JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

Crashworthiness - Certification by Analysis

Gerardo Olivares Ph.D., NIAR-WSU

JAMS 2018 Technical Review
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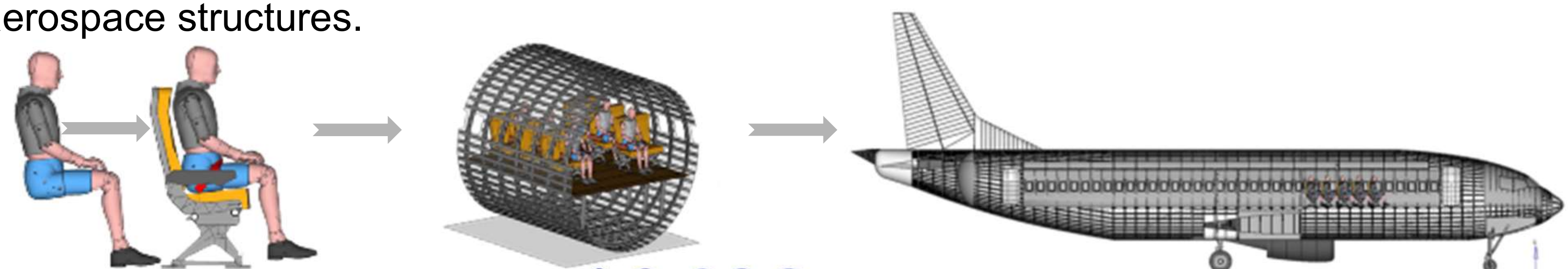
WICHITA STATE UNIVERSITY
NATIONAL INSTITUTE FOR AVIATION RESEARCH

Crashworthiness - 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
  - The advances in computational tools combined with the building block approach allows for a cost-effective approach to study in depth the crashworthiness behavior of aerospace structures.



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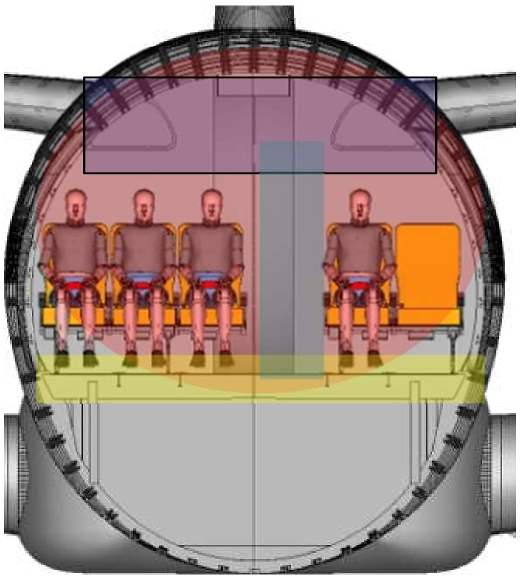
Crashworthiness - Certification by Analysis

- **Principal Investigators & Researchers**
  - **PI:** G. Olivares Ph.D.
  - **Researchers NIAR-WSU:** S. Keshavanarayana Ph.D. , Chandresh Zinzuwadia, Luis Gomez Adrian Gomez, Nilesh Dhole, , Hoa Ly, Armando Barriga, Rob Huculak Ph.D., Marcus Pyles
  - **8 Students [Graduate and Undergraduate]**
- **FAA Technical Monitor**
  - Allan Abramowitz
- **Other FAA Personnel Involved**
  - Joseph Pelletiere Ph.D.
- **Industry\Government Participation**
  - ARAC Transport Airplane Crashworthiness and Ditching Working Group [FAA, EASA, Transport Canada, NASA, Aircraft OEMs (Boeing, Embraer, Bombardier, Cessna, Mitsubishi, Gulfstream, Airbus), DLR]
  - KART – Spirit, Textron Aviation, Bombardier/Learjet
  - Gerard Elstak and Gerard Schakelaar – Dutch Politie
  - Hiromitsu Miyaki , Japan Aerospace Exploration Agency, JAXA

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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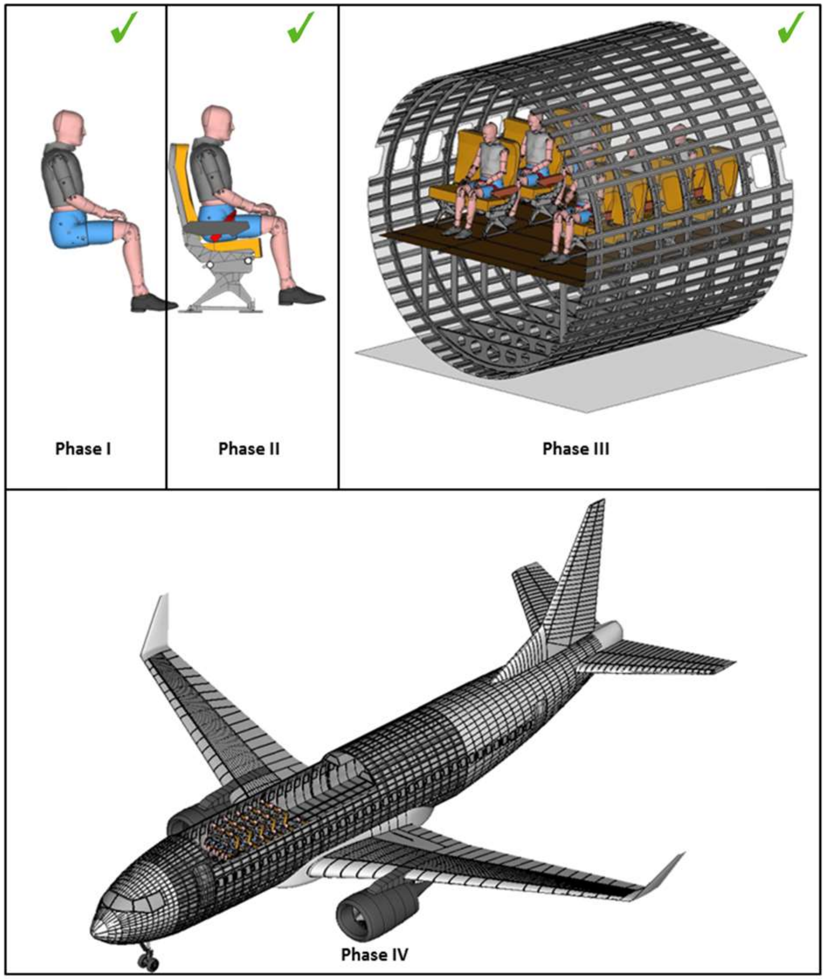
Crashworthiness CBA R&D Phases



- **Phase 0:** Define Occupant Injury Limits **|** **FAR** *.562 **|** ✓
- **Phase I:** Develop and validate occupant ATD numerical models **| SAE ARP** 5765 **|** ✓
- **Phase II**: Define Modeling and Certification by Analysis Processes of Aerospace Seat Structures and Installations **|AC** 20-146**|SAE ARP** 5765 | Aircraft OEMS and Seat Suppliers Modeling and CBA Standards | ✓
- **Phase III:** Define Crashworthiness Building Block Approach for Aircraft Structures **|CMH-17| ARAC** Transport Airplane Crashworthiness and Ditching Working Group| Aircraft OEMS Methods| ✓
- **Phase IV:** Define Structural CBA Methodology **|CMH-17| ARAC** Transport Airplane Crashworthiness and Ditching Working Group|

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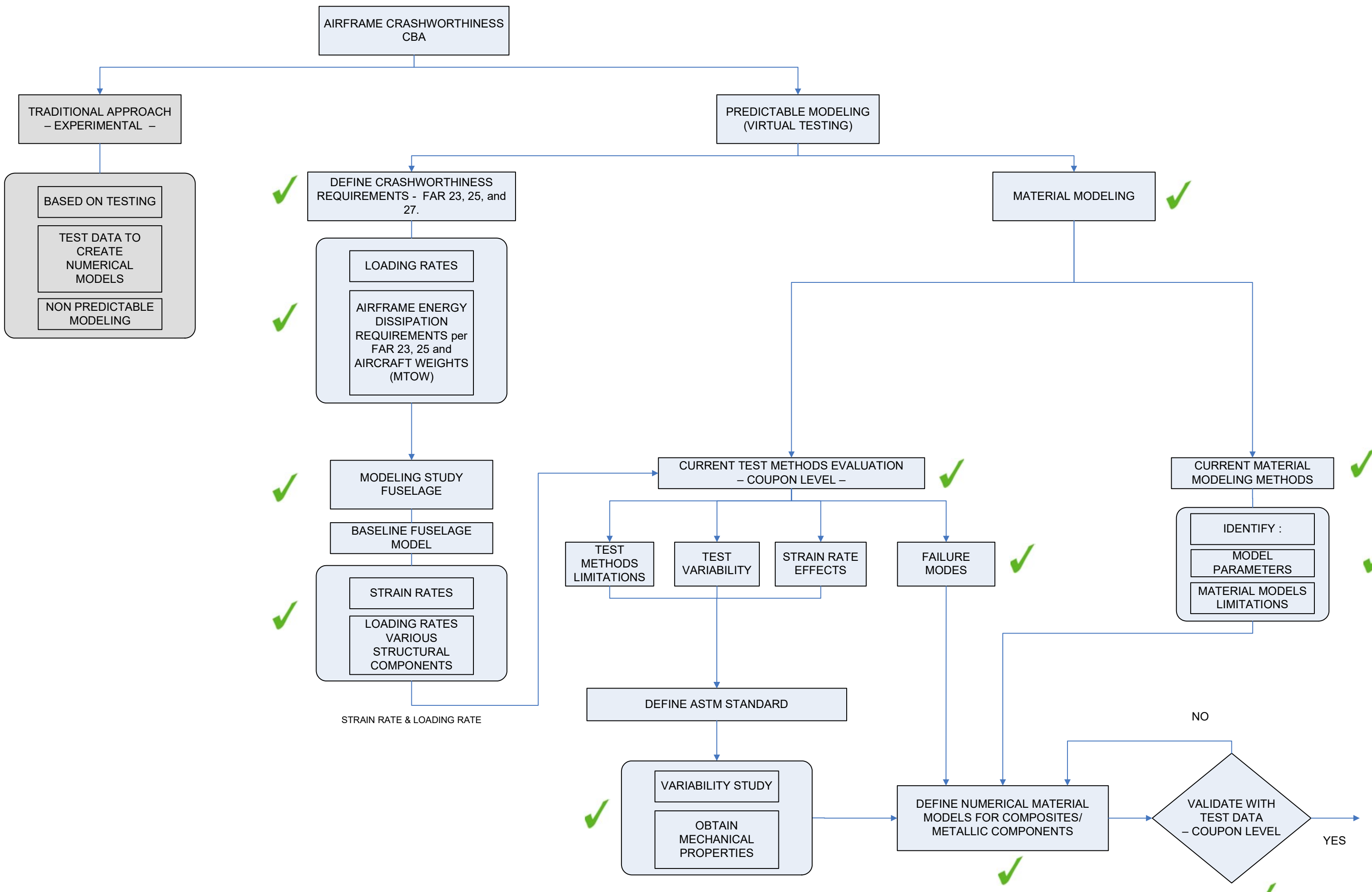
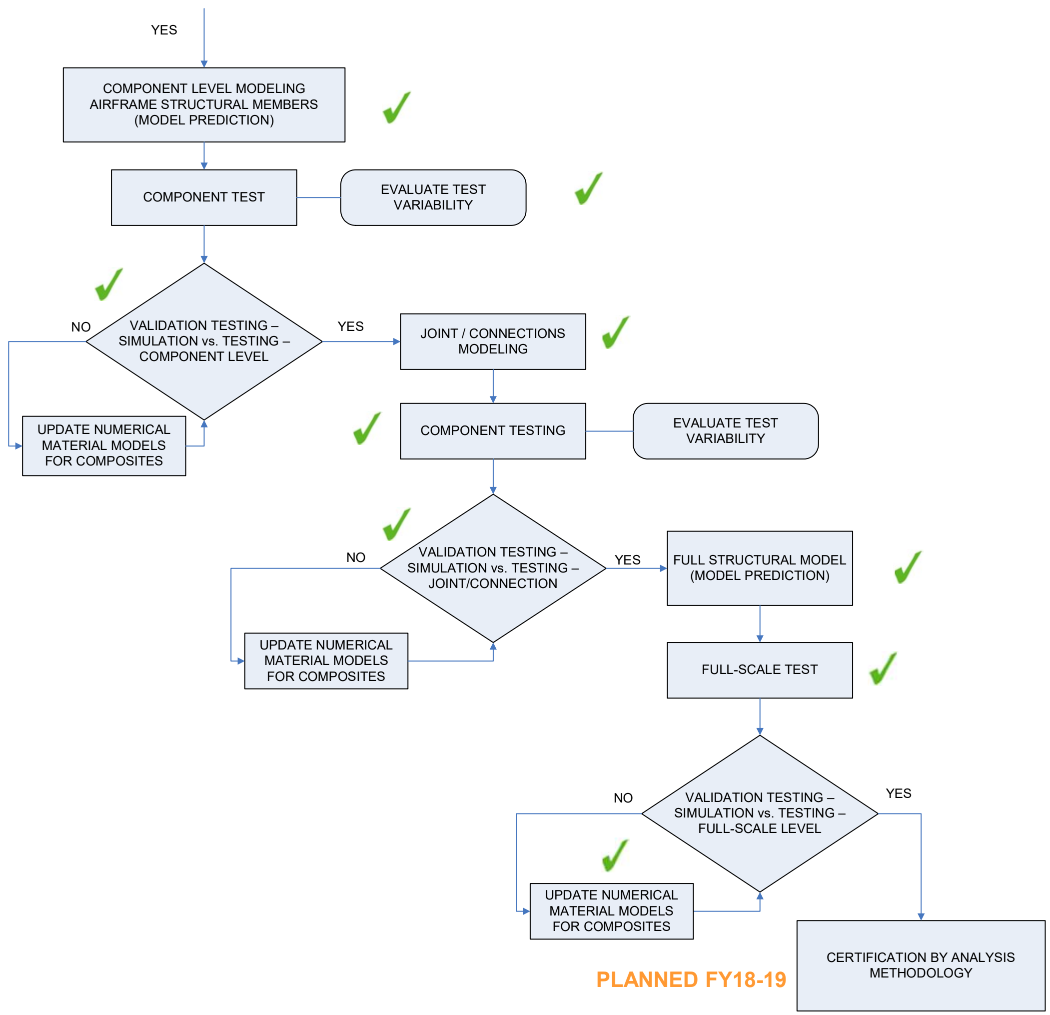
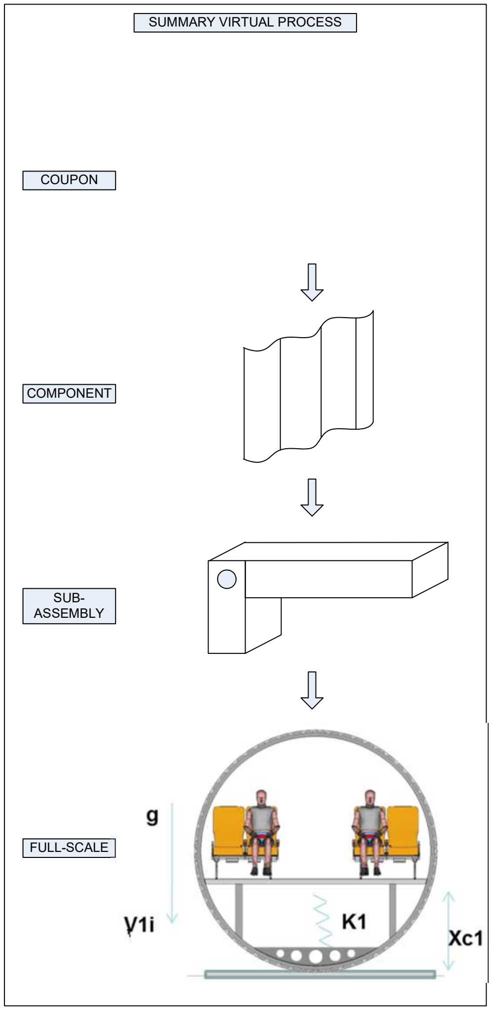
CBA: Composite Structures Crashworthiness



