JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

Crashworthiness of Composites - Certification by Analysis

2015 Technical Review

Gerardo Olivares

J. F. Acosta

National Institute for Aviation Research, WSU

NIAR National Institute for Aviation Research

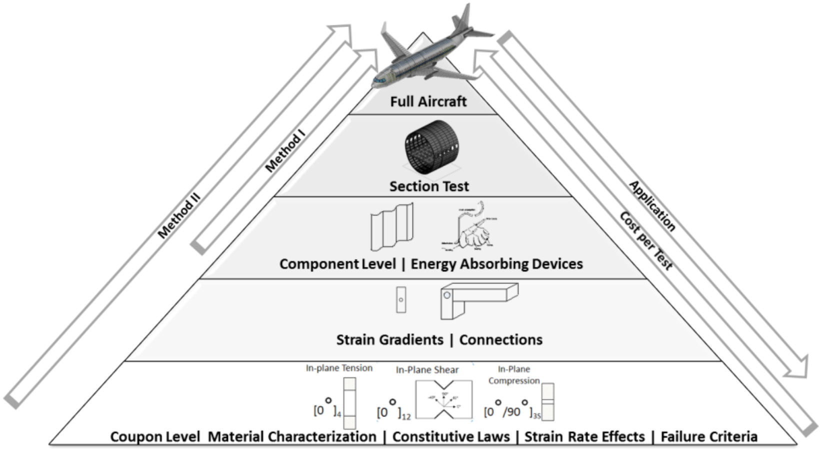
WSU Wichita State University

Crashworthiness Certification by Analysis

- Principal Investigators & Researchers
  - G. Olivares Ph.D. (PI)
  - S. Keshavanarayana Ph.D.
  - J.F. Acosta Ph.D.
  - Chandresh Zinzuwadia, Nilesh Dhole…..
  - NIAR Computational Mechanics
- FAA Technical Monitor
  - Allan Abramowitz
- Other FAA Personnel Involved
  - Joseph Pellettiere

Crashworthiness of Composites - Certification by Analysis

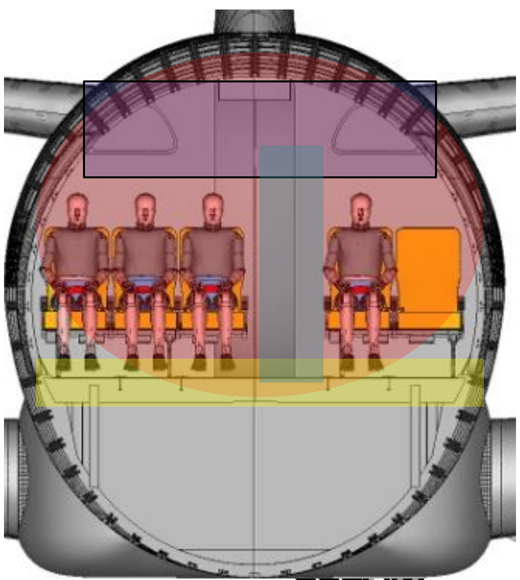
- Motivation and Key Issues
  - The introduction of composite airframes warrants an assessment to evaluate that their crashworthiness dynamic structural response provides an equivalent or improved level of safety compared to conventional metallic structures. This assessment includes the evaluation of 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
  - Building Block Methodology Development



CECAM JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE AMTAS A Center of Excellence Advanced Materials in Transport Aircraft Structures

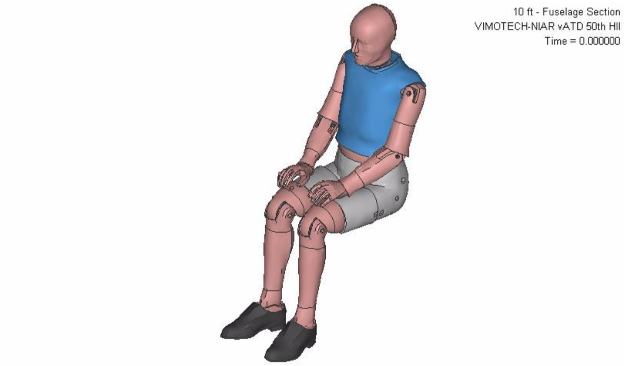
Aerospace Structural Crashworthiness

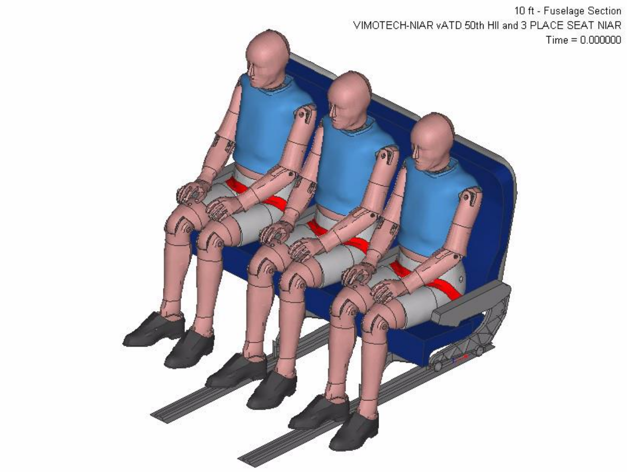
- **Crashworthiness performance of composite structures to be equivalent or better than traditional metallic structures**
- **Crashworthiness design requirements**:
  - Maintain survivable volume
  - Maintain deceleration loads to occupants
  - Retention items of mass
  - Maintain egress paths

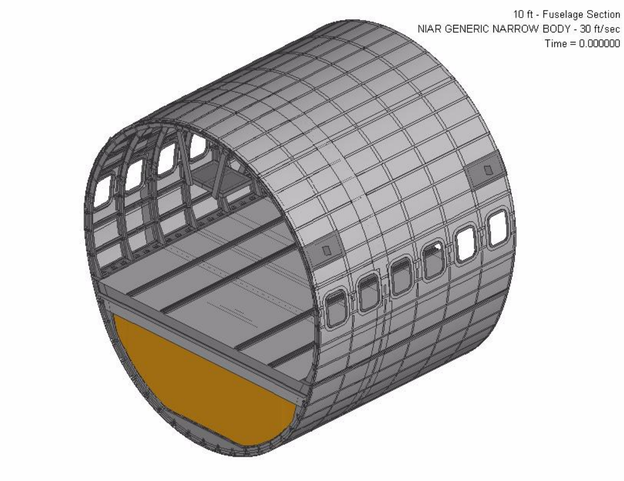


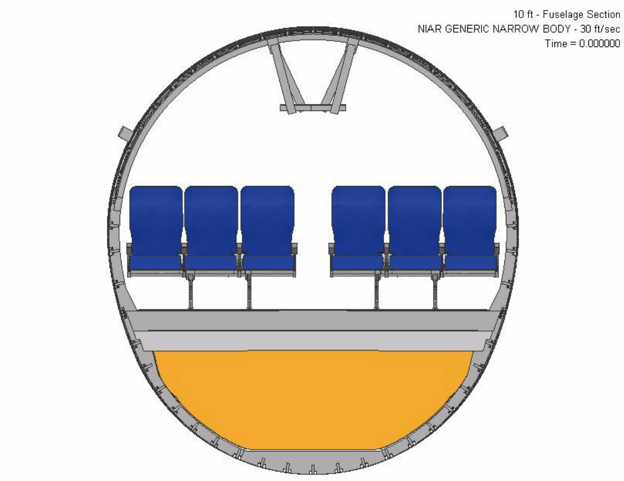
- **Currently there are two approaches that can be applied to analyze this special condition:**
  - **Method I:** Large Test Article Approach
    - **Experimental:**
      - Large Test Articles (Barrel Sections)
      - Component Level Testing of Energy Absorbing Devices
    - **Simulation** follows 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

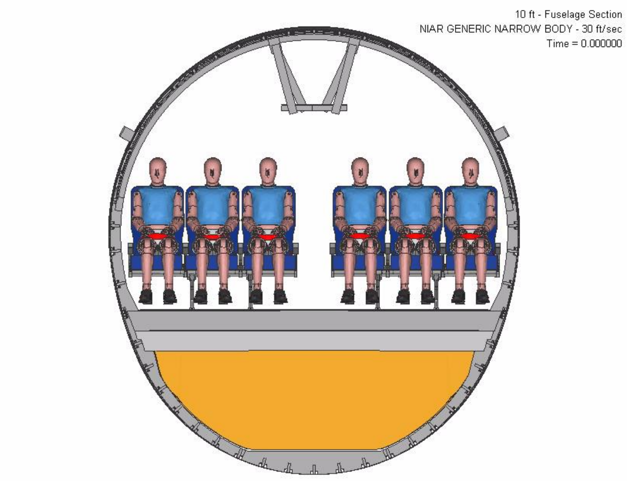
Technical Approach – Aerospace Crashworthiness CBA









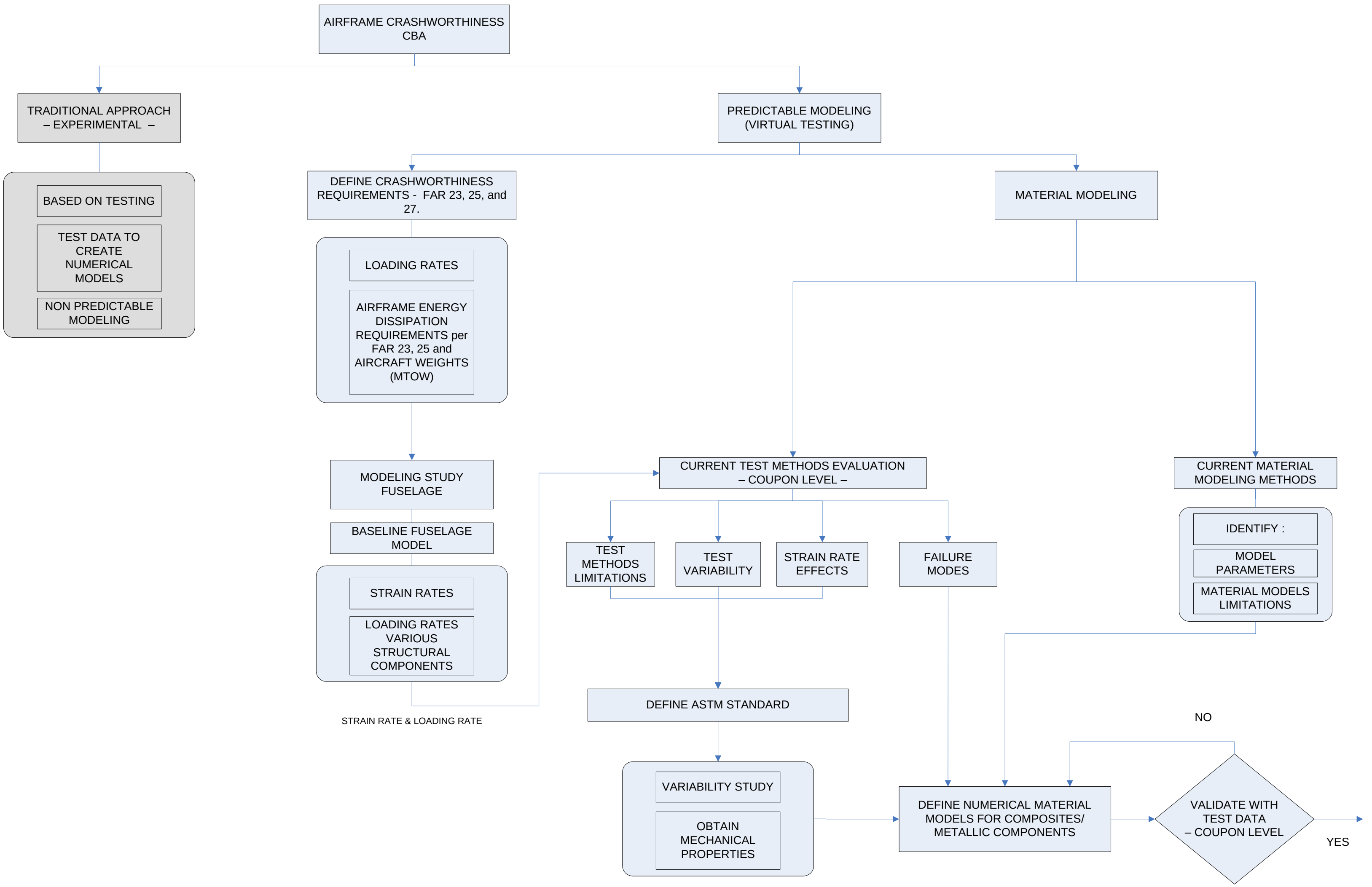


CECAM center of excellence for composites and advanced materials

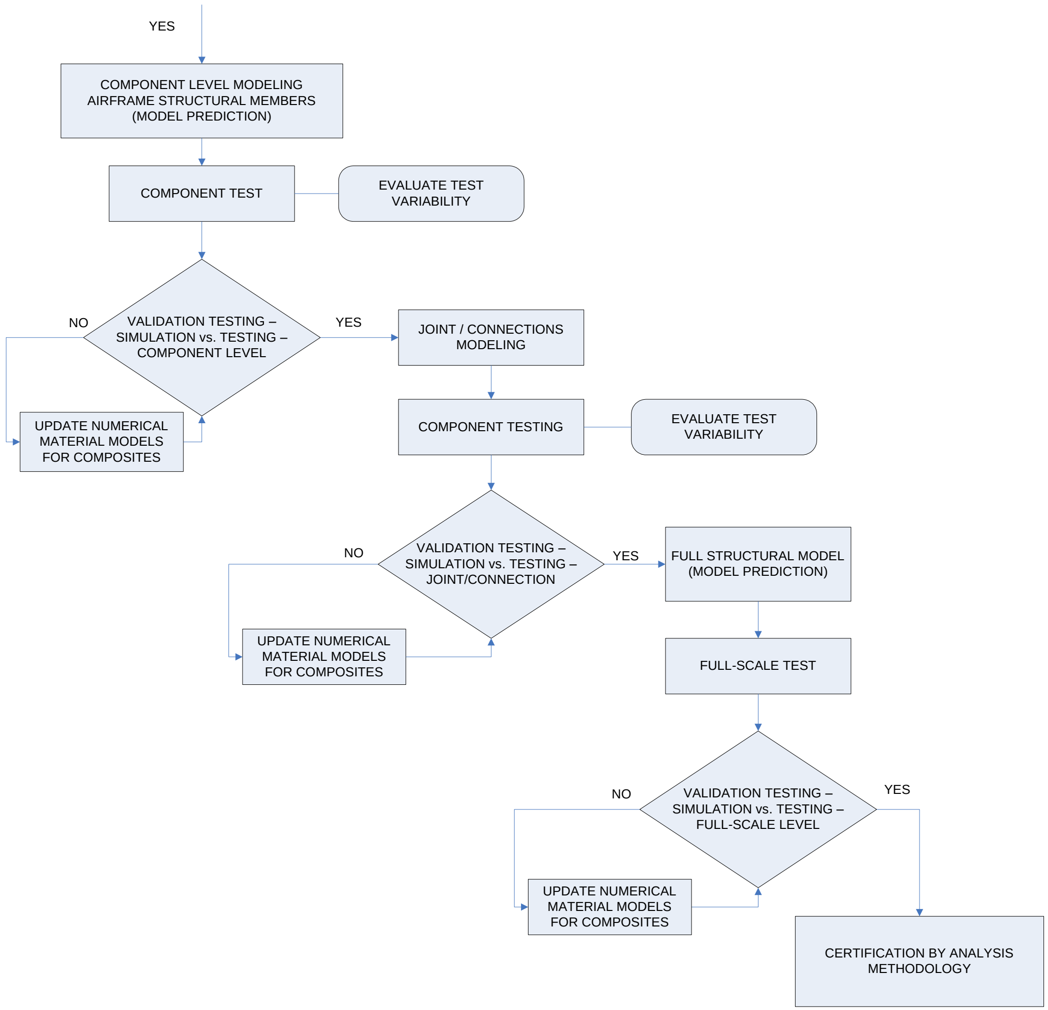
JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

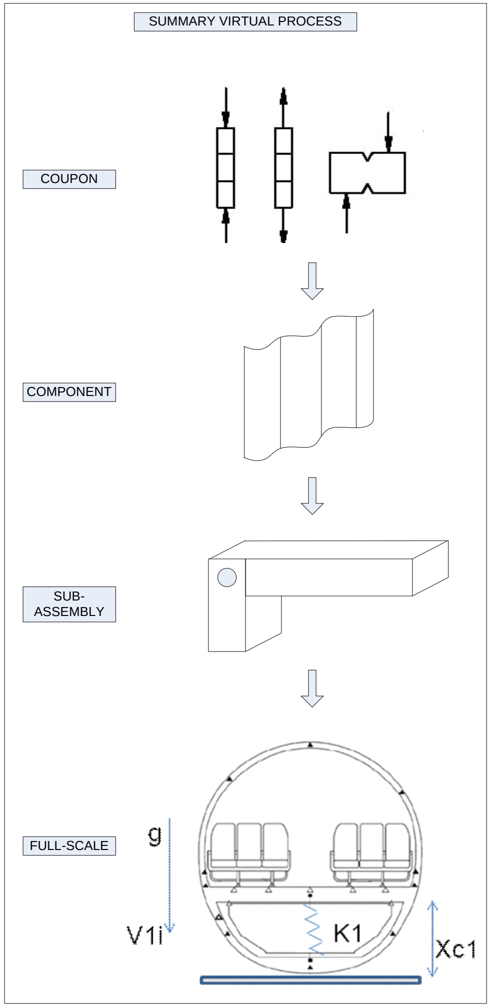
A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

