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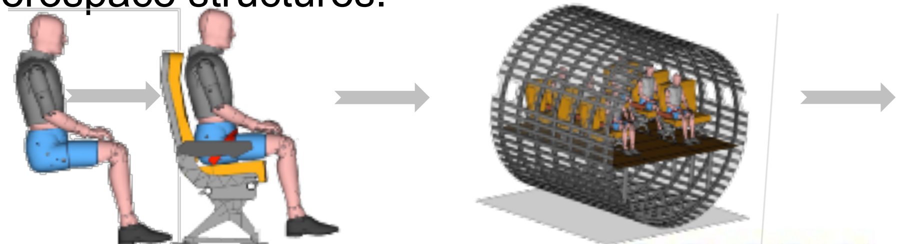
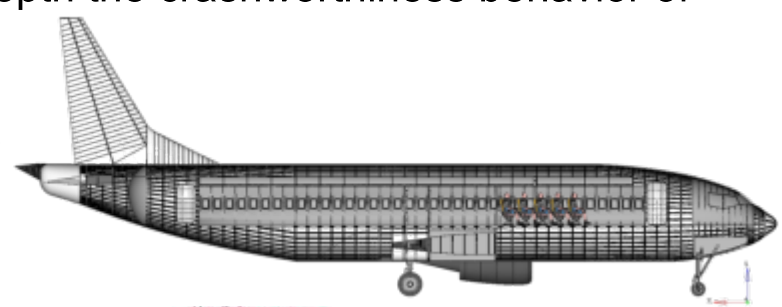
Crashworthiness Evaluation of Composite Aircraft Structures

2012 Technical Review

Gerardo Olivares
National Institute for Aviation Research, WSU

- # Motivation and Key Issues
  - The introduction of composite airframes warrants an assessment to evaluate that their crashworthiness dynamic structural response provides an equivalent or improved level of safety compared to conventional metallic structures. This assessment includes the evaluation of the survivable volume, retention of items of mass, deceleration loads experienced by the occupants, and occupant emergency egress paths.
- # Objective
  - In order to design, evaluate and optimize the crashworthiness behavior of composite structures it is necessary to develop an evaluation methodology (experimental and numerical) and predictable computational tools.
- # Approach
  - The advances in computational tools combined with coupon/component level testing allows for a cost-effective approach to study in depth the crashworthiness behavior of aerospace structures.





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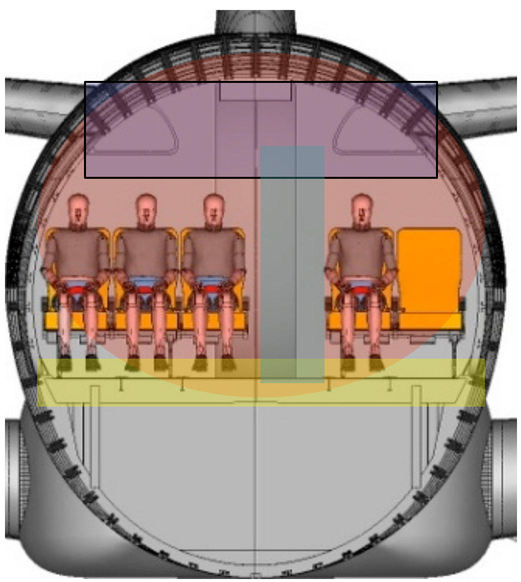
Crashworthiness of Aerospace Composite Structures

- **Principal Investigators & Researchers**
  - G. Olivares Ph.D.
  - S. Keshavanarayana Ph.D.
  - J. Acosta, V. Yadav
- **FAA Technical Monitor**
  - Allan Abramowitz
- **Other FAA Personnel Involved**
  - Joseph Pelletiere Ph.D.
- **Industry Participation**
  - Bombardier/Learjet, Hawker Beechcraft
- **Research Institutes\Universities Participation**
  - Arizona State University (B. Mobasher), DLR (A.Johnson, M.David), Ohio State University (A. Gilat), Oakridge National Labs (Y.Wang, D.Erdman III, M.Starbuck)

Aerospace Structural Crashworthiness

- **Crashworthiness performance of composite structures to be equivalent or better than traditional metallic structures**
- **Crashworthiness design requirements**:
  - Maintain survivable volume
  - Maintain deceleration loads to occupants
  - Retention items of mass
  - Maintain egress paths



- **Currently there are two approaches that can be applied to analyze this special condition:**
  - **Method I: Large Scale Test Article Approach**
    - **Experimental:**
      - Large Scale Test Articles (Barrel Sections)
      - Component Level Testing of Energy Absorbing Devices
    - **Simulation** follows testing – Numerical models are **"tuned"** to match large test article/EA sub-assemblies results. Computational models are only predictable for the specific configurations that were tested during the experimental phase. For example if there are changes to the loading conditions (i.e. impact location, velocity, ..etc.) and/or to the geometry, **the model may or may not predict** the crashworthiness behavior of the structure.
  - **Method II:** Building Block Approach
    - **Experimental and Simulation**
      - Coupon Level to Full Scale
    - **Simulation**: Predictable modeling

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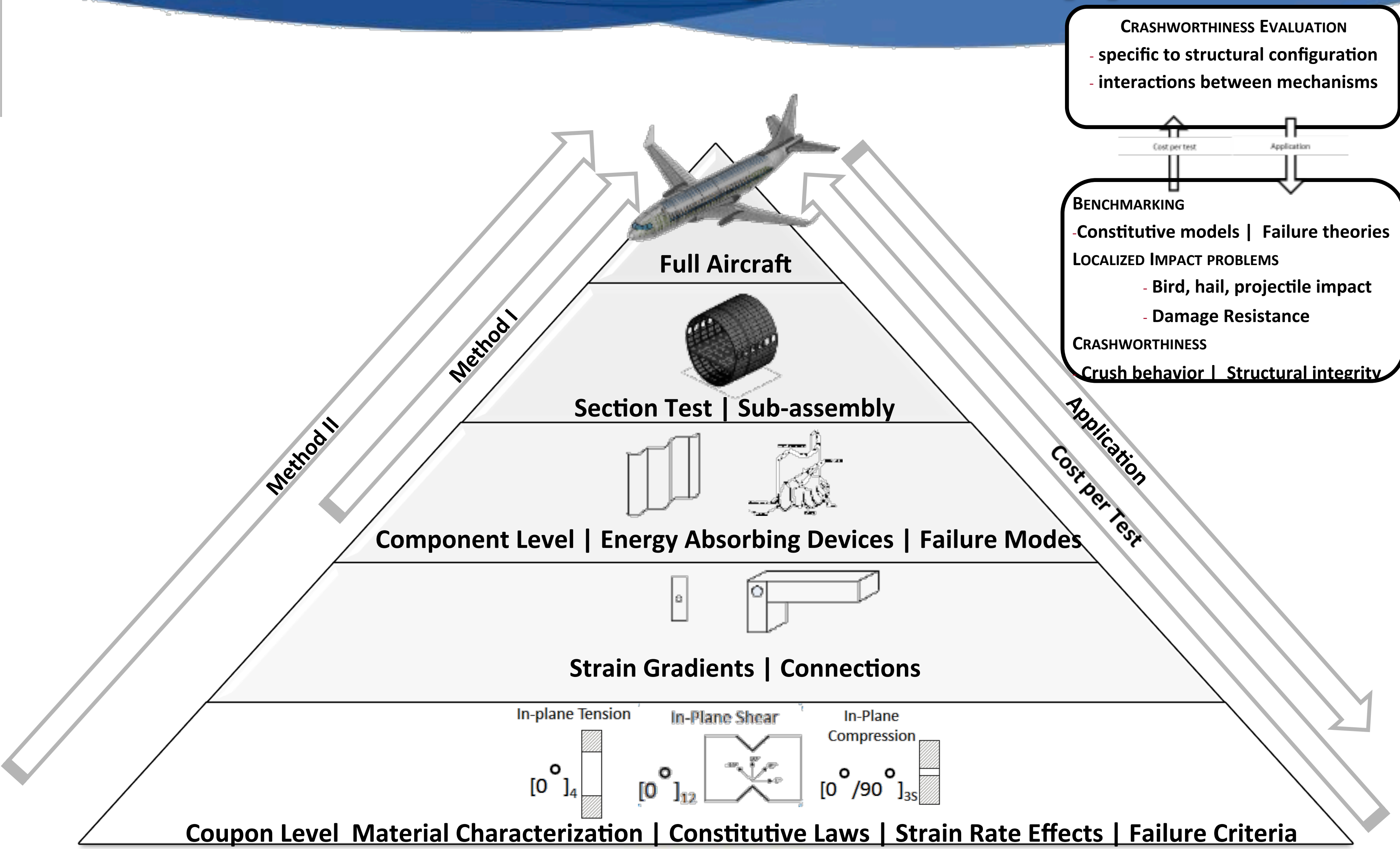
Experimental Building Block Approach



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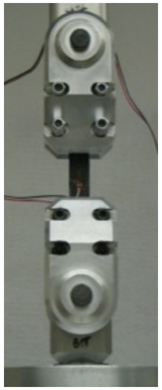
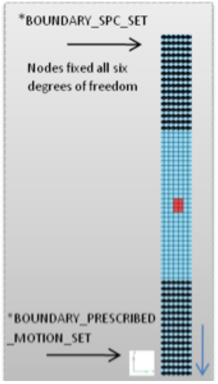
Coupon Level Material Model Evaluation

- Material Testing for Simulation
  - Dynamic material property generation faces several challenges
    - Limited guidelines
    - Experimental data variability
    - Lack of standard methods
    - Experimental work limitations
  - Simulation of dynamic events require material properties generated at representative rates
  - A cooperative exercise between laboratories is required where comparable data is generated
- Material Model Evaluation
  - Ls-Dyna material models for laminated composite Mat-22, Mat-54, and Mat-58 were evaluated with material properties generated at strain rates ranging from quasi-static to 10 s^{-1}
  - Material models showed limited correlation with experimental data for off-axis orientations of weaved materials architectures as Plain Weave (PW) and Satin Weave (SW)
  - Non-linearity observed in the material response of off-axis orientations was only captured by Ls-Dyna Mat-58. In contrast to Mat-22 and Mat-54, damage evolution pre-failure detection introduces a smooth change in the material behavior than can be calibrated using experimental failure strain.
  - However, caution is required due to the sensibility of the material response to the measured failure strain. Variability in the experimental measurement will simply translate to the simulation results.
  - The Mat-58 implementation of Hashin failure criterion is observed to overestimate failure for tensile failure modes and to underestimate failure for matrix failure modes.

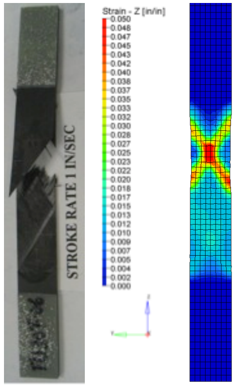
Test Set-up



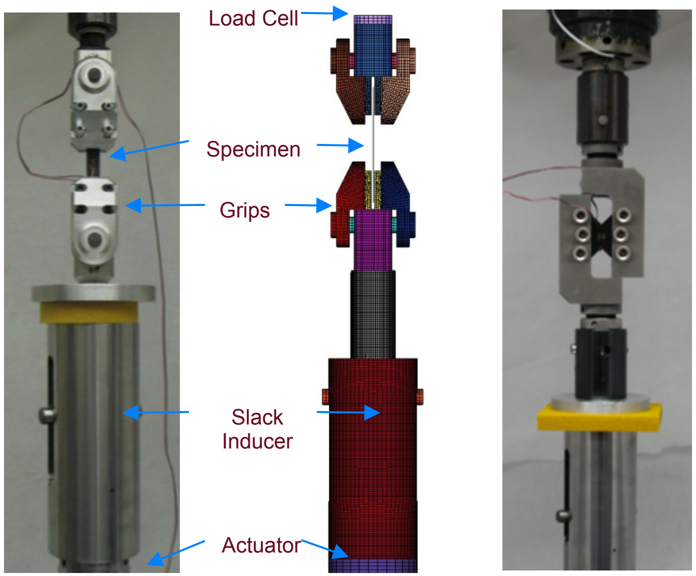
Boundary Conditions



Carbon Unitape-$[30/-30]_{2S}$



Test Equipment Model



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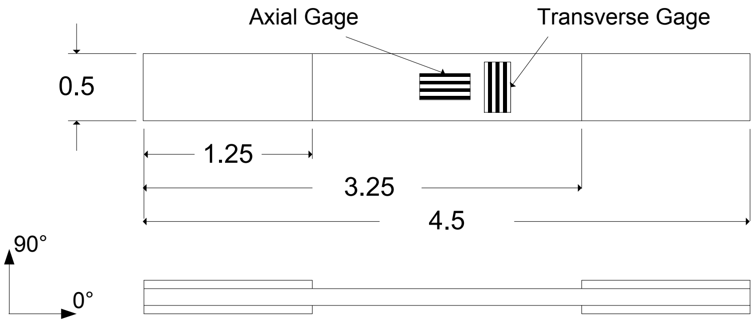
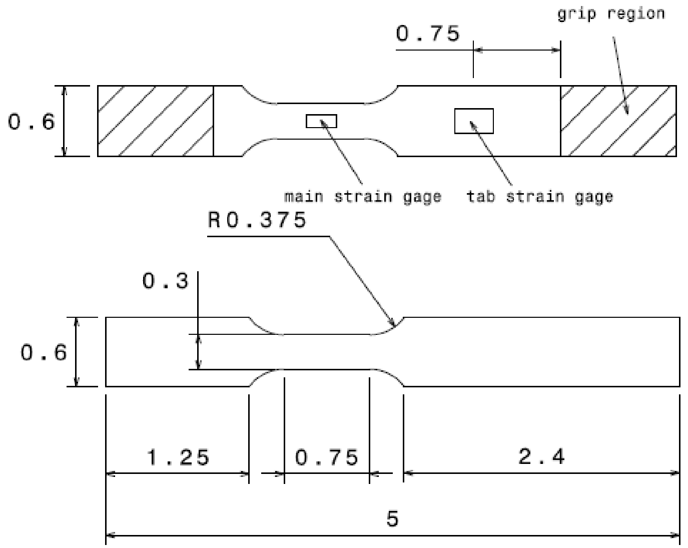
Round Robin Dynamic Material Characterization – Coupon Level

- Scope
  - Characterization of the dynamic in-plane material properties of CMH-17 material in tension over a wide range of loading rates
- Primary Objective
  - Characterize the strain rate sensitivity of Toray - T700G/2510 Plain Weave carbon/epoxy (F6273C-07M) material at strain rates ranging between 0.01 to 250 s^{-1}
- Secondary Objective
  - Evaluate test methods/apparatus and load measurement methods employed by the participating laboratories using an extended tab 2024-T3 aluminum specimen

Composite Specimen



Aluminum Specimen



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Participating Labs and Agencies (POCs)

- Coordination and Reporting
  - FAA (*A. Abramowitz*)
  - NIAR/WSU (*G.Olivares, K.S.Raju, J.F.Acosta, M.T.Siddiqui*)
- Specimen fabrication, fixturing, instrumentation
  - NIAR/WSU
- Material
  - Toray America (*S. Tiam*)
- Testing
  - Arizona State Uni. (*B. Mobasher*)
  - DLR (*A.Johnson, M.David*)
  - NIAR/WSU
  - Ohio State Uni. (*A. Gilat*)
  - Oakridge National Labs (*Y.Wang, D.Erdman III, M.Starbuck*)