CBA Composite Structures Crashworthiness



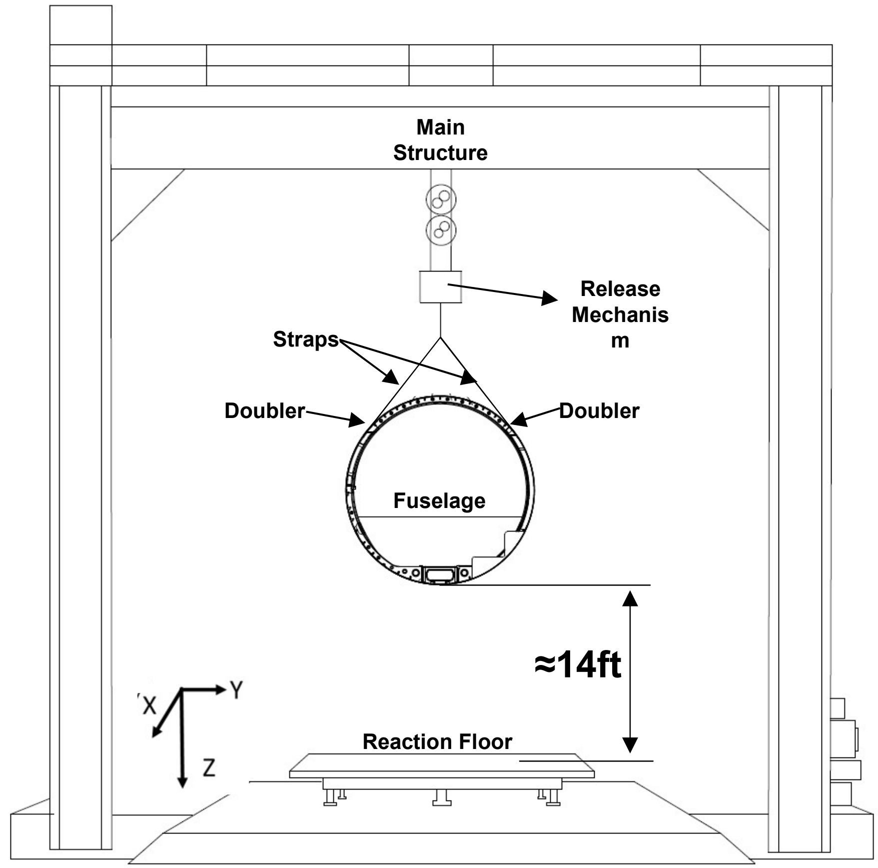


Experimental Work

FULL SCALE TESTING COMPOSITE AND METALLIC FUSELAGE SECTIONS

NIAR Drop Tests

- NIAR Crash Dynamics Laboratory
- Support ARAC for business jet size aircraft configurations
- Fuselage Section Drop Tests
  - Support the development of airframe level crash requirements for business jet airplanes
  - Two tests will be conducted:
    - Composites (Hawker 4000)
    - Metallic (Cessna Citation 650)
  - Impact velocity 30 ft/s
  - Instrumented Reaction Floor
  - Hardware
    - Digital Image Correlation
    - Strain-gages
    - Load Cells
    - High Speed Videos



Metallic Airframe Test Article

Performance	
Power	2 × Garrett TFE731-3B-100S Turbofans 3,650 lbf (16.2 kN) thrust each
Cruise Speed	554 mph (875 kmph)
Range	2345 mi (3774 km)
Service Ceiling	51000 ft

Interior	
Cabin Height	5 ft 8 in
Cabin Length	18 ft 7in
Cabin Width	5 ft 6 in
Cabin Volume	762 ft^3

General Characteristics	
Seating	2+7/9
External Length	55 ft 6 in
External tail Height	16 ft 10 in
Wing Span	53 ft 6 in
Empty Weight	11670 lb (5293 kg)
Gross Weight	22000 lb (9979 kg)

Metallic Test Section – Specifications

- Complete Fuselage Available
- Tentative Test Article Dimensions
  - Length: ≈9 ft
  - Diameter: ≈6 ft
- Tentative Test Article Configuration:
  - One Exit Door Opening (Right Side)
  - Seven Window Openings:
    - 3 Right Side
    - 4 Left Side
- Floor Structure with Seat tracks
- Seat Track Width: 15” (wall mounted)
- No wing box structure
- No upper panels/PSUs
- This article could not be used to support the ARAC program since during the accelerometer instrumentation process we found subfloor modifications to the structure
- The fuselage section was dropped to evaluate the Release and DIC system
- An additional test is planned with a Bombardier Metallic Fuselage:
  - NIAR purchased the fuselage and seats
  - Testing September-October 2019 depending on funding availability

Composite Airframe Test Article

Performance	
Power	2 × Pratt & Whitney Canada PW308A turbofan 6,900 lbf/ ISA + 22 °C () each
Cruise Speed	Mach 0.84
Range	6075 km
Service Ceiling	45000 ft

Interior	
Cabin Height	6ft
Cabin Length	25 ft
Cabin Width	6 ft 6 in
Cabin Volume	762 ft^3

General Characteristics	
Seating	2+8/12
External Length	69 ft 6 in
External tail Height	19 ft 9 in
Wing Span	61ft 9 in
Empty Weight	23500 lb (10659 kg)
Gross Weight	26000 lb (11793 kg)

Composite Test Section – Specifications

- Dimensions
  - Length: ≈8 ft 2in
  - Diameter: ≈7 ft
- One Exit Door Opening (Right Side)
- Seven Window Openings:
  - 3 Right Side
  - 4 Left Side
- Floor Structure with Seat tracks
- Seat Track Width: 8' ¾"
- No wing box structure
- No upper panels/PSUs

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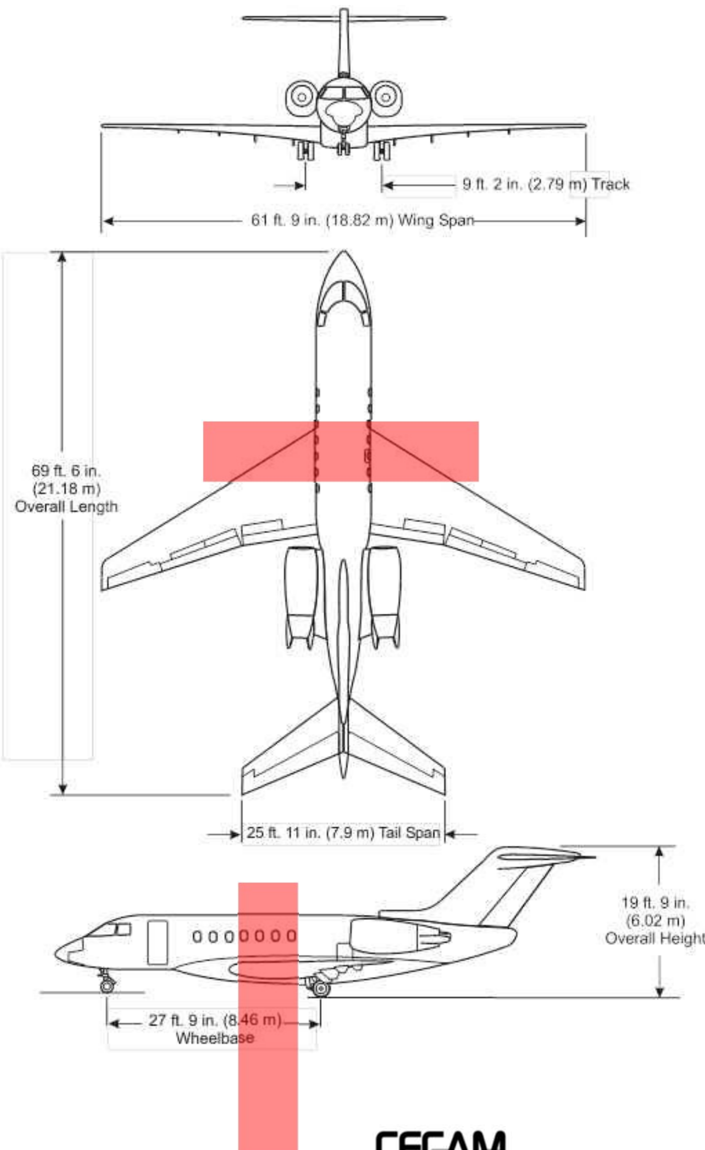
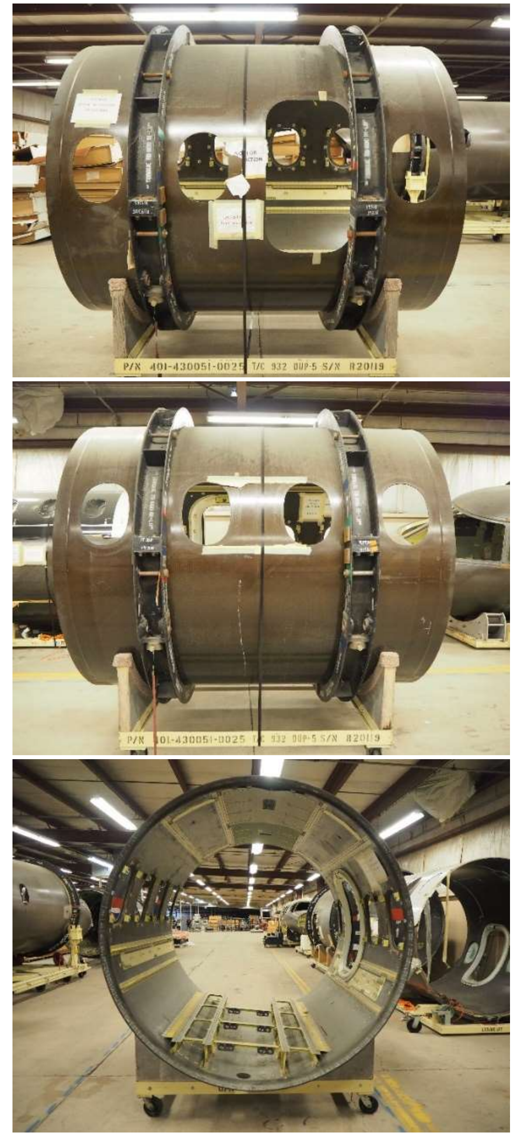
Composite Test Section– Aircraft Location





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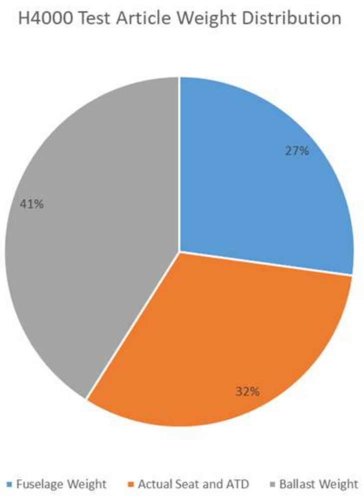
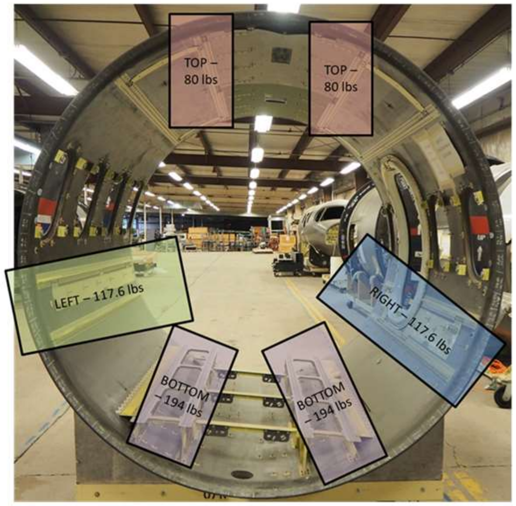
Composite Airframe Drop Test – H4000

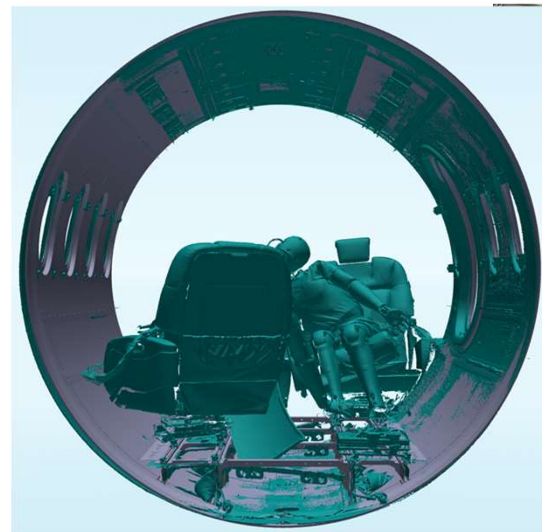
- Dimensions:
  - Length: ≈8 ft 2in
  - Diameter: ≈7 ft
- One Exit Door Opening (Right Side)
- Seven Window Openings:
  - 3 Right Side
  - 4 Left Side
- Floor Structure with Seat tracks
- Seat Track Width: 8’ ¾”
- No wing box structure
- No upper panels/PSUs
- Total Weight: 1553 lbs.
- 4 Occupants:
  - 2 Seats: HII and FAA HII
  - 2 Seats: Ballast Weights representative of seats and occupants

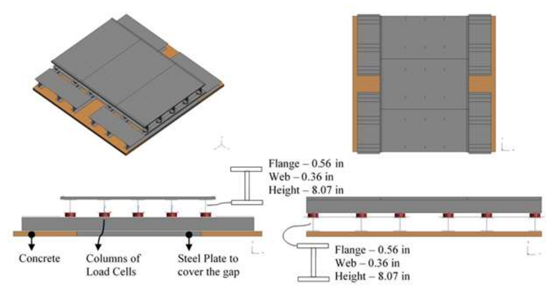


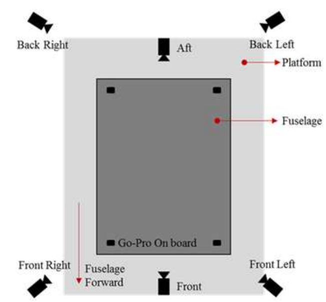


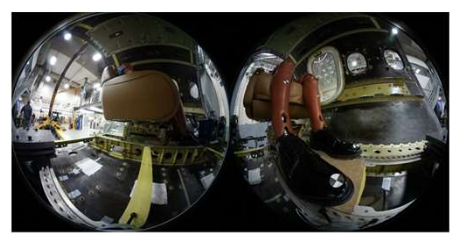
Drop Test Instrumentation

- DTS Slice Pro Data Acquisition System, 108 channels
  - 72 channels will be used for the ATDs (32 sensors)
  - H4000 barrel section (40 sensors)
- Endevco 7264C accelerometers with measuring capability of 2000 g's vertical and 500 g's on the lateral axis will be used. 4 triaxial accelerometers will be used for the seat track corners. 8 biaxial accelerometers will be used on the seat tracks and 4 biaxial accelerometers will be used at the top center of the barrel section. The accelerometer data will be filtered using the SAE J211 CFC60 filter.
- Six S-VIT AOS Tech. AG High Resolution Color (900 x 700 pixel) – 1000 fps
- 360 HD camera system - 4 GO-PROs
- Two pairs of high speed cameras will be used to perform digital image correlation (DIC) analysis in the fuselage: A pair of monochrome Photron SA-Z 16 Gig RAM high speed cameras and a pair of color Photron SA-Z 16 Gig RAM high speed cameras. Both camera sets are capable to record 20,000 fps at a full resolution of 1024 x 1024 pixels.
- Four Strain Gages EP-08-250BF-350
- HII and FAA HIII ATDs









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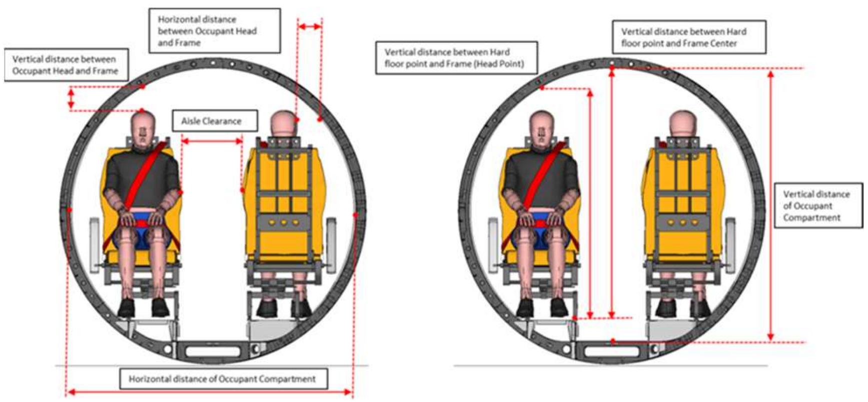
Proposed Evaluation Criteria

NIAR Drop Test – Hawker 4000

- Maintain Survivable Volume
  - Overall Survivable Space Dimensional Check (Peak during Dynamic Event and Post Test Deformations)
  - Avoid Occupant to Interior Structure Contacts during impact
- Maintain Deceleration Loads to Occupants
  - Injury Criteria Limits per 14 CFR 25.562) :
    - 1500 lbf, HIC 1000, Shoulder Strap Loads….
- Retention Items of Mass
  - No items of mass such as overhead bins
  - Occupants and Seat Structures supported throughout the crash event (14 CFR 25.562)
- Maintain Egress Paths
  - Maintain Aisle Distance (Min 12-15 inches per 14 CFR 25.815 and 25.807(d)(4))
  - Evaluate Plastic deformations of the supporting structure near the exit door
  - Floor Warping
  - Floor Beam Failures – Reduced Strength to support passenger weight



