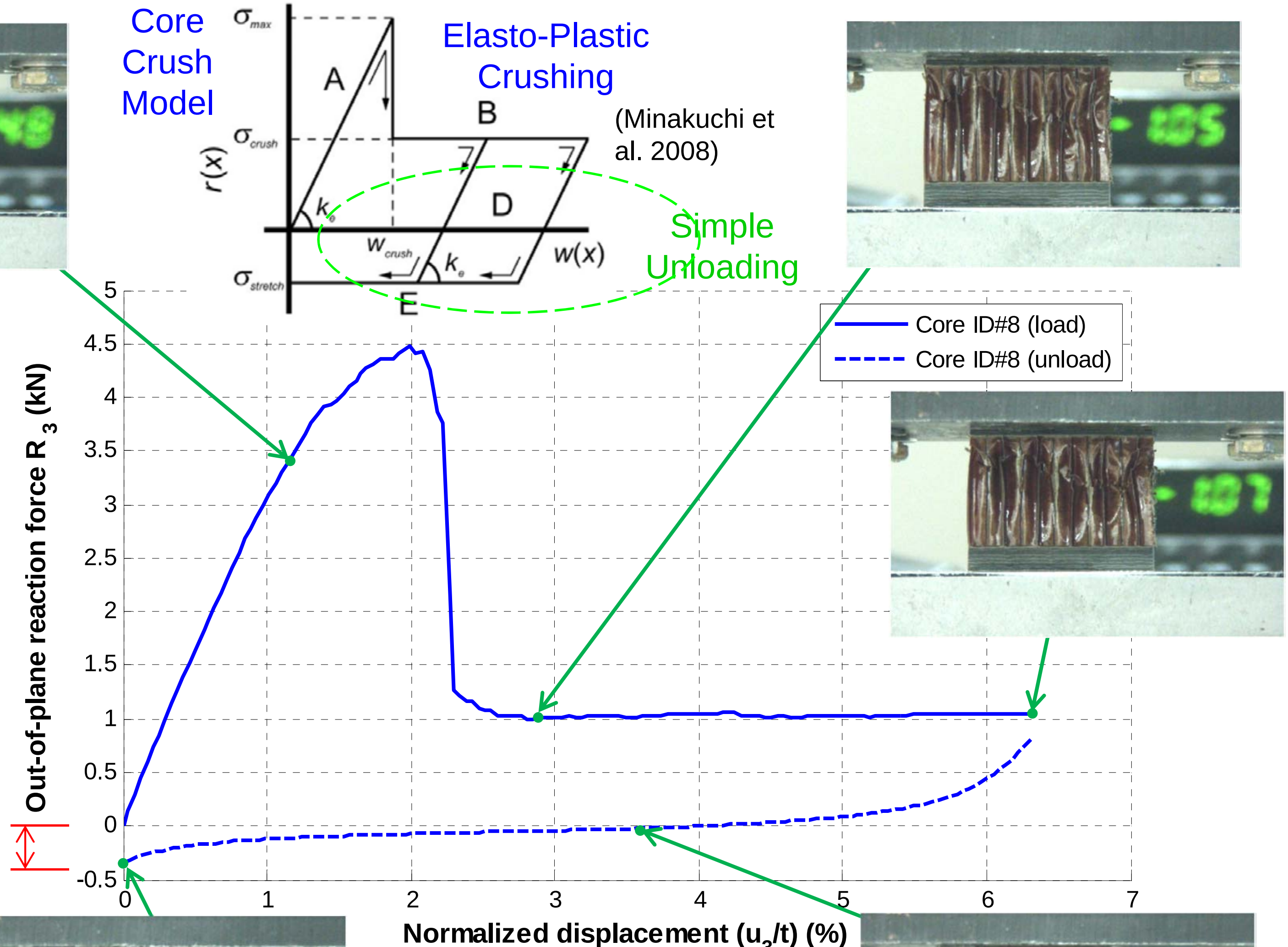
Hail Ice (Sphere)
Impact: 50.8 mm ice at
25 m/s, 40° glancing)

Damage:
- core fracture
- non-visible dent
(0.008 mm)