Test Matrix

Material System	Nominal Strain rate (1/s)			
	0.01	1	100	250
2024-T3 Aluminum	×3	×3	×3	×3
TORAY T700/2510 plain weave/epoxy (F6273C-07M)				
$[0]_4$	×3	×3	×3	×3
$[90]_4$	×3	×3	×3	×3
$[\pm 45]_4$	×3	×3	×3	×3

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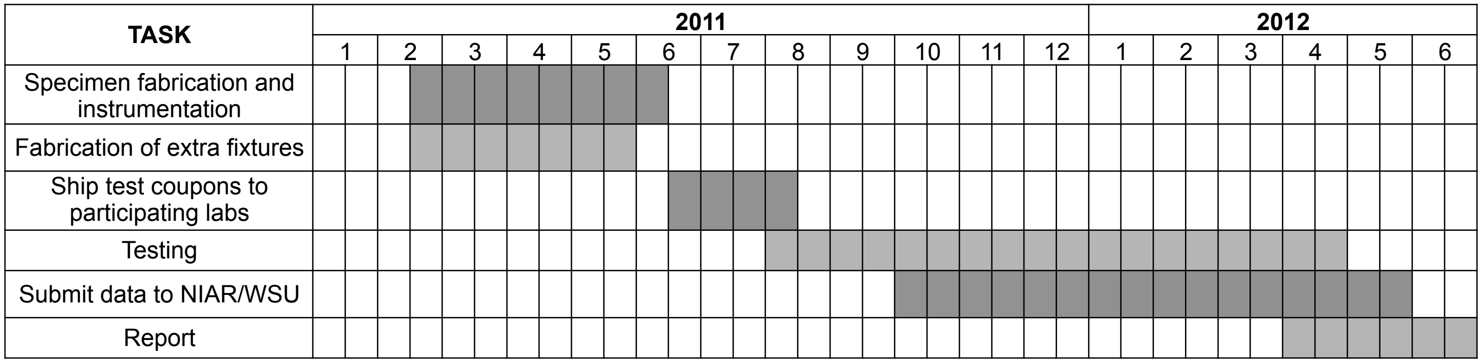
Schedule and Status

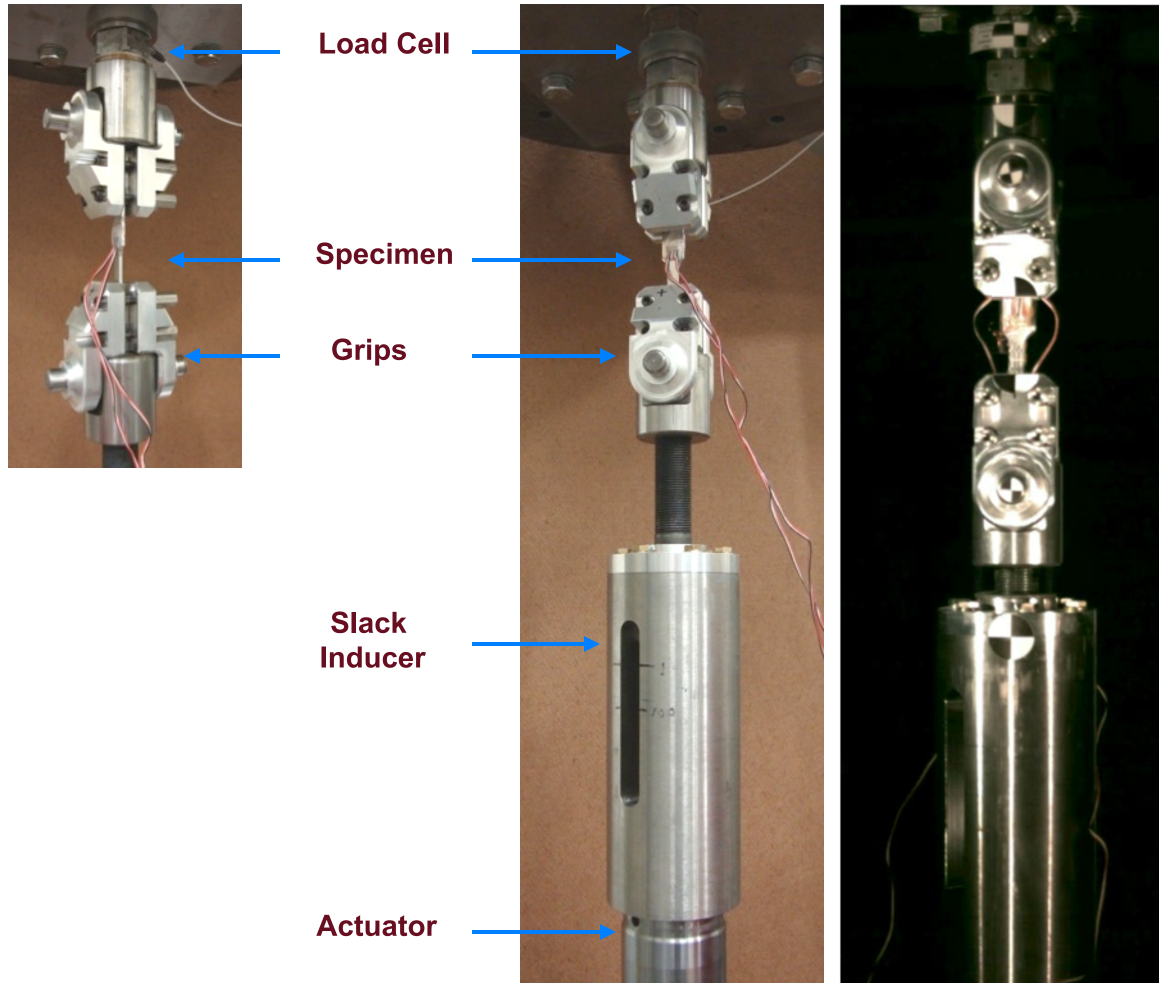


- Specimen fabrication ✓
- Fabrication extra fixtures ✓
- Test coupons distribution ✓
- Testing
  - Ohio State Uni. ✓
  - NIAR/WSU ✓
  - DLR Ongoing
  - Oakridge National Labs ✓
  - Arizona State Uni. April\May 2012
- Data submission… on process!
- Report

NIAR/WSU – Test Set-up

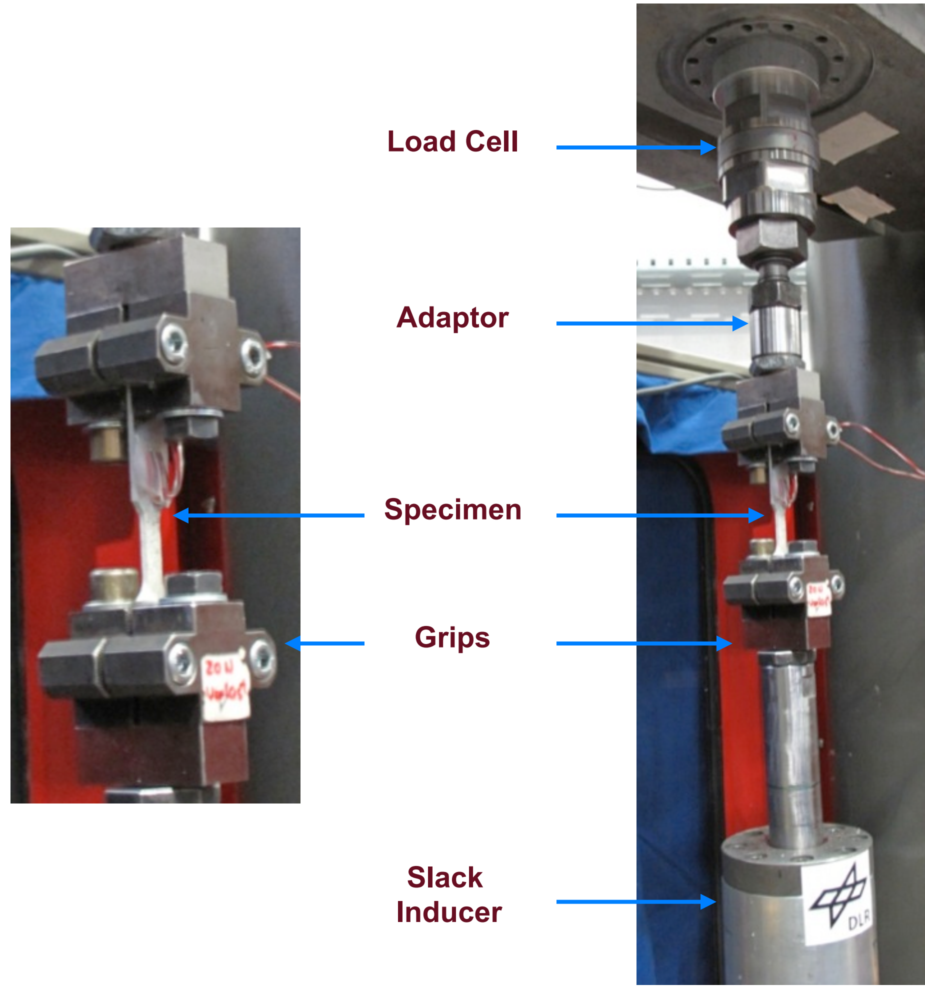
Test Video 75 in/s

- Test apparatus
  - High Stroke Rate Servo-hydraulic
  - MTS
  - Dynamic load up to 5 kip
- Test rate
  - 0.5 to 500 in/s
- Load measurement
  - Piezoelectric load cell
  - PCB 206C
  - 10 kip
- Strain measurement
  - strain gage
    - Axial – CEA-00-250UN-350
    - Biaxial – CEA-00-125UT-350
    - Aluminum
      - Gage – EP-08-250BG-120
      - Tab – CEA-06-250UN-120
  - Signal conditioner Vishay 2210
  - 1 to 5 V



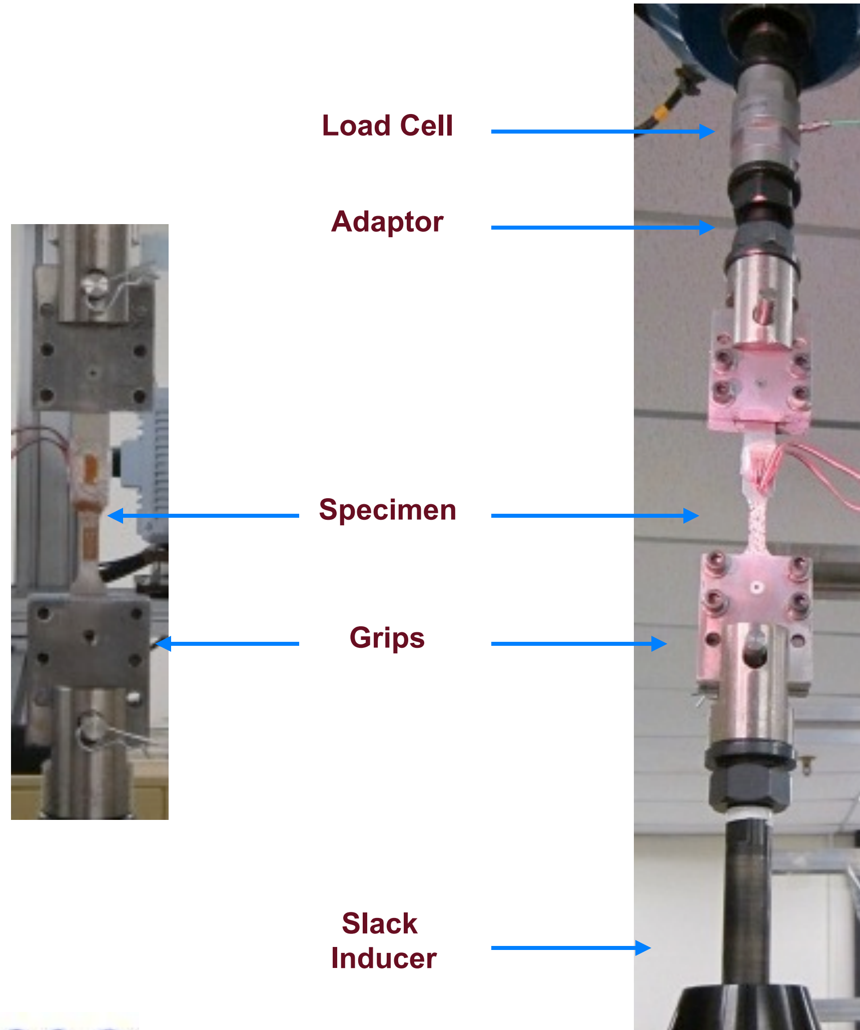
DLR – Test Set-up

- Test apparatus
  - High Stroke Rate Servo-hydraulic
  - Instron VHS 100/20
  - Dynamic load up to 22.5 kip
- Test rate
  - Up to 780 in/s
- Load measurement
  - Piezoelectric load cell
  - KISTLER 9361B
  - 13.5 kip
- Data acquisition
  - Gould Nicolet Tech. BE256XE
- Strain measurement
  - Provided strain gages
    - Signal conditioner - Peekel SIGNALOG 4000
  - High speed camera
    - Photon Fastcam Ultima APX 250 K

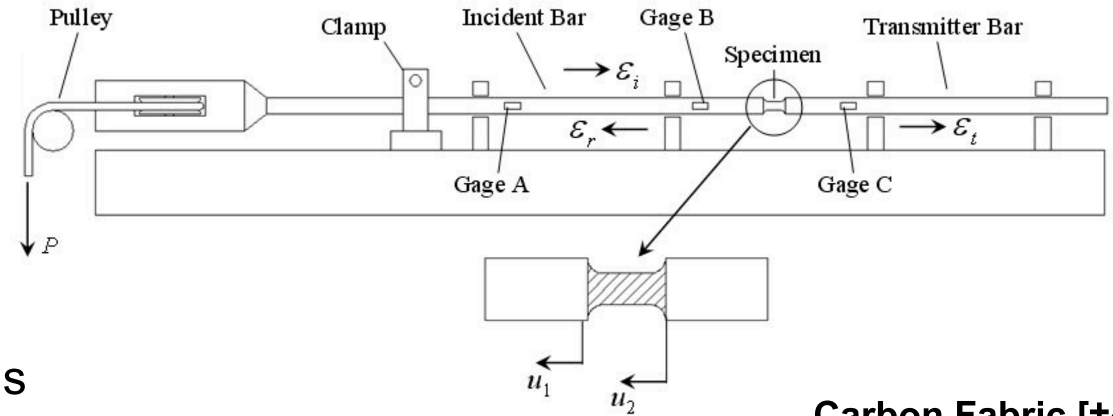


Oakridge National Research Lab – Test Set-up

- Test apparatus
  - High Stroke Rate Servo-hydraulic
- Load measurement
  - Piezoelectric load cell
  - KISTLER 9051A
  - 9 kip
  - Natural Freq. 55 KHz
- Data acquisition
  - Load and Stroke - NI PXI 6251
  - Strain – NI PXI 6259
- Strain measurement
  - Provided strain gages
    - Vishay 2310A
  - Laser extensometer