Evaluation H4000 Composite Fuselage Drop Test

MAINTAIN SURVIVABLE VOLUME

Proposed Evaluation Criteria

NIAR Drop Test – Hawker 4000

- **Maintain Survivable Volume**
  - **Overall Survivable Space Dimensional Check (Peak during Dynamic Event and Post Test Deformations)** ✓
  - **Avoid Occupant to Interior Structure Contacts during impact** ✓
- Maintain Deceleration Loads to Occupants
  - Injury Criteria Limits per 14 CFR 25.562) :
    - 1500 lbf, HIC 1000, Shoulder Strap Loads….
- Retention Items of Mass
  - No items of mass such as overhead bins
  - Occupants and Seat Structures supported throughout the crash event (14 CFR 25.562)
- Maintain Egress Paths
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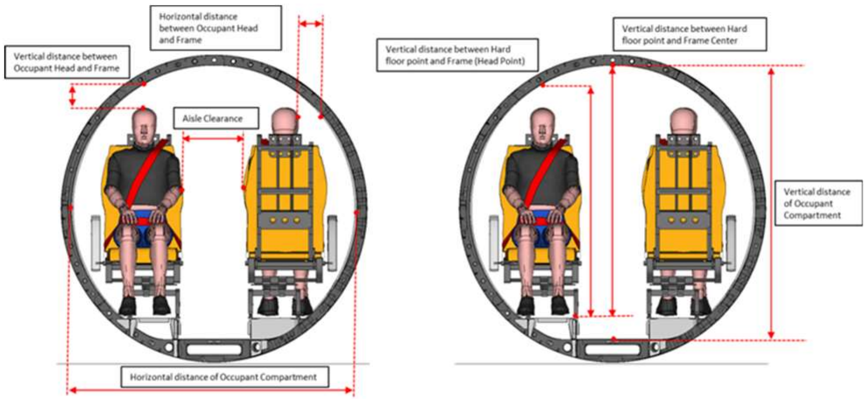
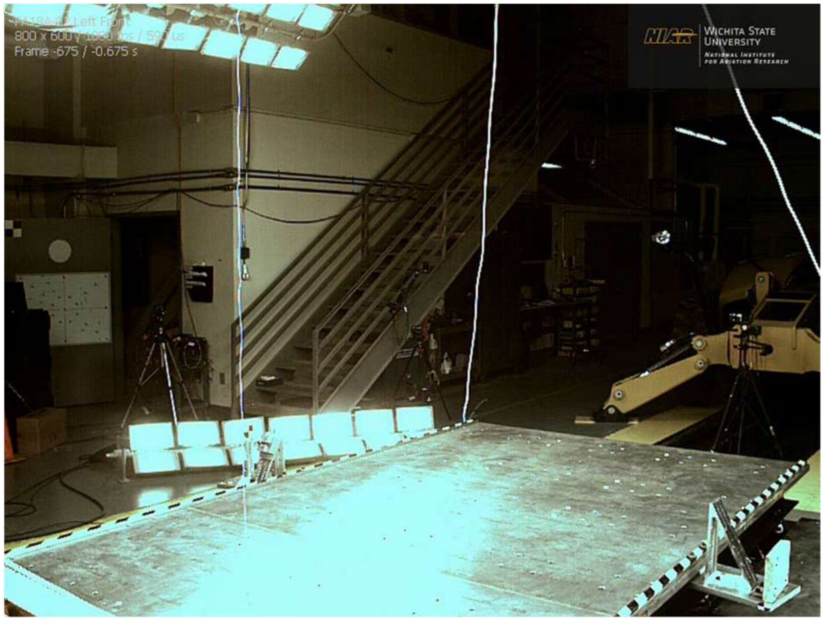
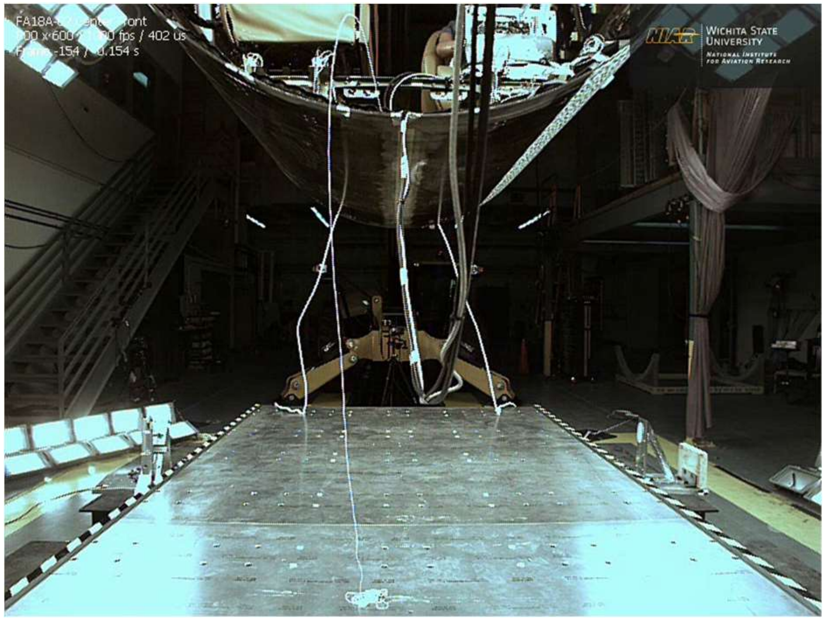


HSV FWD Side and Center View

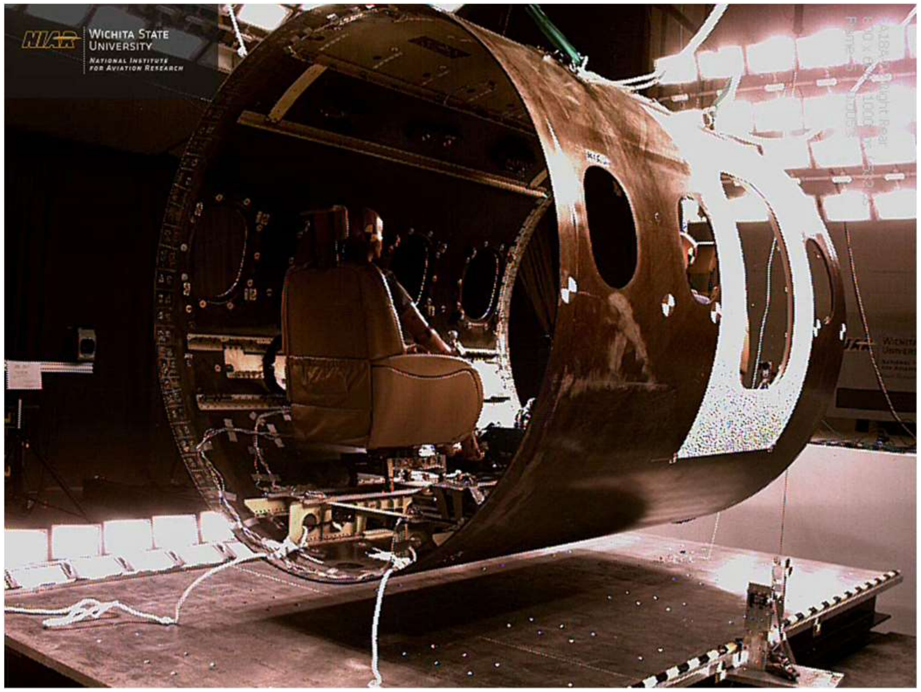
NIAR Drop Test – Hawker 4000

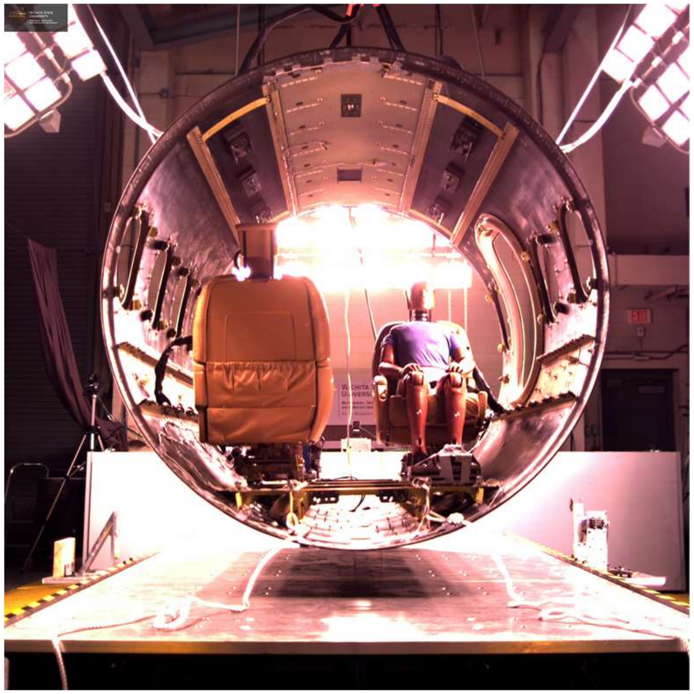




HSV RWD Side and Center View

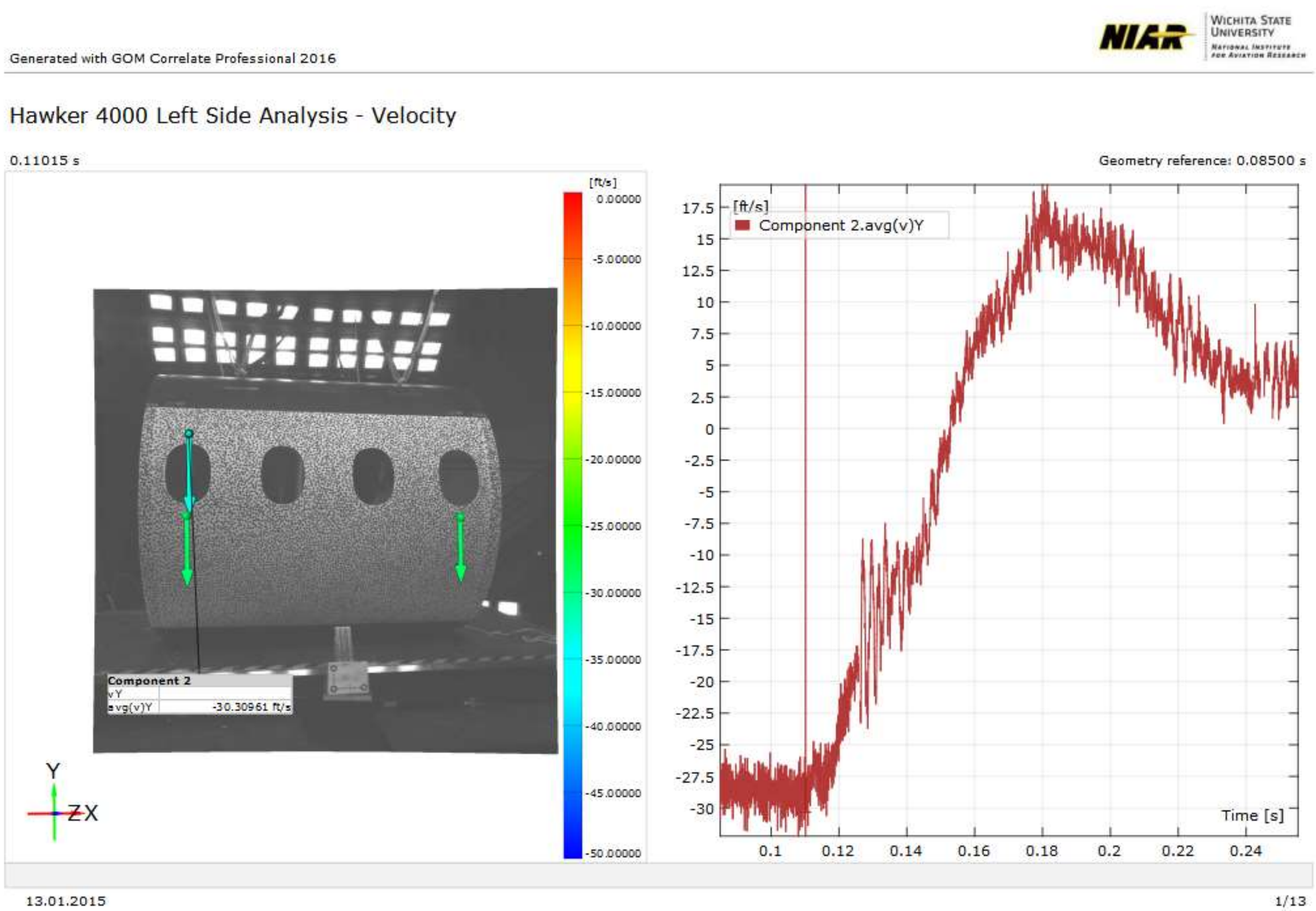
NIAR Drop Test – Hawker 4000





Vertical Velocity Change

NIAR Drop Test – Hawker 4000



CAD vs. Post Test Deformations

NIAR Drop Test – Hawker 4000

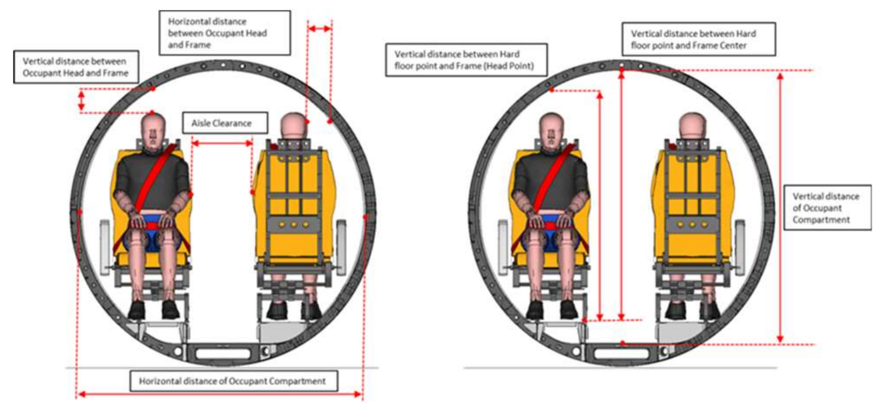
Evaluation H4000 Composite Fuselage Drop Test

MAINTAIN DECELERATION LOADS TO OCCUPANTS

Proposed Evaluation Criteria

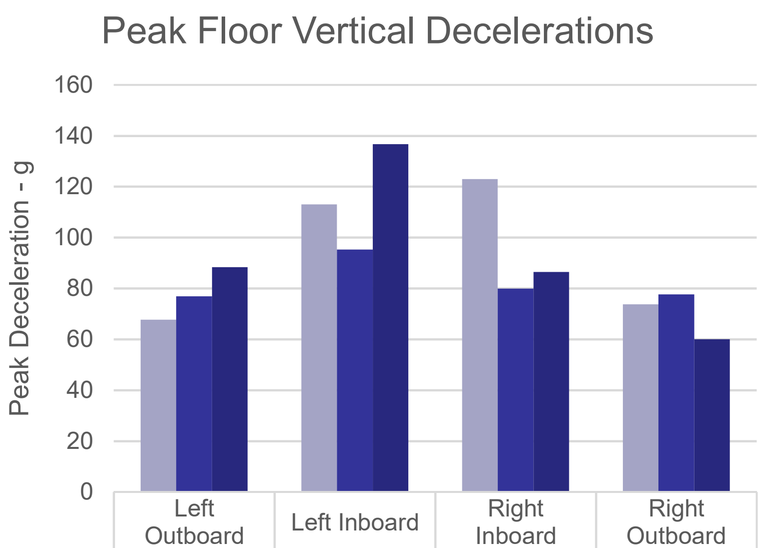
NIAR Drop Test – Hawker 4000

- **Maintain Survivable Volume**
  - **Overall Survivable Space Dimensional Check (Peak during Dynamic Event and Post Test Deformations)** ✓
  - **Avoid Occupant to Interior Structure Contacts during impact** ✓
- **Maintain Deceleration Loads to Occupants**
  - **Injury Criteria Limits per 14 CFR 25.562) :** ✗
    - **1500 lbf, HIC 1000, Shoulder Strap Loads….**
- Retention Items of Mass
  - No items of mass such as overhead bins
  - Occupants and Seat Structures supported throughout the crash event (14 CFR 25.562)
- Maintain Egress Paths
  - Maintain Aisle Distance (Min 12-15 inches per 14 CFR 25.815 and 25.807(d)(4))
  - Evaluate Plastic deformations of the supporting structure near the exit door
  - Floor Warping
  - Floor Beam Failures – Reduced Strength to support passenger weight