Sandwich Core Crush Response – For Model Input



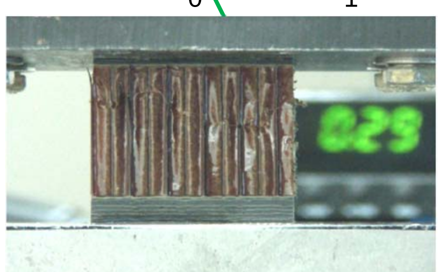


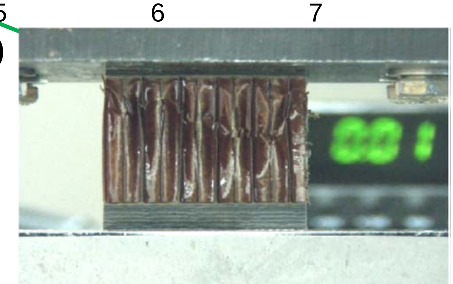
Core crush data needed for model:

- elastic facesheet on elasto-plastic foundation

Core crush + unloading tests:

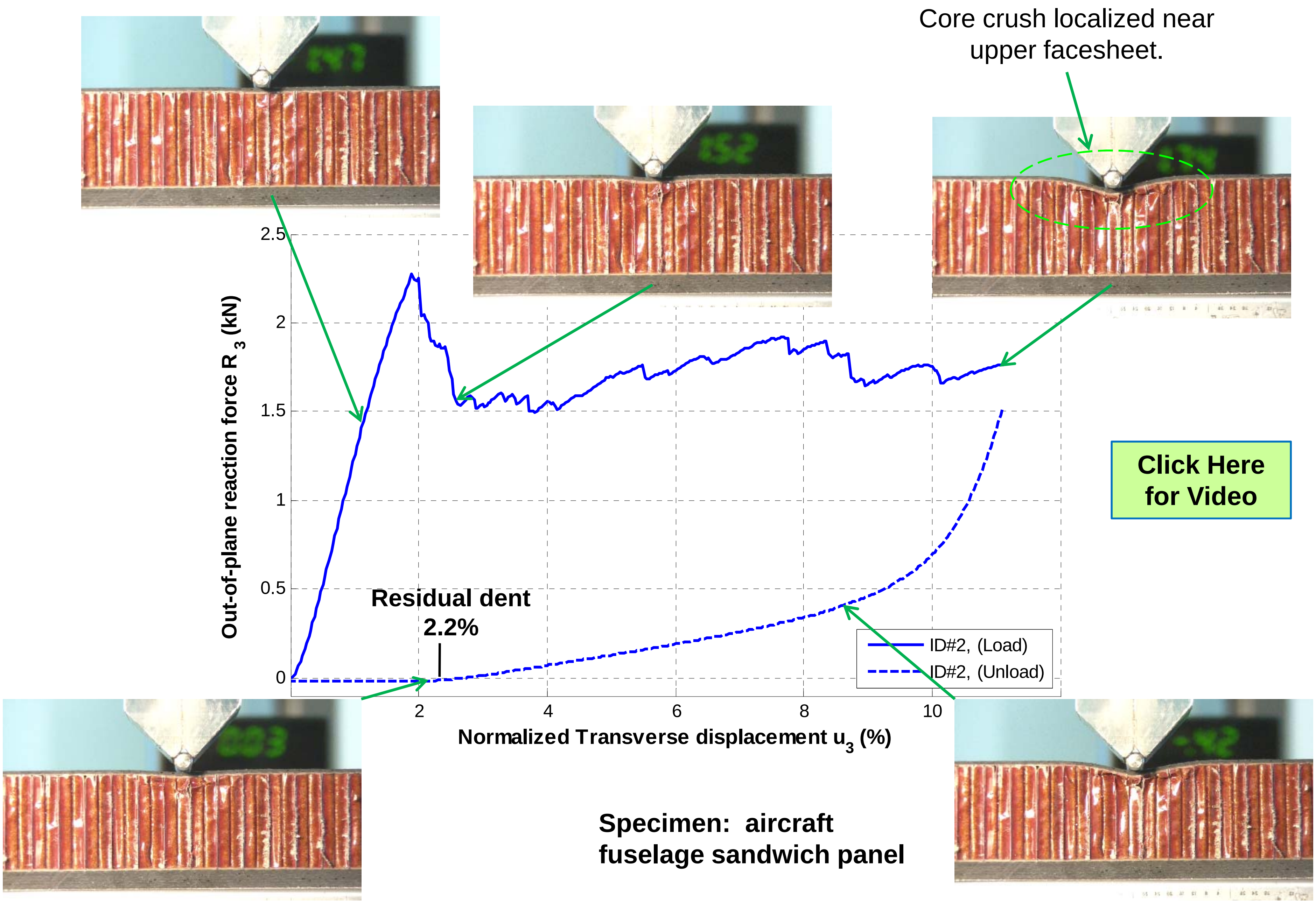
- buckling followed by constant stress
- unloading: tensile stress to return back to initial height (dent driving force)