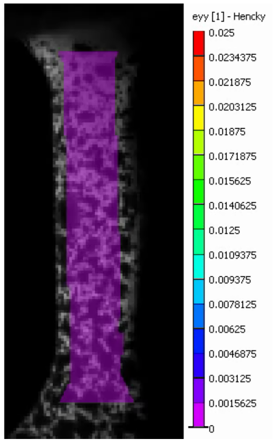


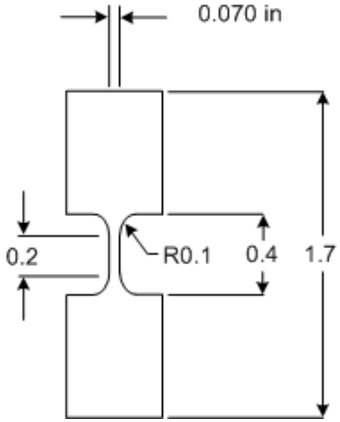
Ohio State University – Test Set-up



- Test Apparatus
  - Tensile Split Hopkinson Pressure Bar*
- Specimen*
  - Per Split Hopkinson Bar requirements
- Material
  - Toray - T700G/2510 Plain Weave carbon/epoxy
  - No Aluminum specimens
- Testing
  - Accounts for strain rates above 100 s-1
- Strain measurement
  - High speed cameras – Aramis image correlation

Carbon Fabric $[\pm 45]_4$ - 369 s^{-1}





Dimensions [in]

** Ref. Ohio State University, Dynamic Mechanics of Materials Lab. , www.mecheng.osu.edu/lab/dmm/node/35*

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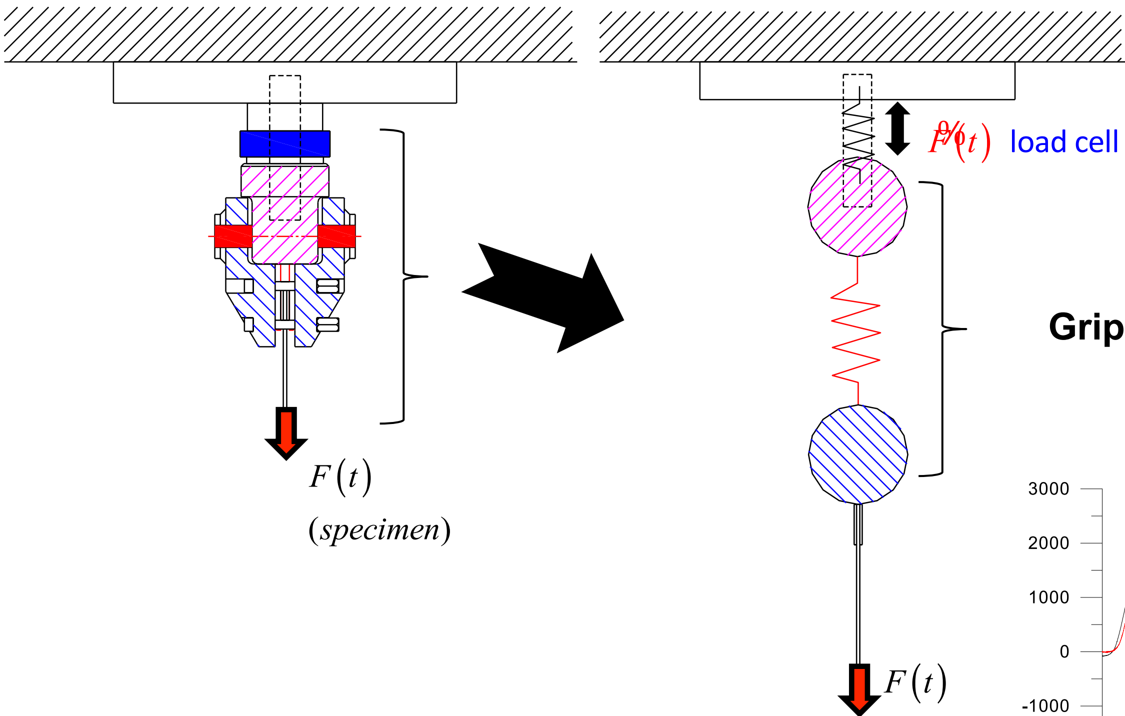
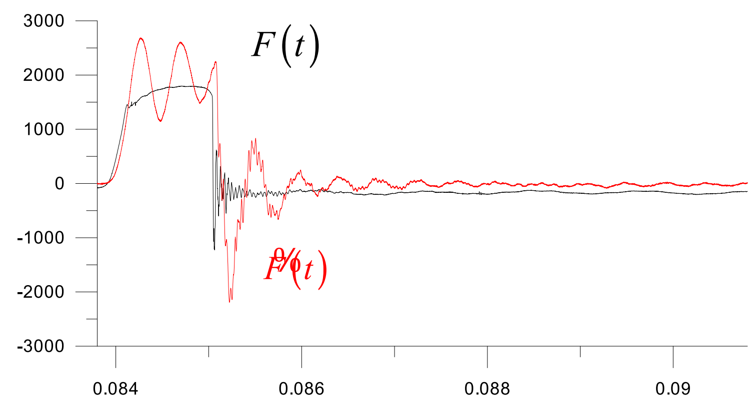
Force Measurement..



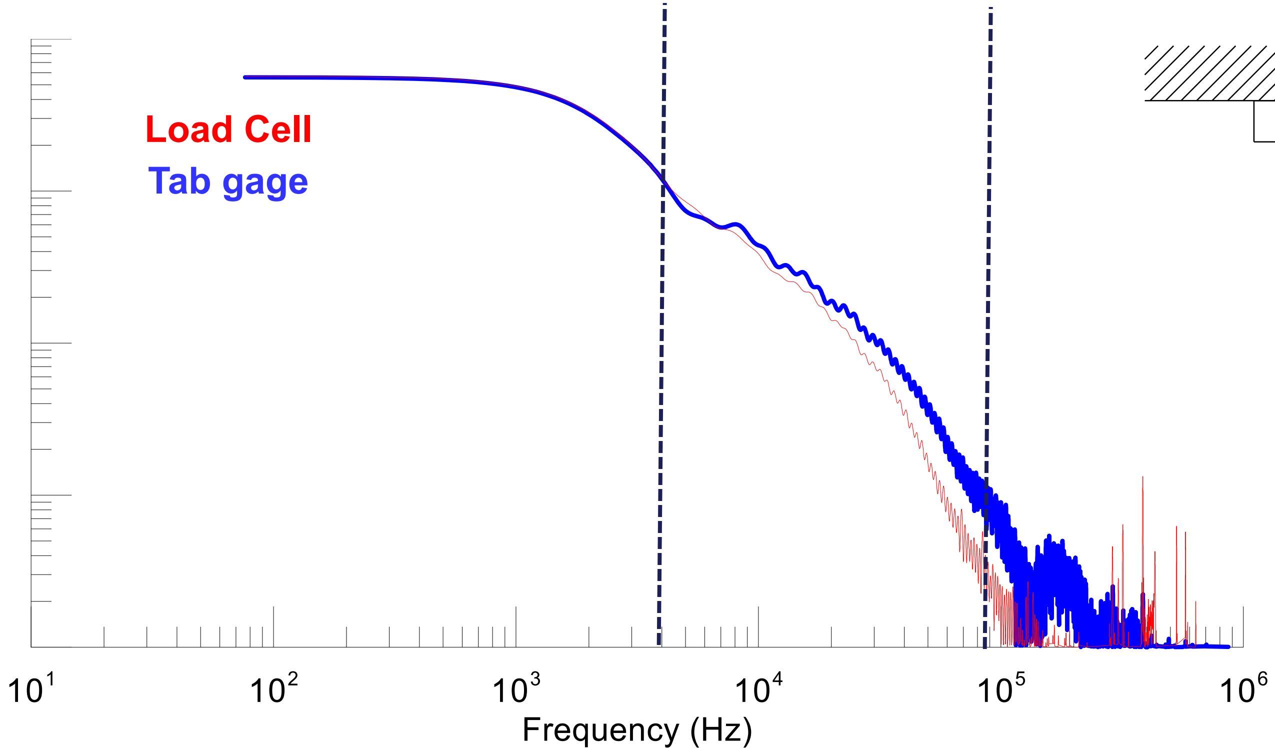
Grips, adapters, pins, etc

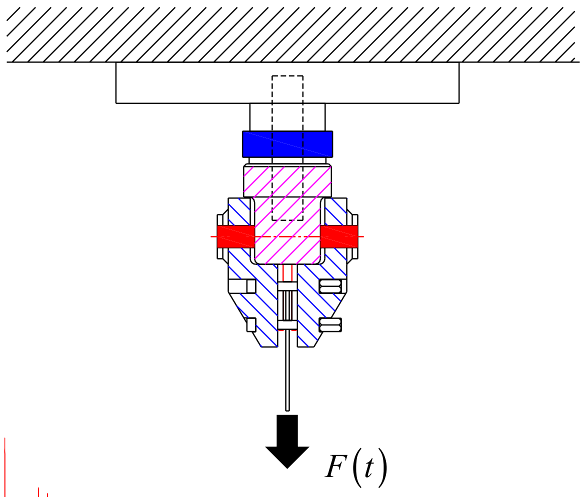


Force signal modulation

- **load cell characteristics**
- **presence of masses between load cell and specimen**
- **wave propagation & reflections**

Load Measurement : Evaluation & Correction





Extended tab Aluminum Specimen → TRANSFER FUNCTION → Correct test data for Composite Specimens

Extended tab Aluminum Specimen → Simulations to improve /develop recommendations for test apparatus

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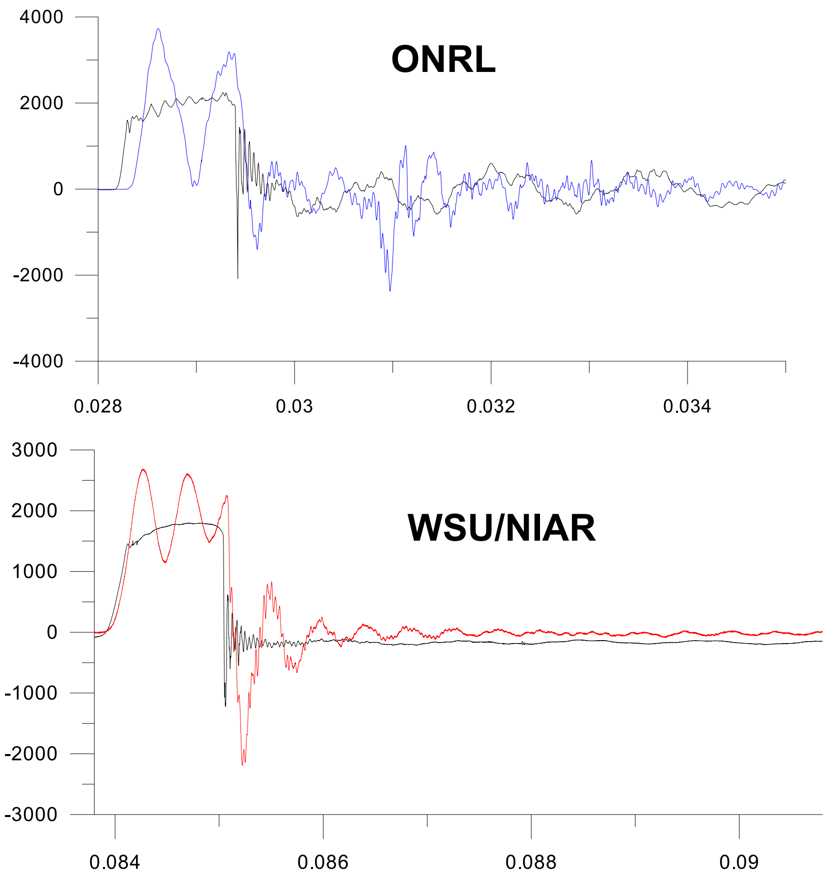
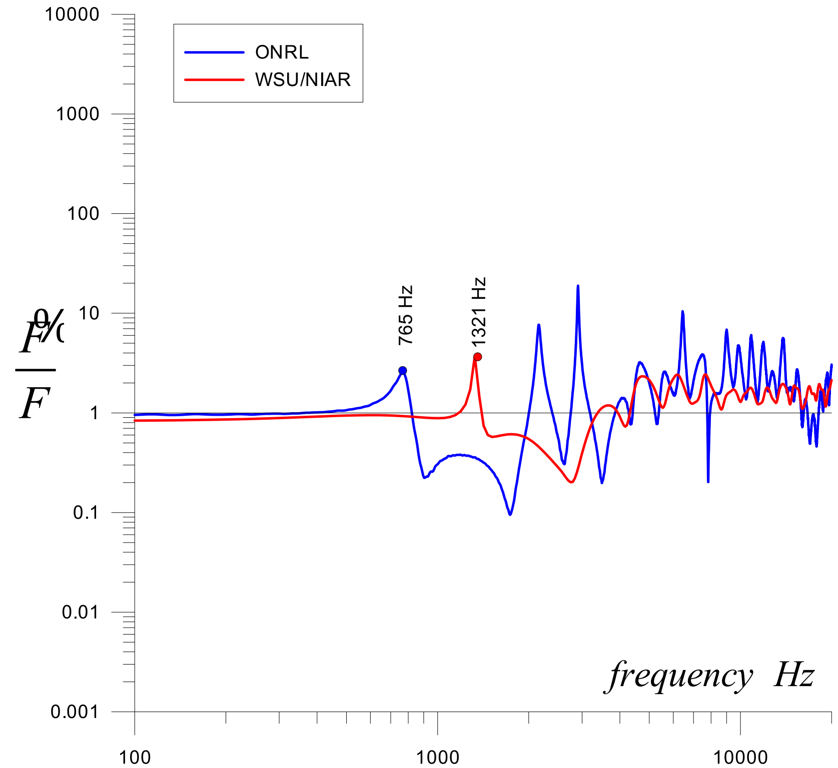
Load Measurement : Preliminary data