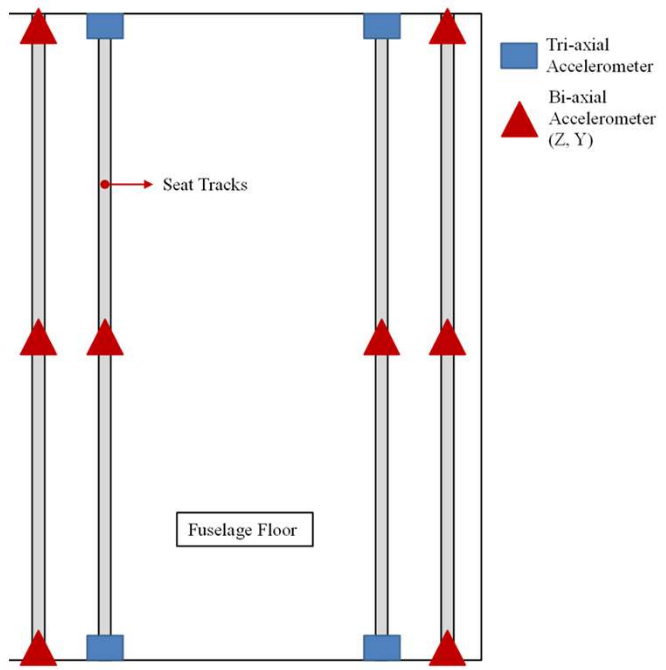


Floor Accelerations

NIAR Drop Test – Hawker 4000

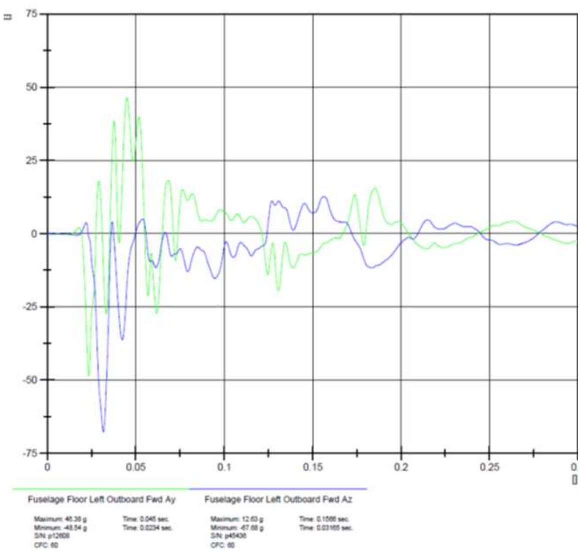


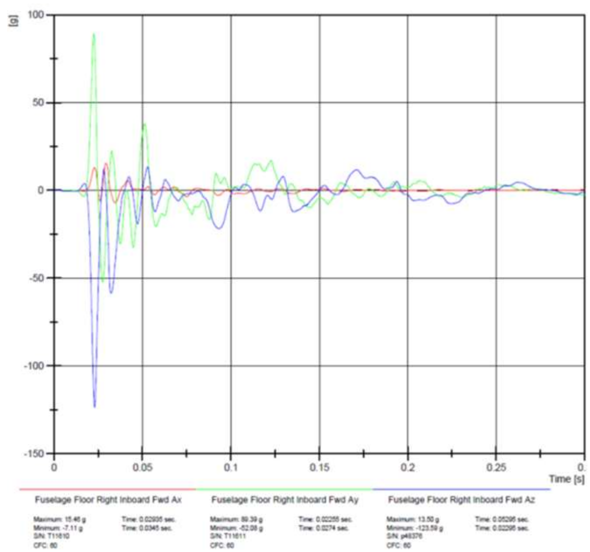
	Left Outboard	Left Inboard	Right Inboard	Right Outboard
FWD	67.68	113	123	73.72
MID	76.92	95.22	79.9	77.64
REAR	88.28	136.72	86.46	60

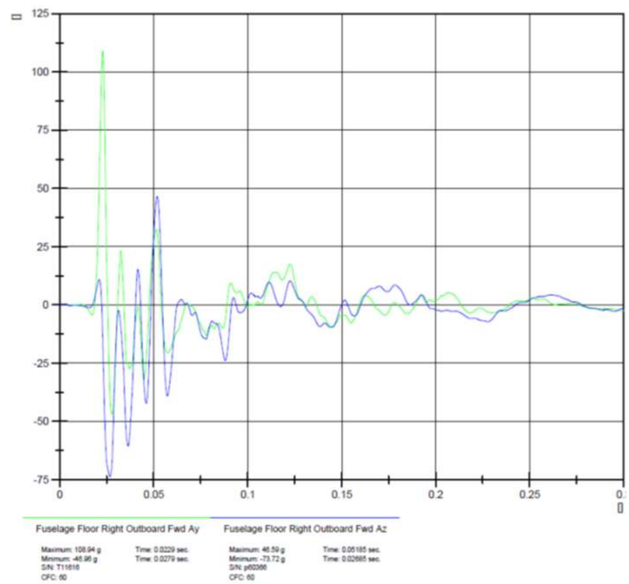


FWD Floor Accelerometer

NIAR Drop Test – Hawker 4000







Passenger Evaluation – HII and FAA HIII

NIAR Drop Test – Hawker 4000

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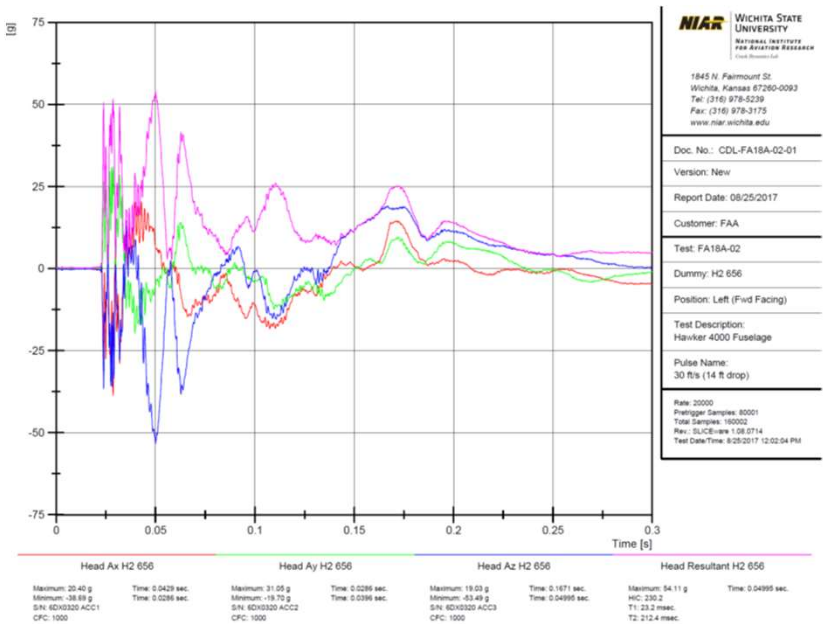
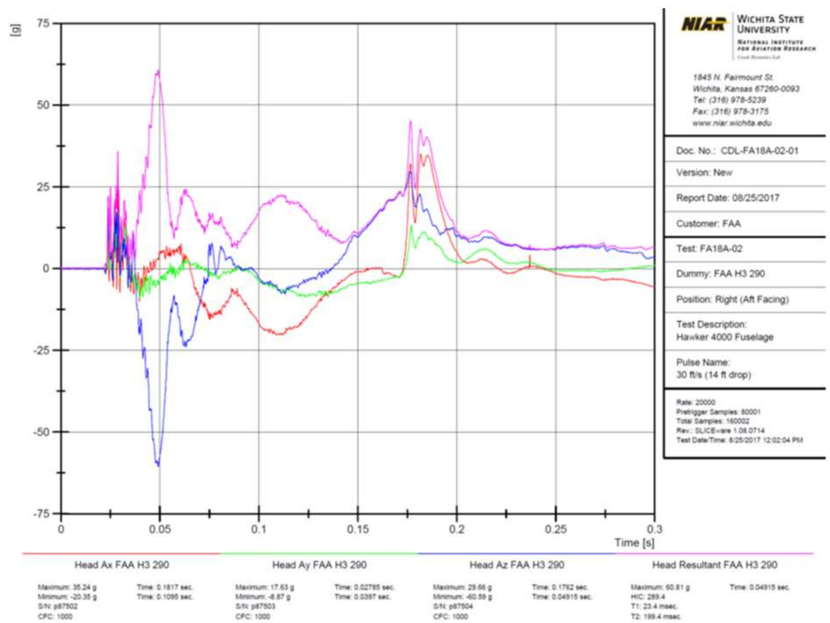
Head Accelerations – HII vs. FAA HIII

NIAR Drop Test – Hawker 4000





HIC values under 300

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Lumbar Load – HII vs. FAA HIII

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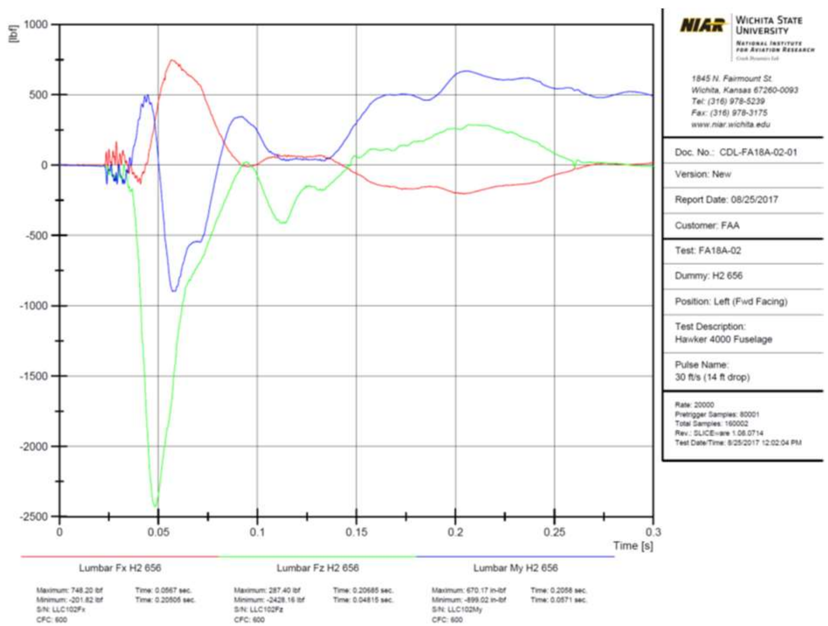
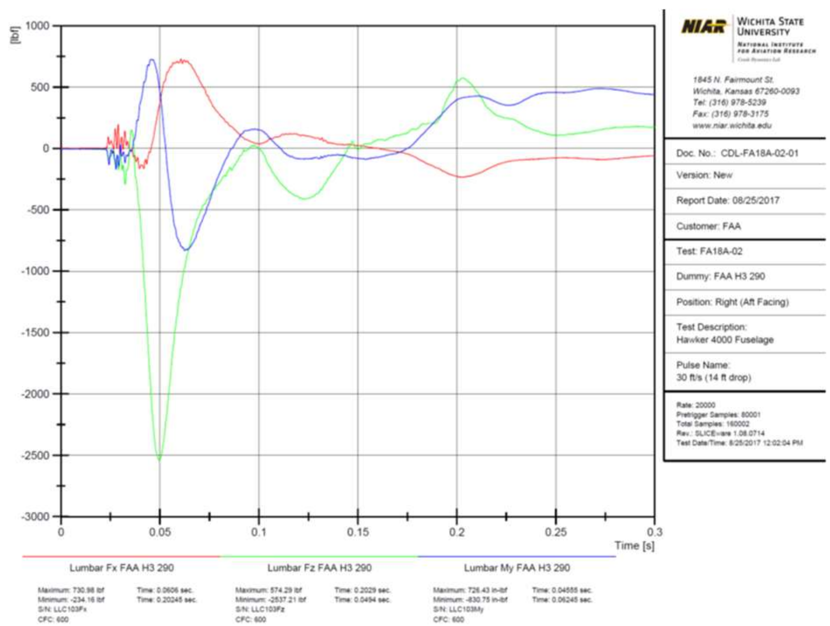
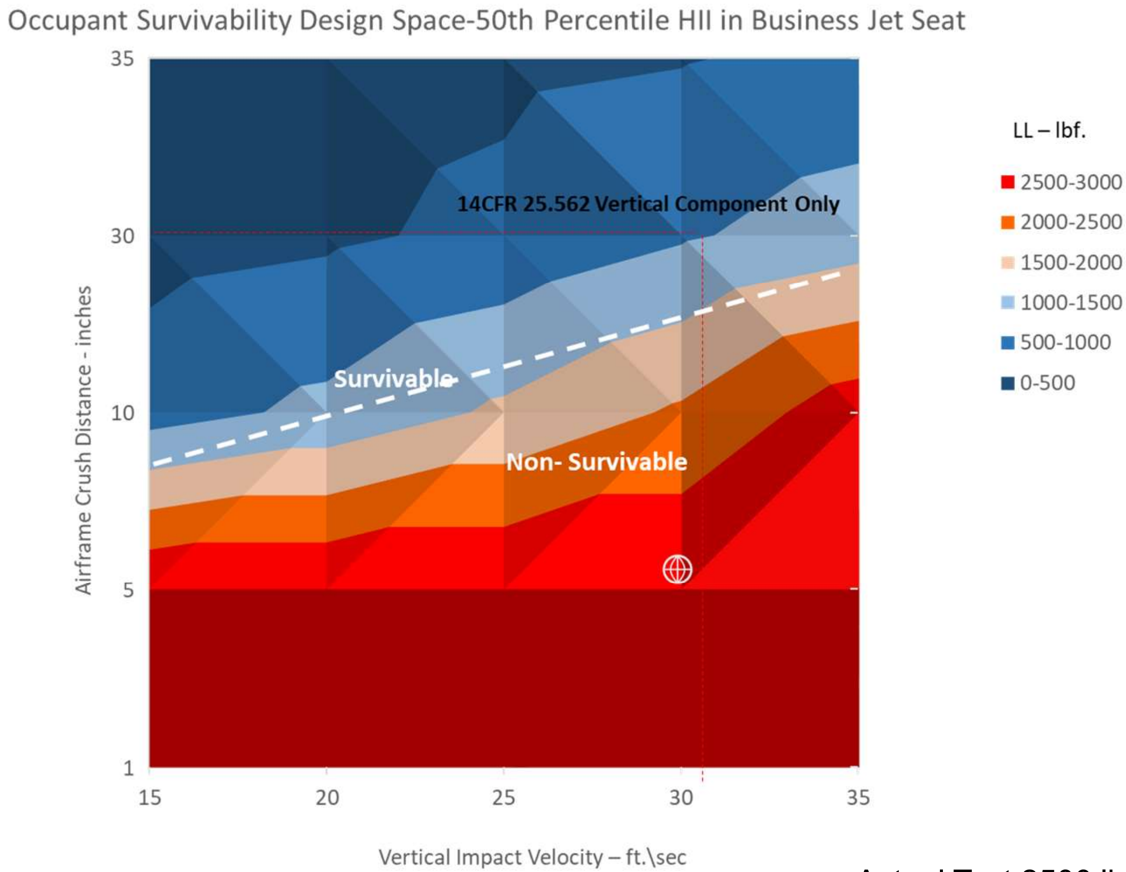


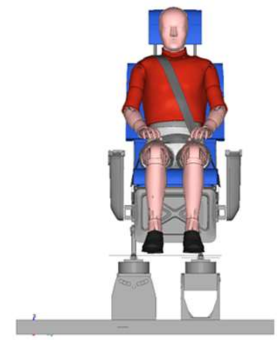


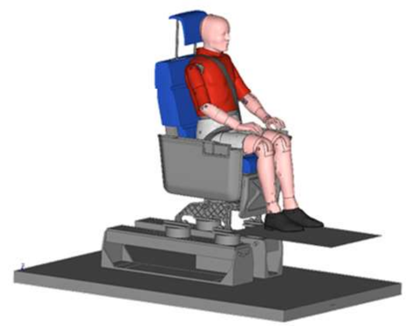
Lumbar Loads: 2500 lbs for both the HII and FAA HIII

Occupant Survivability Check

NIAR Survivability Curves –Business Jet Seat







Actual Test 2500 lbs – Survivability Curves 2500/3000 lbs

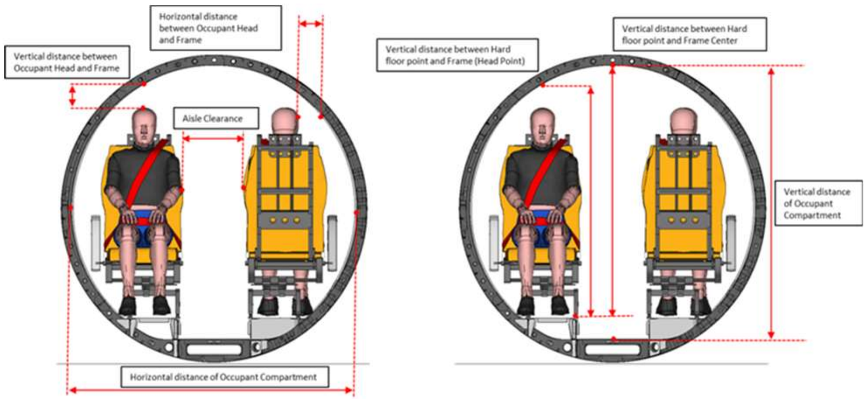
Evaluation H4000 Composite Fuselage Drop Test

RETENTION ITEMS OF MASS

Proposed Evaluation Criteria

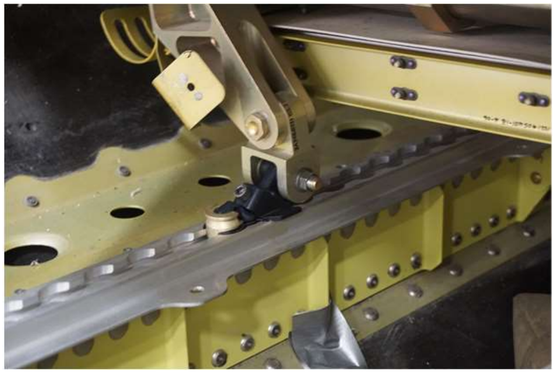
NIAR Drop Test – Hawker 4000

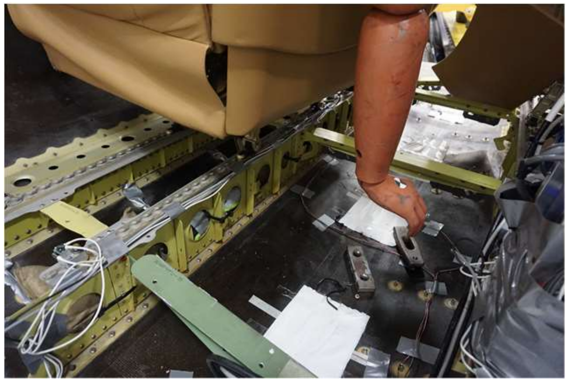
- **Maintain Survivable Volume**
  - **Overall Survivable Space Dimensional Check (Peak during Dynamic Event and Post Test Deformations)** ✓
  - **Avoid Occupant to Interior Structure Contacts during impact** ✓
- **Maintain Deceleration Loads to Occupants**
  - **Injury Criteria Limits per 14 CFR 25.562) :** ✗
    - **1500 lbf, HIC 1000, Shoulder Strap Loads….**
- **Retention Items of Mass**
  - **No items of mass such as overhead bins** ✓
  - **Occupants and Seat Structures supported throughout the crash event (14 CFR 25.562)** ✓
- Maintain Egress Paths
  - Maintain Aisle Distance (Min 12-15 inches per 14 CFR 25.815 and 25.807(d)(4))
  - Evaluate Plastic deformations of the supporting structure near the exit door
  - Floor Warping
  - Floor Beam Failures – Reduced Strength to support passenger weight