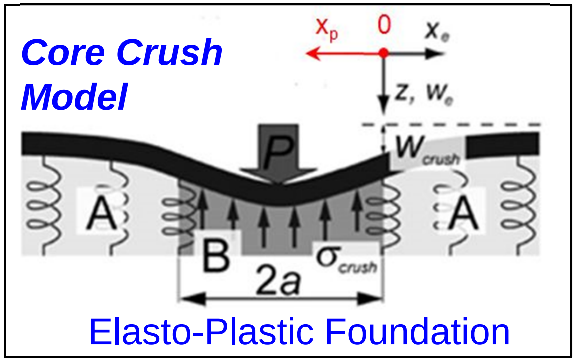
Specimen: aircraft fuselage sandwich panel

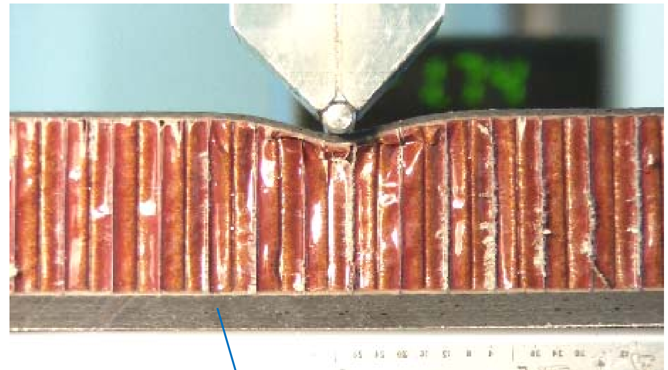
Sandwich Beam Indentation Tests



Sandwich Beam Indentation Model Comparison

UCSD
Department of Structural Engineering

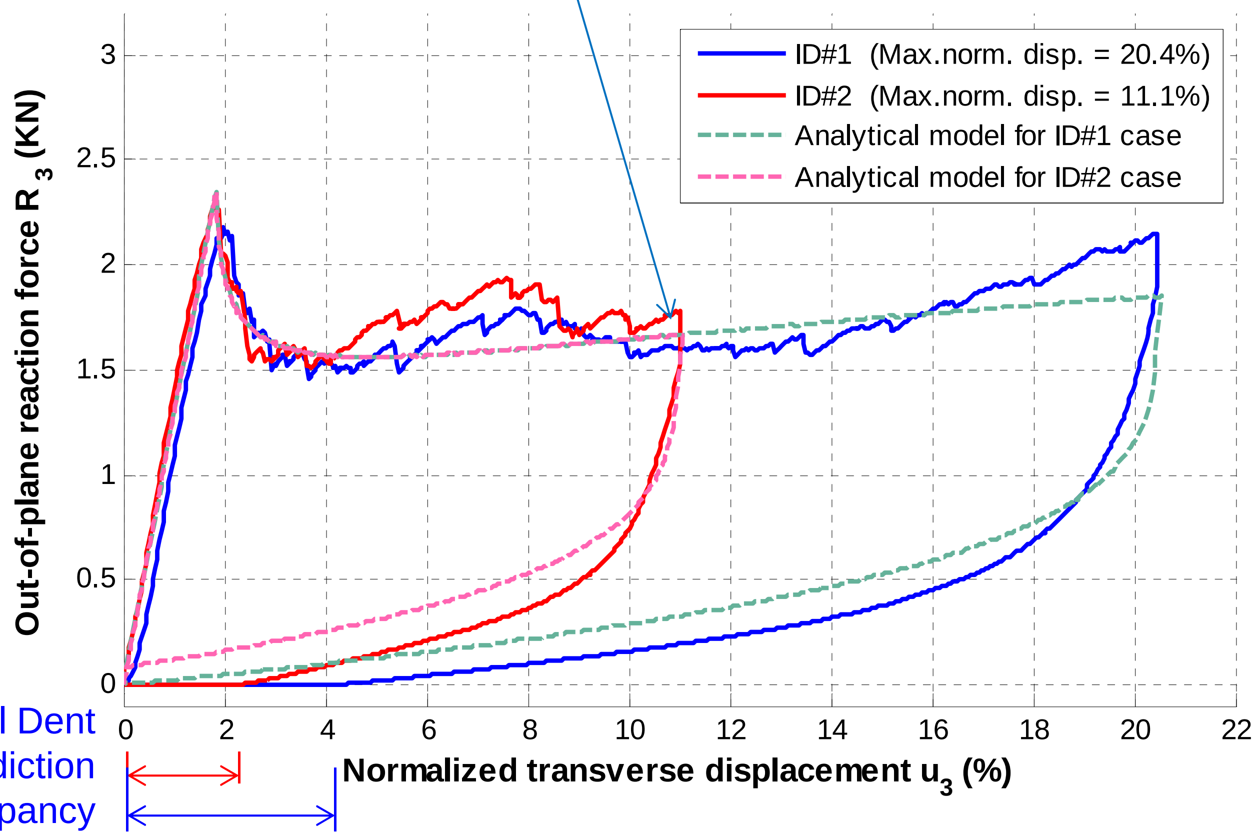




(Minakuchi et al. 2008)

Model Correlation:

- **crushing/ indentation accurately predicted**
- **unloading does not predict residual dent**
  - **due to simplistic unloading core constitutive representation**



Residual Dent Prediction Discrepancy

Outline

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

Conclusions

Ground Service Equipment (GSE) High Energy Blunt Impact

- Element-level experiments enabled accurate analysis procedure development due to their simplified geometries, loading conditions, and isolated failure modes.
- Accurate full-panel model established with latest-generation shear tie model; element distortion issues resolved allowing simulation to run to completion.
- Frame element-level bending test successful – supports focus on frame failure modeling and study of frame-to-floor interaction.

Blunt Impact Damage to Sandwich Panels

- Core fracture can be induced by blunt/soft impact with almost no surface dent; core wrinkling is concentrated near the impacted facesheet.
- Core crush/indentation: peak force defined by local cell wall elastic buckling; further crushing displacement drives postbuckling/wrinkling and eventually cell wall fracture.
- Indentation/core-crushing model found to accurately predict crushing but not unloading (thus residual dent not well predicted) – need improved core unloading constitutive model and extension to 2D.