Technical Approach – Airframe Crashworthiness



Technical Approach – Airframe Crashworthiness



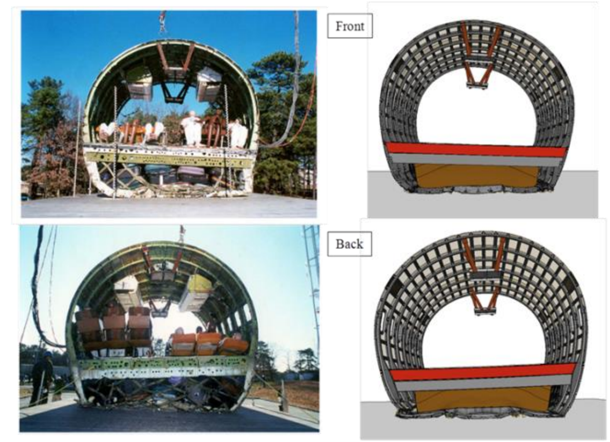


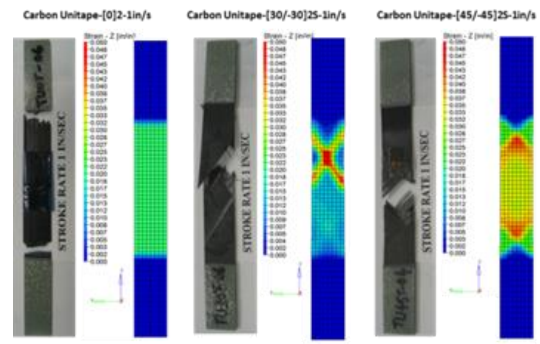
Phase III – Aerospace Crashworthiness Structural Requirements

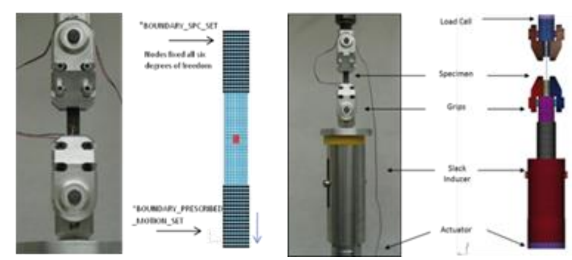
The following working packages were defined to develop NIAR Building Block Approach Methodology:

- **WP 1. Aerospace Crashworthiness Structural Requirements Scope:**
  - Develop Detailed FE models of metallic narrow-body transport aircraft to study the crashworthiness behavior of typical metallic aircraft structures during survivable impacts on hard surfaces, soft soil, and water.
  - Study dynamic response and energy absorbing capabilities of the individual structural members (i.e. stanchions, frames, stringers, skin)
  - Effect on the structural response of various cargo (empty to full cargo configurations) and impact surfaces (rigid, soil, & water) configurations.
  - Results defined range of typical energy absorbing requirements, loading, and strain rates for the various airframe structural components.
  - Quantify Boundary Condition effects on the crashworthiness response from full aircraft models to half barrel type vertical drop test configurations.

- **WP 2. Coupon Level R&D:**
  - Designers require dynamic material properties that take into account the material response at strain rates higher than quasi-static.
  - Dynamic material properties are generated from coupon level testing. Not from component level testing.
  - Coupon-level tests were conducted over a range of strain rates for which testing techniques have not yet been standardized.
  - Round Robin Exercise to develop High Rate Tension Testing.







CECAM

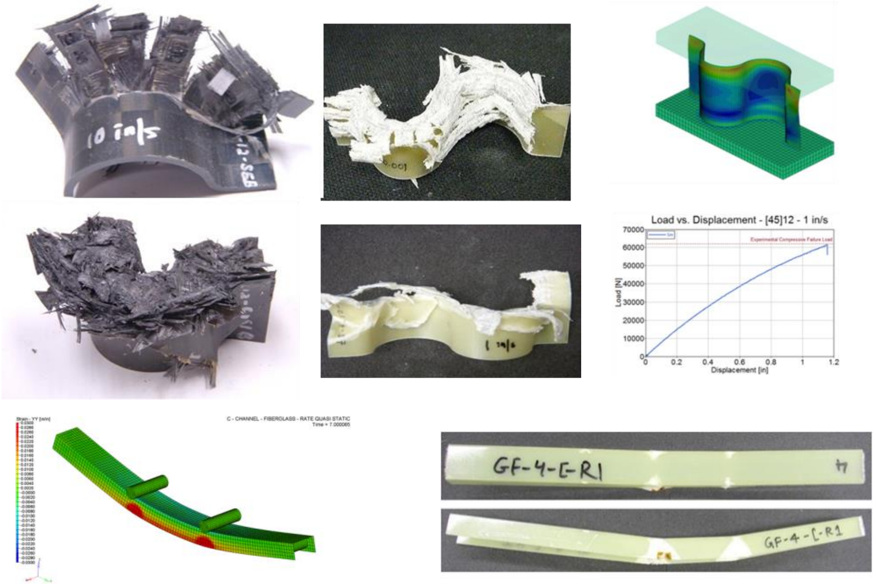
JAMS
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

AMTAS
A Center of Excellence
Advanced Materials in Transport Aircraft Structures

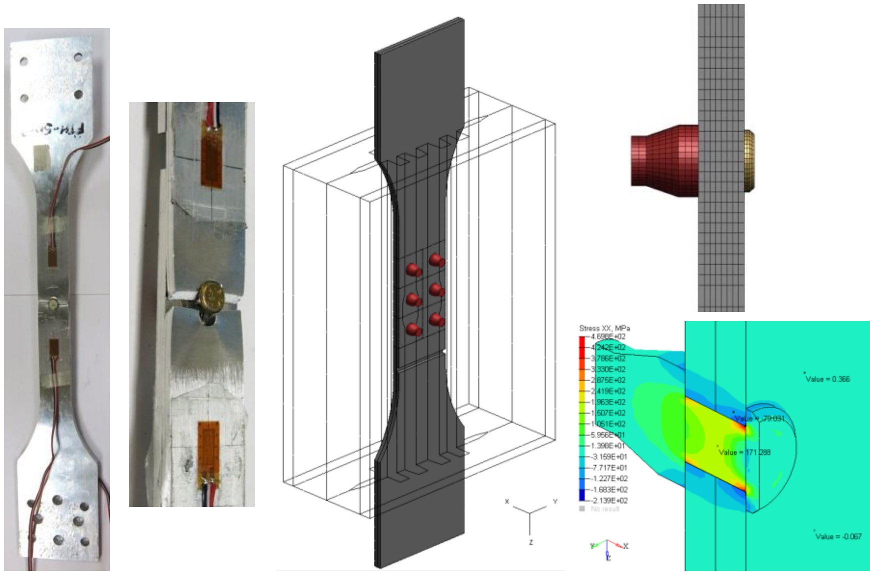
Phase III – Aerospace Crashworthiness Structural Requirements

Working packages for NIAR Building Block Approach Methodology:

- **WP 3. Component Level R&D:**
  - Used to validate the coupon level material data generated in WP2
  - Study the strain rate sensitivity of these composite material systems at the component level.
  - Pin-Bearing, C-Section Beams, and Sine Wave Beams.
  - Results obtained in WP0 defined component level testing protocols (loading rates, strain rates, energy absorbing requirements and component level test configurations).

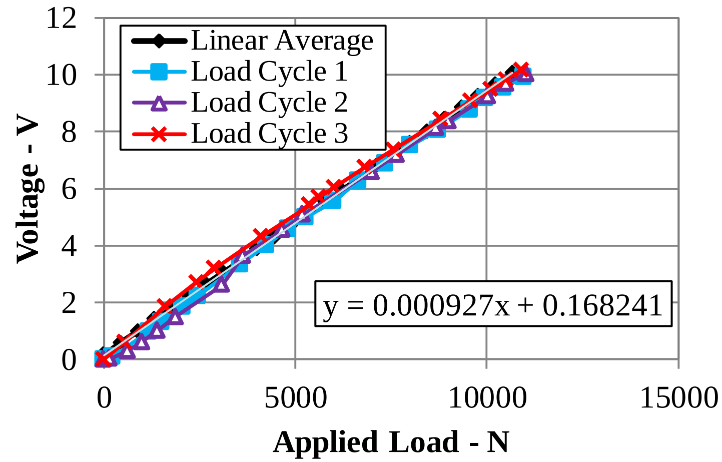


- **WP 4. Joints and Connections R&D:**
  - Understand limitations of different modelling techniques that can be used to join the various airframe structural members.
  - Evaluate single and multiple point load transfer mechanisms between airframe structural members.
  - Characterize the effect of loading rates.
  - Evaluate various modeling techniques and validate them with test data.

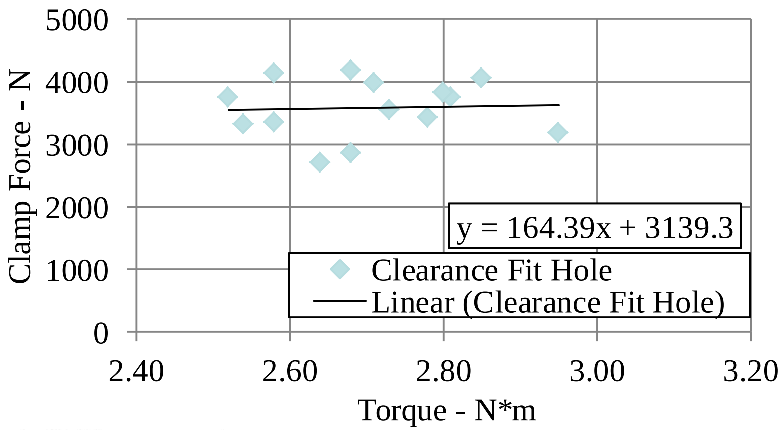


Experimental Testing – Bolt Preload

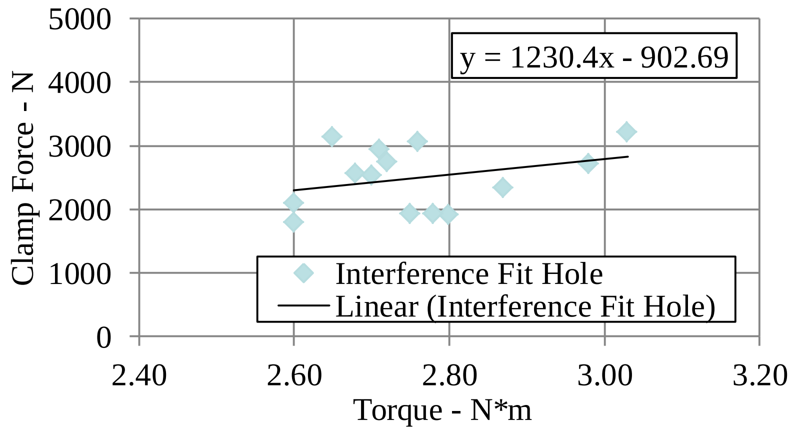
- Experimental Testing – Bolt Preload
  - Test Procedure
    - ✓ Load Cell Verification and Signal Conditioner Calibration
    - ✓ Mounting of Test Article on Vise
    - ✓ Bolt Installation using Torque Wrench
    - ✓ Record Torque at Shear off and Voltage on Voltmeter
  - Test Matrix
    - ✓ 3 Specimen (5 Holes on Each) for Interference Fit
    - ✓ 3 Specimen (5 Holes on Each) for Clearance Fit



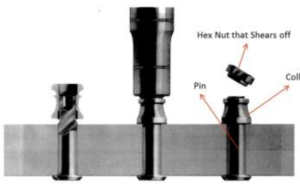
Load Cell Verification and Signal Conditioner Calibtarion



Clearance Fit



Interference Fit



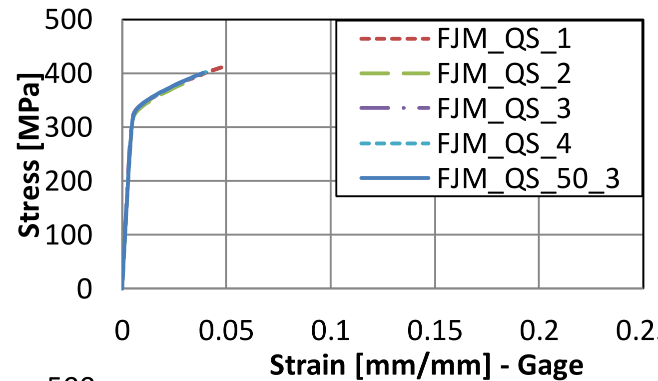
CECAM

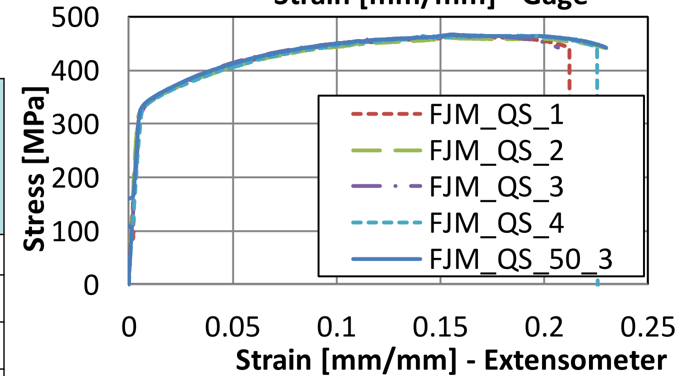
JAMS
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

Experimental Testing – Material Characterization

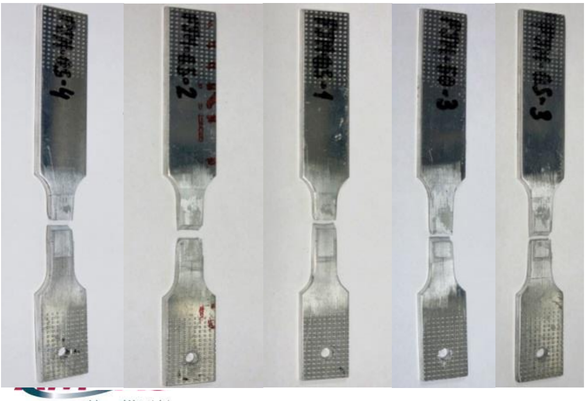
- Experimental Testing – Material Characterization
  - Test Procedure
    - ✓ Method – In-plane Tension
    - ✓ Rate – Quasi-static (0.0008 in/s)
    - ✓ Mount Specimen, Set-up Laser Extensometer, Load until failure





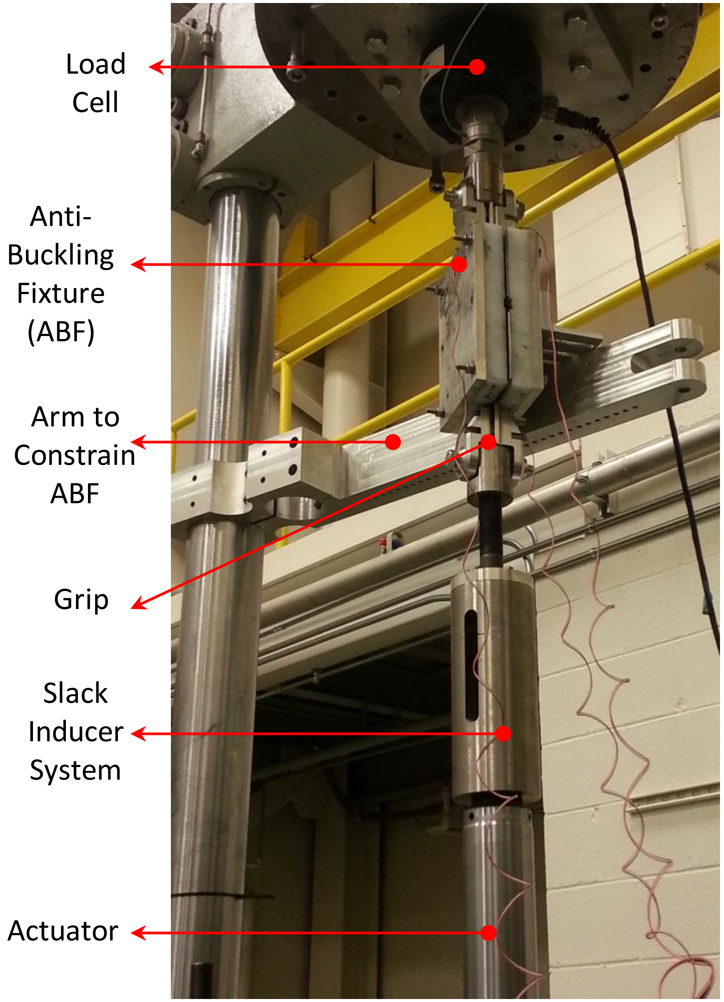
	Youngs Modulus (Strain Gage)	Yield Stress (Sgage)	Youngs Modulus (Ext.)	Yield Stress (Ext.)	Ultimate Stress (Ext.)	Failure Strain (Ext.)
	Mpa	Mpa	Mpa	Mpa	Mpa	Mm/mm
FJM_QS_1	69019.27	329.76	61347.23	334.00	464.17	0.2122
FJM_QS_2	68622.34	327.33	76493.22	328.11	461.33	0.2329
FJM_QS_3	72866.73	331.97	55837.36	333.57	464.87	0.2066
FJM_QS_4	69010.77	331.29	50307.26	335.98	464.42	0.2255
FJM_50_3_QS	69513.27	331.58	58026.73	338.50	466.68	0.2298
Average	**69806.48**	**330.38**	**60402.36**	**334.03**	**464.29**	**0.22**
Standard Deviation	1739.7	1.9	9851.4	3.8	1.9	0.0
Coefficient of Variation (%)	2.5	0.6	16.3	1.2	0.4	5.2