Post Impact Seat

NIAR Drop Test – Hawker 4000





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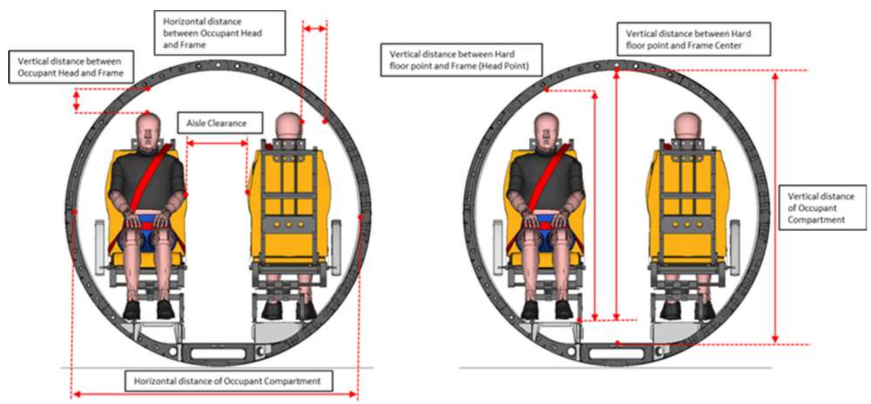
Evaluation H4000 Composite Fuselage Drop Test

MAINTAIN EGRESS PATHS

Proposed Evaluation Criteria

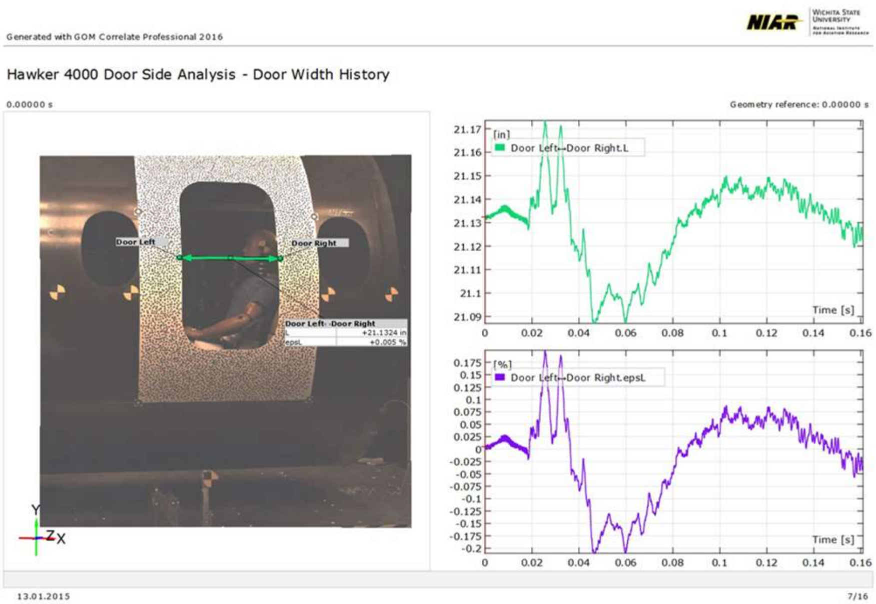
NIAR Drop Test – Hawker 4000

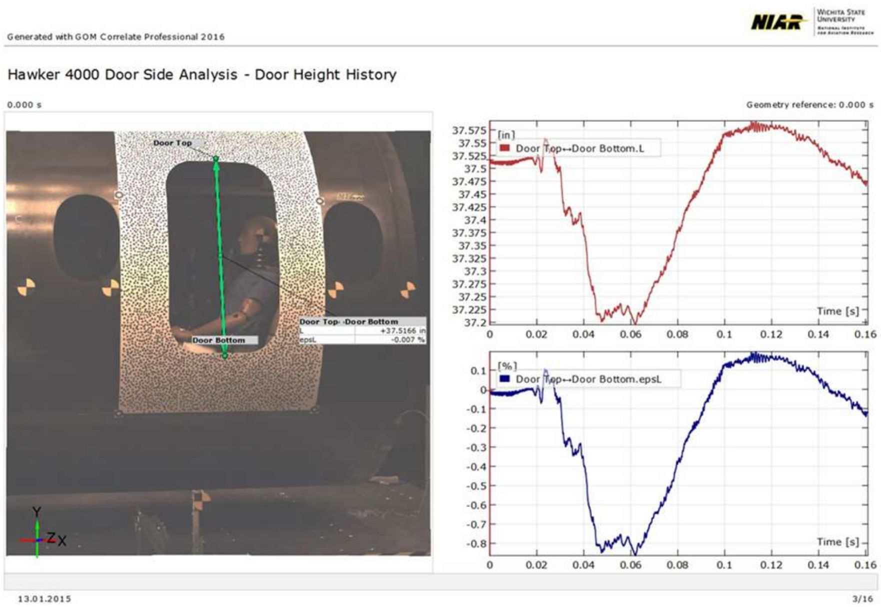
- **Maintain Survivable Volume**
  - **Overall Survivable Space Dimensional Check (Peak during Dynamic Event and Post Test Deformations)** ✓
  - **Avoid Occupant to Interior Structure Contacts during impact** ✓
- **Maintain Deceleration Loads to Occupants**
  - **Injury Criteria Limits per 14 CFR 25.562) :**
    - **1500 lbf, HIC 1000, Shoulder Strap Loads….** ✗
- **Retention Items of Mass**
  - **No items of mass such as overhead bins** ✓
  - **Occupants and Seat Structures supported throughout the crash event (14 CFR 25.562)** ✓
- **Maintain Egress Paths**
  - **Maintain Aisle Distance (Min 12-15 inches per 14 CFR 25.815 and 25.807(d)(4))** ✗
  - **Evaluate Plastic deformations of the supporting structure near the exit door** ✓
  - **Floor Warping** ✓
  - **Floor Beam Failures – Reduced Strength to support passenger weight** ✗



Emergency Exit Evaluation

NIAR Drop Test – Hawker 4000





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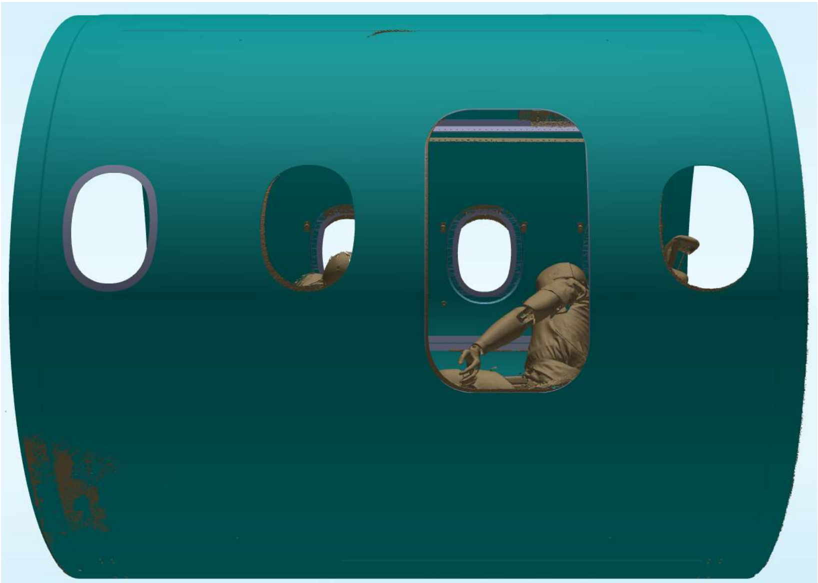
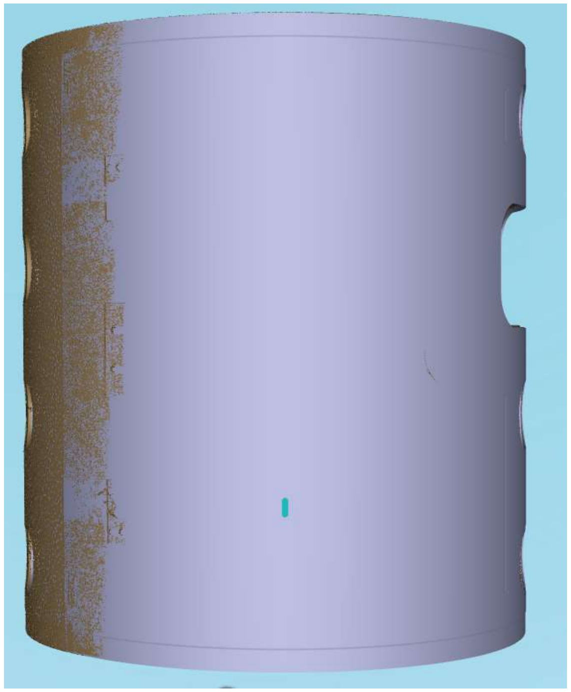
CAD vs. Post Test Deformations

NIAR Drop Test – Hawker 4000





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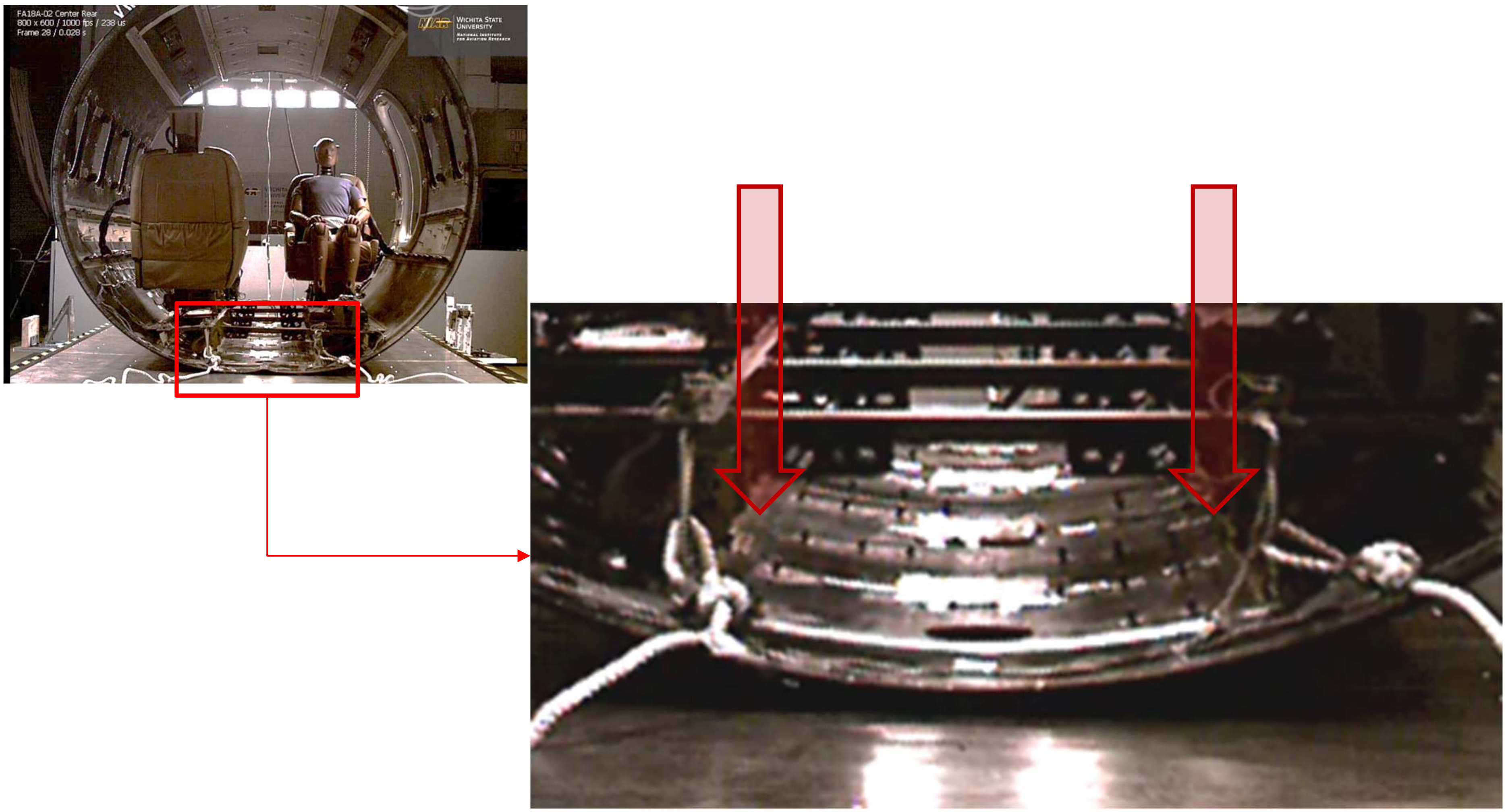
Egress Path Evaluation

NIAR Drop Test – Hawker 4000

Evaluation H4000 Composite Fuselage Drop Test

STRUCTURAL DAMAGE EVALUATION

Structural Failures Fuselage Structure



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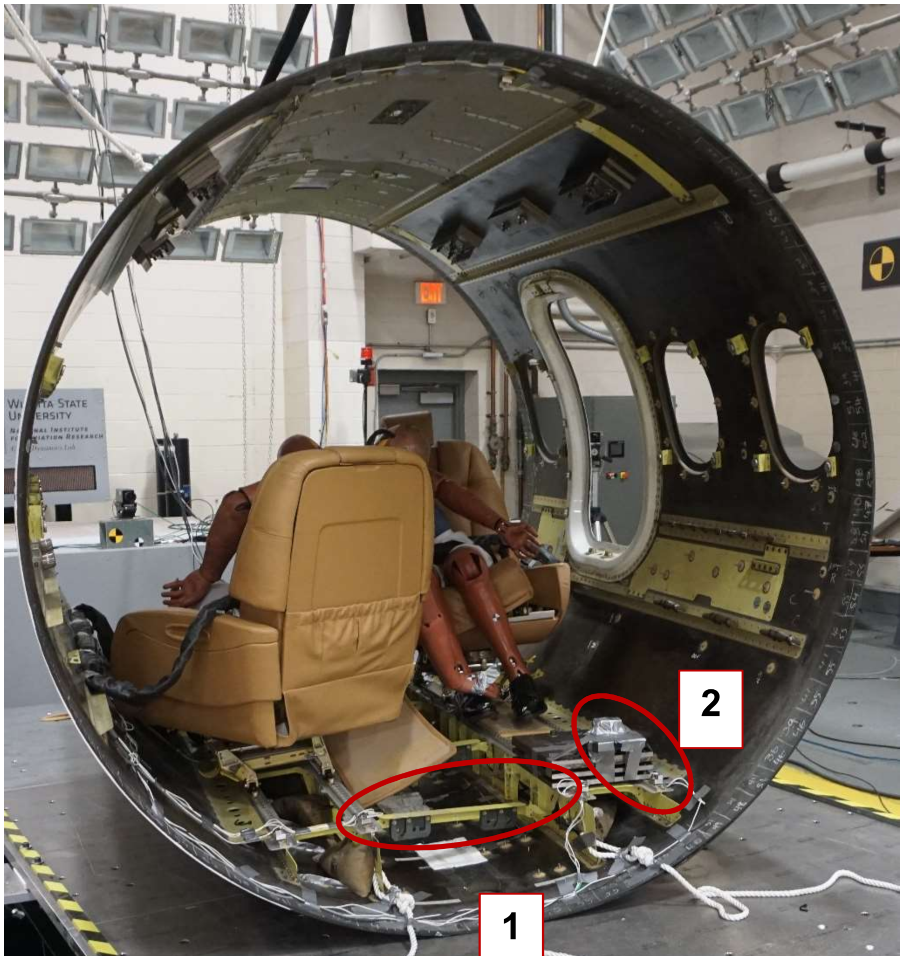
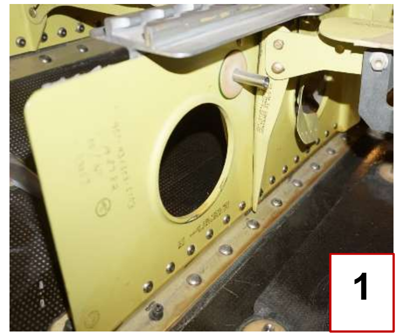
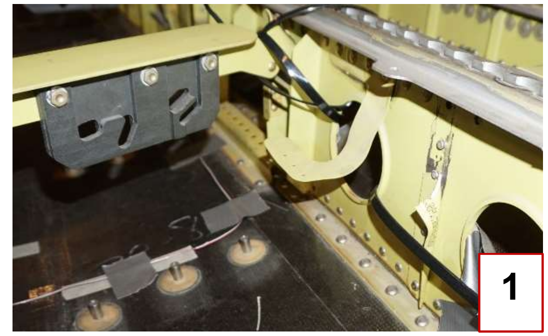
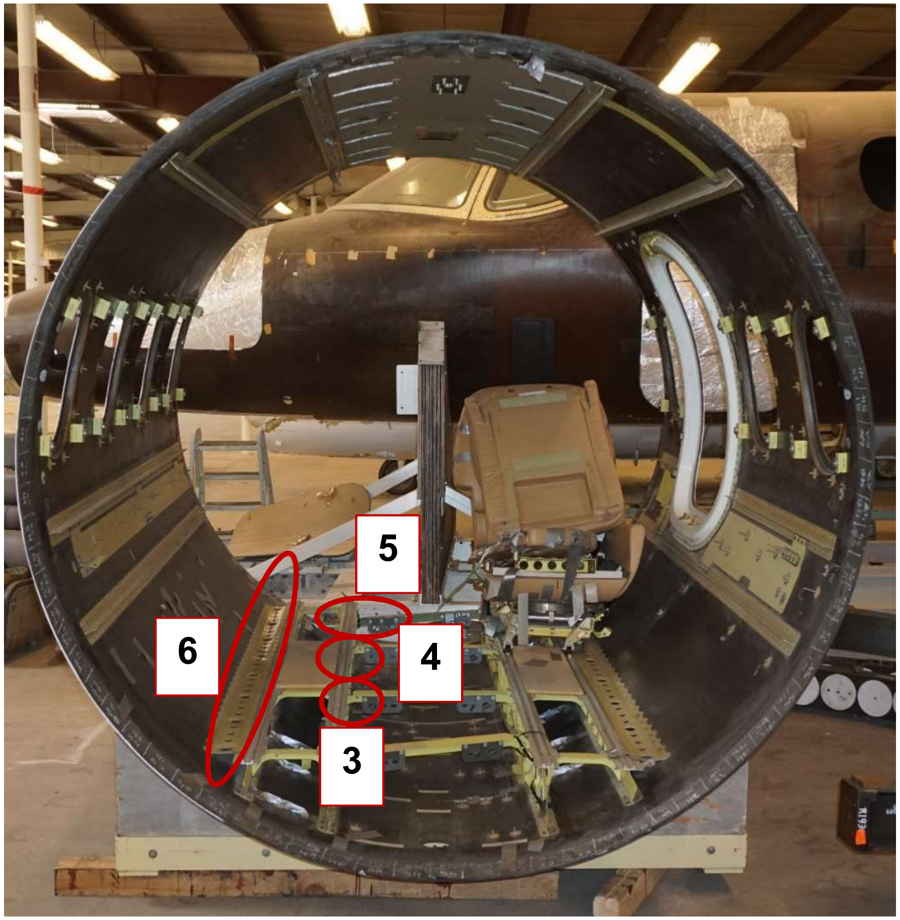
Test Results - Metallic Parts