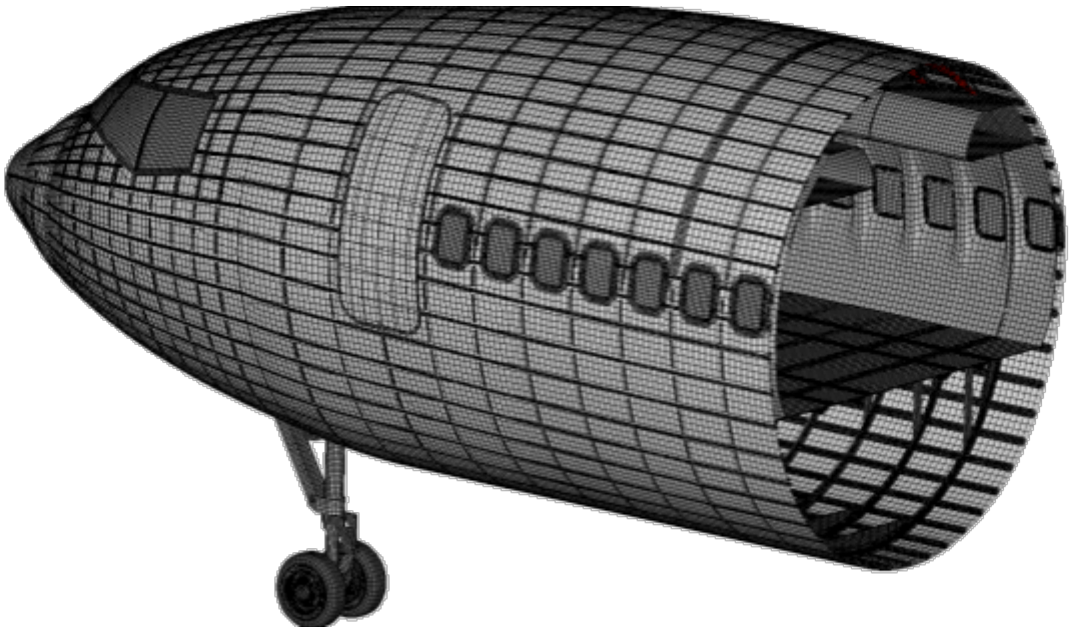


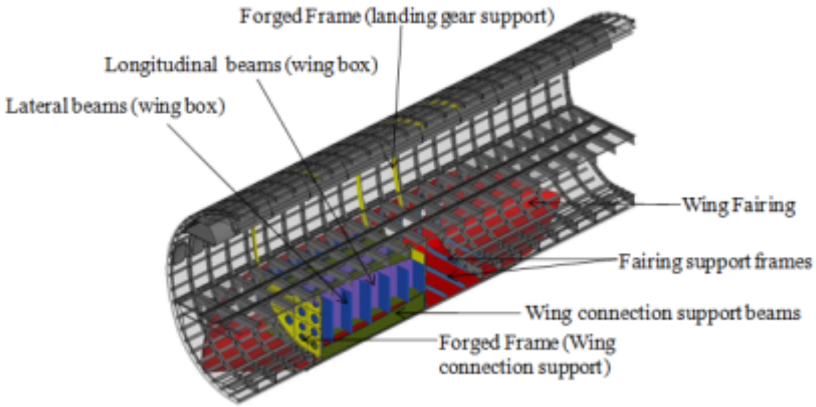


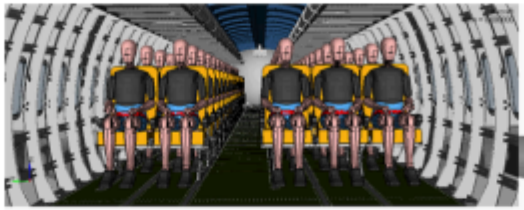
Aerospace Crashworthiness Analytical Studies

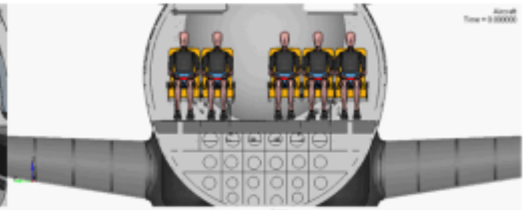
- Current airframe designs are based mostly on airworthiness requirements.
- Limited guidelines for the crashworthiness design of aircraft structures (except rotorcraft).
- Most of the public domain crashworthiness research conducted in the past was experimental .
- The advances in computational tools combined with the building block approach allows for a cost-effective method to study in depth the crashworthiness behavior of aerospace structures.
- Numerical tools are useful from the concept design stages all the way to supporting the certification process.
- Since the crashworthiness behavior of composite structures needs to be equivalent or better than metallic structures we have concentrated the initial part of the research on evaluating the crashworthiness response of typical metallic narrow body transport, and business jet structures.
- These studies address the following areas:
  - Study the crashworthiness behavior of aircraft structures for typical impact surfaces (hard, soft soil, water) , sub-floor designs and cargo configurations (identify loading rates, strain rates… and other parameters required to define coupon and component level conditions)
  - How to select a representative test and/or analysis section
  - Identify computational models limitations
  - Study in depth survivable crash events through physics based accident reconstruction and FE simulation techniques
  - Develop modeling methodologies

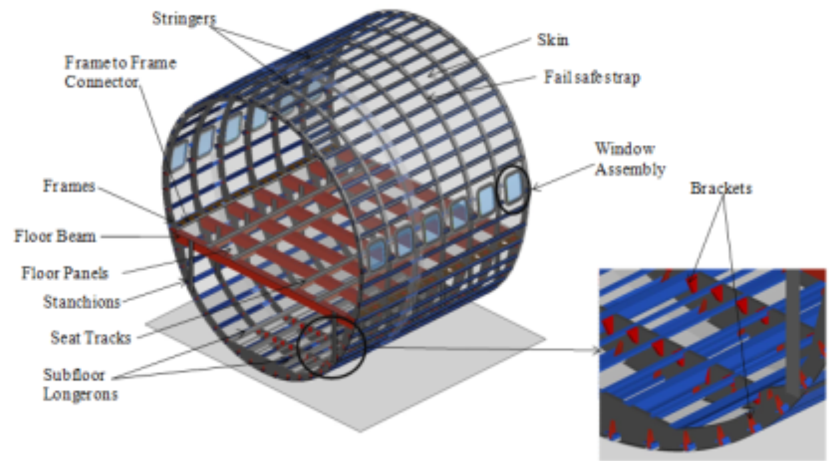
NIAR Narrow Body Transport FE Model



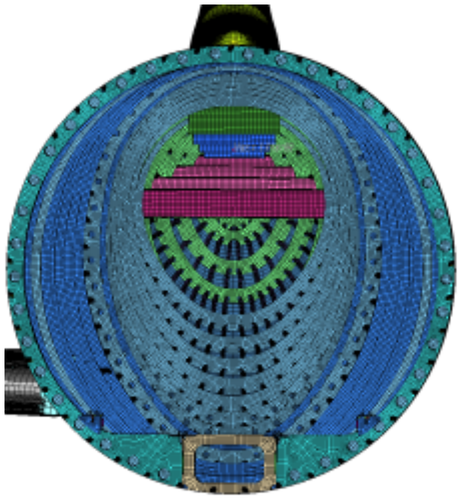


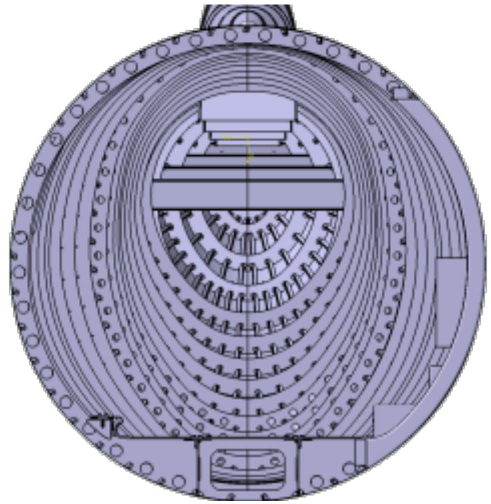


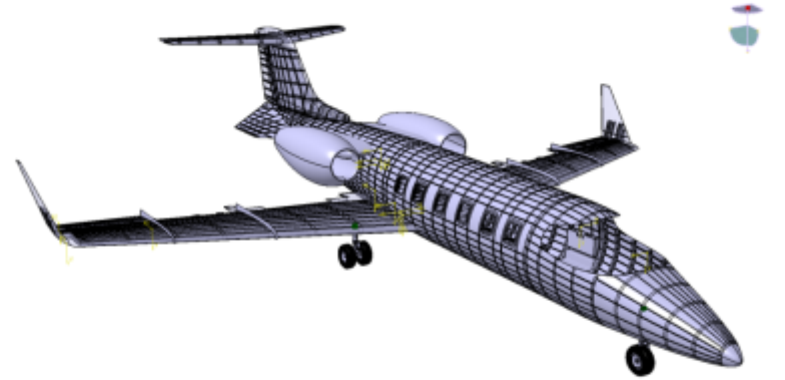


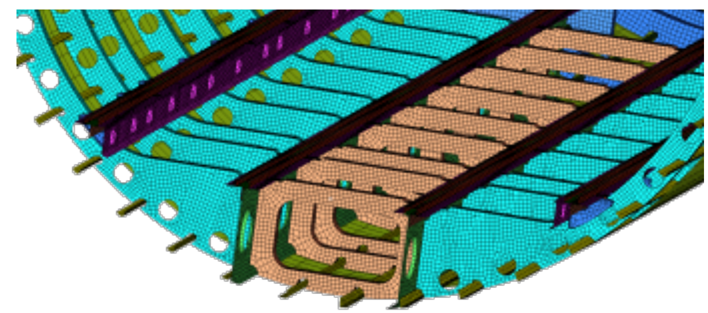


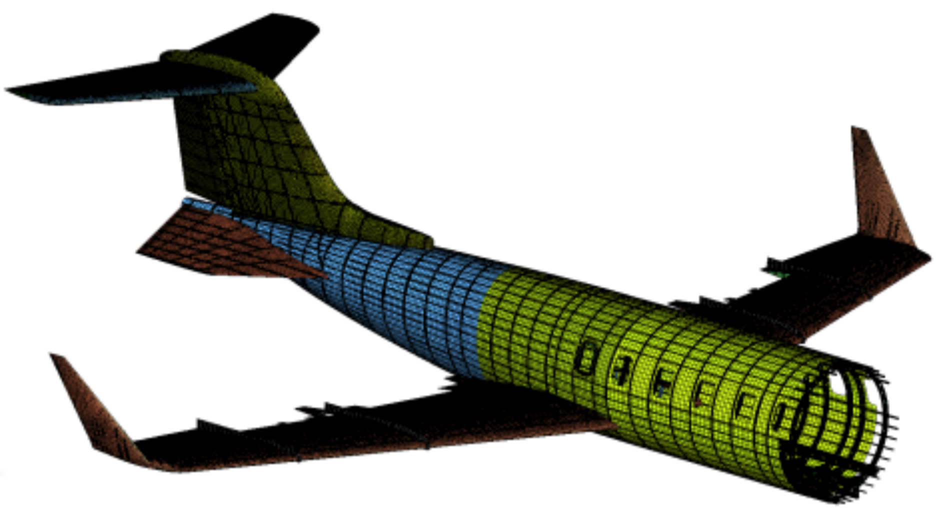
NIAR Business Jet FE Model



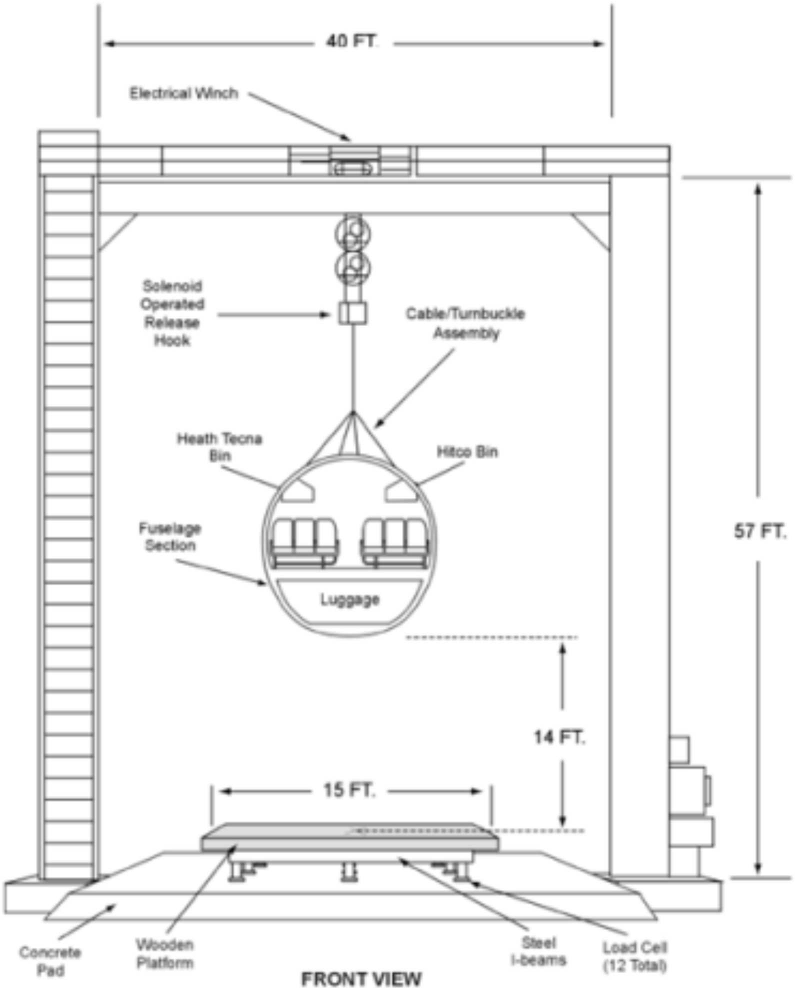


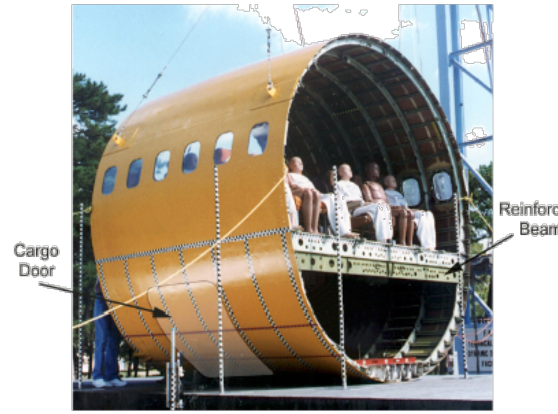


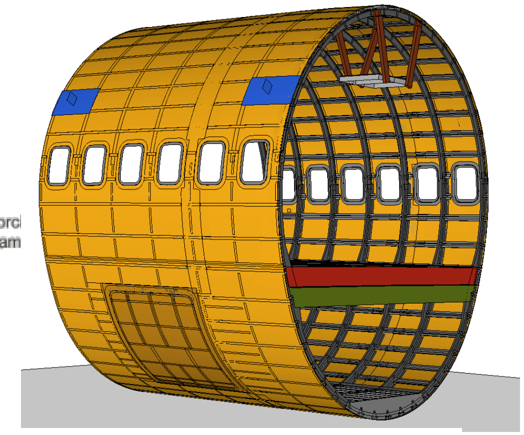




Modeling Techniques Validation







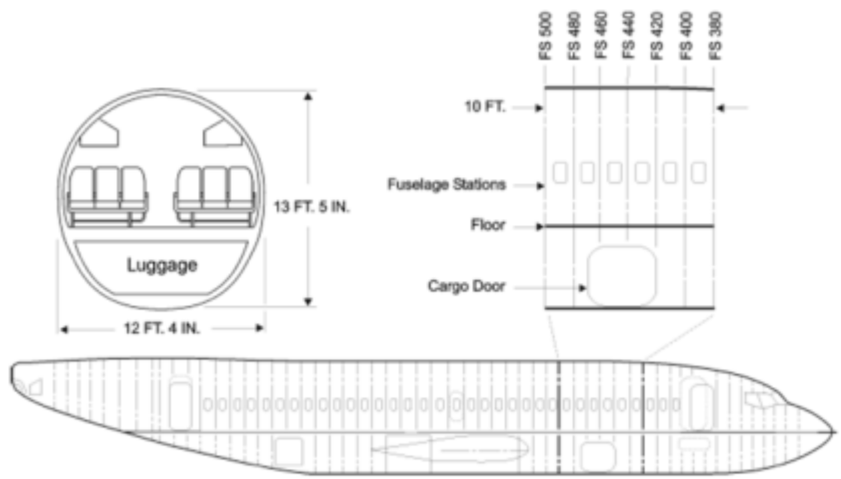


FIGURE 3. FUSELAGE SECTION
(From a Boeing 737-100 Airplane)