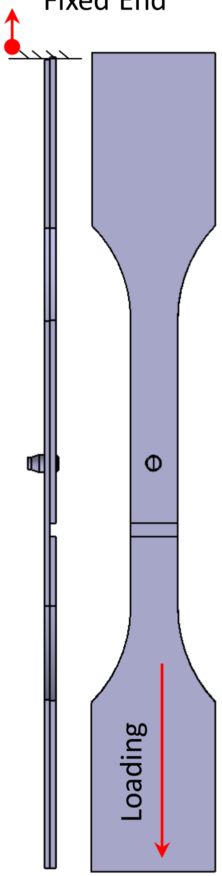
Note: Ext. - Laser Extensometer

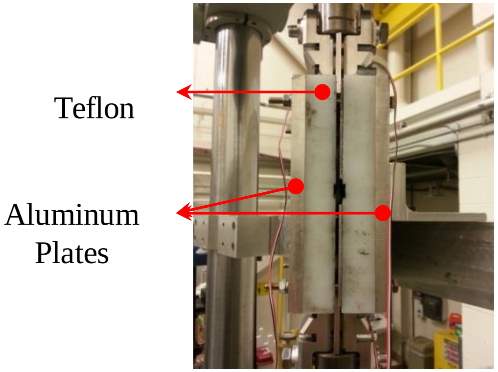


Testing – Load Transfer Tests – Setup

- Experimental Testing – Load Transfer Tests
  - Test Article
    - ✓ One-Half Dog Bone Specimen
    - ✓ Hi-Lok Fastener - HL18 Pin/ HL70 Nut
  - Test Apparatus
    - ✓ MTS High Stroke Servo-Hydraulic Machine
    - ✓ Slack Inducer System
    - ✓ Anti-Buckling Fixture (ABF)
    - ✓ Arm to constrain ABF
  - Data Acquisition
    - ✓ 11 Kip Strain Gage Based LoadCell
    - ✓ 3 Axial Strain Gages – CAE-06-250UN-350







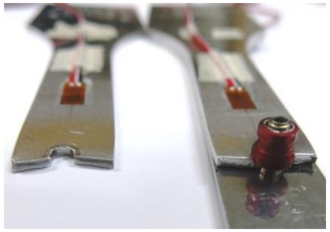
CECAM

JAMS

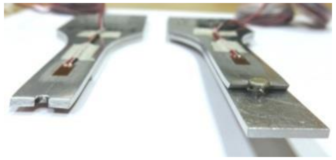
AMTAS

Testing – Load Transfer Tests - Results

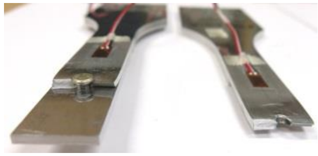
Test 3

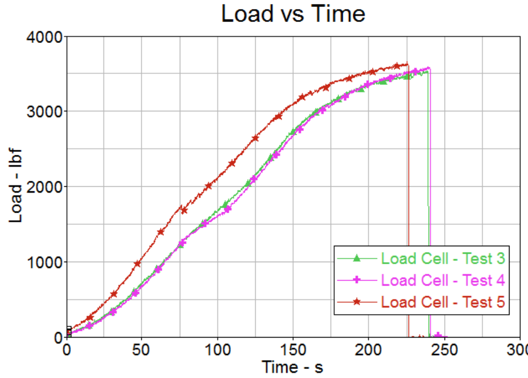


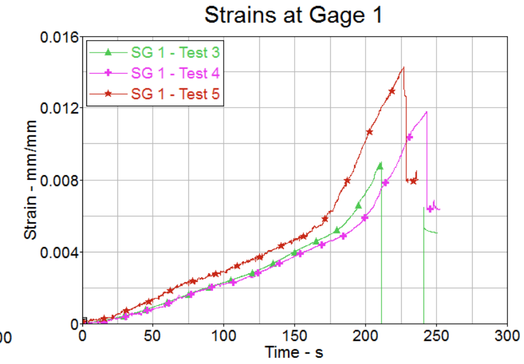
Test 4

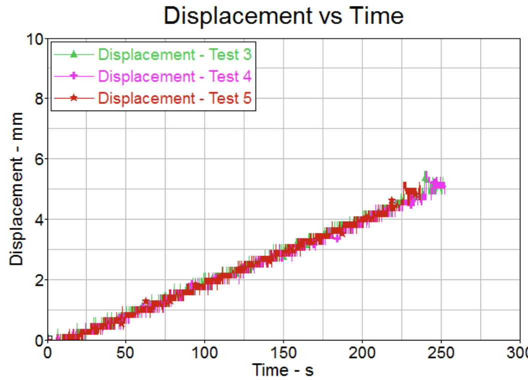


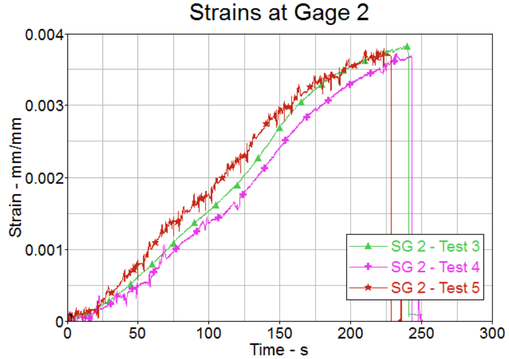
Test 5

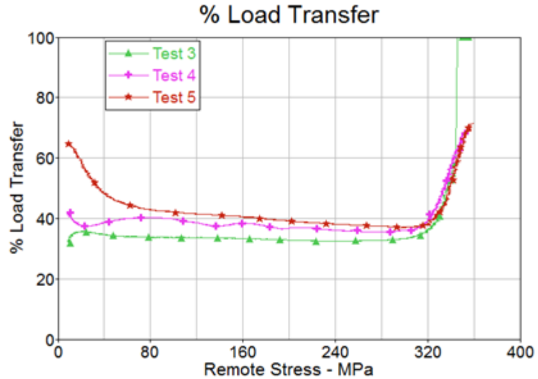


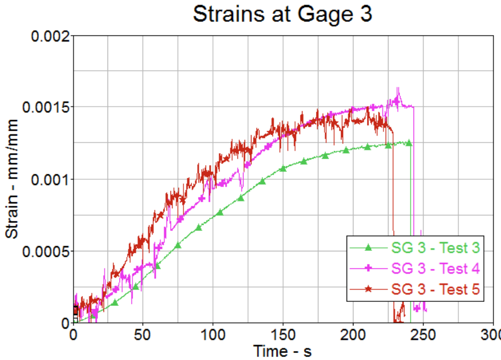


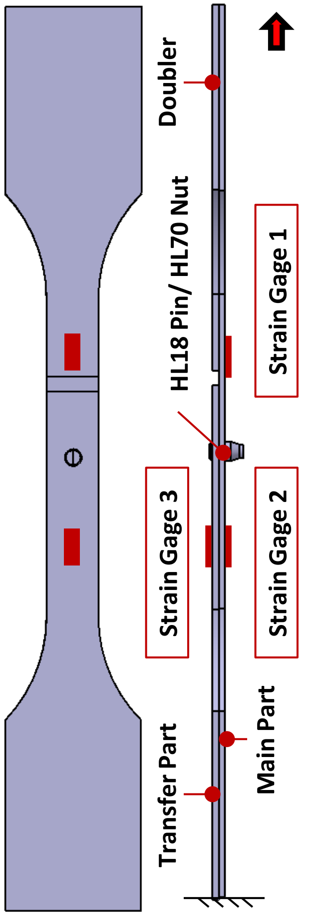




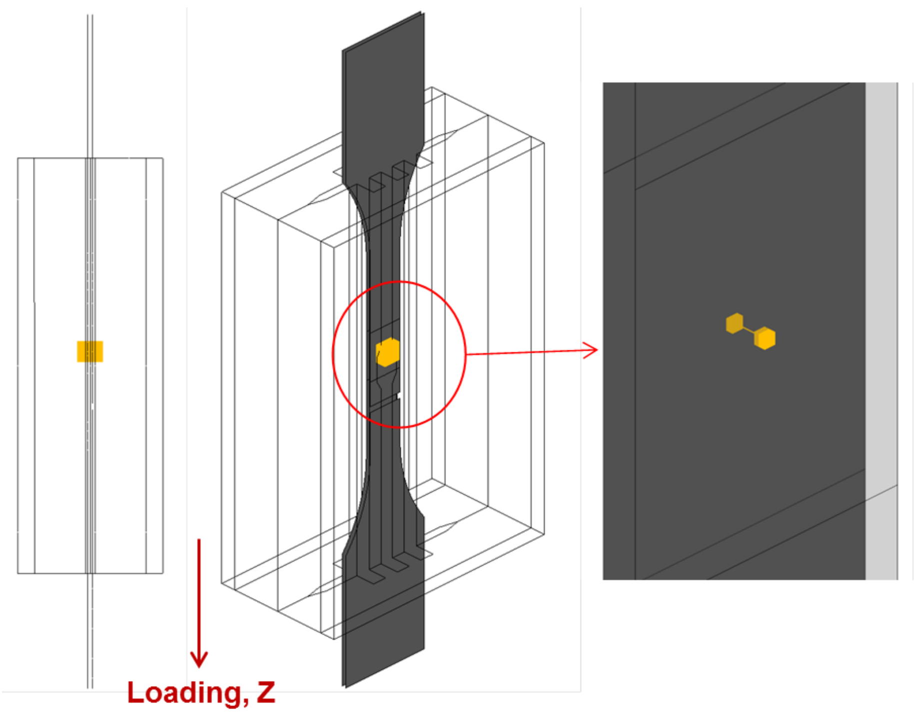


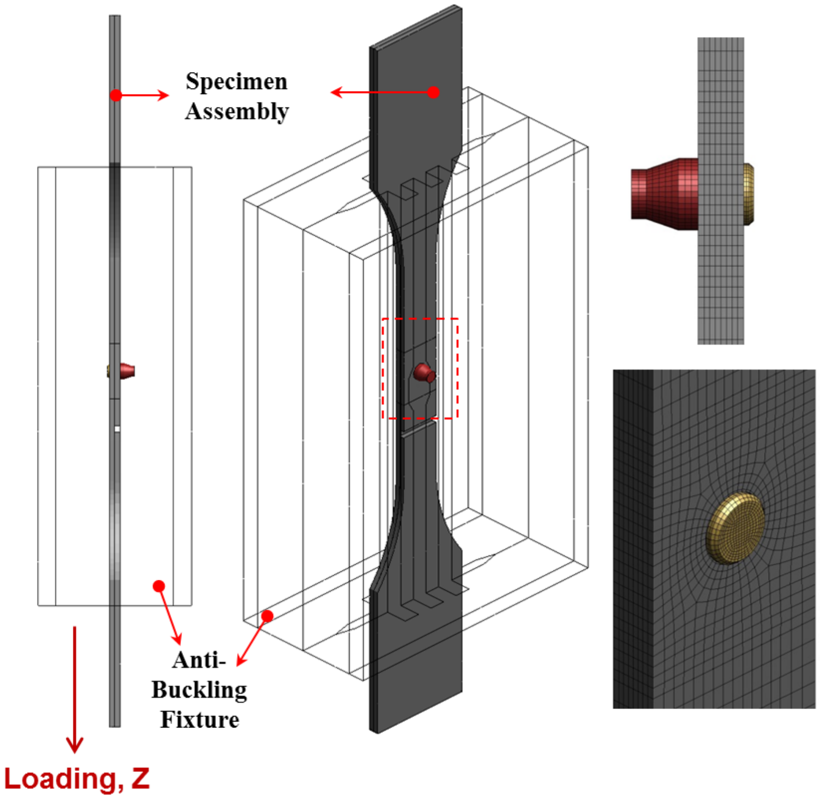




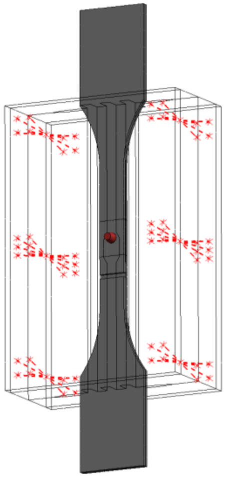


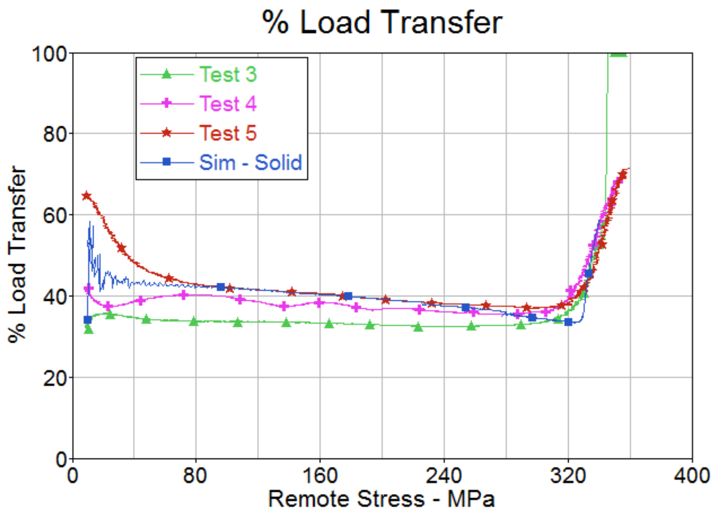
FE Model – Solid and Spot-weld Beam Models



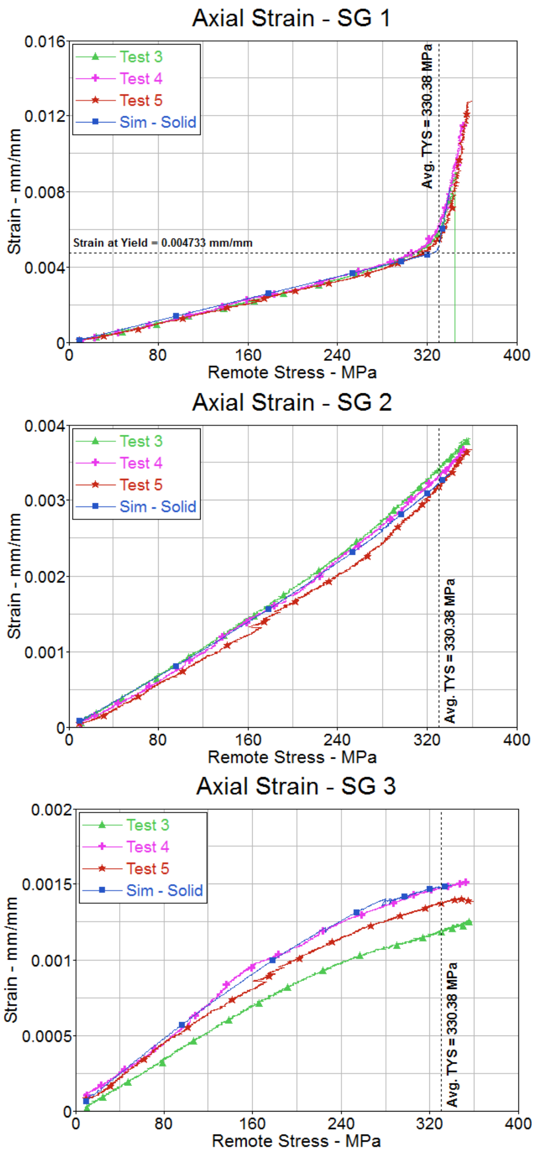


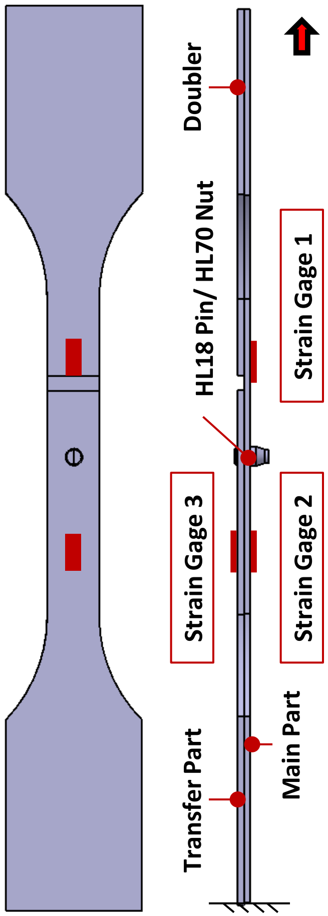
FE Model – Validation of Modeling Methods