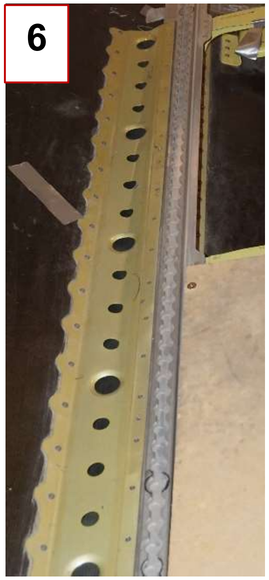






Test Results - Metallic Parts





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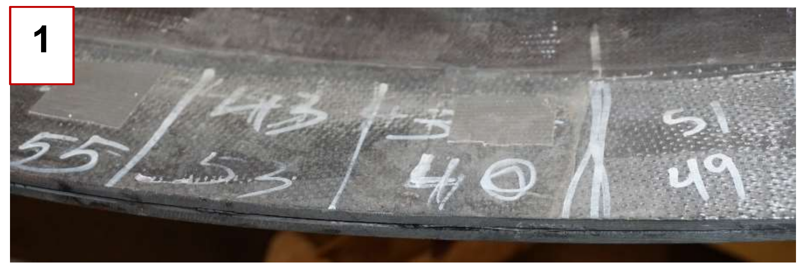
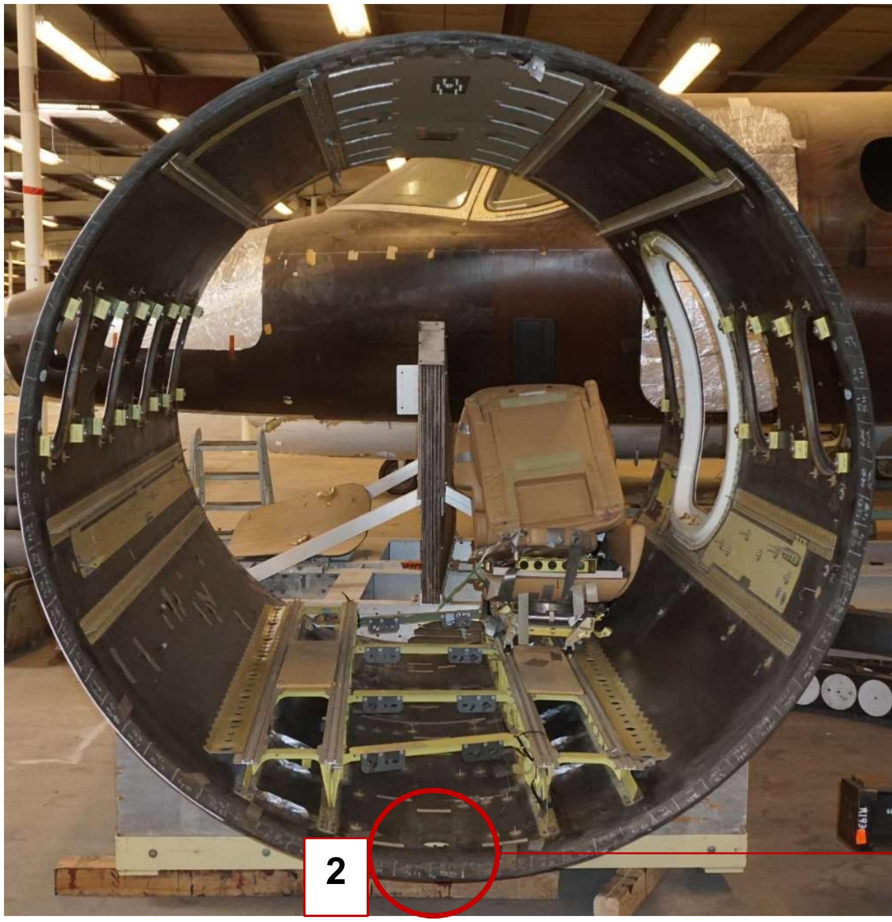
Test Results - Fwd



Test Results - Fwd



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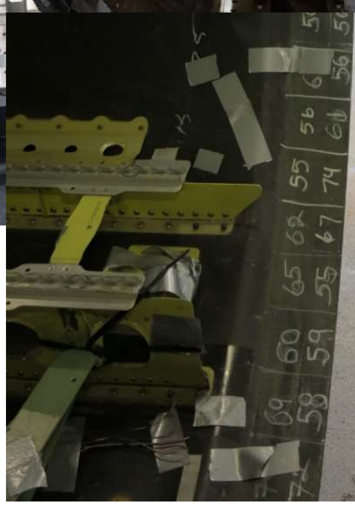
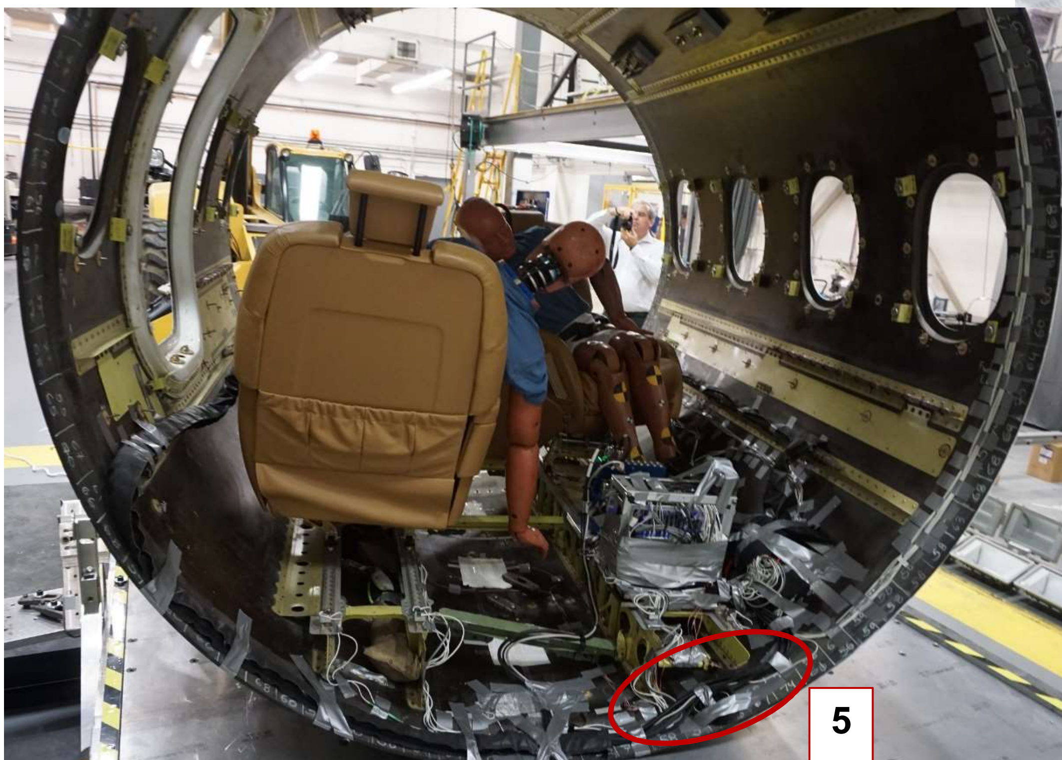
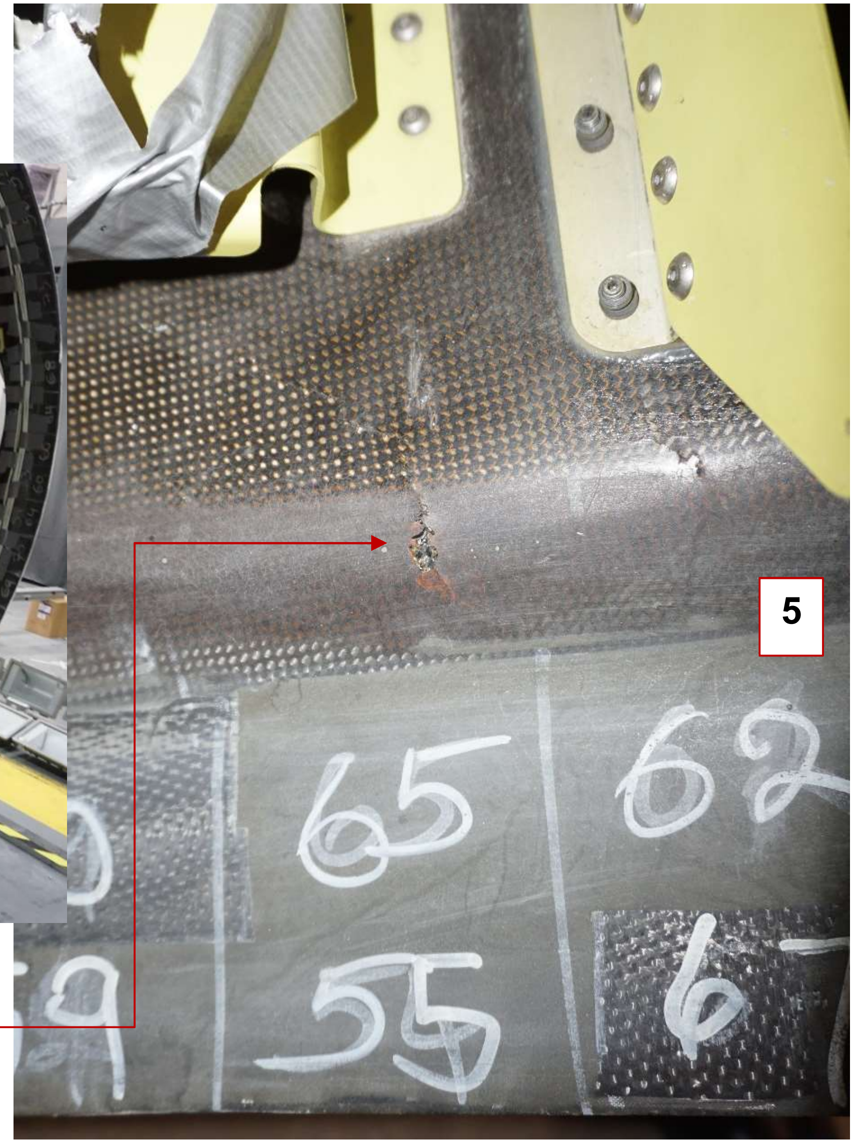
Test Results - Aft



Test Results - Aft





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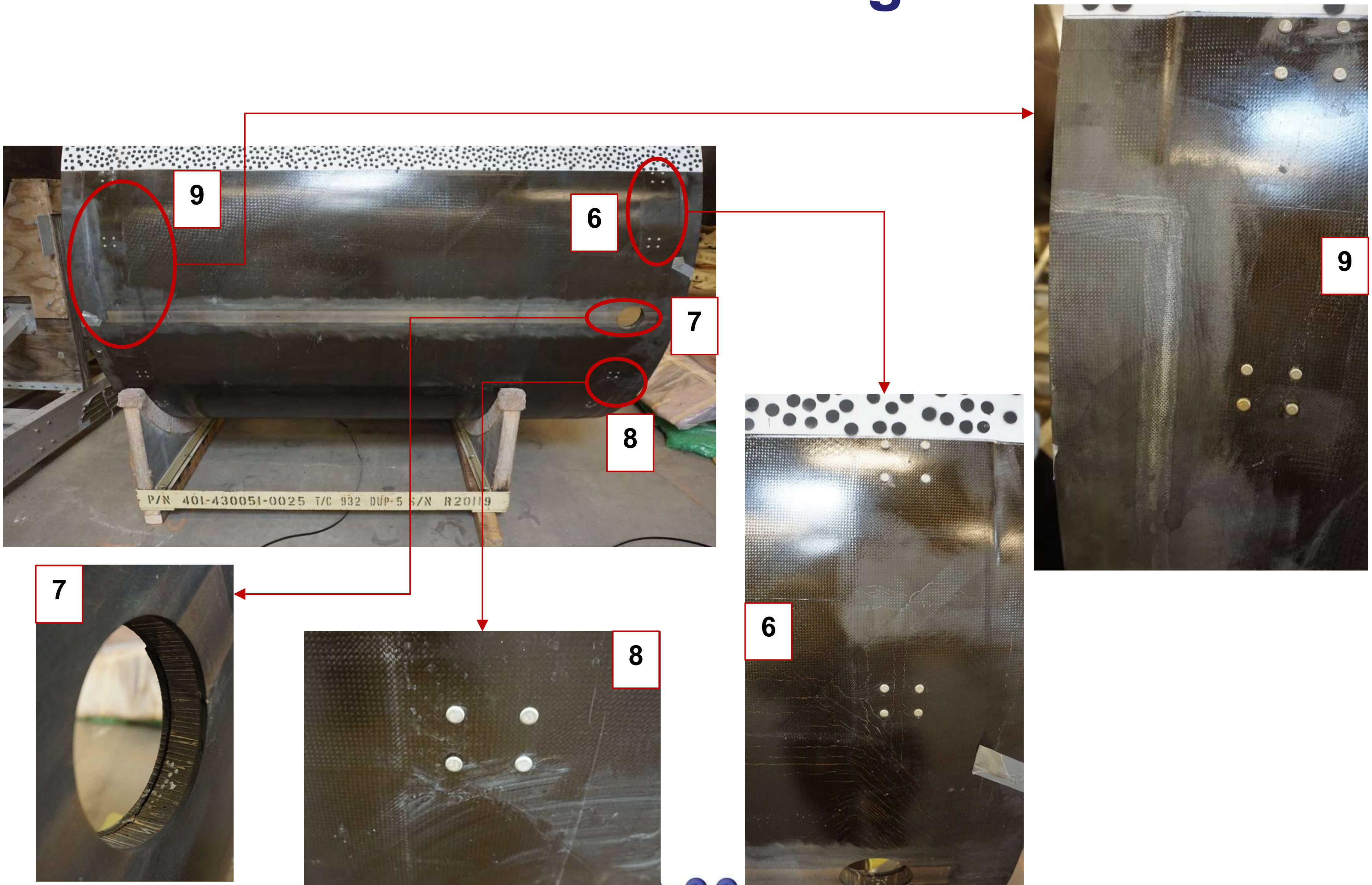
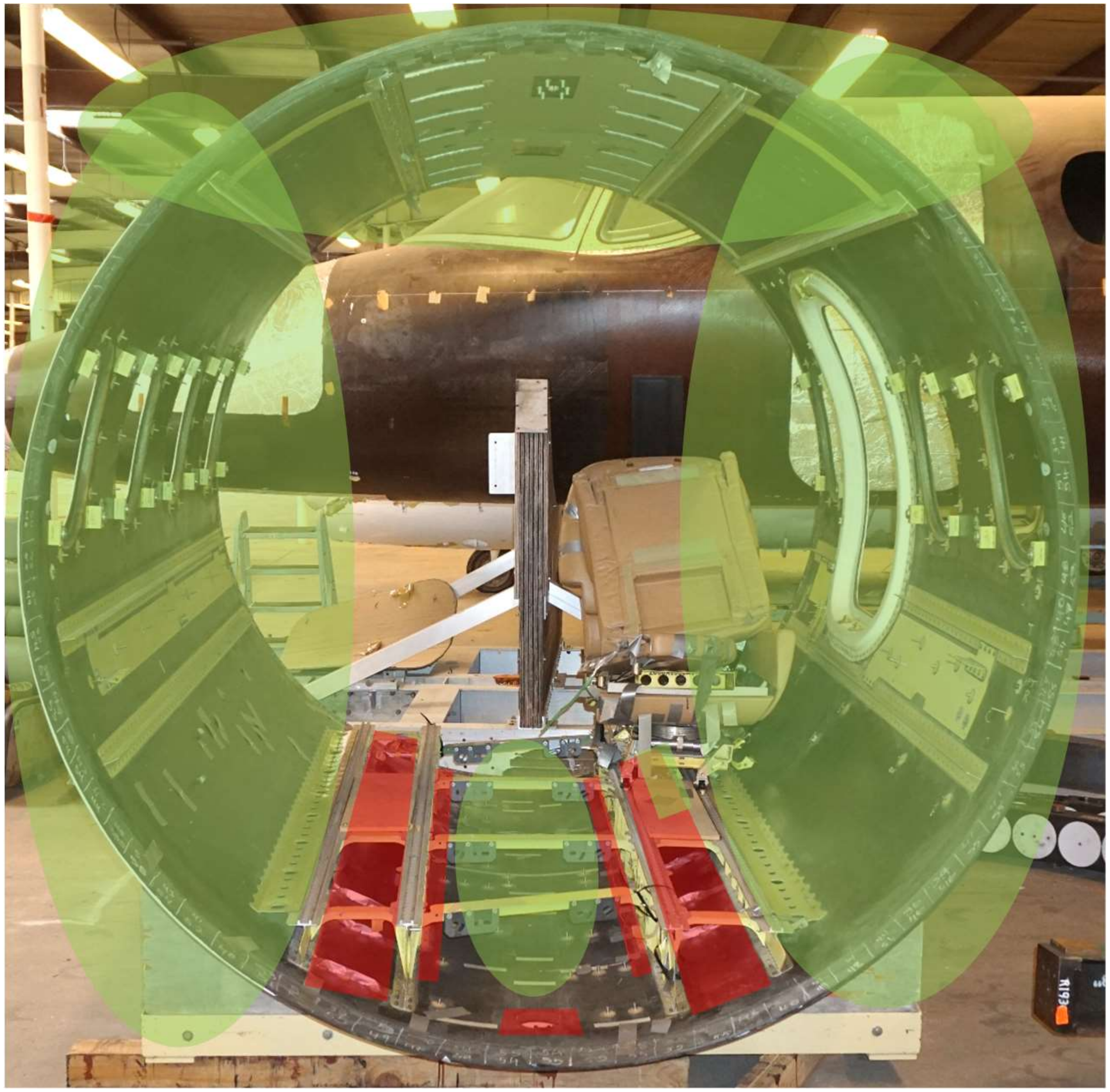
Test Results - Bottom Fuselage