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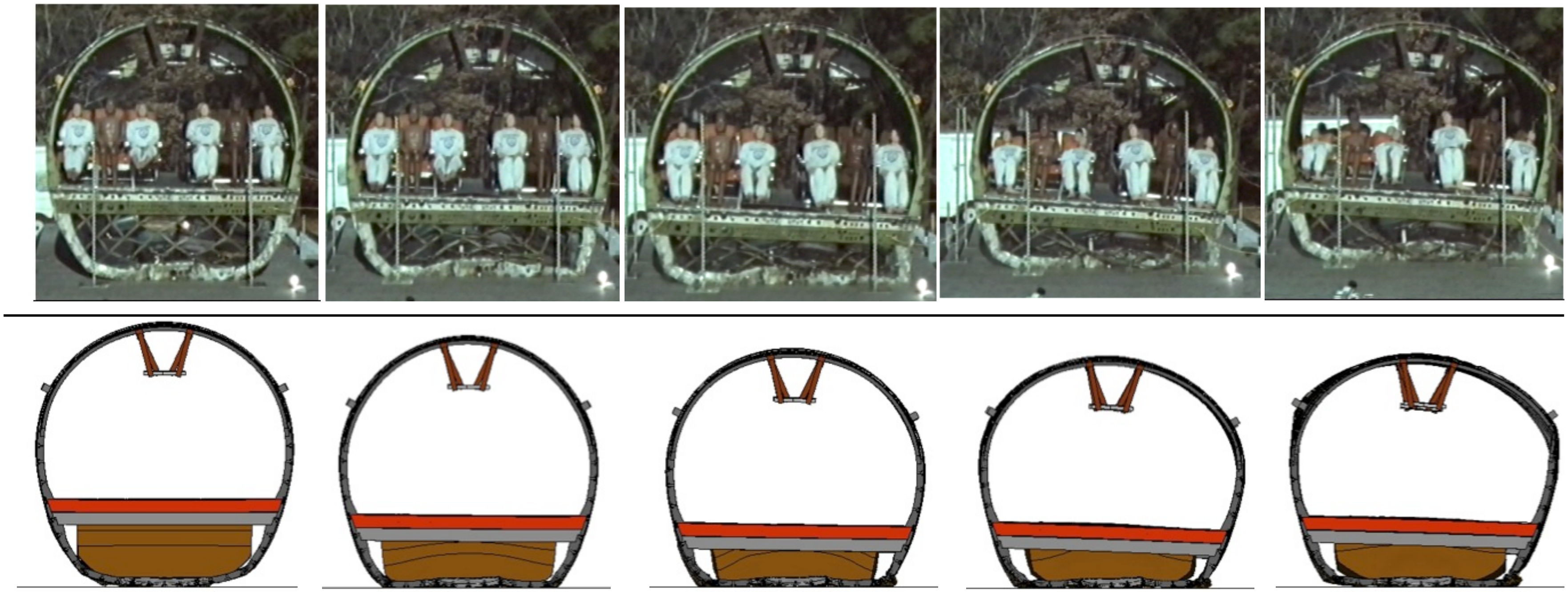
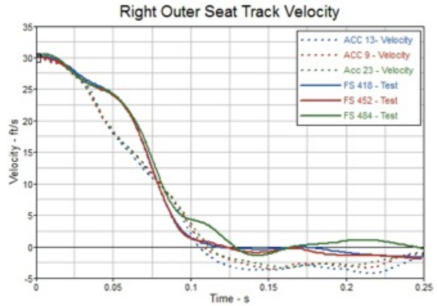
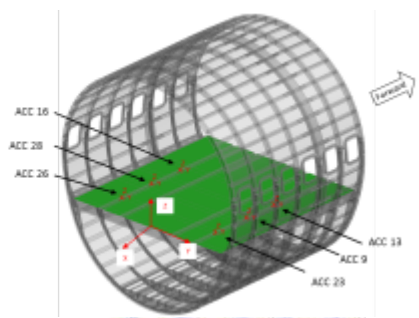
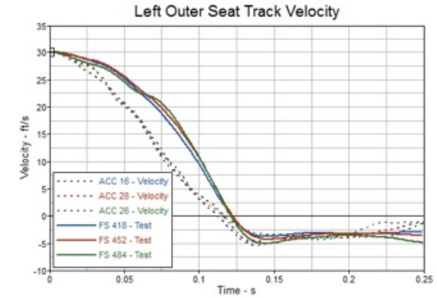
Kinematic Frames Comparison



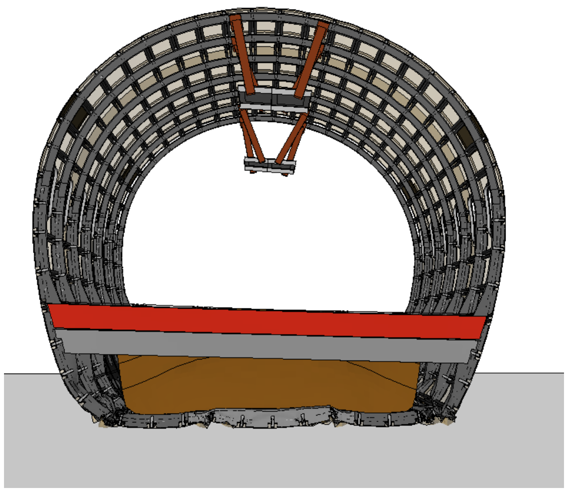
T= 0.03 s | T= 0.06 s | T= 0.09 s | T= 0.12 s | T= 0.15 s

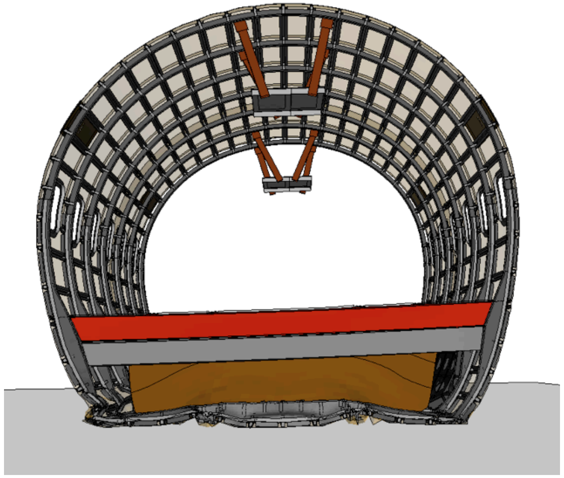






Post-Test Deformation





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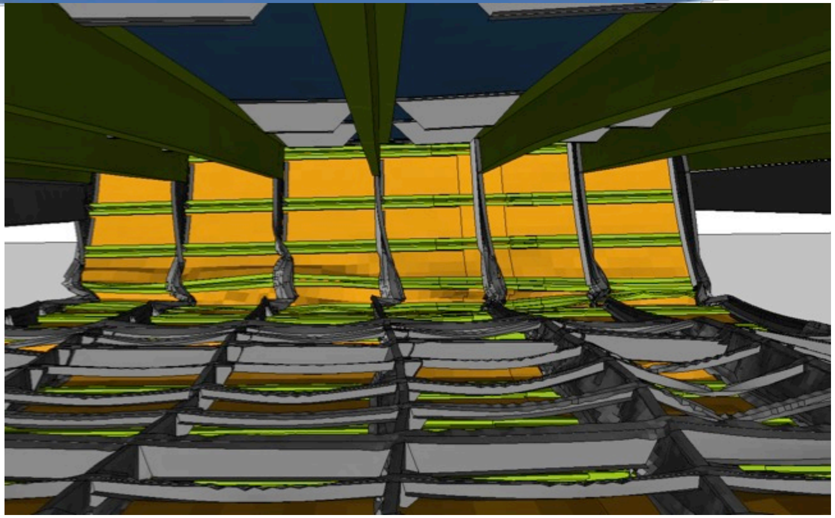
Post-Test Deformation

FIGURE C-75. CARGO AREA—LEFT SIDE



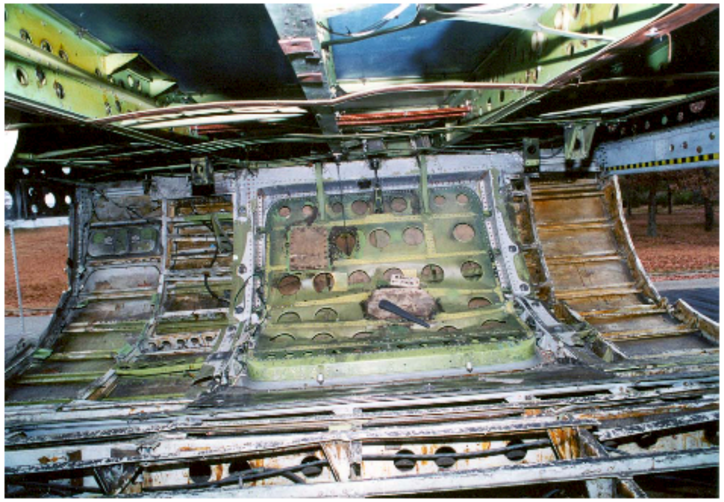
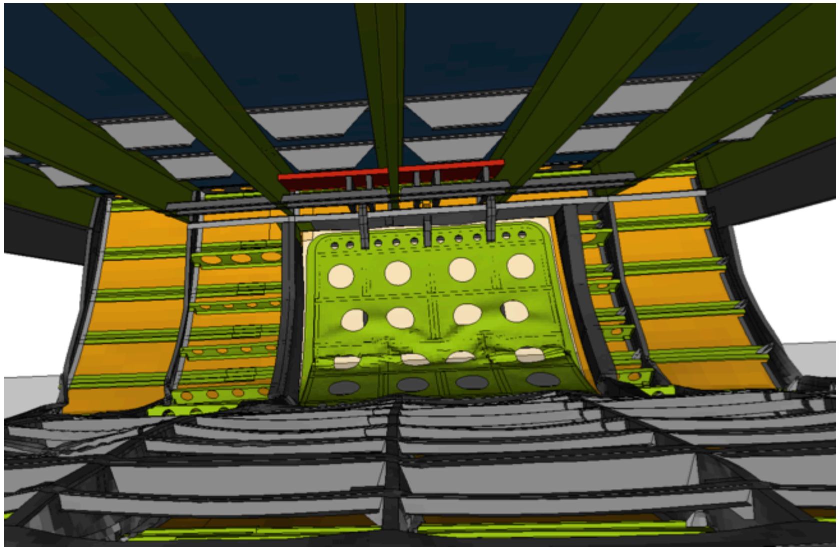


FIGURE C-77. CARGO AREA—RIGHT SIDE



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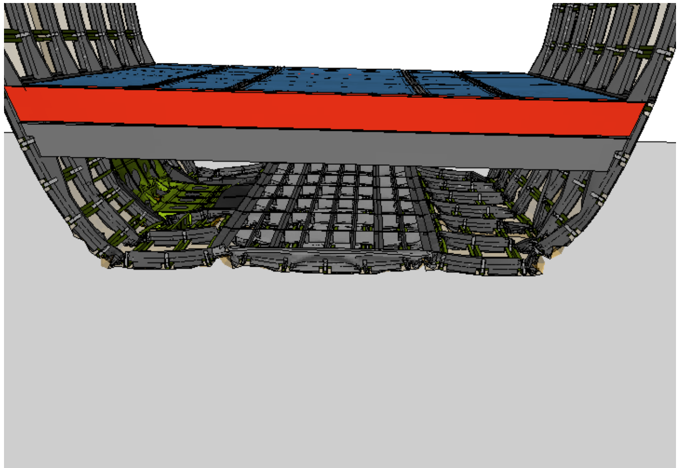
Post-Test Deformation

FIGURE C-71. CARGO CABIN FLOOR BUCKLE—FRONT



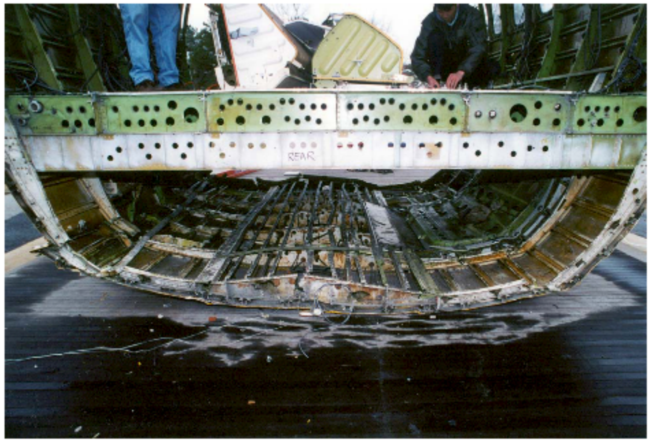
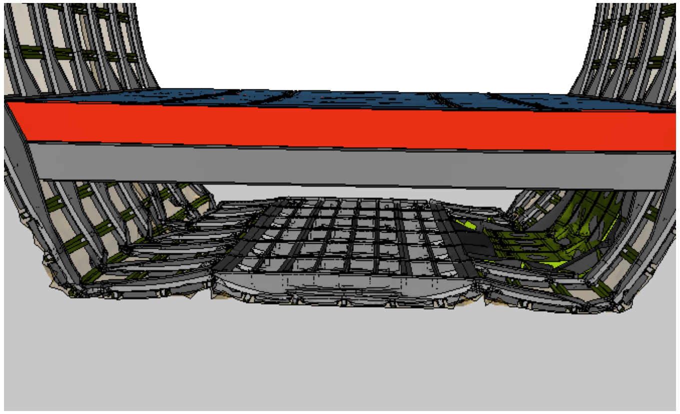


FIGURE C-72. CARGO CABIN FLOOR BUCKLE—REAR



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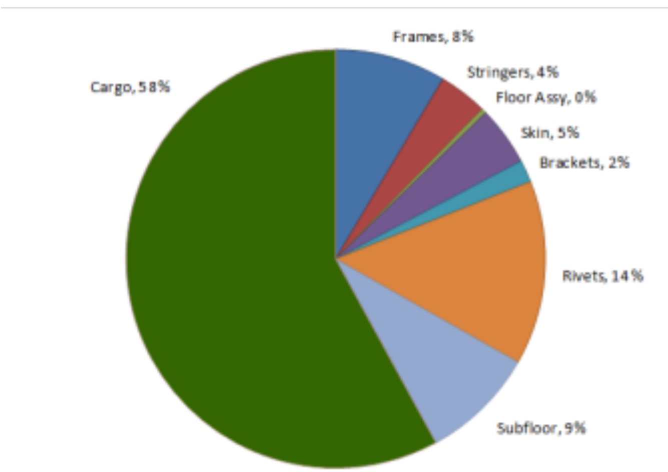
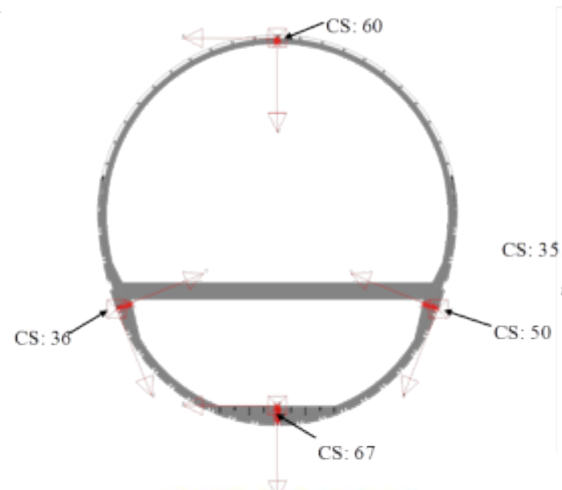
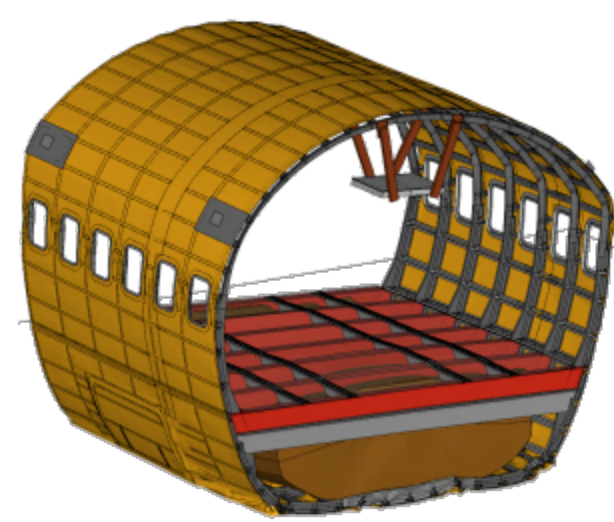
What additional data can be obtained from computational models?