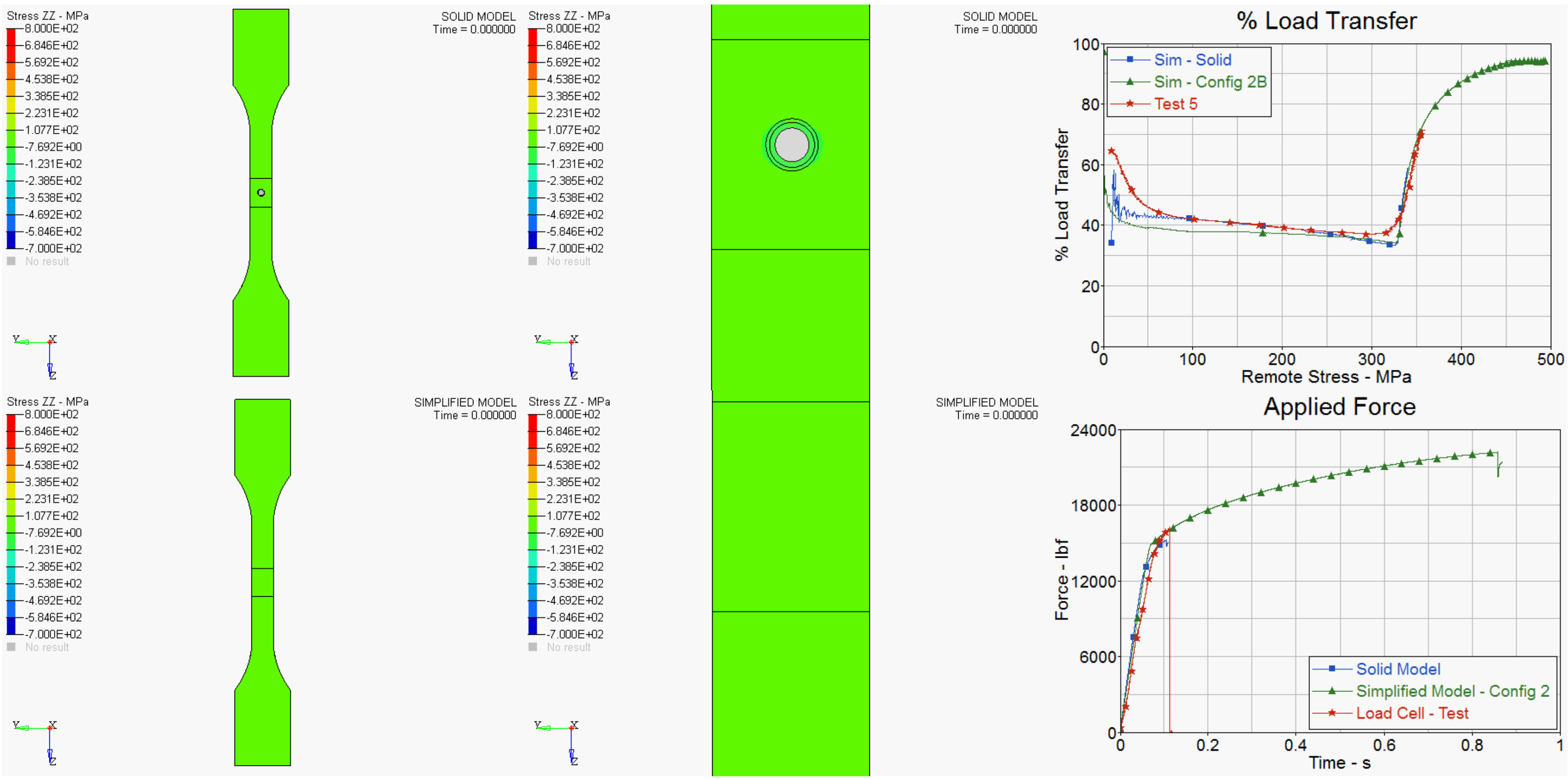


$$\% \, Load\, Transfer = \left[1 - \left(\frac{SG\,2}{SG\,1}\right)\right] \times 100\%$$



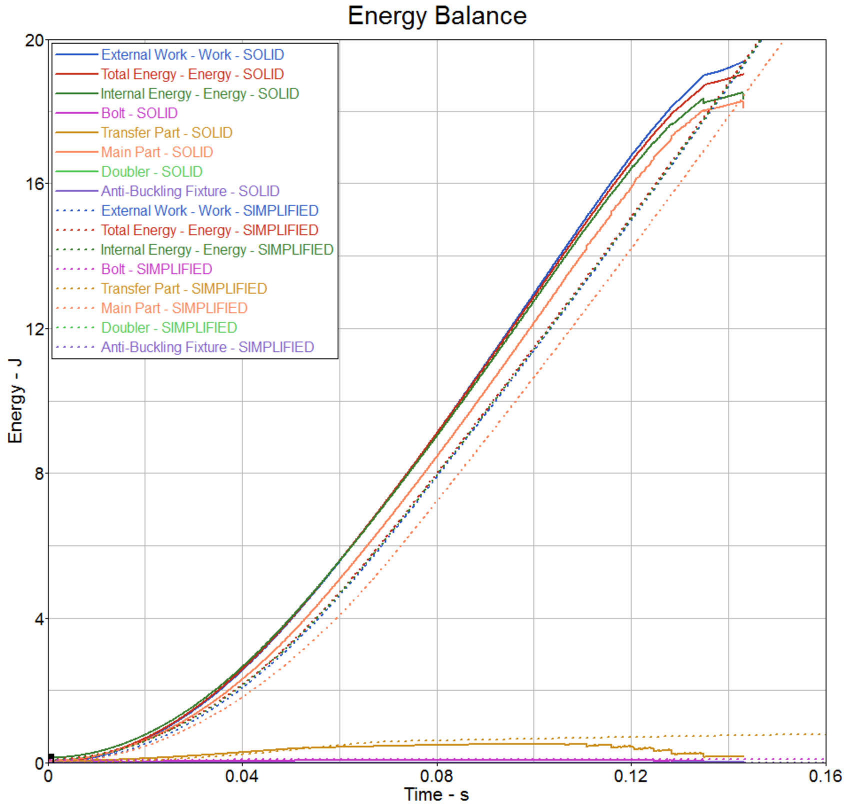


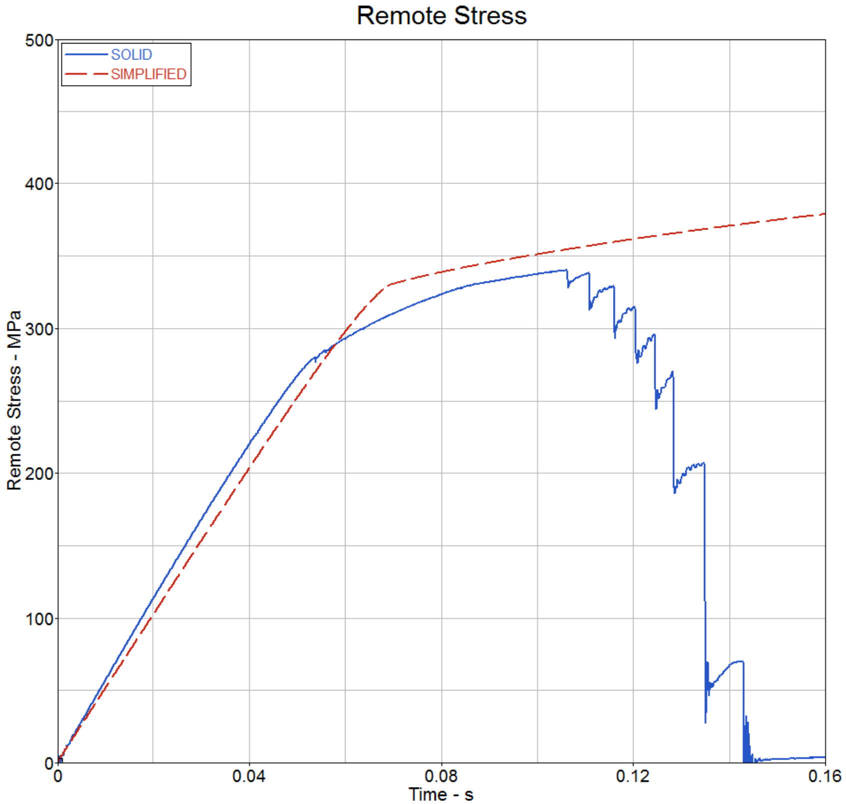
Solid vs. Beam Spot Weld



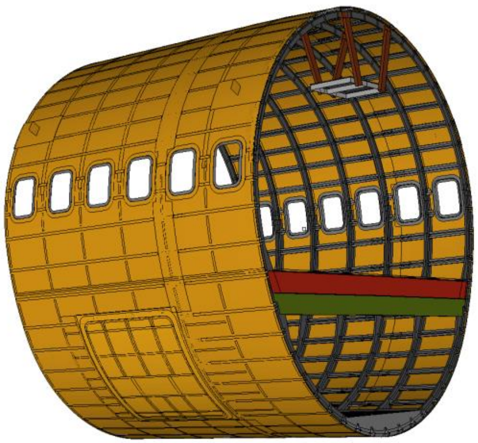
Single Point Load Transfer – Energy Balance

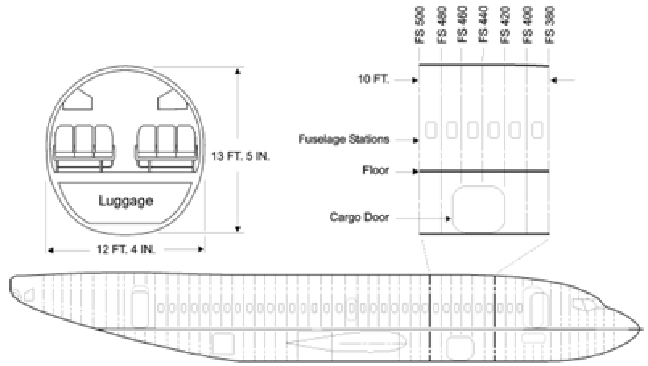
- **Solid vs. Simplified**





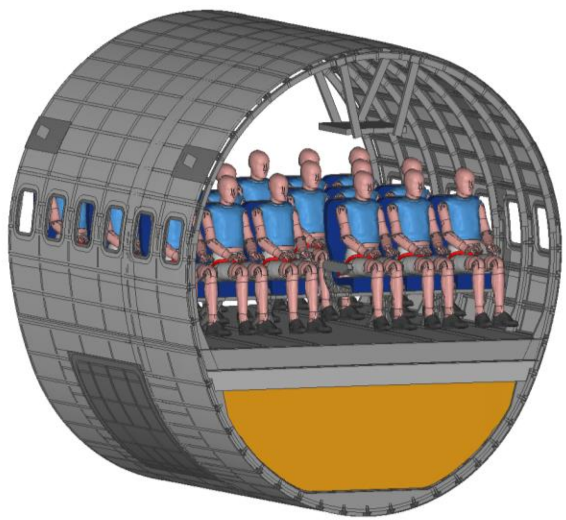
Section Level – Drop Test Model Update

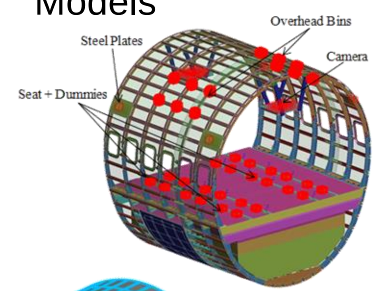


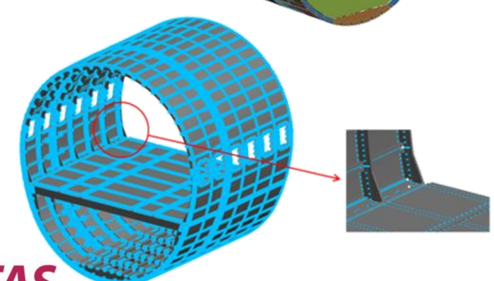


Model Updates:

- **Coupon Level R&D:** Updated Material Models for Structural Members
- **Joint Level R&D:** Updated Joint Types, Contacts, Friction and Material Type Definitions
- **Updated vATD** Occupant and Seat Models





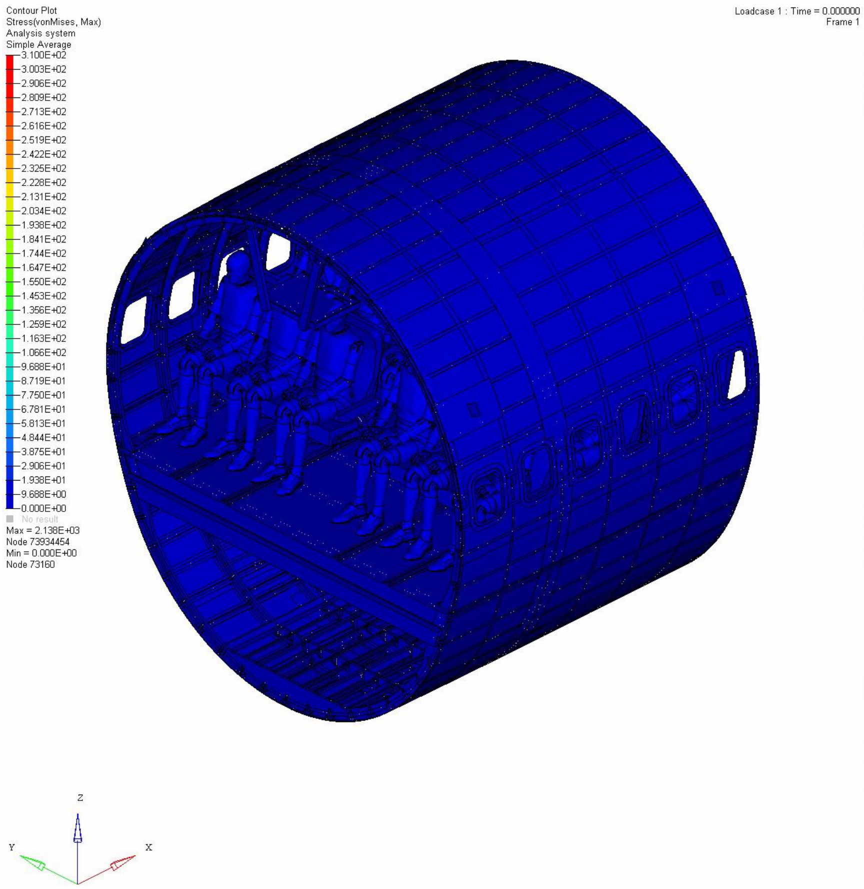


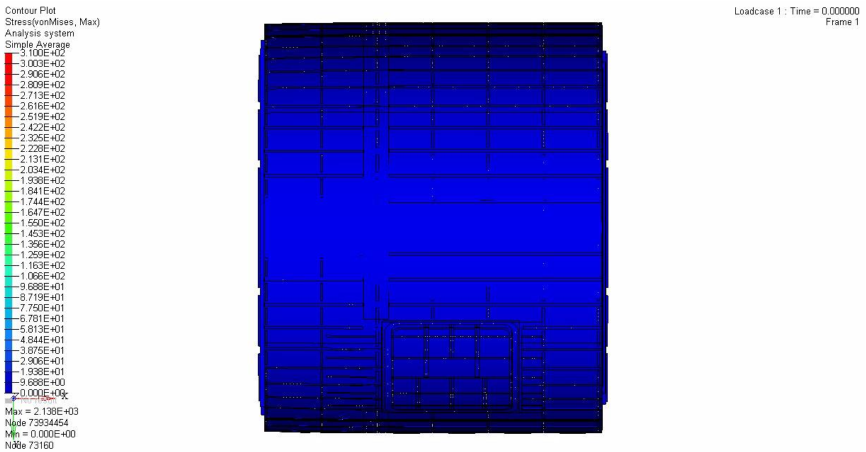
CECAM

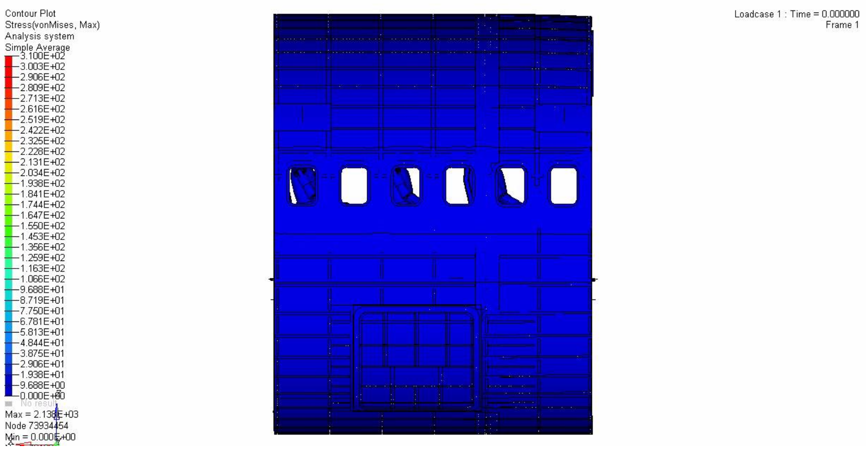
JAMS
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

Section Level – Kinematics and Stress Distribution



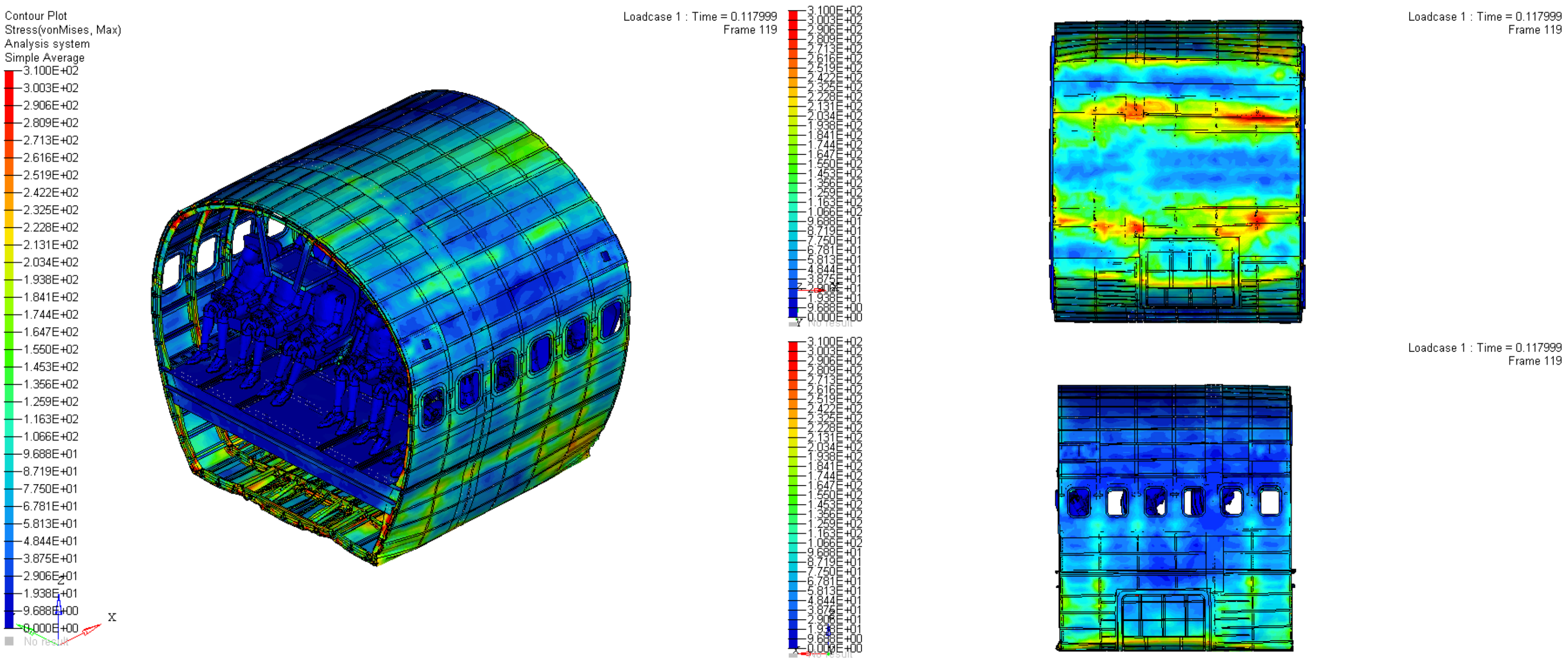




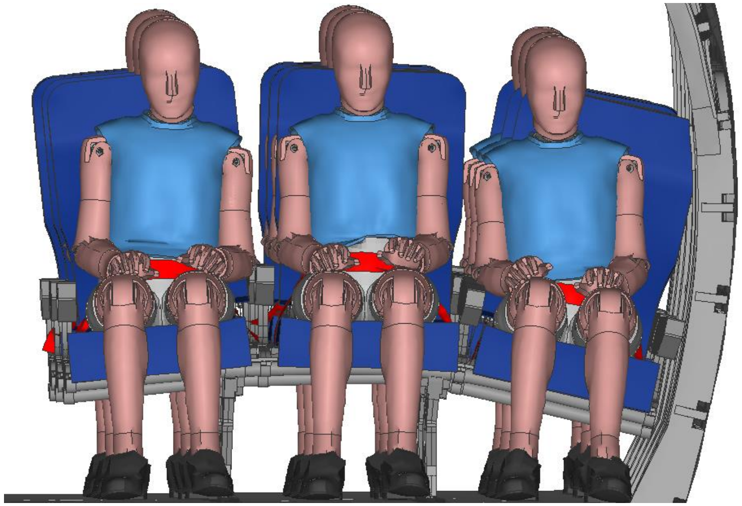
CECAM
JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE
A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

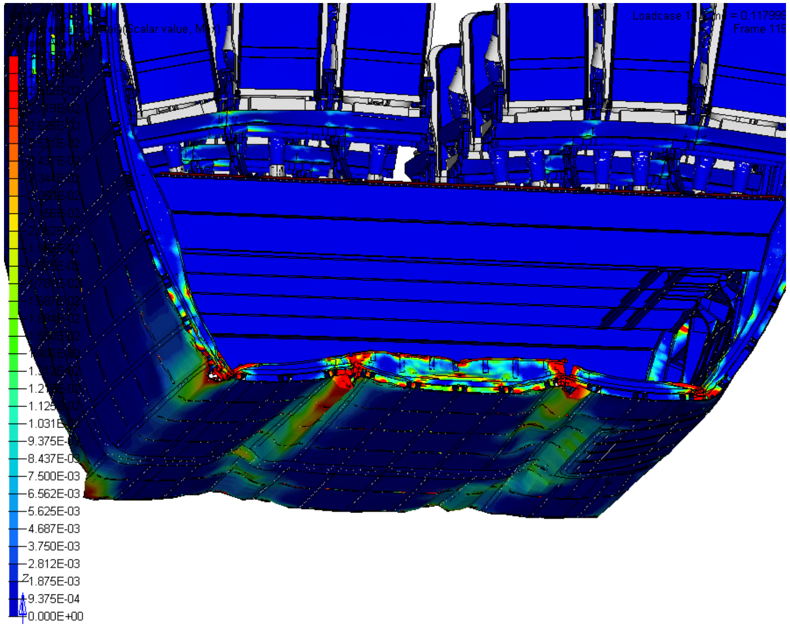
Section Level –Stress Distribution (MPa)

- Time Max. Compression – 117 ms
- Yield Stress 310 Mpa

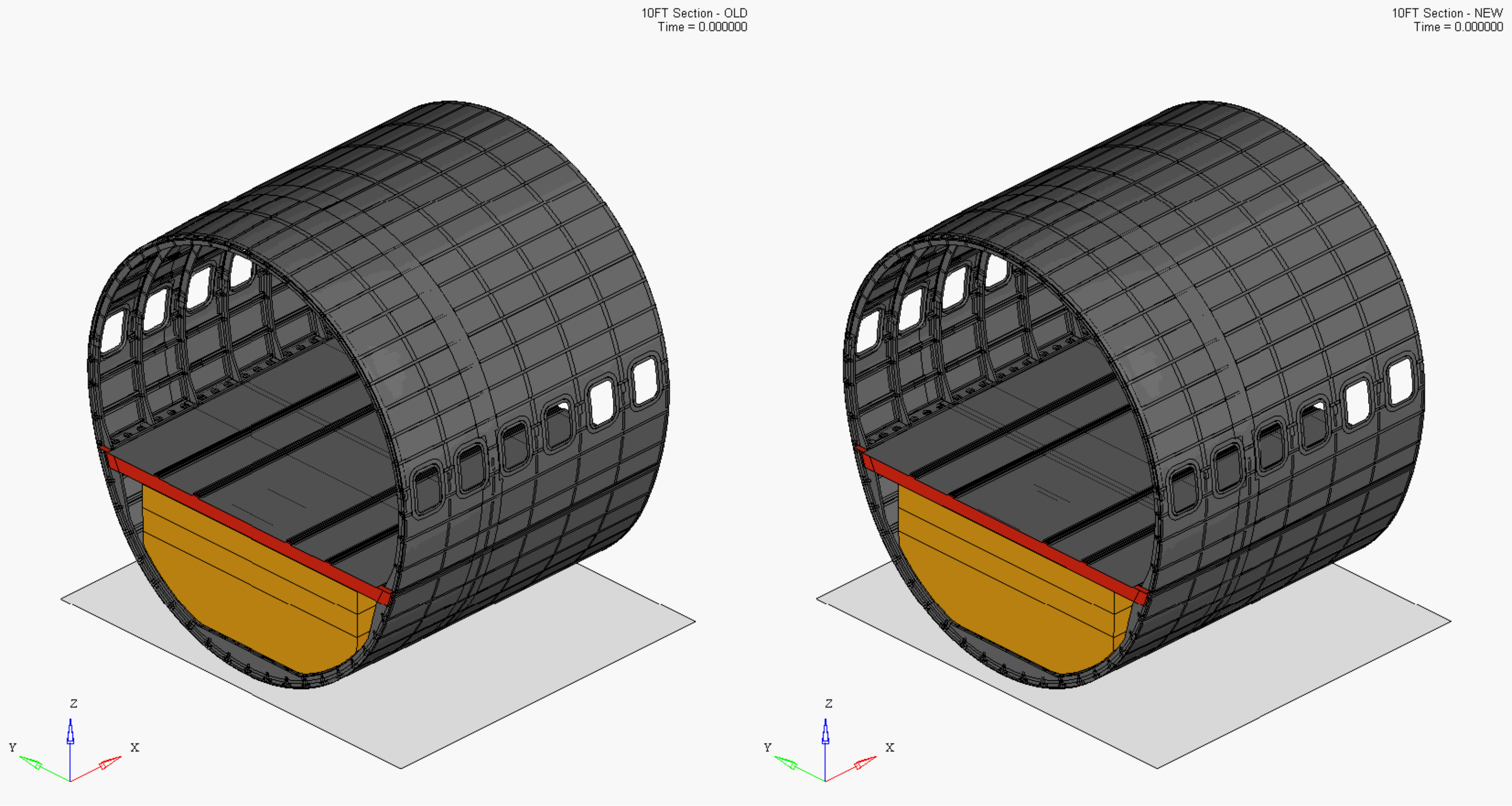


Effective Plastic Strain – Post Damage Eval





30 ft/s - Full Cargo Symmetric Configuration

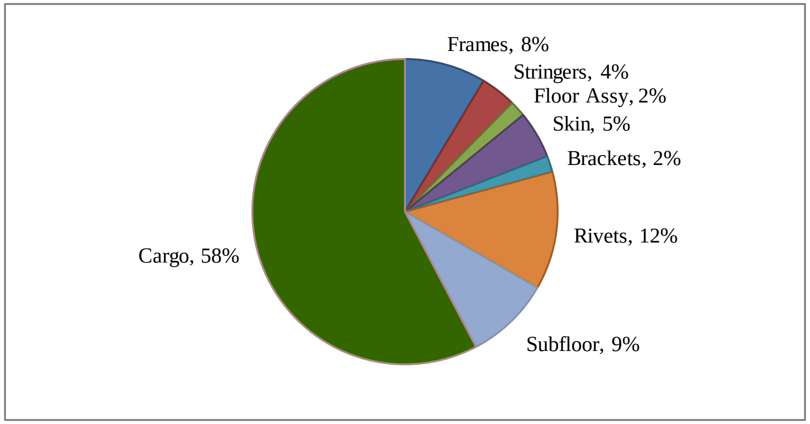


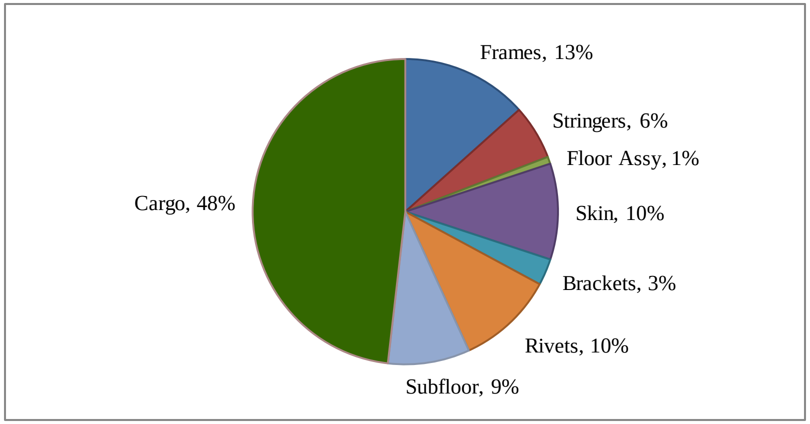
CECAM JAMS AMTAS

Cargo Configuration – Energy Distribution

Old Model | Updated Model

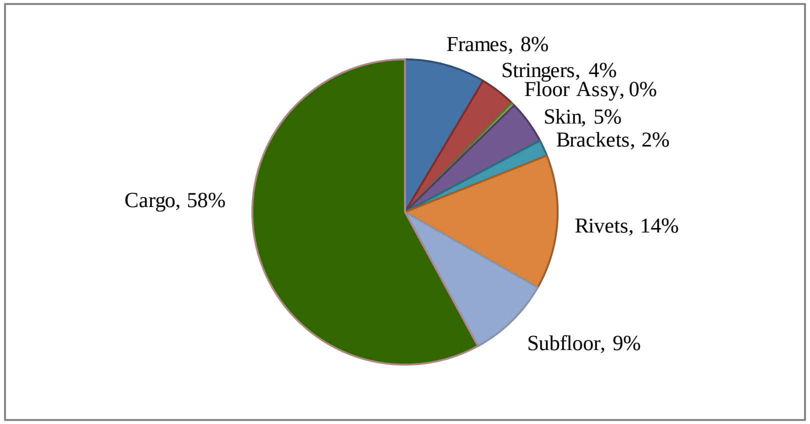
Time = 110ms

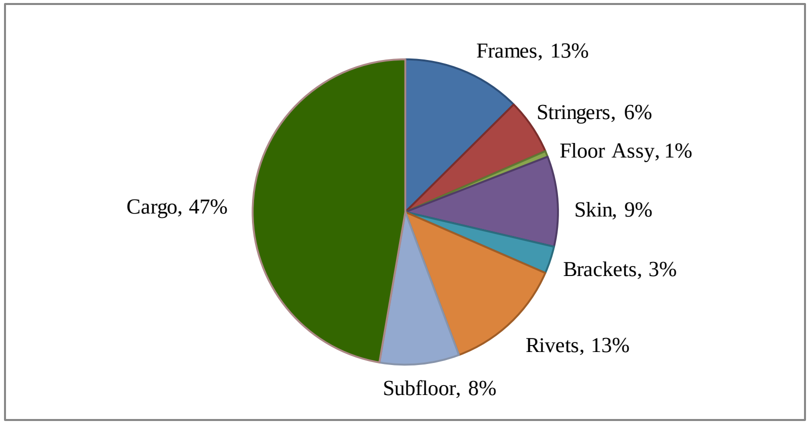




Time = 118ms

Time = 300ms

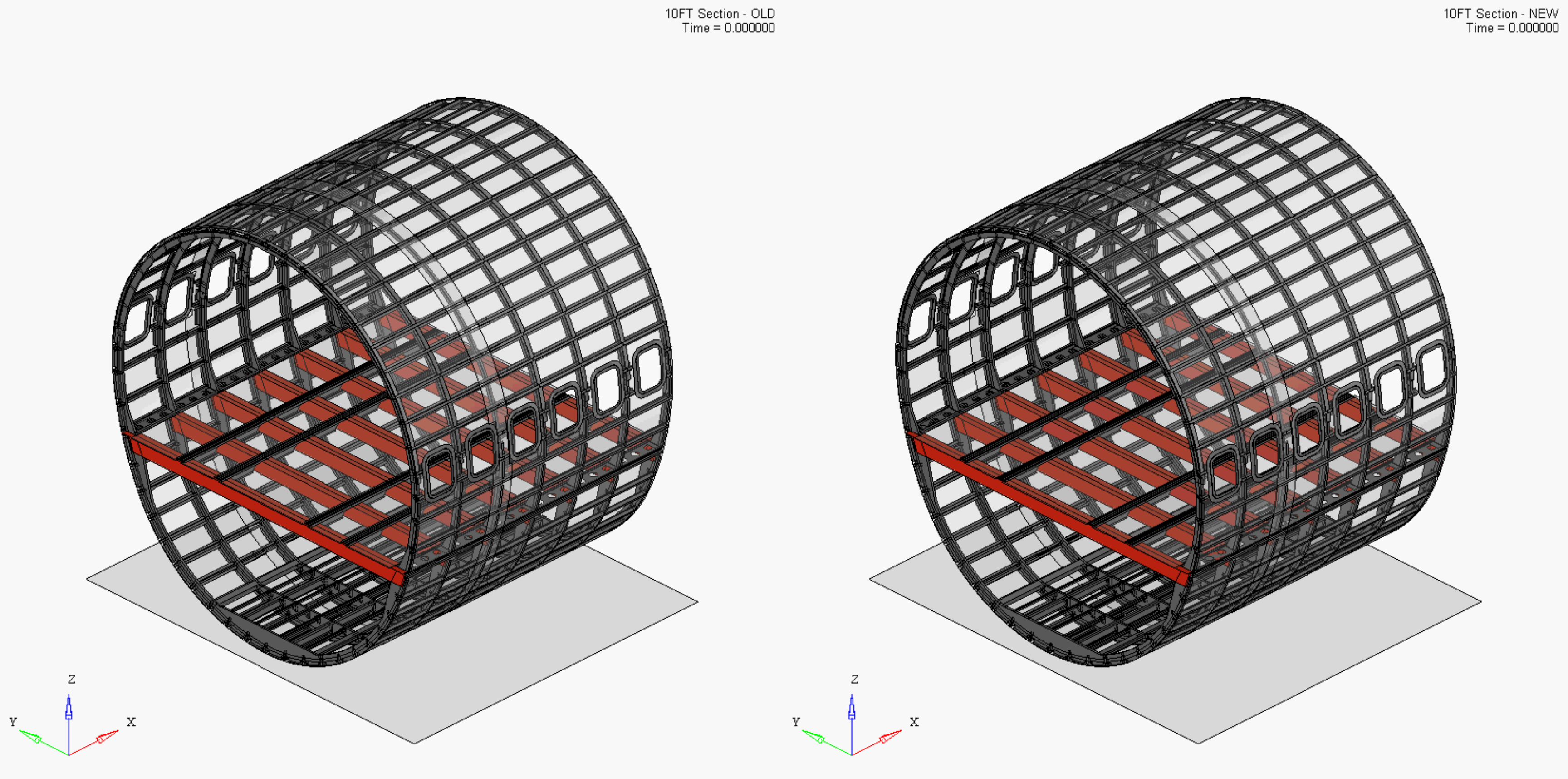




Time = 300ms

Old Model | Updated Model

30 ft/s - no Cargo Symmetric Configuration



CECAM

JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

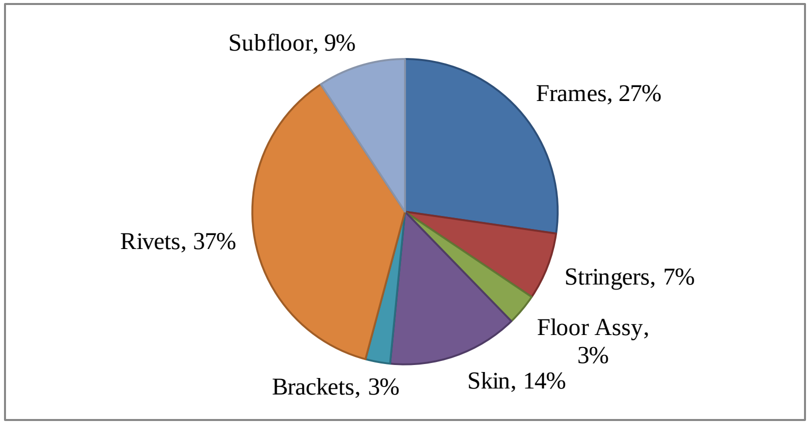
A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

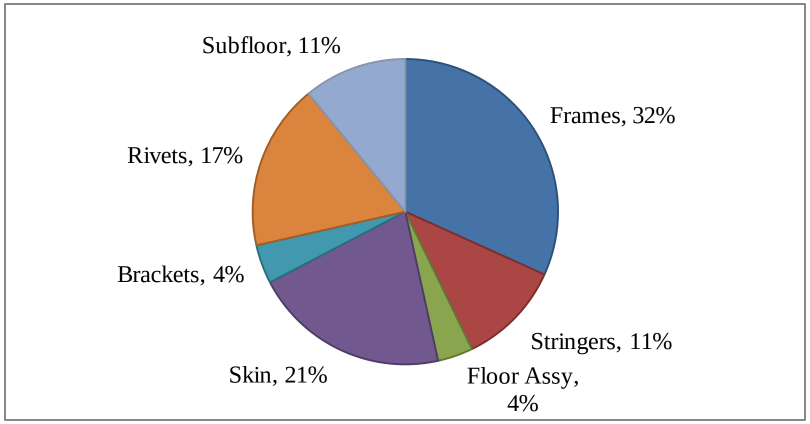
30 ft/s - no Cargo Configuration

Old Model

Updated Model

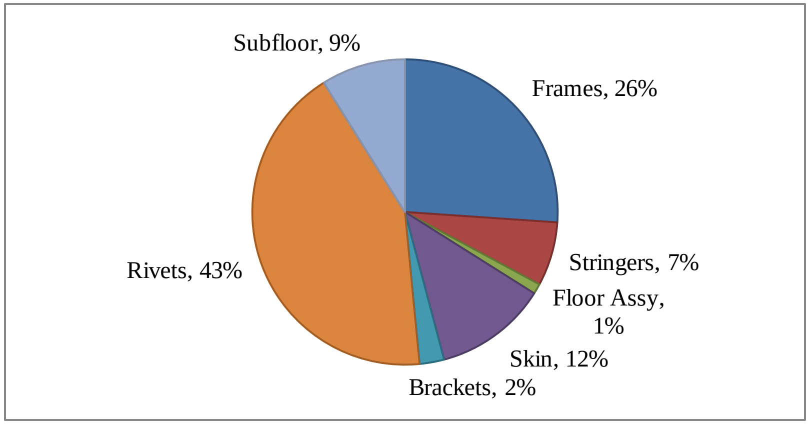
Time = 157ms

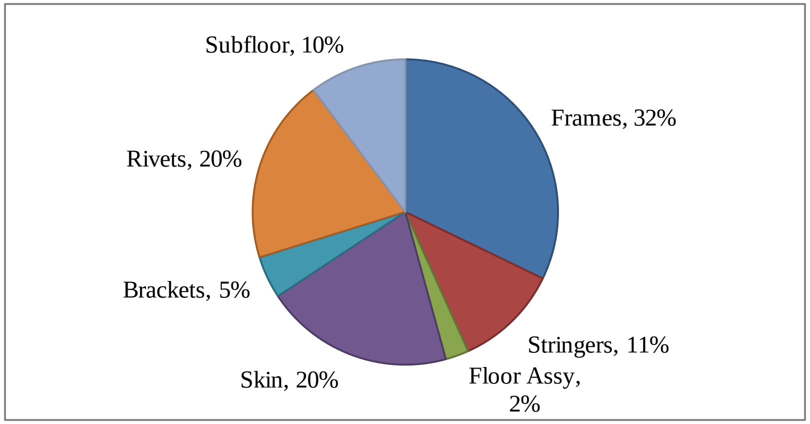




Time = 157ms

Time = 300ms





Time = 300ms

Old Model

Updated Model

JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

Modeling Fastener Joints – Observations

- Solid Model
  - Shows good correlation to Test Data
- Simplified Techniques
  - Rigid Body Element (RBE) – Load Transfer shows good correlation to Solid Model
  - Mesh Independent Spotweld Beam – Some configurations show good correlation of Load transfer to Solid Model while others deviate. The location of the beam model with respect to element is difficult to control in large models where parts are meshed independently
  - Mesh Independent Spotweld Beam with Patch - Some configurations show good correlation of Load transfer to Solid Model while others deviate
  - Note that although the load transfer may agree with the solid model, for some of the simplified techniques the absence of fastener hole means that Stress Concentrations around hole are not present. This alters the stress distribution and profile of the joint and will also affect the failure mode
  - It was also noted that Simplified techniques failed at different locations (not necessarily in the vicinity of the hole) and at a later time (since no hole allows more load to be transferred)
- Preload
  - Solid Model – Shows 2.5% Drop in load transfer with no preload
  - Beam Model – Shows no drop in load transfer

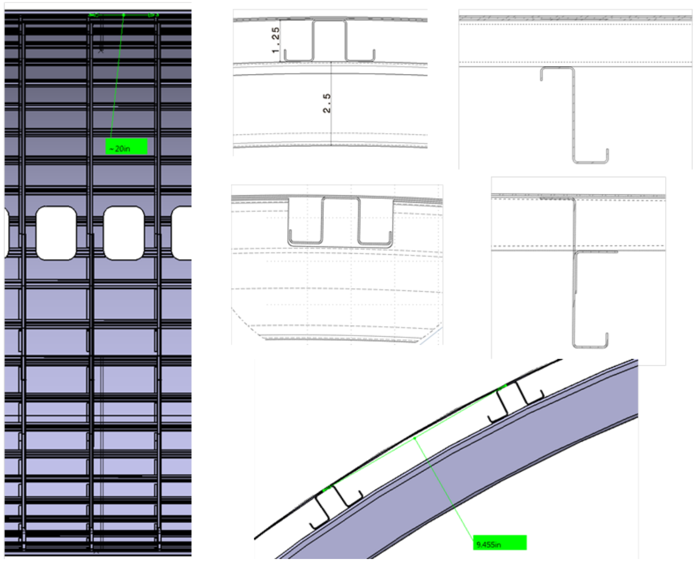
Accident Reconstruction 737 Flight TK 1951

Full Scale Structural Evaluation

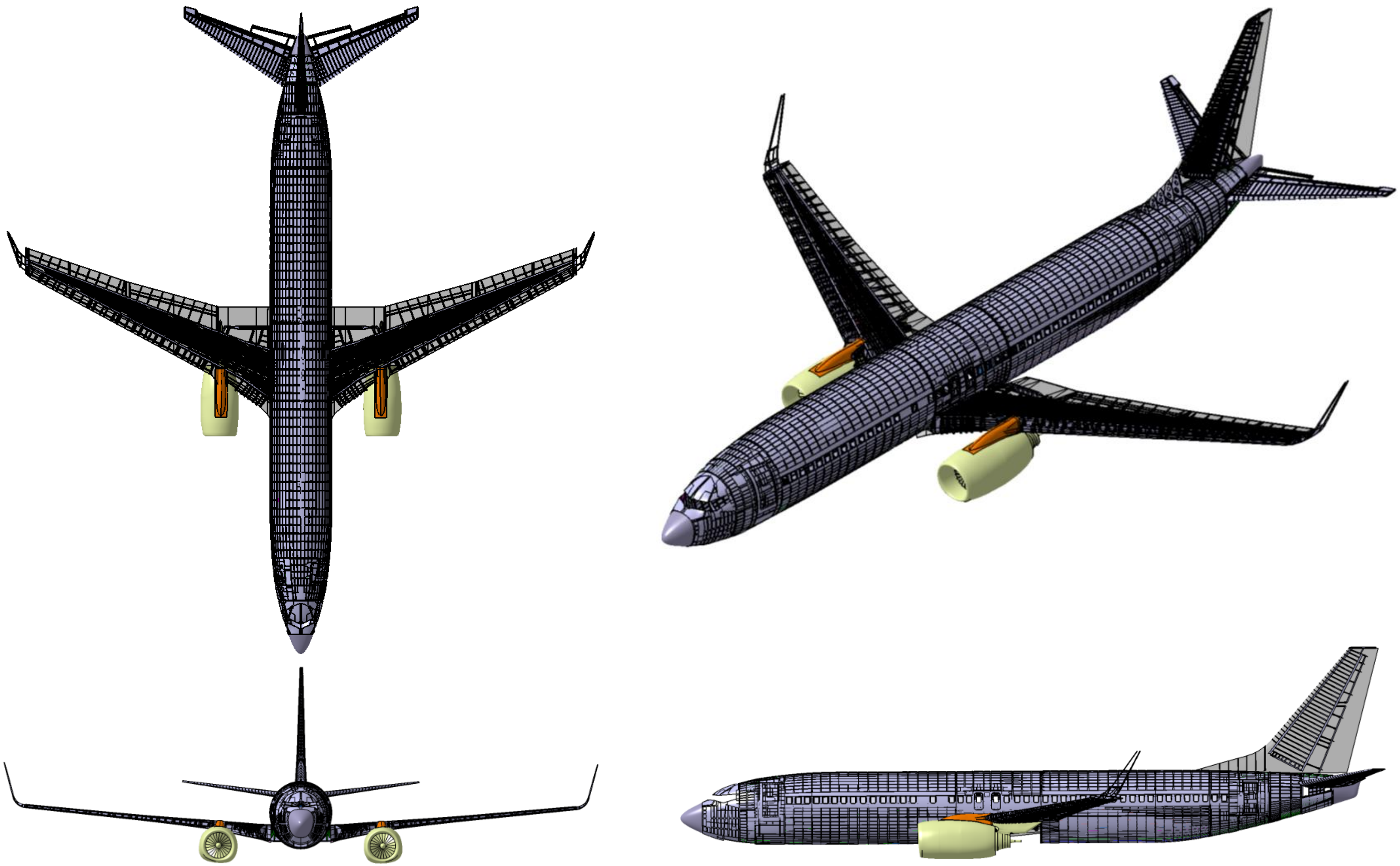
JAMS 2015 Technical Review
April 1, 2015

Accident Reconstruction 737 Flight TK 1951

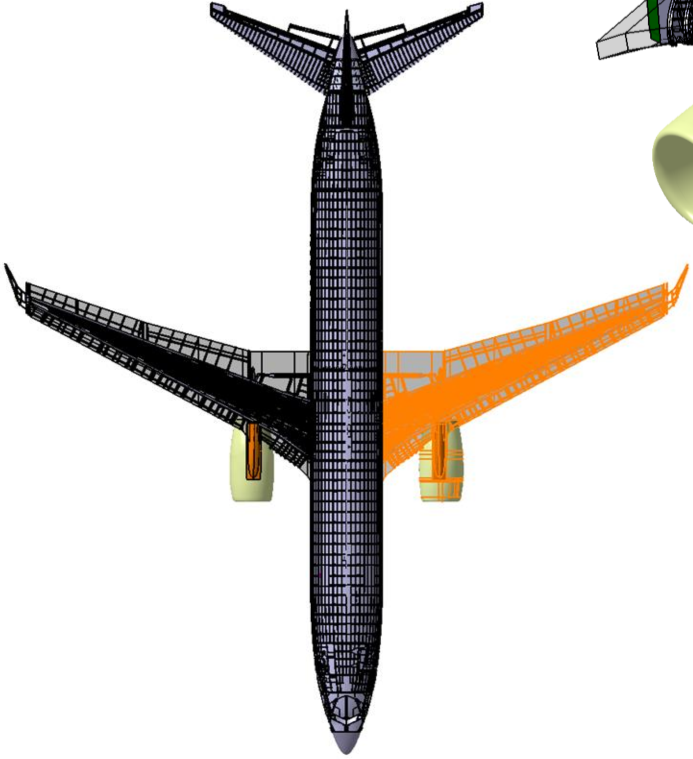
- Full Scale Structural Evaluation
  - Accident Reconstruction
    - Validate the full aircraft model response with the data available from the Turkish Airlines Flight that crashed during landing to Amsterdam Schiphol Airport, Netherlands, on February 25th, 2009
  - Structural Evaluation
    - Define a new CAD Model of Narrow Body - 800 configuration to represent as close as possible the actual geometry
    - Pending Work
      - Interface between the engine
      - Wing structure
      - Exit doors structure
      - Supporting structure for the landing gear system
    - Soil Model Validation and Evaluation - complete
  - V&V Accident Dataset:
    - Pending meeting with FAA, EASA, and Dutch Authorities after legal issues are clear

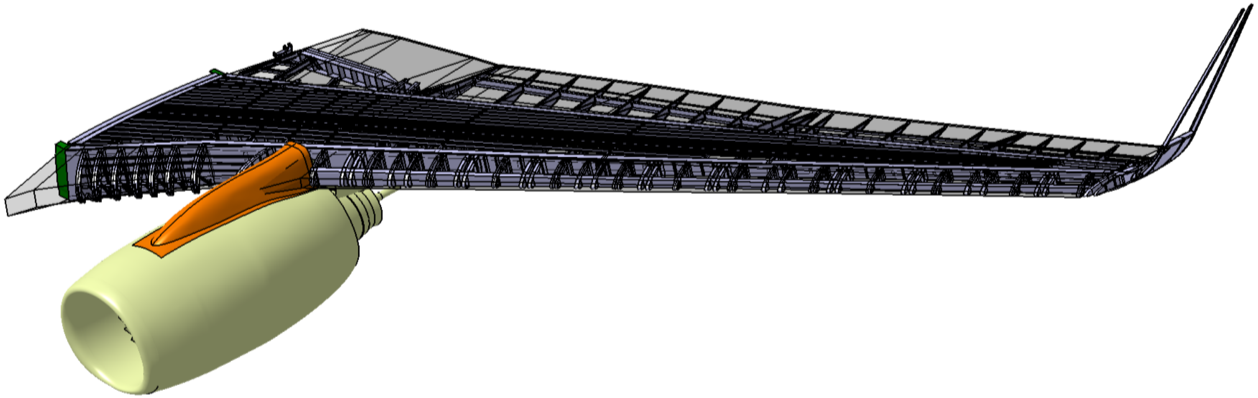


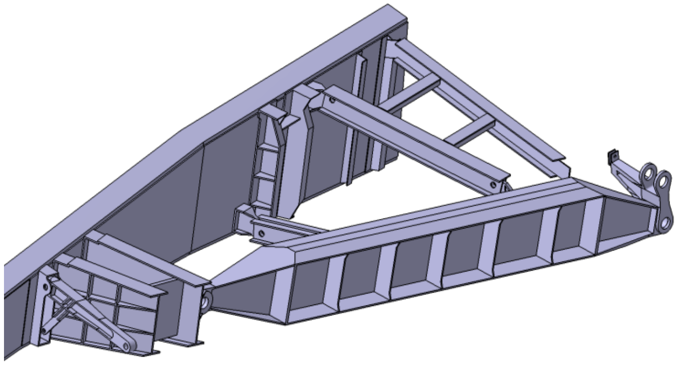
CAD Model Definition



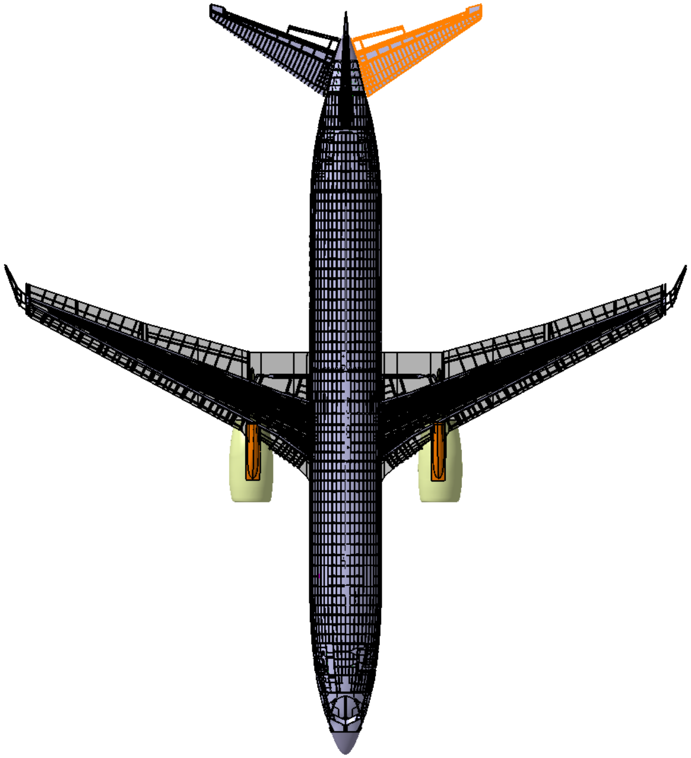
Wing- Trailing Edge Fittings

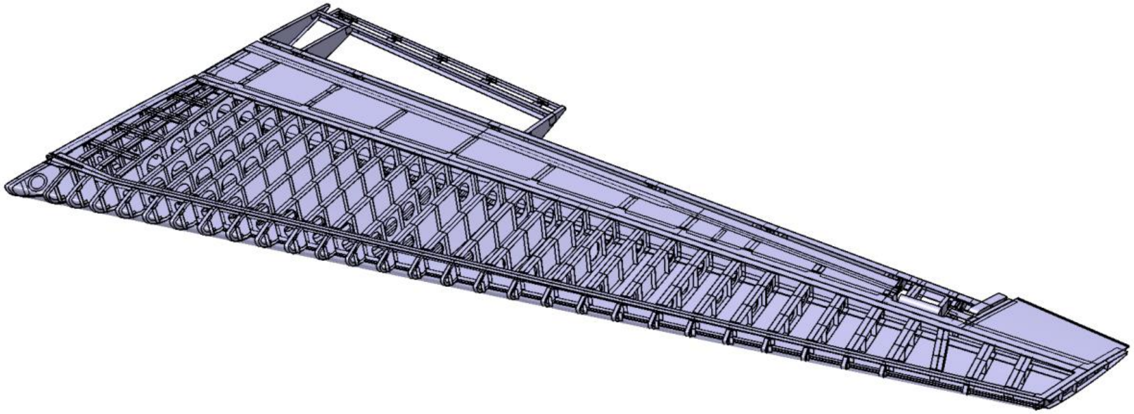


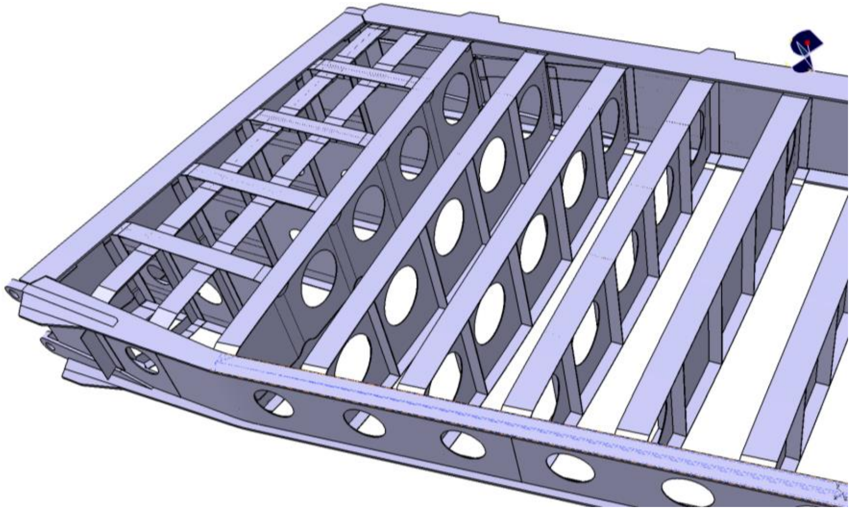




Horizontal Tail- Front Spar w/ Ribs

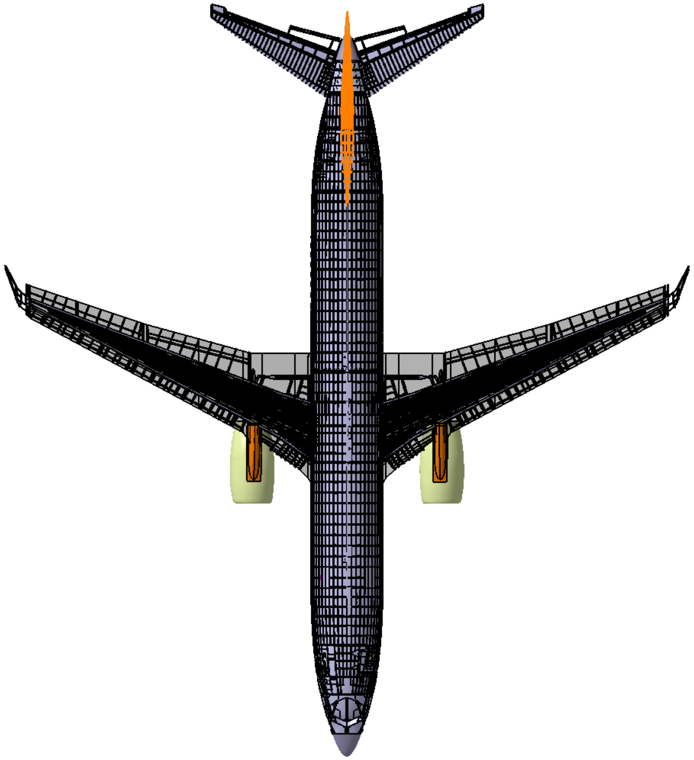


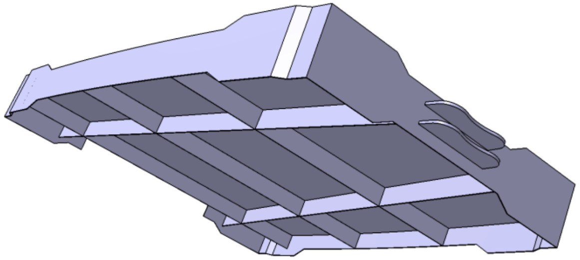




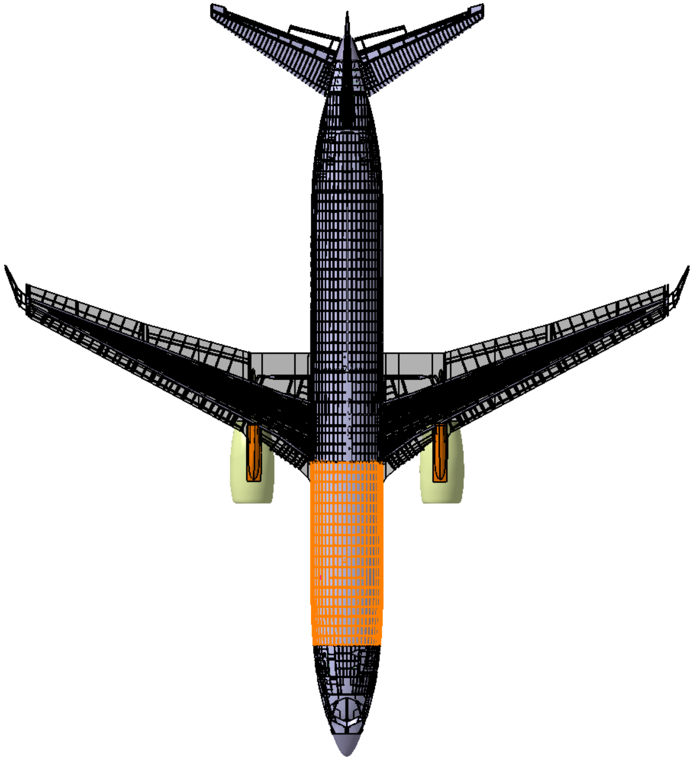
CECAM JAMS AMTAS

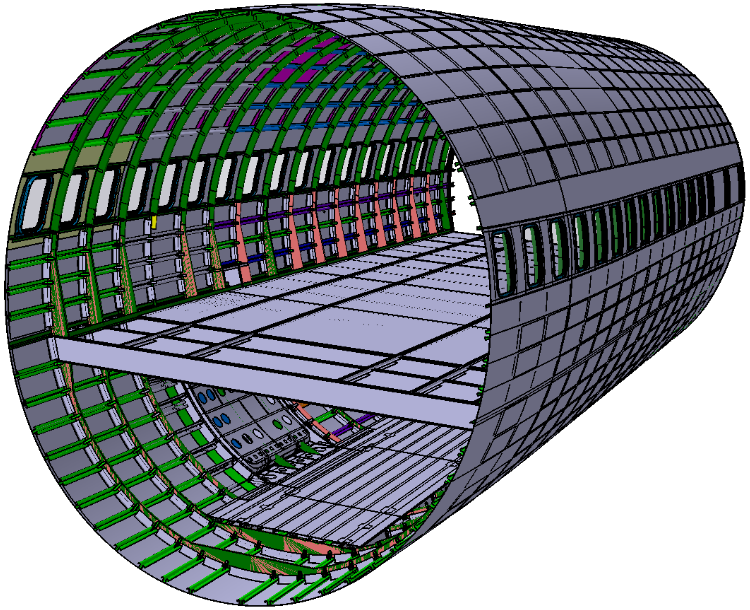
Vertical Tail- Rudder Hinge Fitting

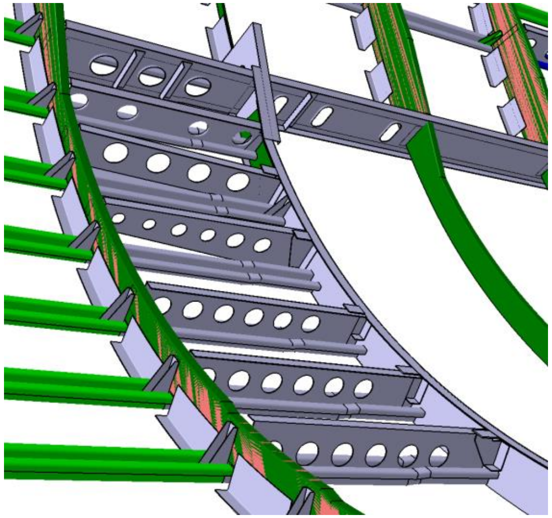




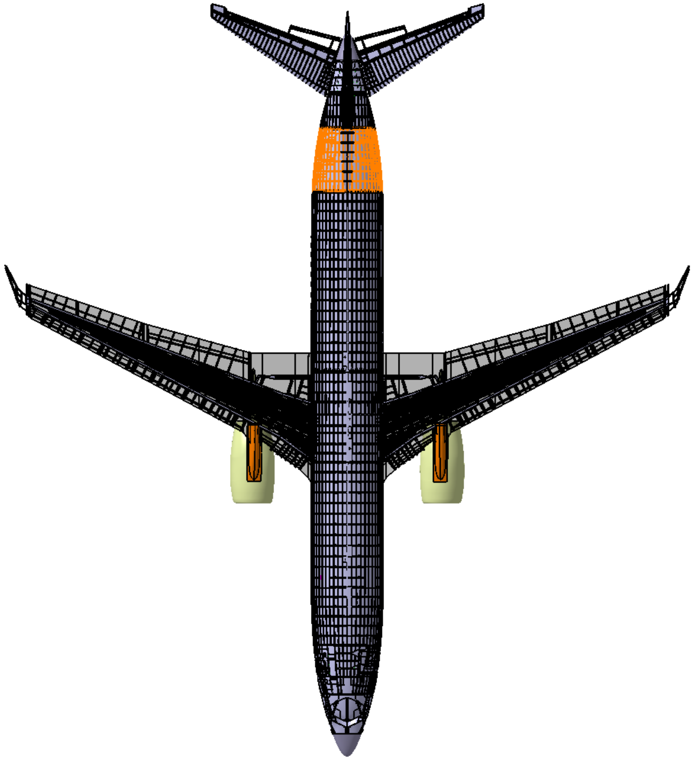
SEC 43- Door Surround Structure

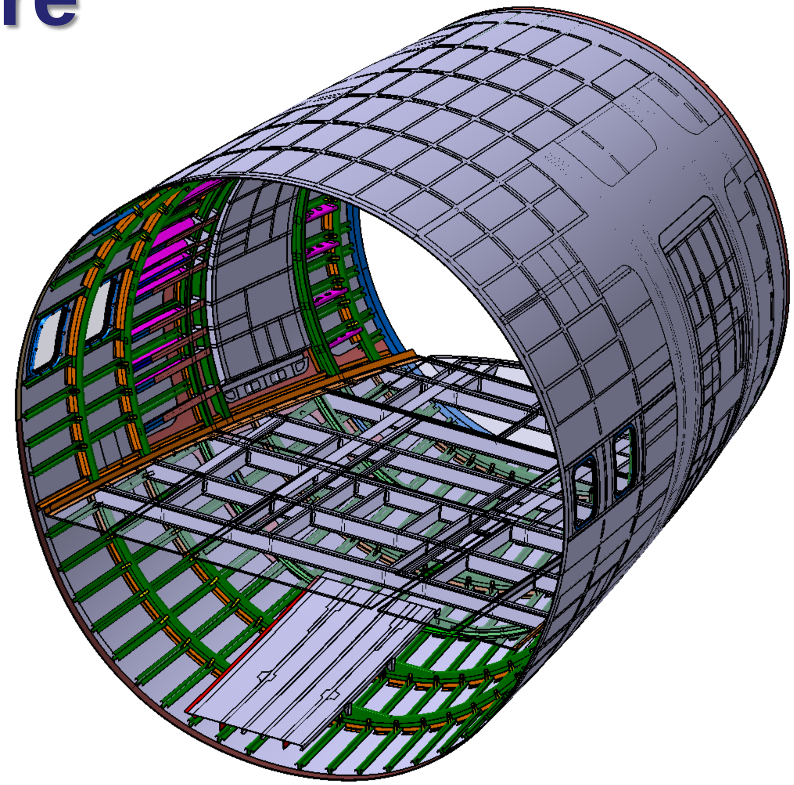


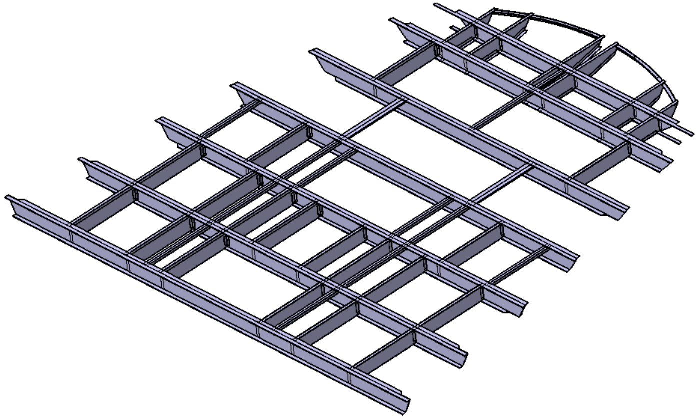




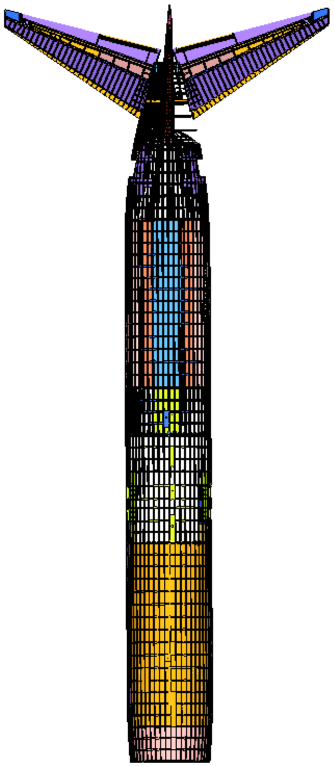
SEC 47- Floor Structure

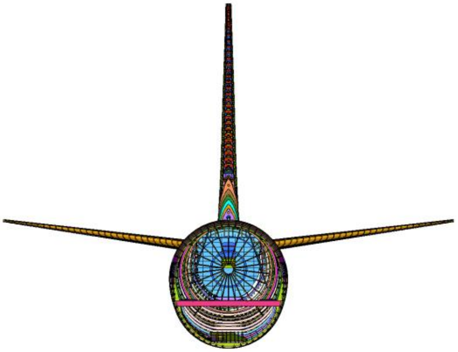


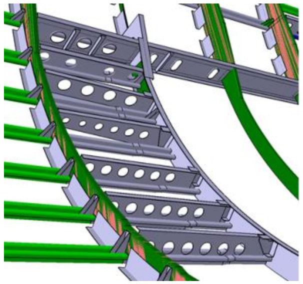


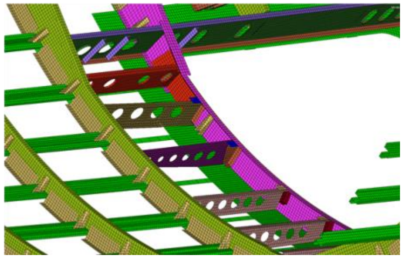


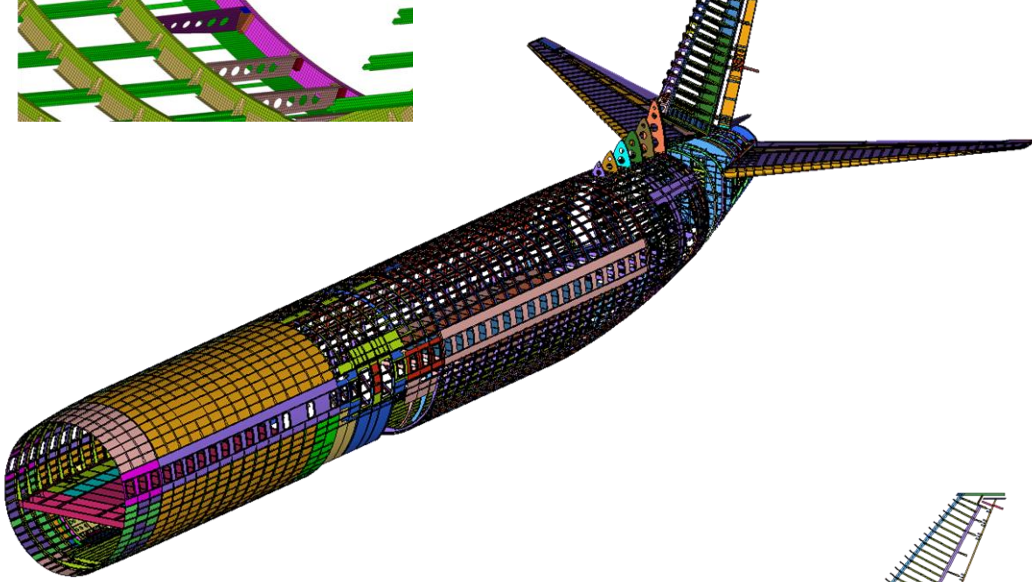
Meshing Process Status

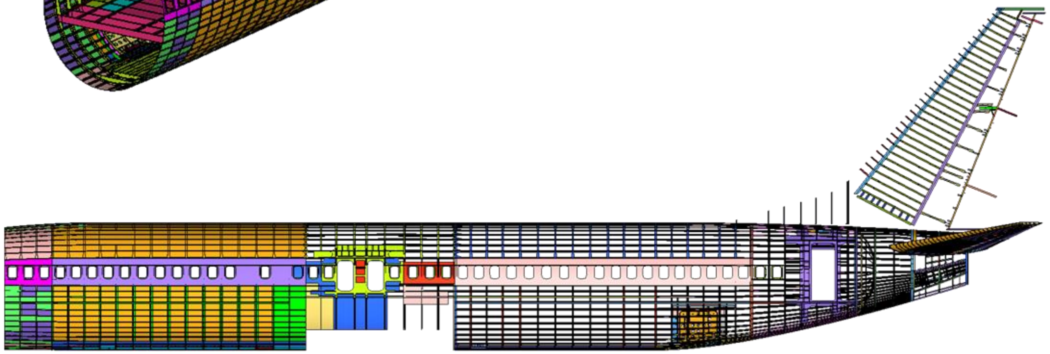












CECAM
center of excellence for composites and advanced materials

JAMS
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

High End Visualization Accident Data Methods

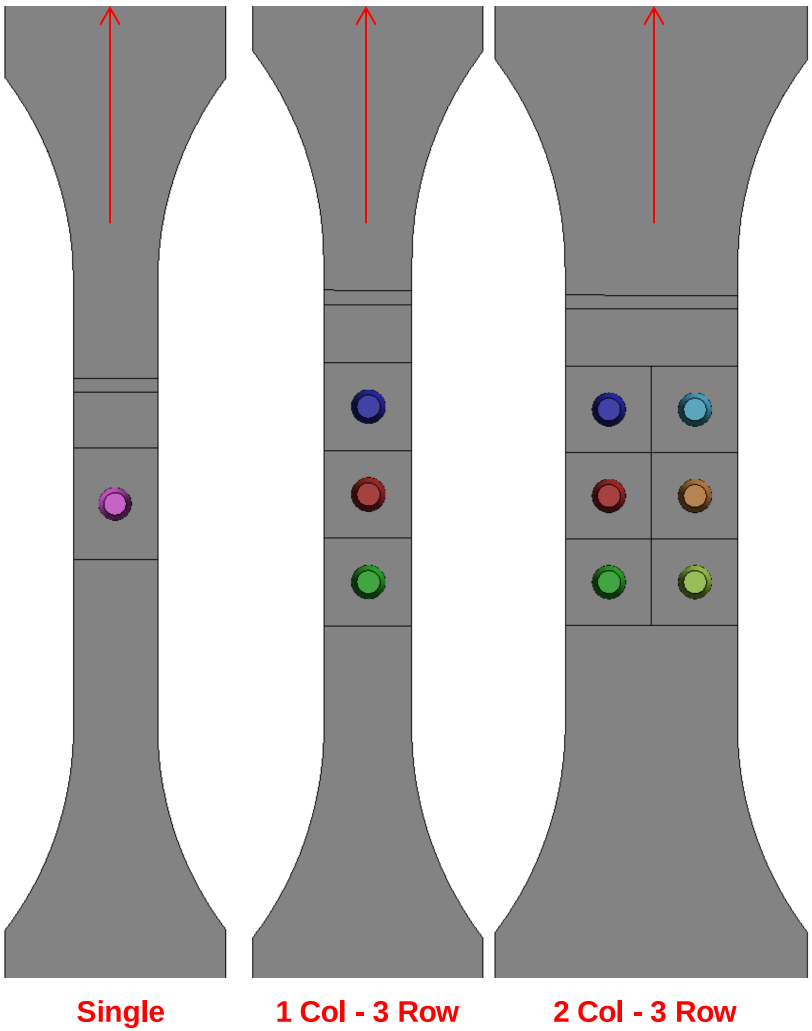
CECAM
center of excellence for composites and advanced materials

JAMS
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

Ongoing and Future Work

- Coupon Level WP 2.1: Complete. Report under FAA Review
- Round Robin WP2.2: Complete for Tension, data has been presented (ASC Paper 2014)
  - Future funding required for compression and shear
  - ASTM or SAE Standard should be developed
  - Report Ongoing – October 1st
- Joint WP4: Pending High Strain Rate Tests
  - Future Funding required for multiple joints
  - Future Funding required for composite joints
- Accident Reconstruction Phase IV: Ongoing
  - Present Preliminary results ASIDIC Conference 2015 November
  - Pending Accident Data Approval
- Future Work:
  - **Phase II WP 5. Section Level Experimental and Computational Best Practices:** The objective of this working package will be to summarize the numerical and experimental best practices developed in WP0 through WP in order to define a certification by analysis methodology that can be used the future by the aerospace industry.
  - **Phase V:** Design and evaluate an equivalent composite structure (Narrow Body Section)



2nd Aerospace Structural Impact Dynamics International Conference – Aeropolis, Seville, Spain, November 17-19th 2015

End of Presentation.

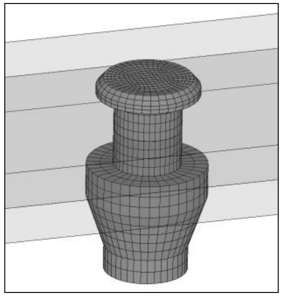
Thank you.

CECAM
center of excellence for composites and advanced materials

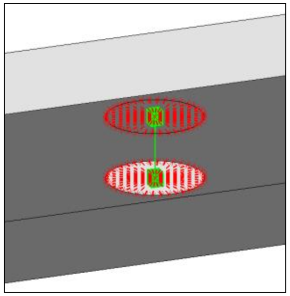
JAMS
JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

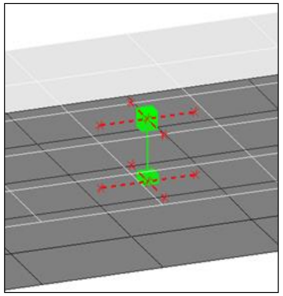
Appendix - Bolt Modeling Techniques



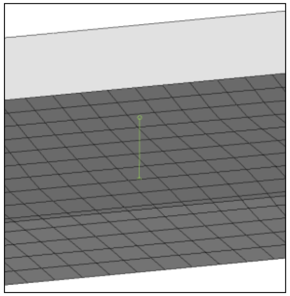
- 3D Solid Elements
- Most accurate FE representation
- Accurately captures bearing stresses and stress around fastener hole



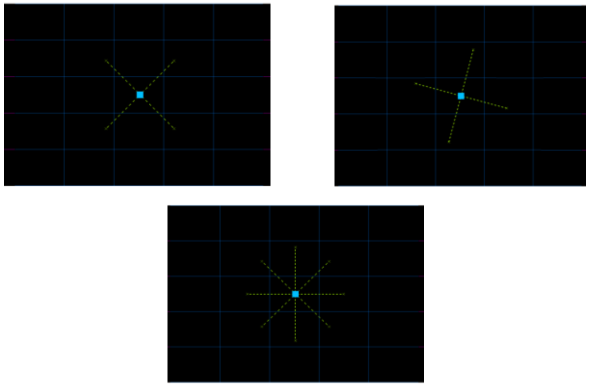
- Bolt shank modeled with beam element and connected to hole using rigid links
- Fastener hole is modeled, therefore meshing of large assemblies will be complicated
- Cannot capture bearing stress since forces are distributed circumferentially around the hole

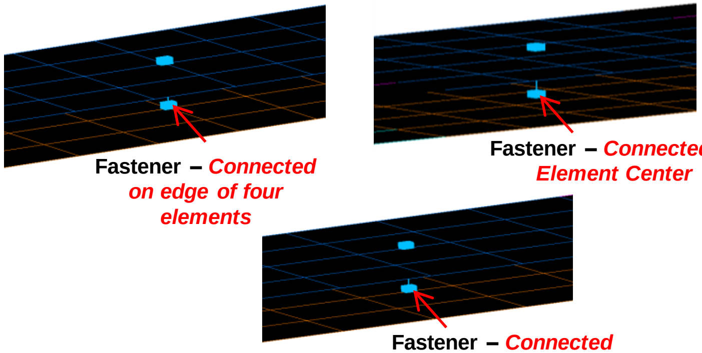


- Bolt shank modeled with beam element and rigid links used to distribute the forces
- Fastener hole not modeled
- Several variations as shown below are possible with this technique



- Type 9 spotweld beam connection to represent the bolt
- Fastener hole not modeled
- Results vary due to both mesh size and location of weld relative to center of contact segment (LS DYNA Keyword Manual). Some variations shown below





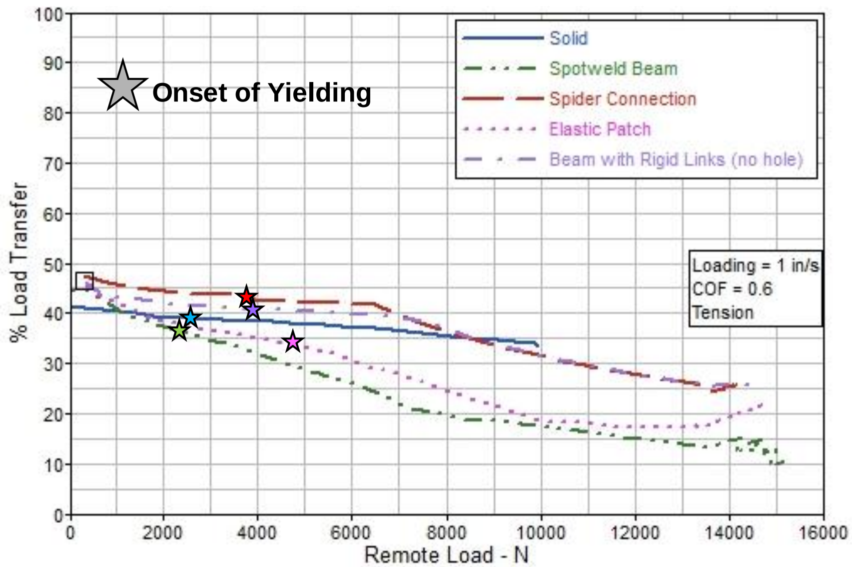
Fastener – *Connected on edge of four elements*

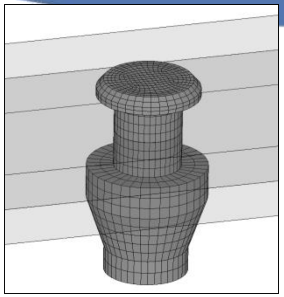
Fastener – *Connected at Element Center*

Fastener – *Connected between 2 elements on center of edge*

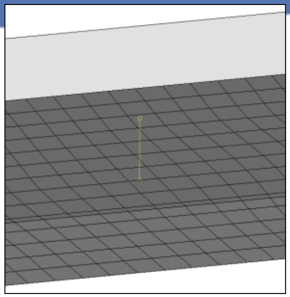
Bolt Modeling Techniques

% LOAD TRANSFER EVALUATION

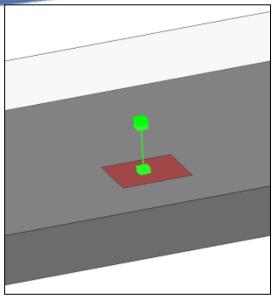




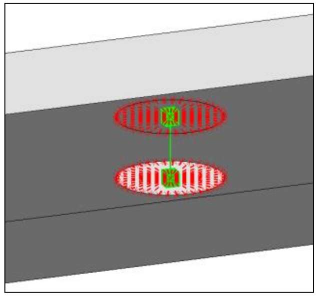
Solid



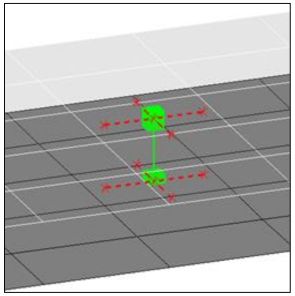
Spotweld Beam



Elastic Patch



Spider Connection



Beam with Rigid Links (no hole)