Preliminary NDT Test Results – Flaw Detection Areas



Equipment: Olympus BondMaster 600

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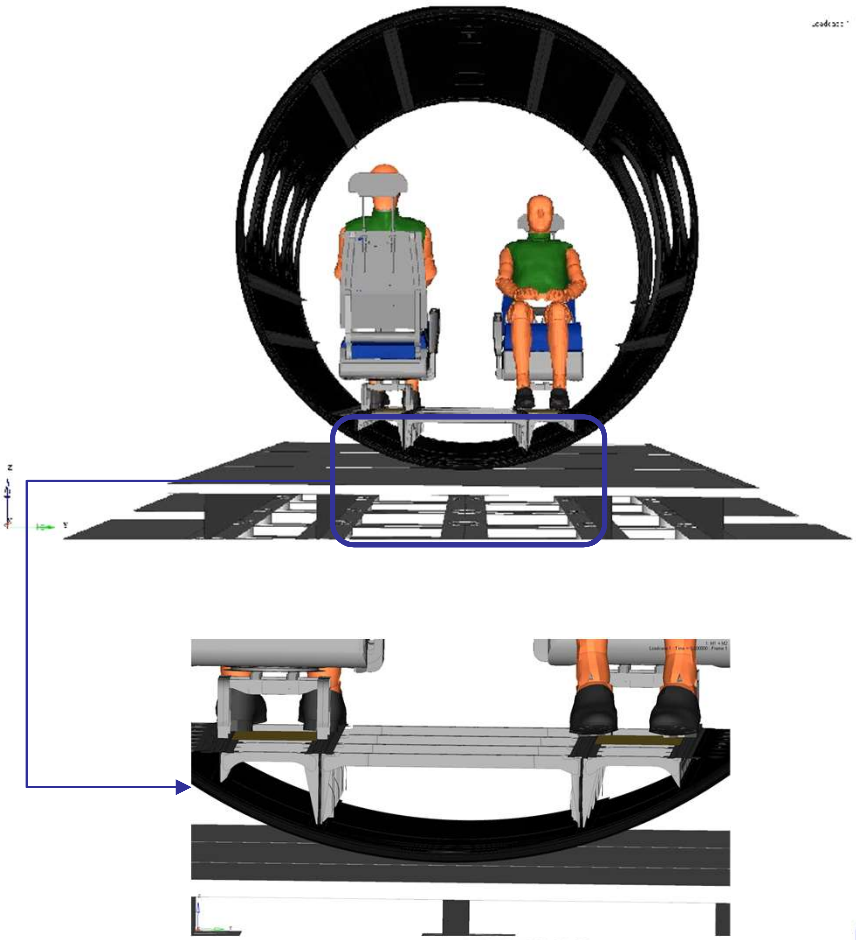
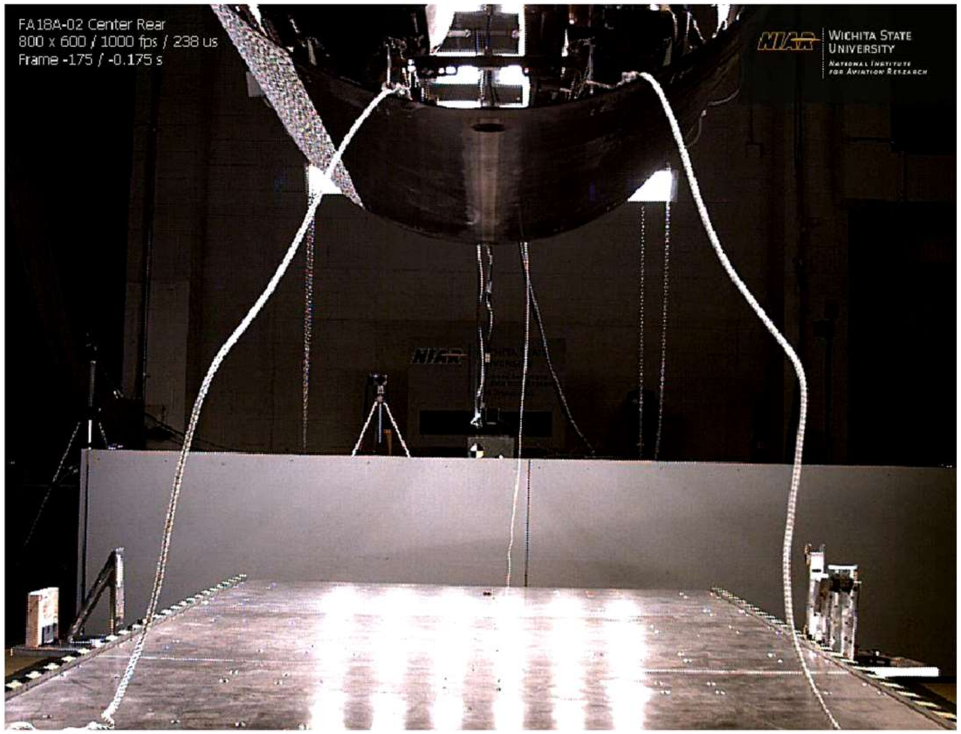
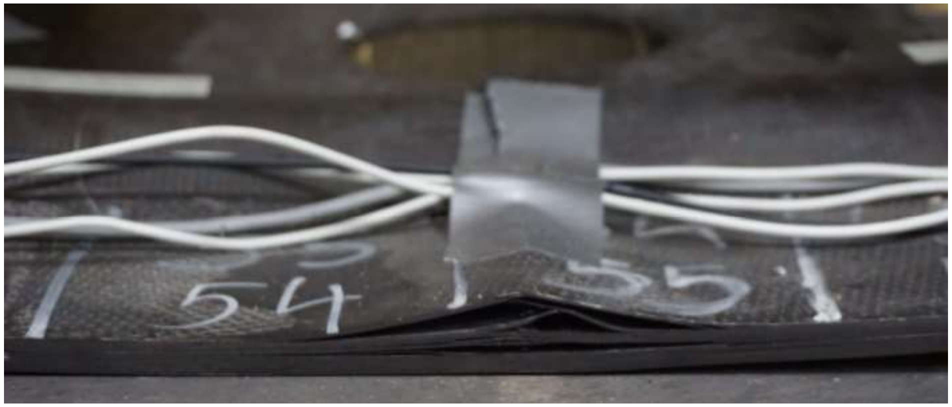
KART-Industry Simulation Model





Proposed Future Research CBA Composite Structures – CBA Modeling Methodology

- **Phase I:** Composite Best Modeling Practices: – 3 months
  - H4000 Fuselage Drop Test: Conduct Damage Evaluation Inspection Techniques:
    - NDE: [Eddy current (EC) method, Ultrasonic (US) method, Radioscopy (X), and/or Thermography]
    - CTSCAN Damage Areas H4000 Fuselage Drop Test to identify failure modes.
- **Phase II:** Coupon and Component Level Testing program to improve predictions of composite structure failure mechanisms – 6 months
- **Phase III:** Update Global H4000 FEA Model and Validate with Drop Test Data – 3 months
- **Phase IV:** Update Modeling Guidelines



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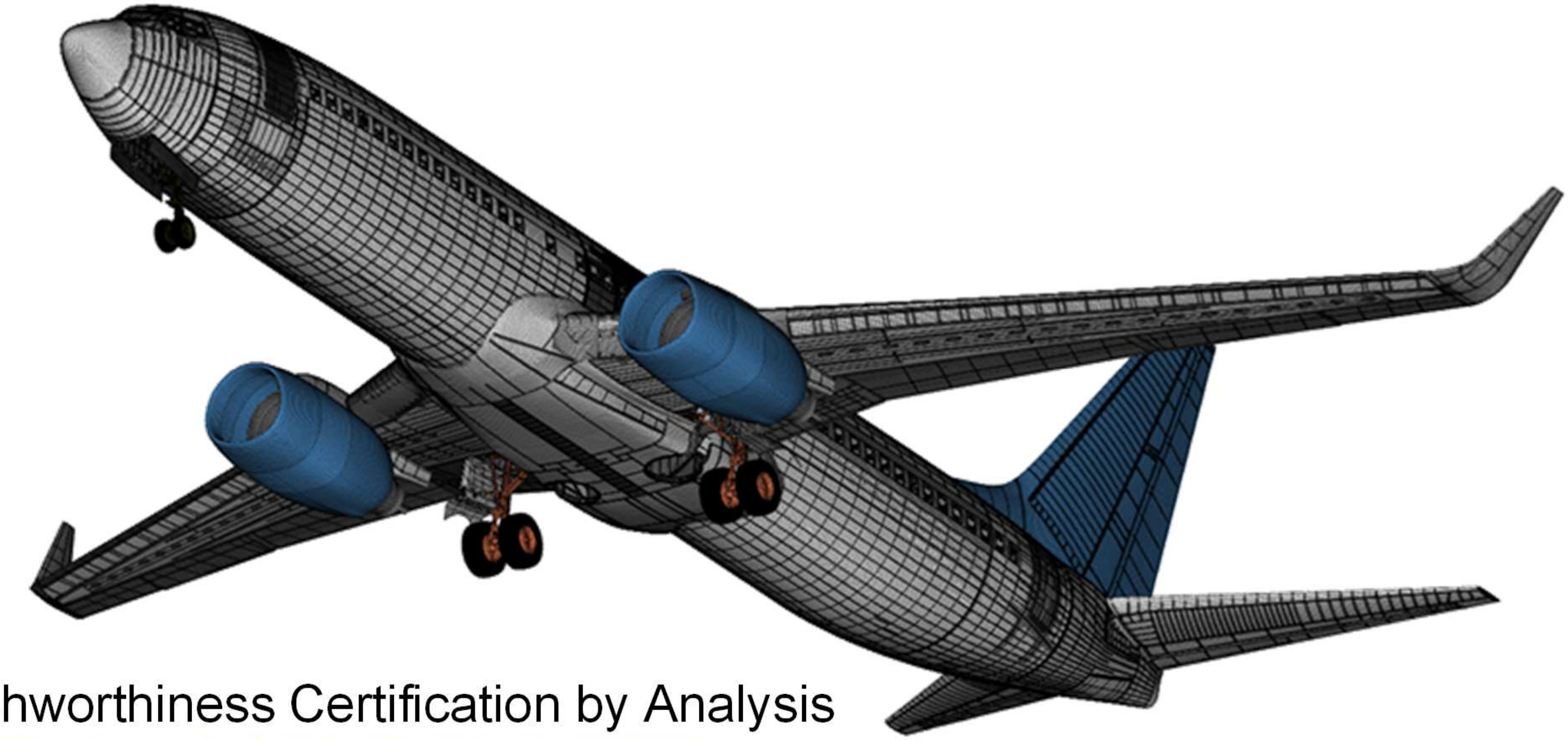

Crashworthiness Certification by Analysis

FULL AIRCRAFT CRASHWORTHINESS AND DITCHING R&D TO SUPPORT ARAC GROUP

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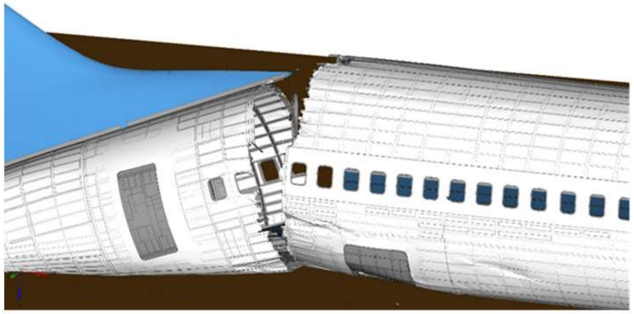
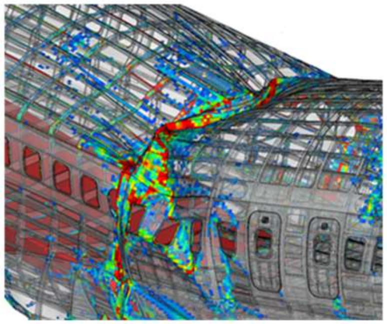
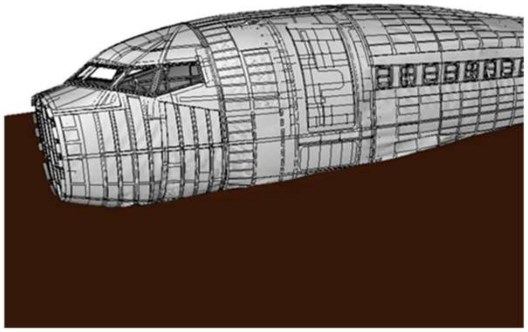
Full Aircraft Model Validation – Emergency Landing

- Final Model and Report will be completed by September 2018
- Solved the challenges of coupling Aerodynamic, Propulsion, and Structural analysis







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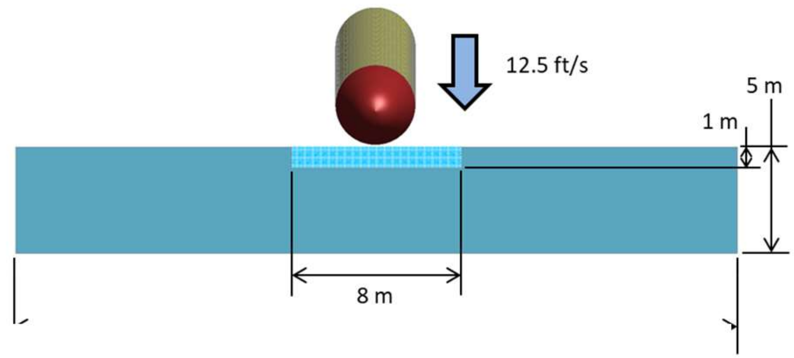
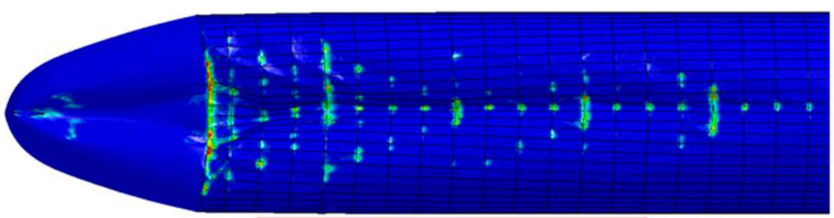
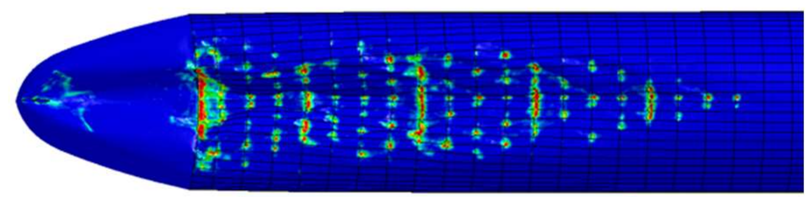
Full Aircraft Modeling Techniques - Ditching

- Project on Schedule
- Evaluating Modeling Techniques
  - SPH
  - Hybrid Methods
- Simplified Model Analysis:
  - Evaluate SPH Particle Pitch
  - Modeling Techniques
- Full Aircraft Simulation:
  - Hudson Ditching Event Conditions
- Draft Report November 2018





Particle pitch: 50mm
Particle mass: 0.125 Kg



Particle pitch: 80mm
Particle mass: 0.492 Kg

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Full Aircraft – ARAC Model – Hudson Ditching

2.4 million SPH (80mm pitch)

- Hudson River landing conditions
  - ARAC aircraft model
  - "Rigid" engines
  - No Landing gear
  - No lift/thrust

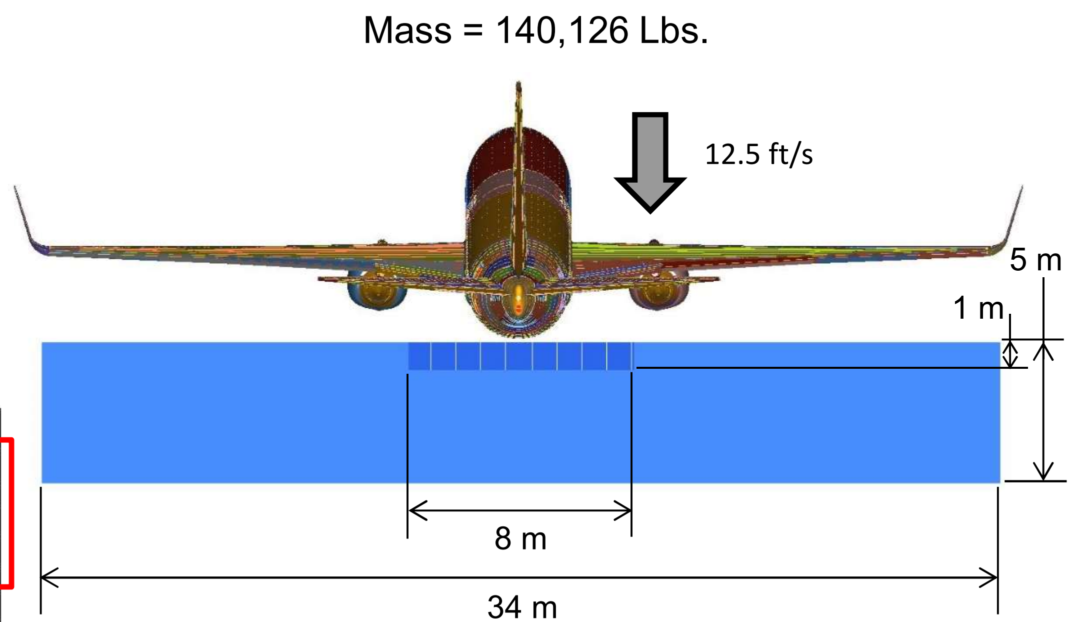
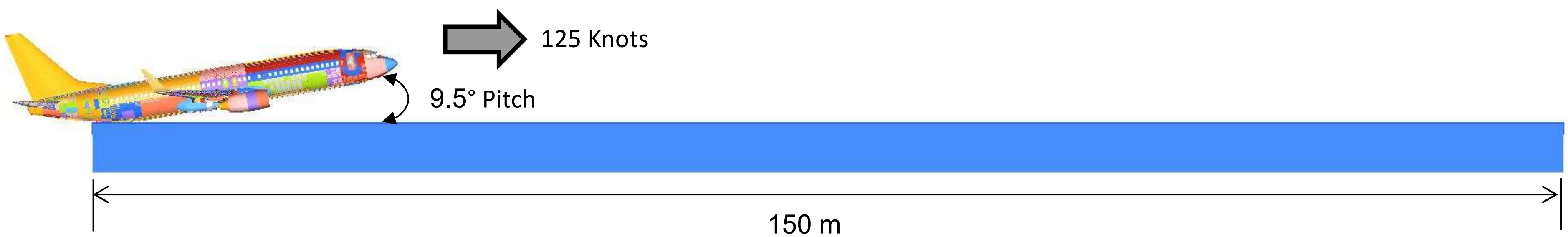


Table 2. Certification and accident flight values.

	Certification	Accident Flight
Mass (in pounds)	145,505	151,017
Pitch attitude (in °)	11	9.5
Airspeed (in knots)	118	125
Glideslope (in °)	-1	-3.5
Descent rate (in fps)	3.5	12.5
Average external pressure (in psi)	7.3	15.1
Maximum external pressure (in psi)	10.9	22.6



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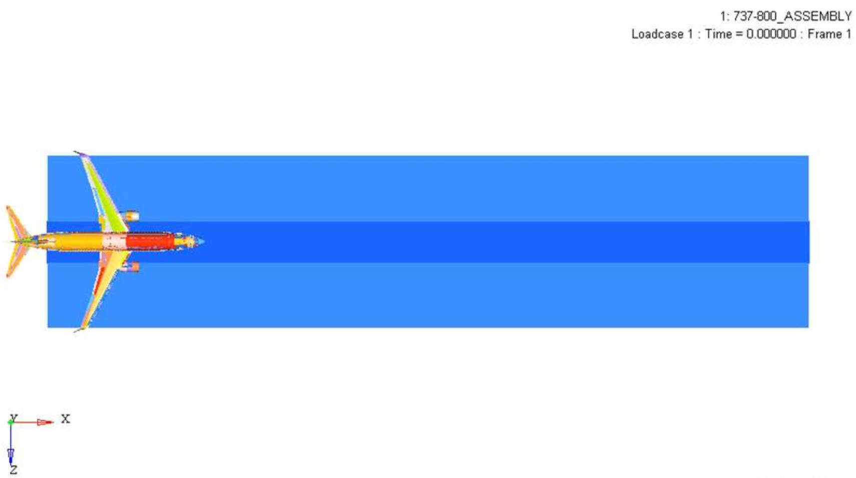
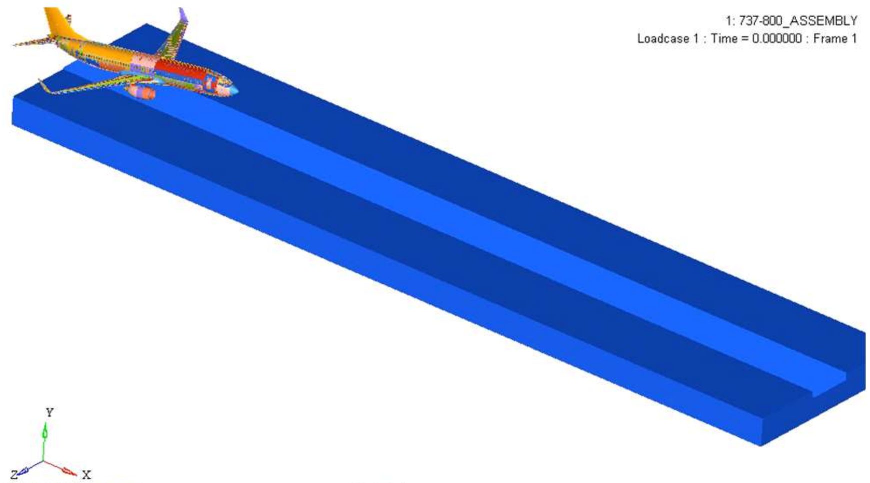
Kinematics

2.4 million SPH (80mm pitch)





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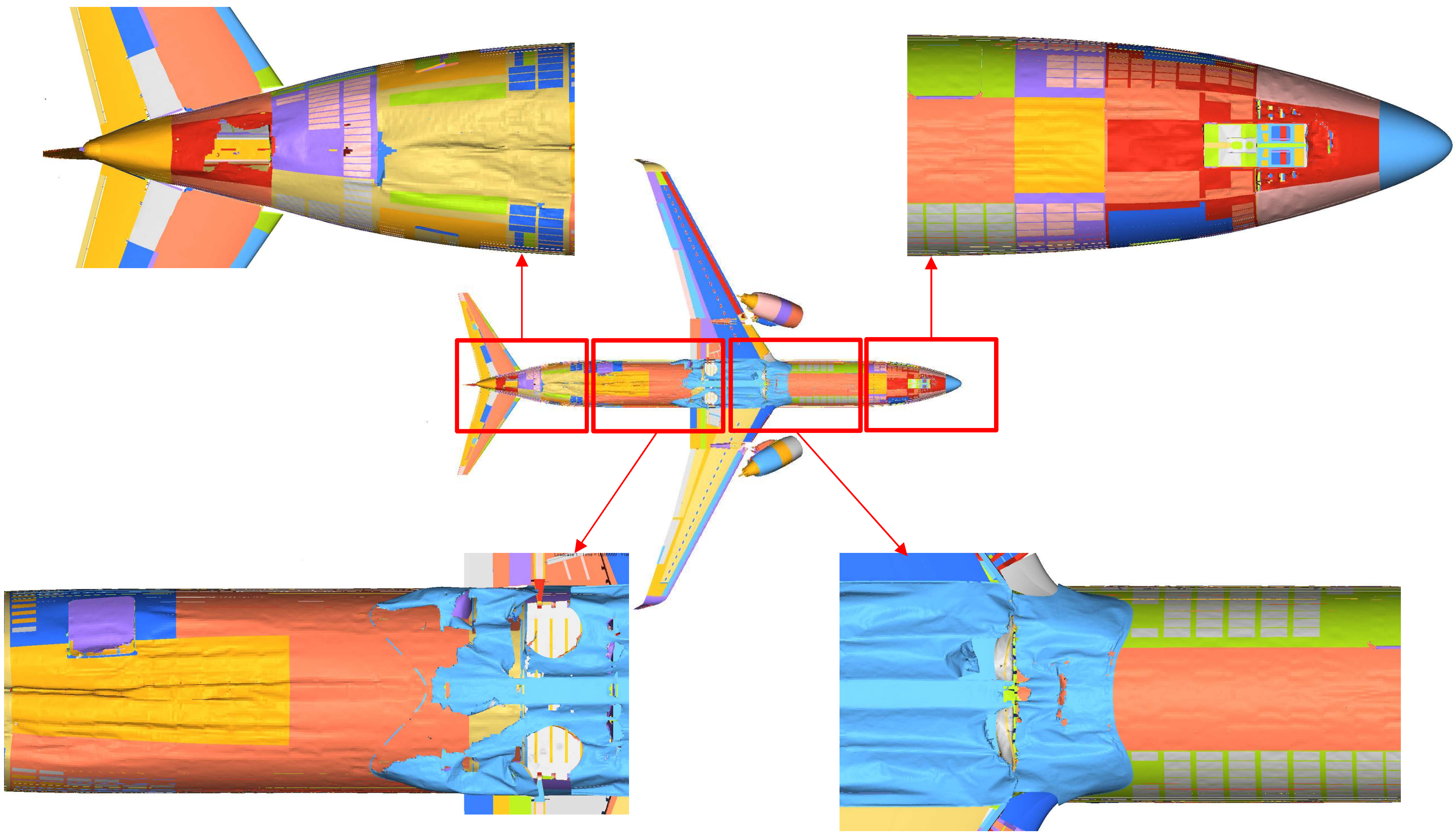
Aircraft Damage Evaluation



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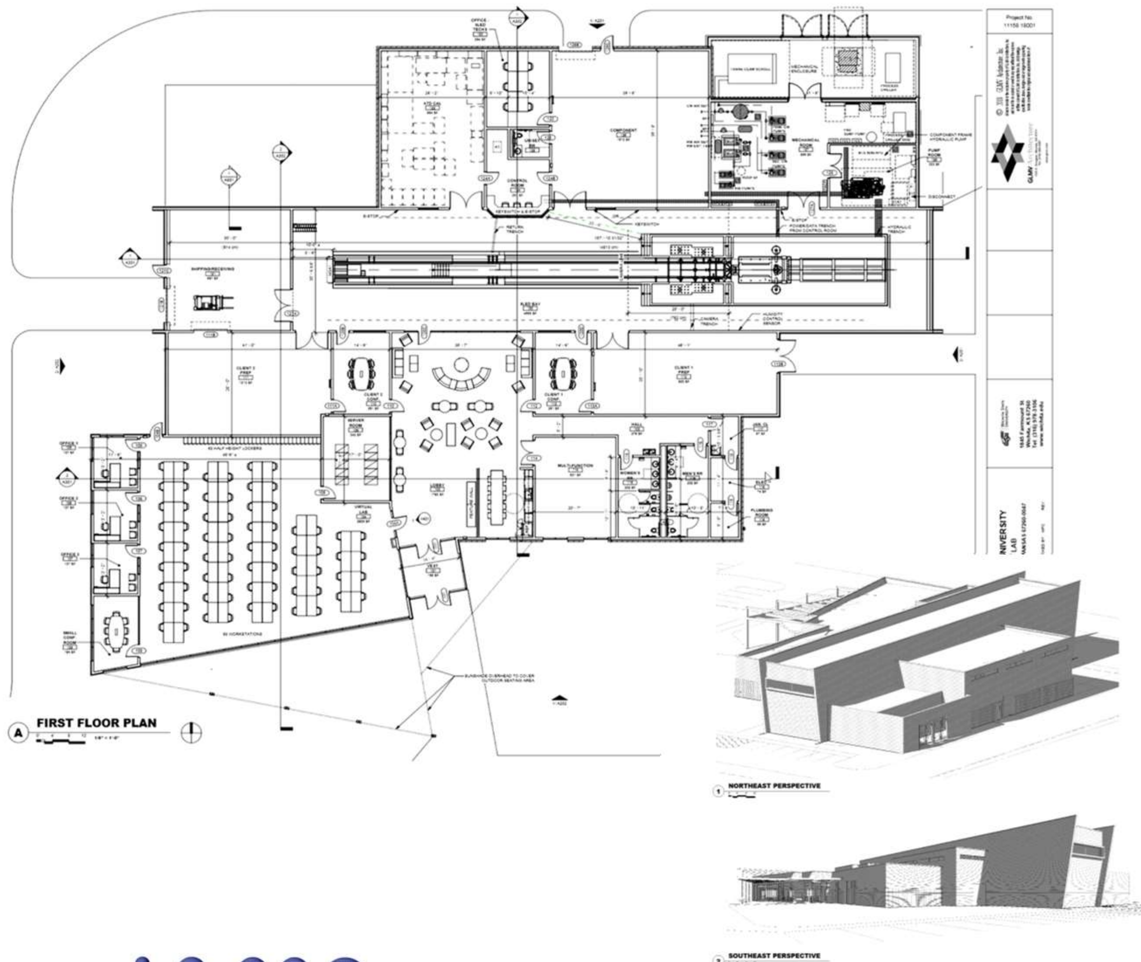
Looking Forward

- Benefit to Aviation
  - Provide a methodology and the tools required by industry to maintain or improve the level of safety of new composite aircraft when compared to current metallic aircraft during emergency landing conditions
  - Improve the understanding of the crashworthy behavior of metallic and composite structures
  - Provide R&D material to the ARAC Transport Airplane Crashworthiness and Ditching Working Group
  - Full Aircraft Ditching Events Structural Performance Evaluation –ongoing
  - The FEA models developed for this program are contributing also to ongoing UAS-Aircraft airborne collision R&D. These models may also be used in the near future for ditching evaluations.
- Future needs
  - Development and Validation of a Metallic and Composites business jet section. Use the experimental data generated in FY 18
  - Develop a representative business jet model to better understand the crashworthiness performance of these type of aircraft certified under 14 CFR 25 – Support ARAC Working group and Industry
  - General Aviation Crashworthiness Design Strategies – Composites Crashworthy Structures
  - Training of Industry and FAA personnel on the use of numerical tools to support the development and certification process

NIAR Crashworthiness R&D Facilities

NIAR 4.0 and vNIAR 5.0

- **September 2019**
- **State of the art aerospace crashworthiness research from coupon level to full scale testing**
- **NIAR 4.0 Labs:**
  - **Coupon Level Testing:**
    - Quasi and High Strain Rate Capabilities
  - **Component Level Tests:**
    - Head Component Level Tester
      - Monitors, Seatbacks, monuments
    - sUAS Ground Collision Certification
    - Seats:
      - Seat Backs EA
      - Seat Cushions
      - Actuators
    - Airbag Drop Towers
  - **Full Scale:**
    - Crash Dynamics Sled
    - Static Seat Testing
    - Fuselage Drop Test Facility
  - **Dummy Calibration Facility**
- **vNIAR 5.0 Labs**
  - **Virtual Engineering Lab**
  - **Virtual Flight Testing Lab**



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