- Individual structural component loads time histories
- Fastener and joints load time histories
- Energy distribution throughout the crash event
- Strain Rates for individual structural components
- The most cost effective method to conduct parametric analyses
- By using analytical tools we can gain a better understanding of the fundamental physics of the crash event

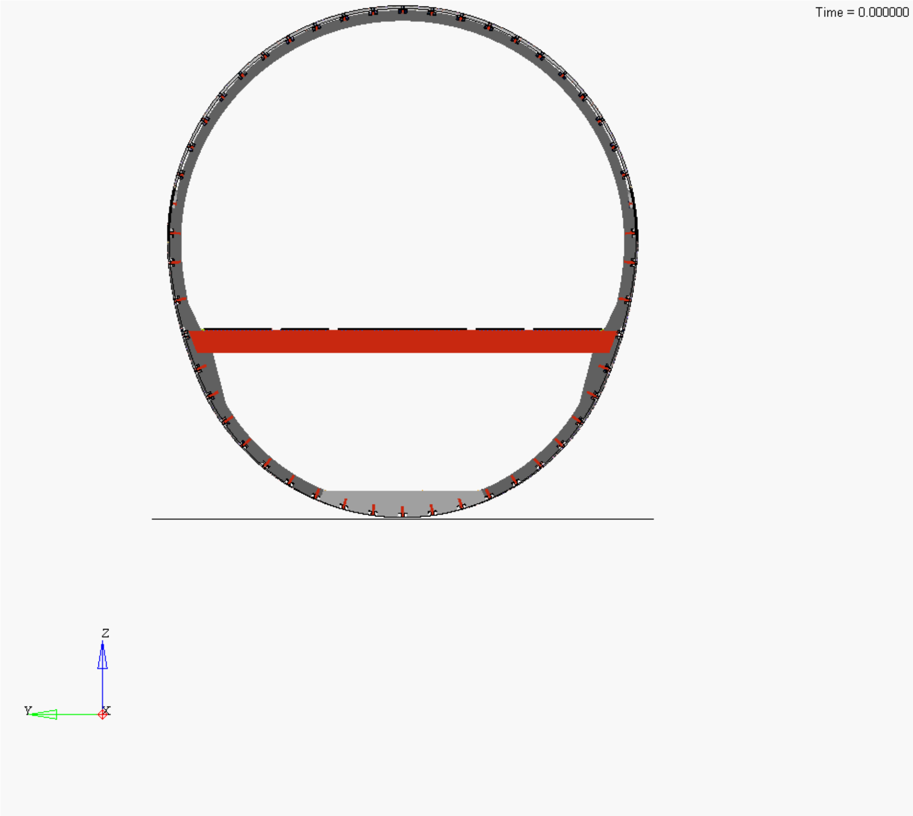
Energy Distribution (t=0.3s)

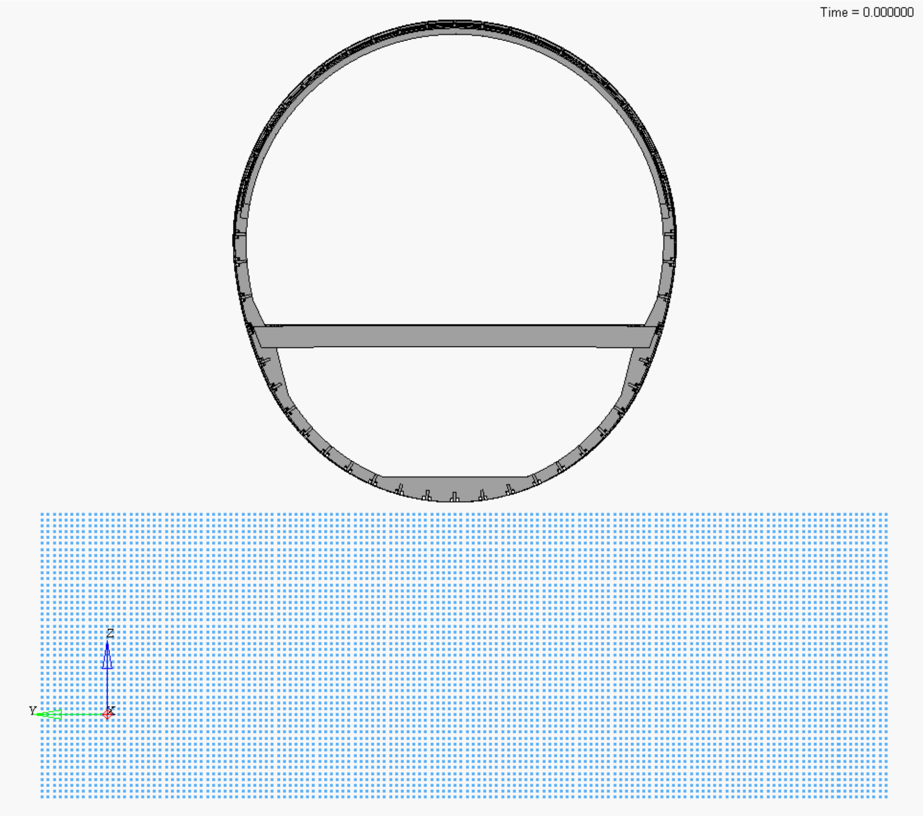






Hard Surface vs. Water Impact Kinematics





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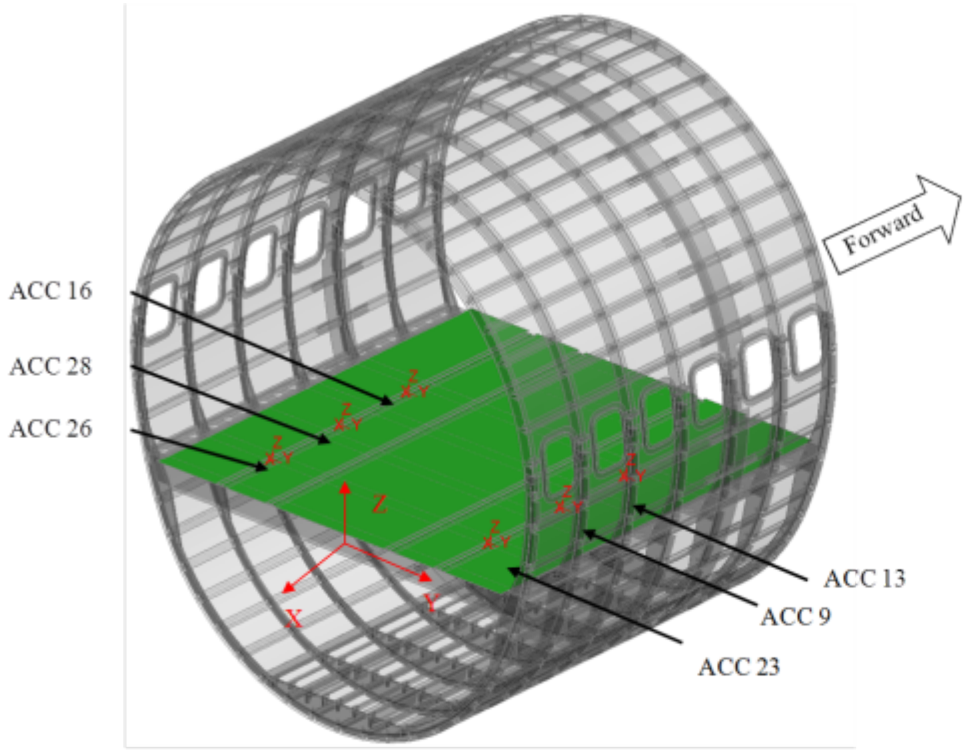
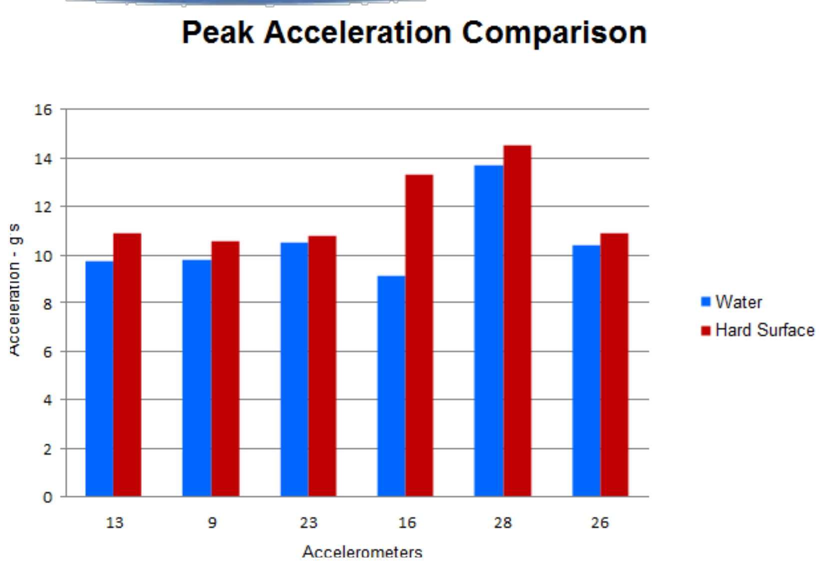
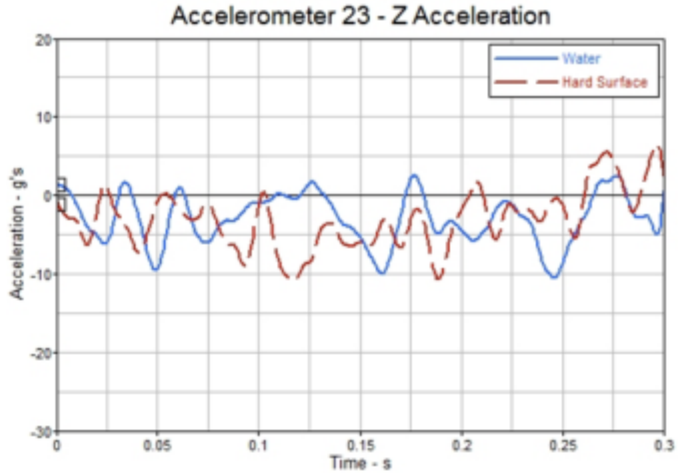
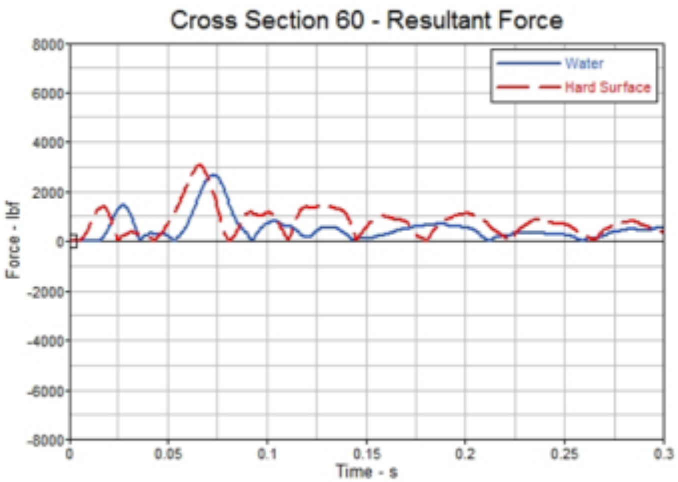
Peak Vertical Acceleration

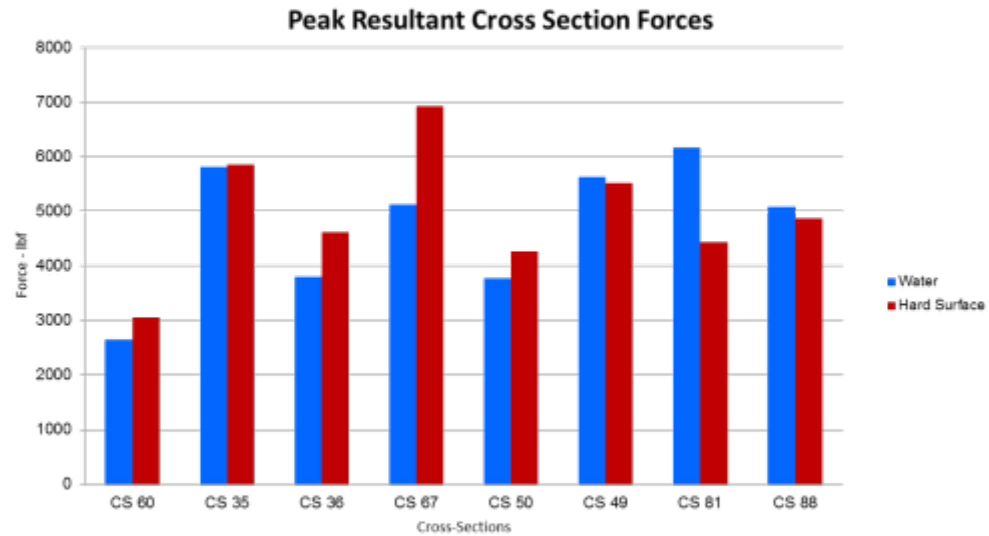


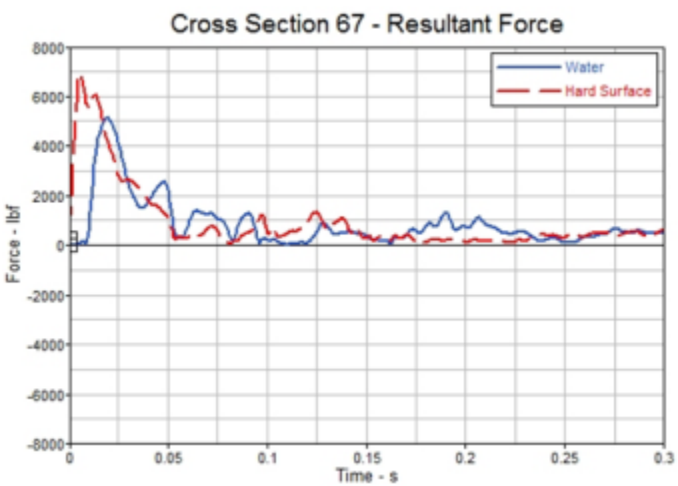


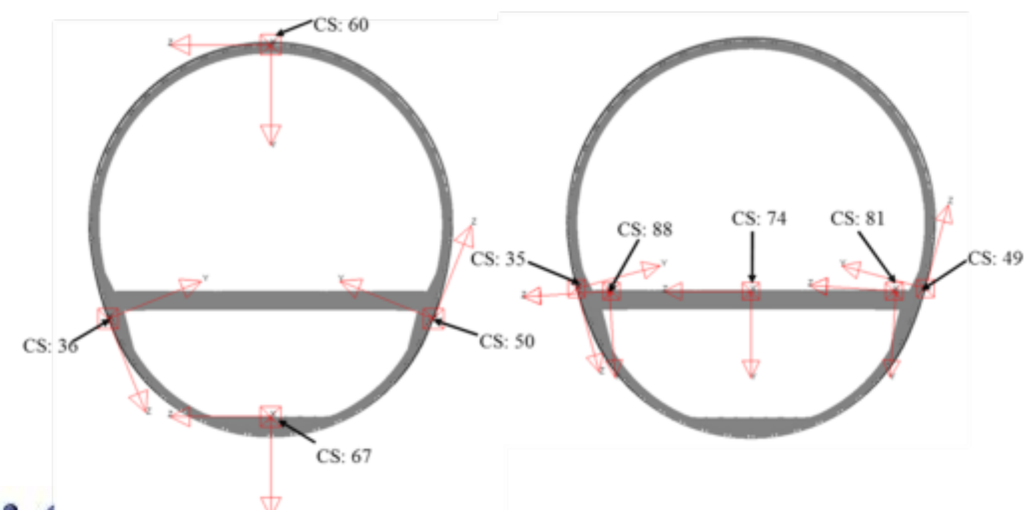


Peak Resultant Internal Section Forces

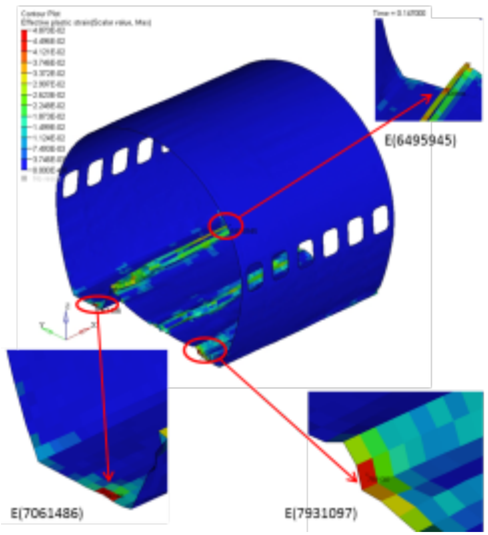


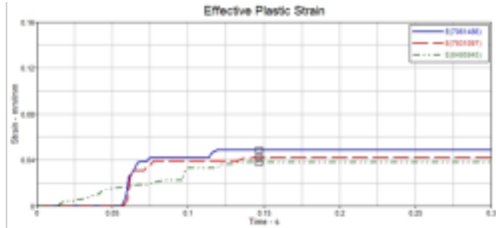


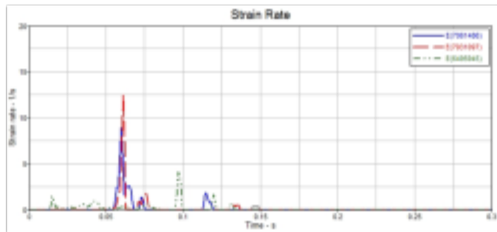


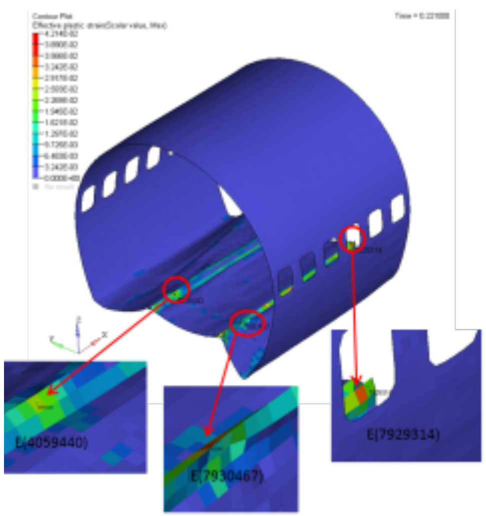


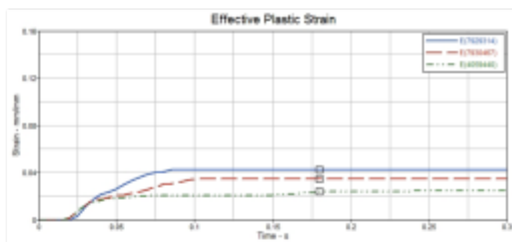
Strain Rates

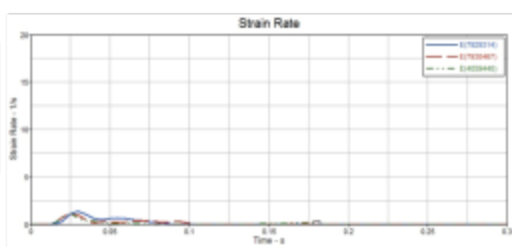


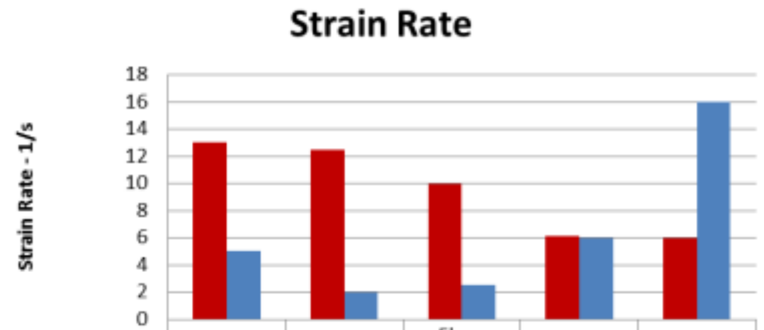




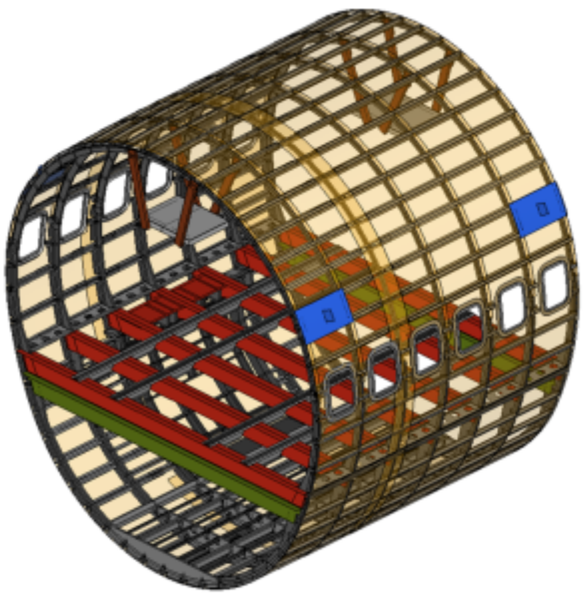








	Frames	Skin	Floor Assembly	Stringers	Subfloor
Hard Surface	13	12.5	10	6.1	6
Water	5	2	2.5	6	16



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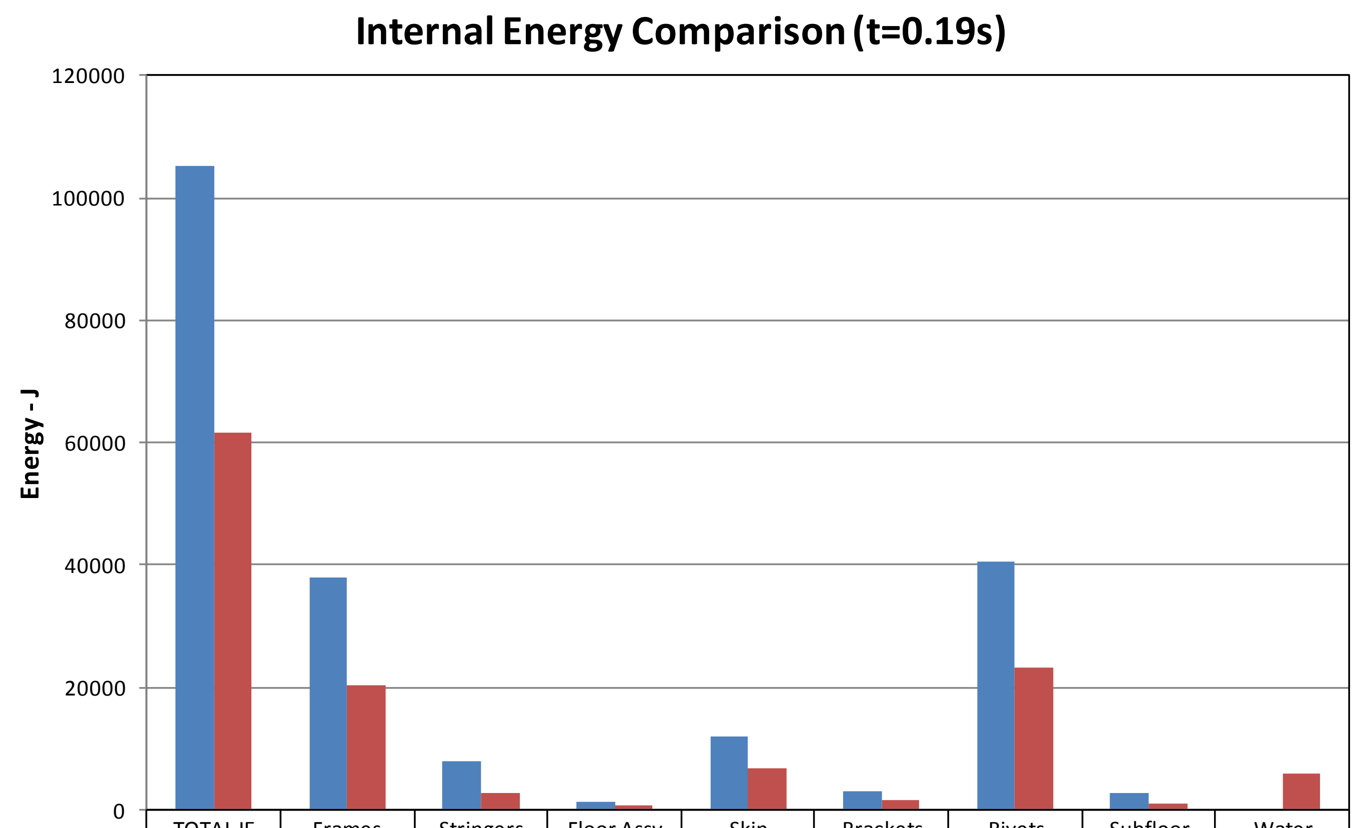
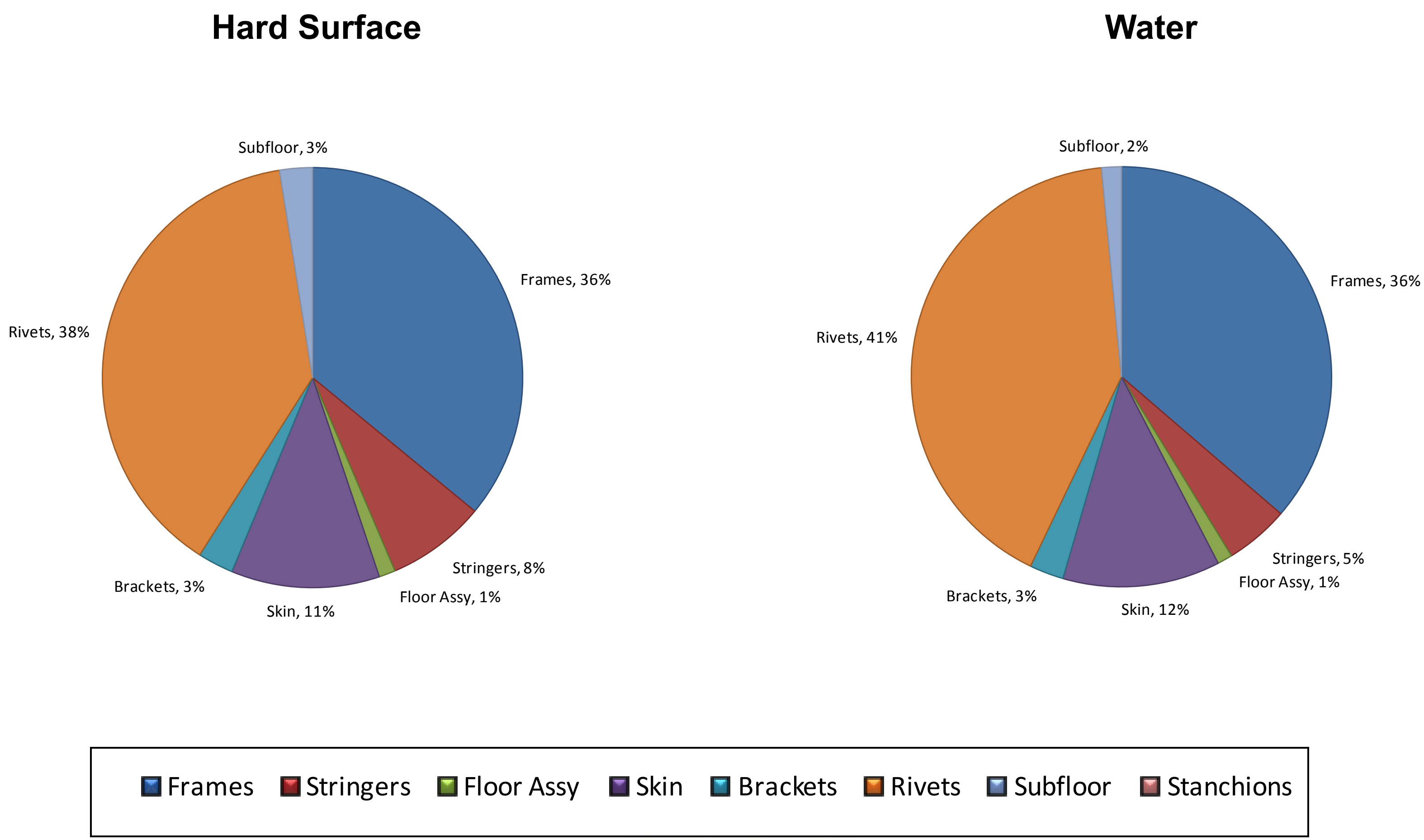
Internal Energy Comparison (0.19 s)



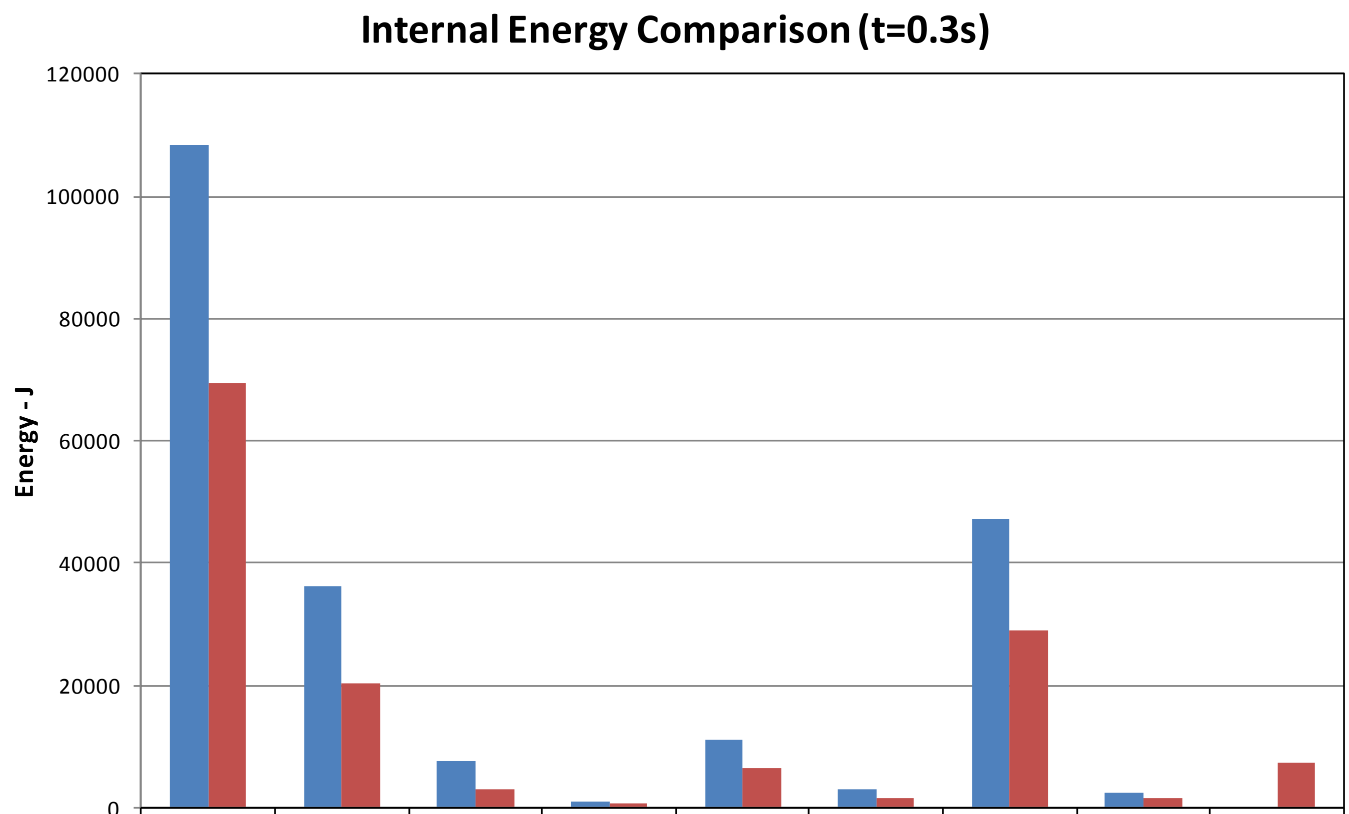
	TOTAL IE	Frames	Stringers	Floor Assy	Skin	Brackets	Rivets	Subfloor	Water
Hard Surface	105197.4	37834.9	8017.6	1331.7	12008.8	2891.4	40468.0	2645.0	0.0
Water	61617.9	20246.5	2746.3	638.4	6685.4	1465.1	23065.9	846.7	5851.0

Note: 0.19s is the max compression time for Hard Surface model but not for water model

Internal Energy Comparison (0.19 s)



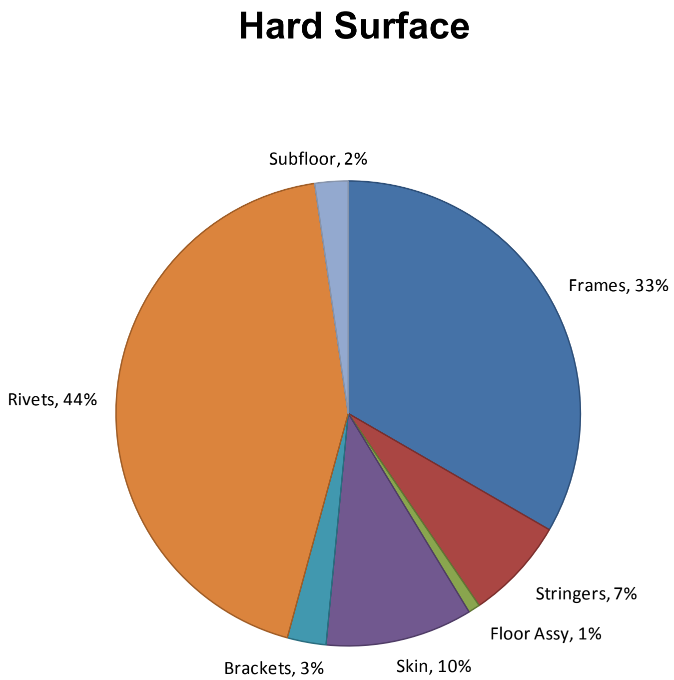
Internal Energy Comparison (0.3s)

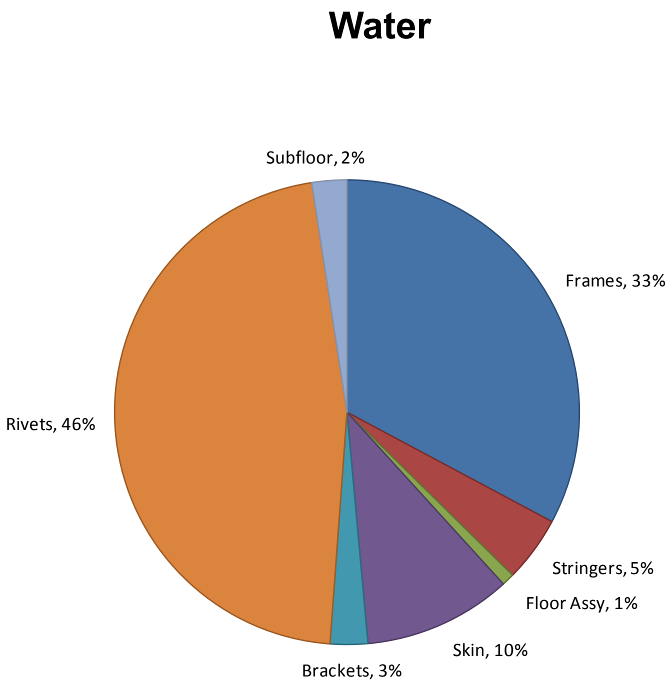


	TOTAL IE	Frames	Stringers	Floor Assy	Skin	Brackets	Rivets	Subfloor	Water
Hard Surface	108297.2	36101.7	7724.9	887.4	11088.3	2924.9	47070.1	2500.0	0.0
Water	69462.3	20398.3	2841.2	537.2	6334.5	1621.0	28856.7	1508.0	7283.4

Note: 0.3s is the end time for the simulations.

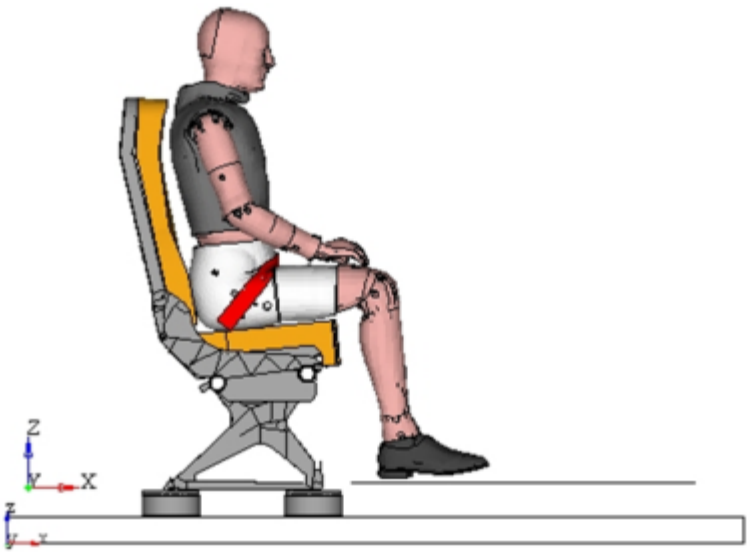
Internal Energy Comparison (0.3 s)

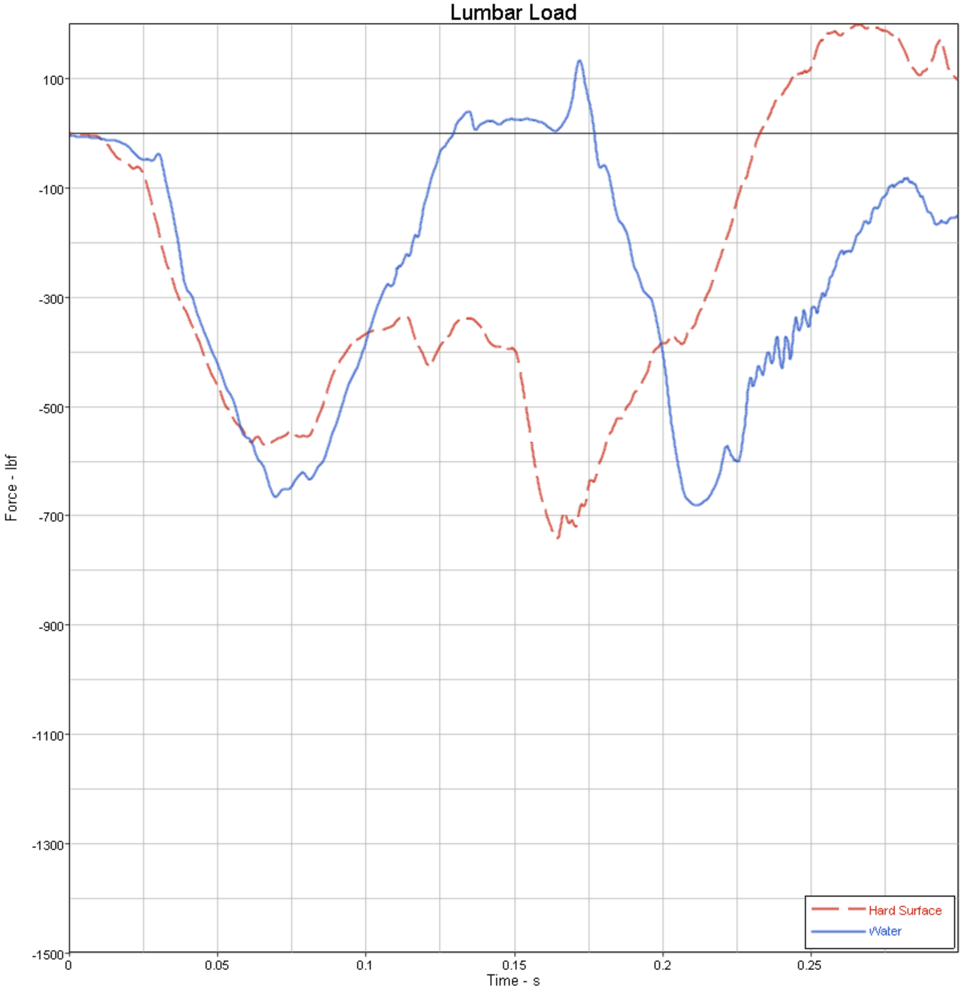




Frames Stringers Floor Assy Skin Brackets Rivets Subfloor Stanchions

Lumbar Load





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Preliminary Conclusions Analytical Studies for Narrow Body Transport Aircraft

- The design/configuration of the cabin-subfloor section significantly affects the dynamic response of the airframe and passengers
- The variability of cargo configurations (shape, stiffness, no-cargo) needs to be addressed in future crashworthiness requirements:
  - Develop structures with stanchions and other structural elements in order to reduce the energy absorbing capabilities of the cargo
  - And/or develop a “standard worst case geometry/stiffness” cargo configuration to be used in the development and certification processes
- Analytical tools have to be used to define the proper boundary conditions for barrel section tests
- Detailed full aircraft analytical models may be used to evaluate the crashworthiness behavior
- Using simulation tools we were able to quantify for all the components in the structure the Strain Rate, Loading Rate, Energy Distribution, Accelerations, Dynamic Structural Efficiency, and Structural Deformations throughout the crash event
- The new detailed numerical aircraft seat and passenger models developed in CBA Phase I provide a predictable tool that can be used to evaluate the passenger’s risk of injury
- This analysis methodology for metallic structures can be applied to composite structures once composite material models are improved (both experimental and computational)

Looking Forward

- The following reports will be completed during FY12:
  - Coupon level material model evaluation – Draft report available
  - Narrow Body Transport Crashworthiness – Draft report available July 2012
  - Round Robin Coupon Level – December 2012
- Present at the next CMH17 Meeting the Round Robin testing results
- Continue the parametric studies of Narrow-Body Transport and Business Jet configurations
- Additional experimental work required to validate the modeling techniques for rivets and joints
- Develop guidance material to design crashworthy metallic, composite and hybrid structures
- Disseminate the findings of the research through collaborative projects with industry, workshops, CMH-17 WG and journal publications.
- Aerospace Structural Impact Dynamics International Conference: November 6-8 2012
- Certification by analysis workshop November 9th 2012

Aerospace Structural Impact Dynamics International Conference

- November 6-8, 2012 @ the National Center for Aviation Training, Wichita, KS
- Topics:
  - Aerospace Crashworthiness: Composites & Metallic Structures, Aircraft Interiors
  - High Velocity Impact: Bird Strike, Hail, Foreign Object
  - Composites & Metallic Materials - Dynamic Behavior Material Characterization
- Workshops:
  - Certification by Analysis: Aircraft Interiors and Structures
- Abstracts due May 1 to callforpapers@niar.wichita.edu
- Registration:
  - Register online at www.niar.wichita.edu/impactconference
  - Registration fee is $150
  - Capacity is limited to 200
- Partners include: NIAR, FAA, EASA, NASA, DLR, Airbus, Boeing & ACS Australia

National Center for Aviation Training

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End of Presentation.

Thank you.

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