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 information on mode and extent of seeded damage, particularly non-visible impact damage (NVID) from blunt impact threats
- FEA modeling capability of blunt impact - can be used for design and trade studies
  - predict damage modes, size, and locations
  - external visibility

Blunt Impact Damage to Sandwich Panels

- Knowledge of internal core damage state based on external damage visibility for different blunt/soft threats
- Insight into properly seeding damage for damage tolerance assessment
- Modeling capability for predicting core impact-crushing and residual dent depth after unloading

Looking Forward

Ground Service Equipment (GSE) High Energy Blunt Impact

- Continued development of high fidelity physics based FEA modeling capability
- Effects of floor joints/beams to better represent fuselage structure; door adjacent structure
- Quarter-barrel or half-barrel fuselage tests; effect of glancing impact (underbody)
- Effect of geometry of components on blunt damage/visibility – GSE and aircraft
- Define visibility metrics and FE failure criterion

Blunt Impact Damage to Sandwich Panels

- Refine internal damage and dent prediction methodology
- Relate actual impact core damage to subsequent facesheet separation (tearing within core model vs. separation at core/skin interface model)
  - conduct post-impact facesheet peel/fracture tests
- Establish capability within explicit FEA simulation to predict impact damage, especially to core and residual dent
- Dynamic impact/rate effects on core crush, indentation tests

CECAM
center of excellence for composites and advanced materials

JAMS

JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures