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Composite Aircraft Crashworthiness - Certification by Analysis

Gerardo Olivares Ph.D., NIAR-WSU

JAMS 2019 Technical Review
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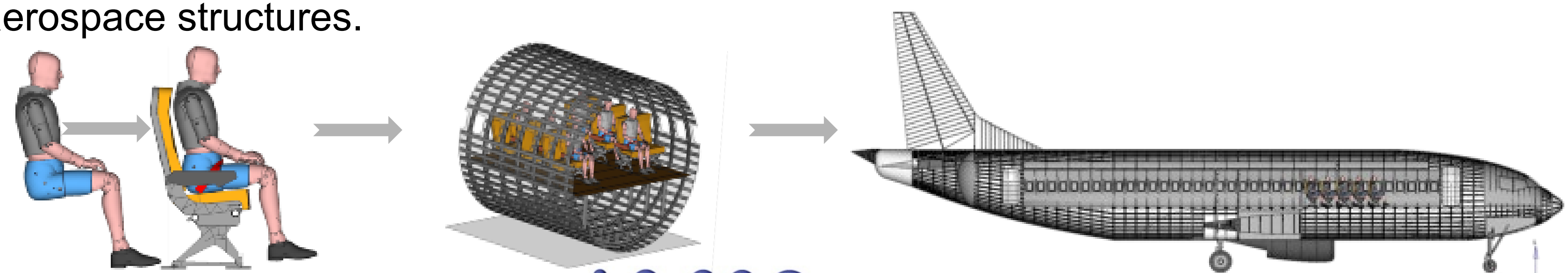
NIAR
WICHITA STATE UNIVERSITY
NATIONAL INSTITUTE FOR AVIATION RESEARCH

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.

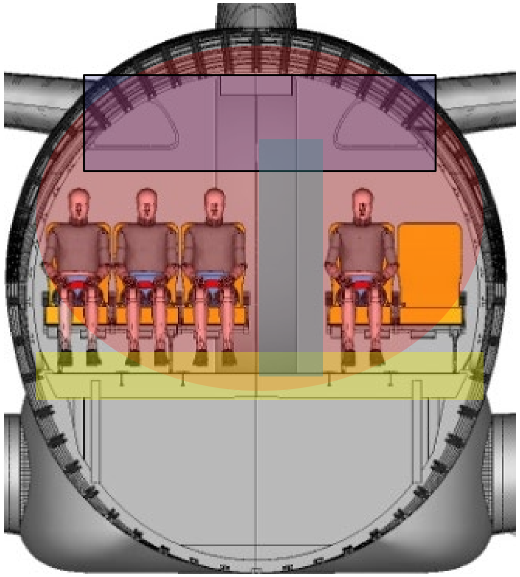


Crashworthiness - Certification by Analysis

- **Principal Investigators & Researchers**
  - **PI:** G. Olivares Ph.D.
  - **Researchers NIAR-WSU:** S. Keshavanarayana Ph.D. , Chandresh Zinzuwadia, Luis Gomez, Nilesh Dhole, Hoa Ly, Armando Barriga, Akhil Bhasin, Aswini Kona
  - **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

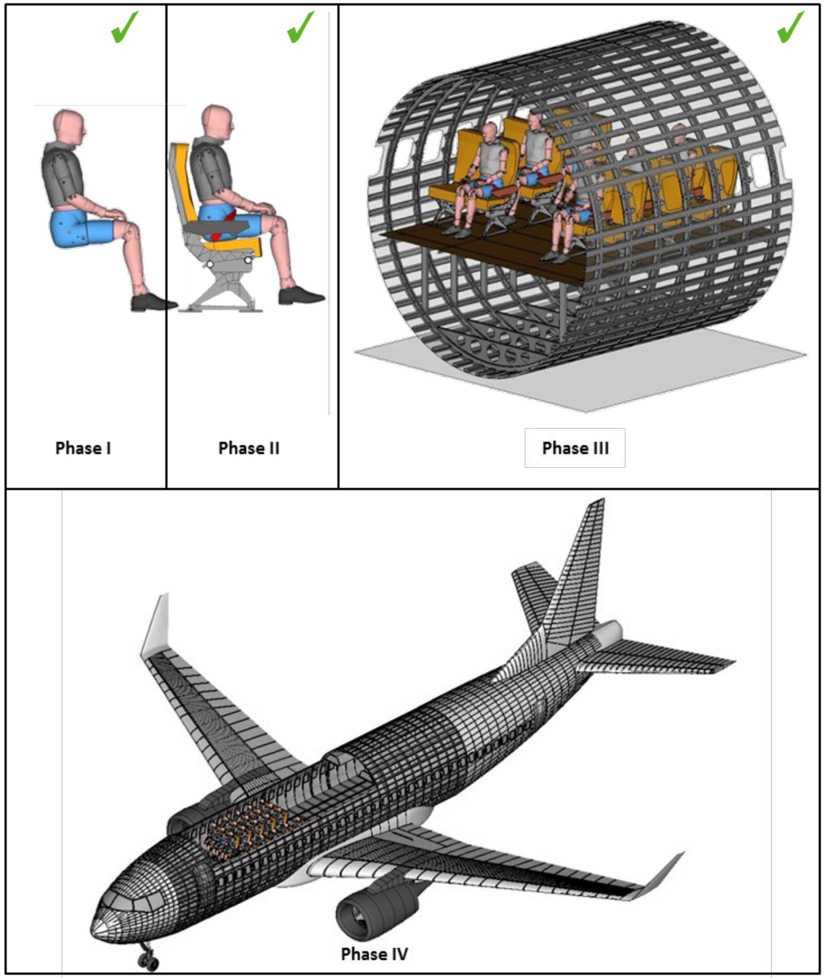
Aerospace Structural Crashworthiness

- **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

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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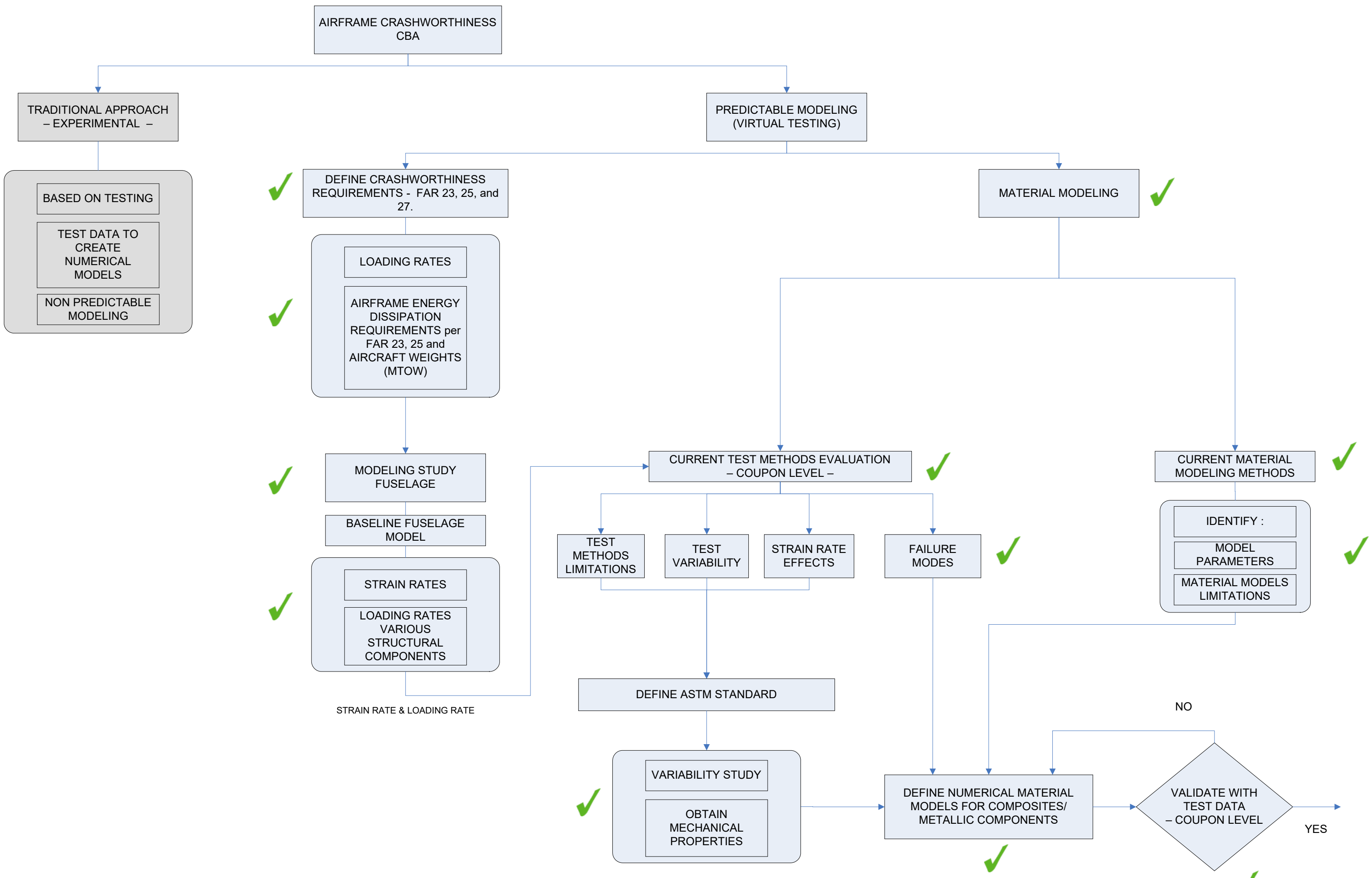
CBA: Composite Structures Crashworthiness



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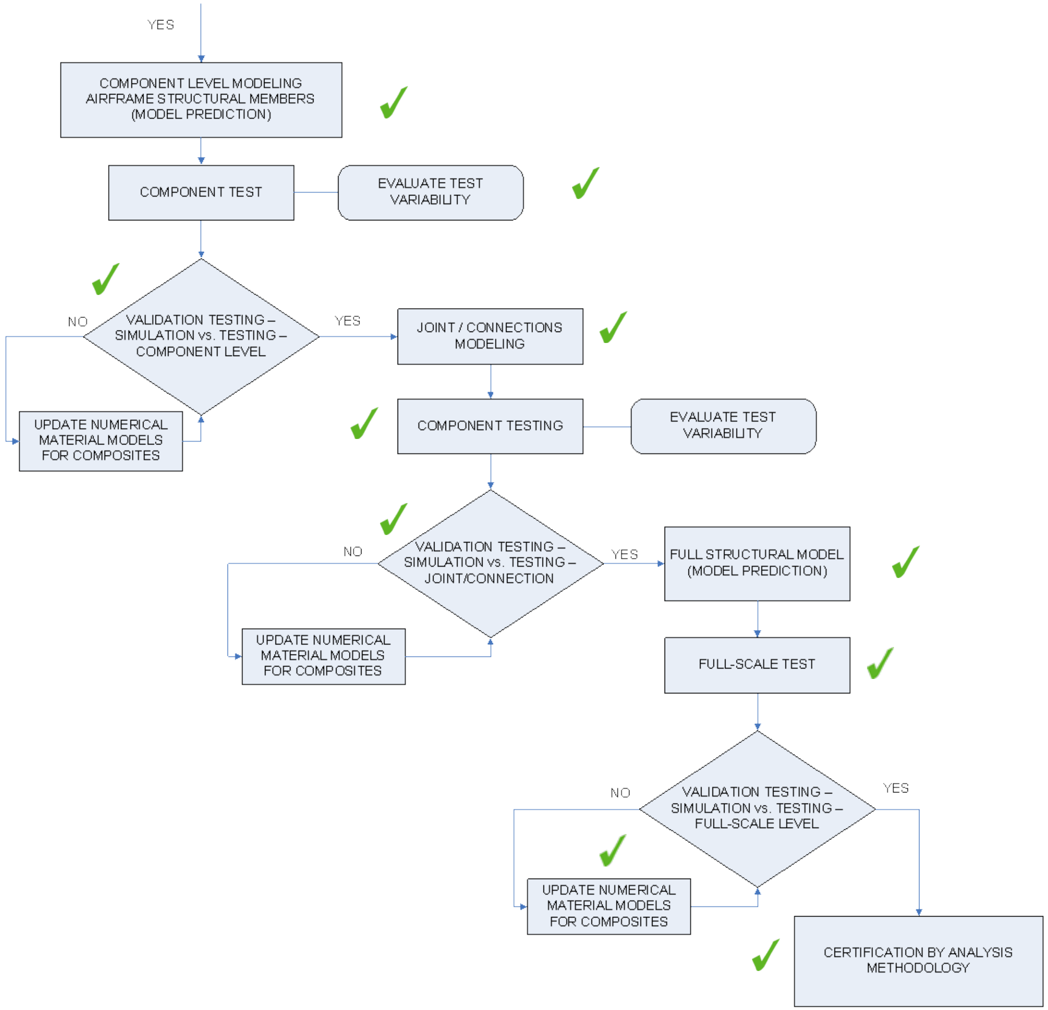
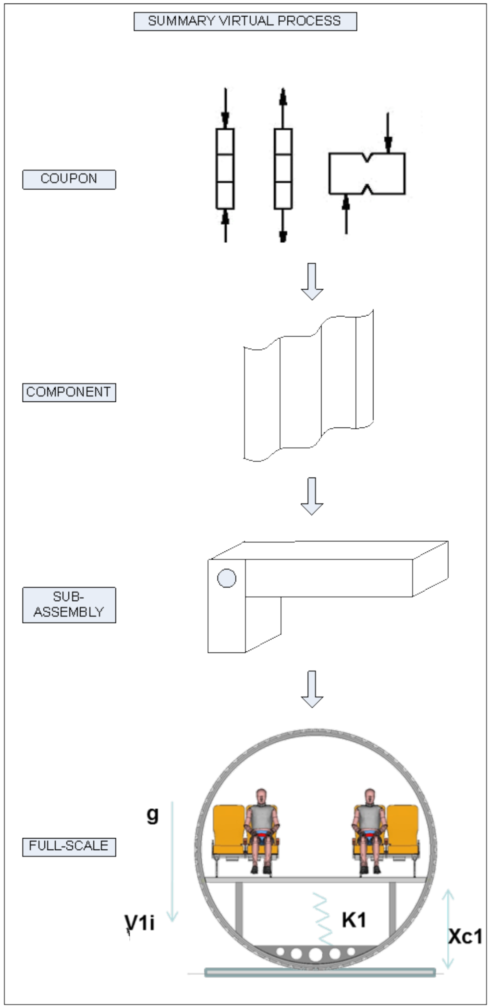
CBA Composite Structures Crashworthiness





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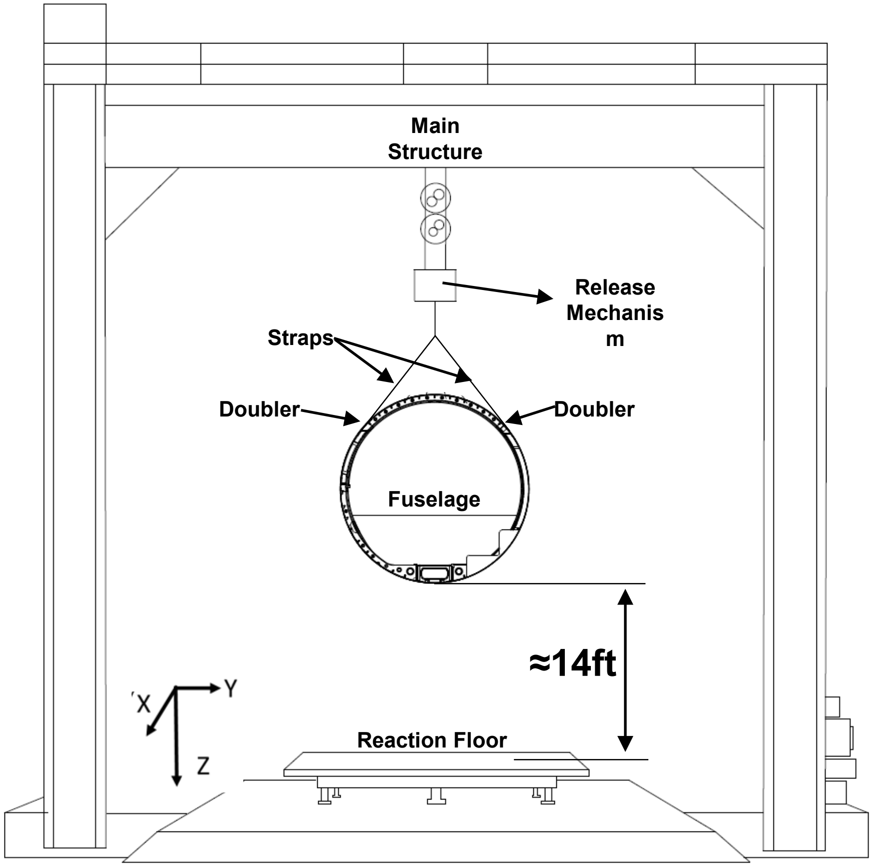
NIAR Drop Tests

- 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 were 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
- If funding is available an additional test is planned with a Bombardier Metallic Fuselage:
  - NIAR purchased the fuselage and seats
  - Testing Q4 2019 or Q1 2020 depending on funding and test facility availability

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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)

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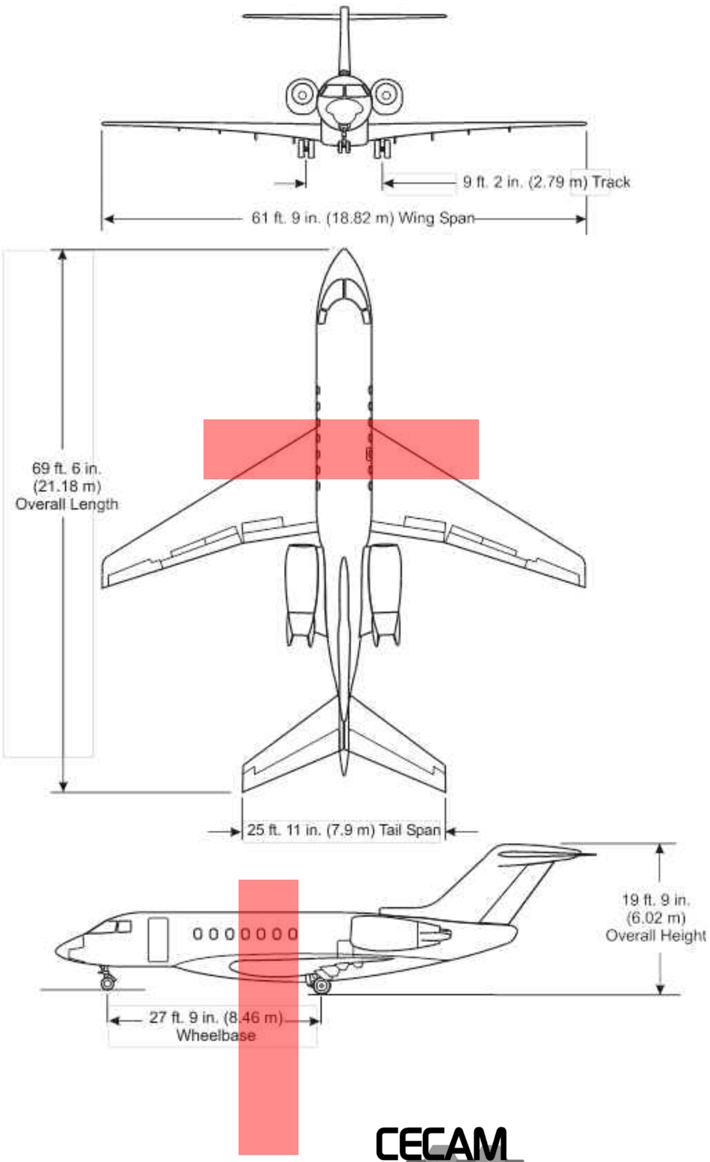
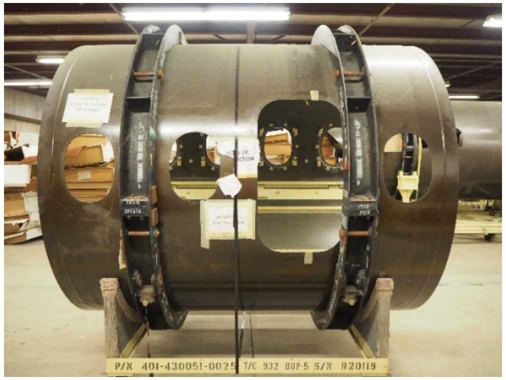
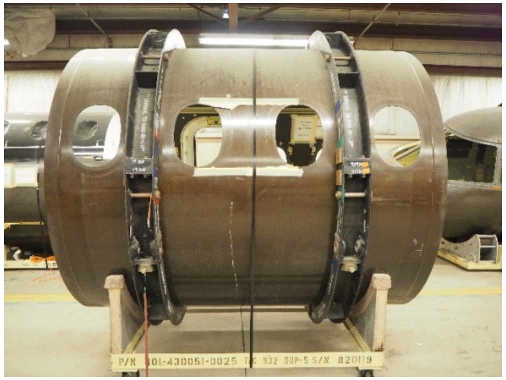
Composite Test Section– Aircraft Location







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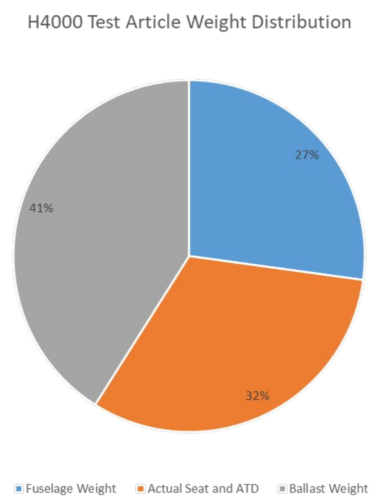
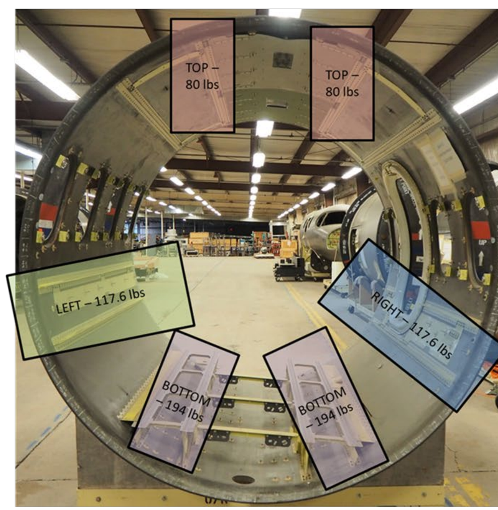
Composite Airframe Drop Test – H4000

- 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





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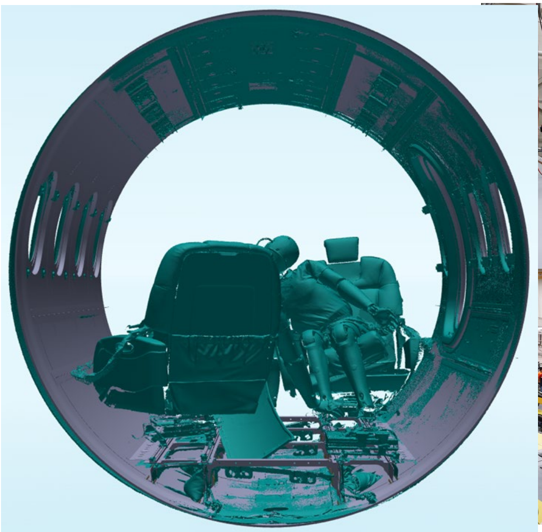
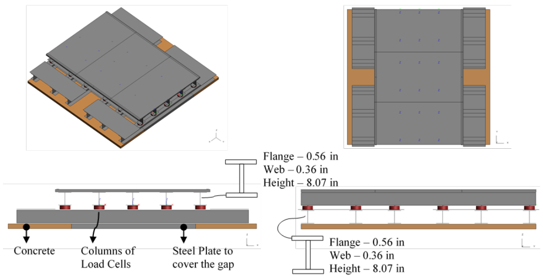
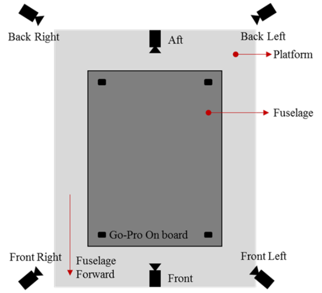
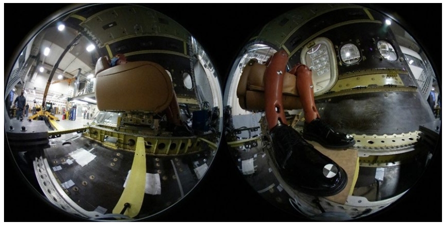
Drop Test Instrumentation

- 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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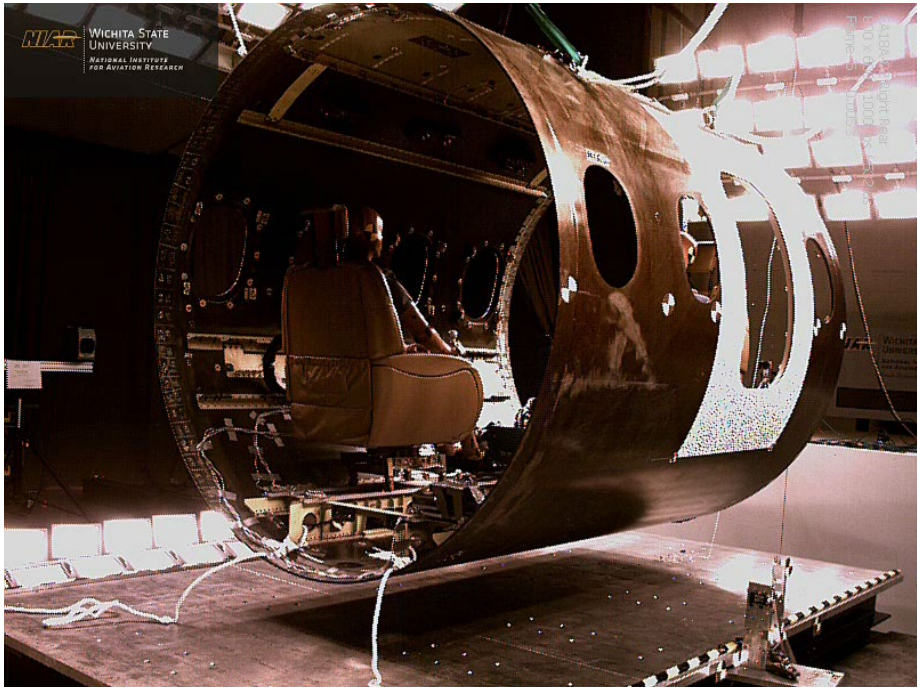
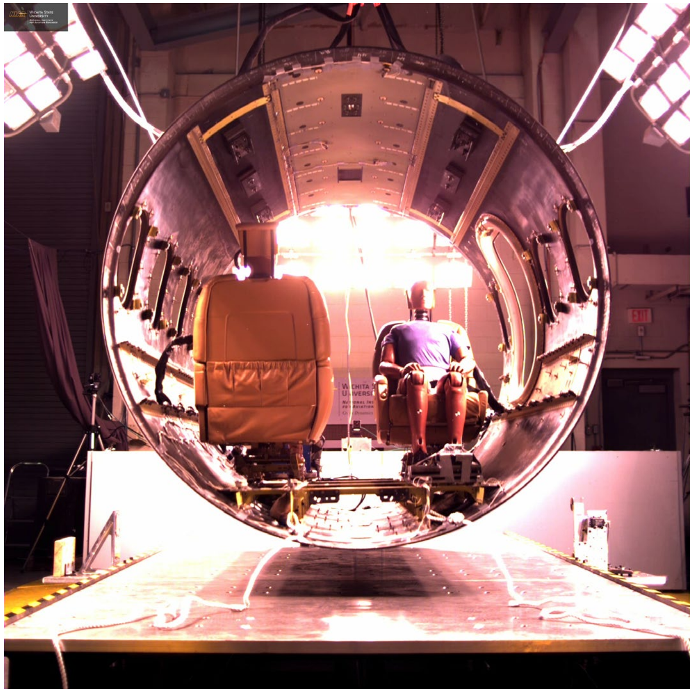
HSV RWD Side and Center View

NIAR Drop Test – Hawker 4000

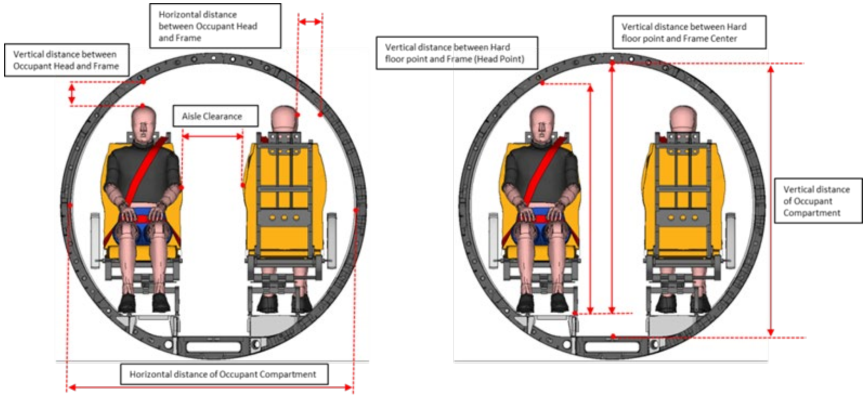


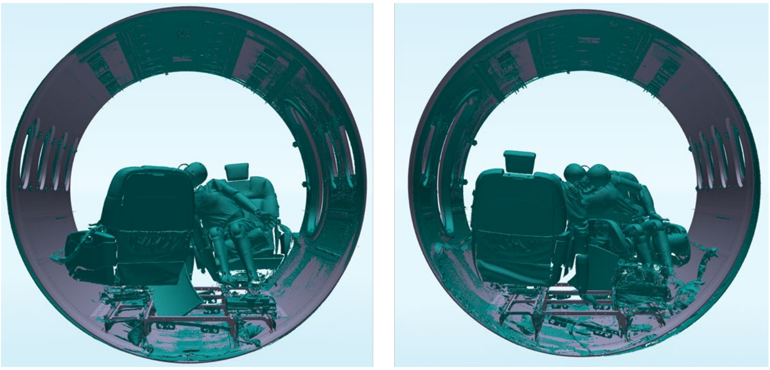


Evaluation Criteria

NIAR Drop Test – Hawker 4000

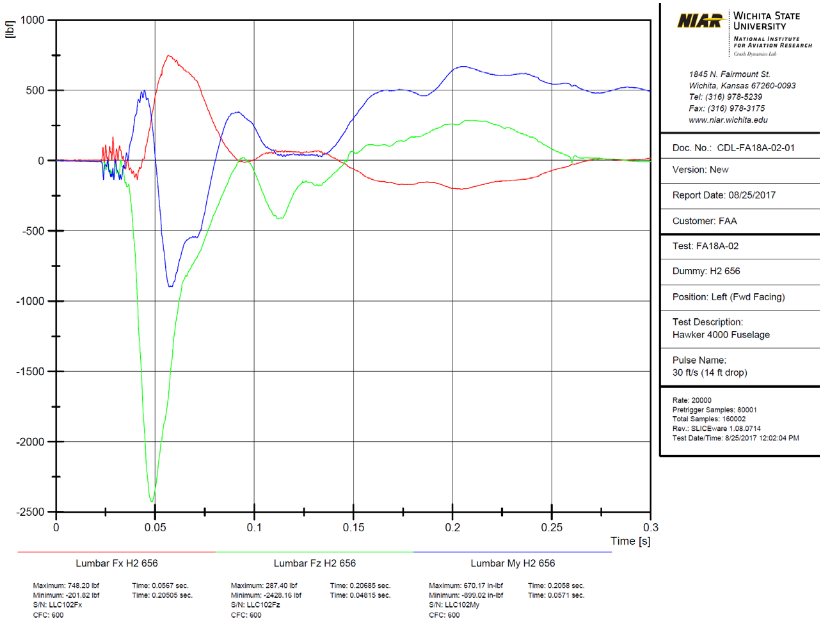
- **Maintain Survivable Volume**
  - **Overall Survivable Space Dimensional Check (Peak during Dynamic Event and Post Test Deformations)** ✓
  - **Avoid Occupant to Interior Structure Contacts during impact** ✓
- **Maintain Deceleration Loads to Occupants**
  - **Injury Criteria Limits per 14 CFR 25.562) :**
    - **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** ✗

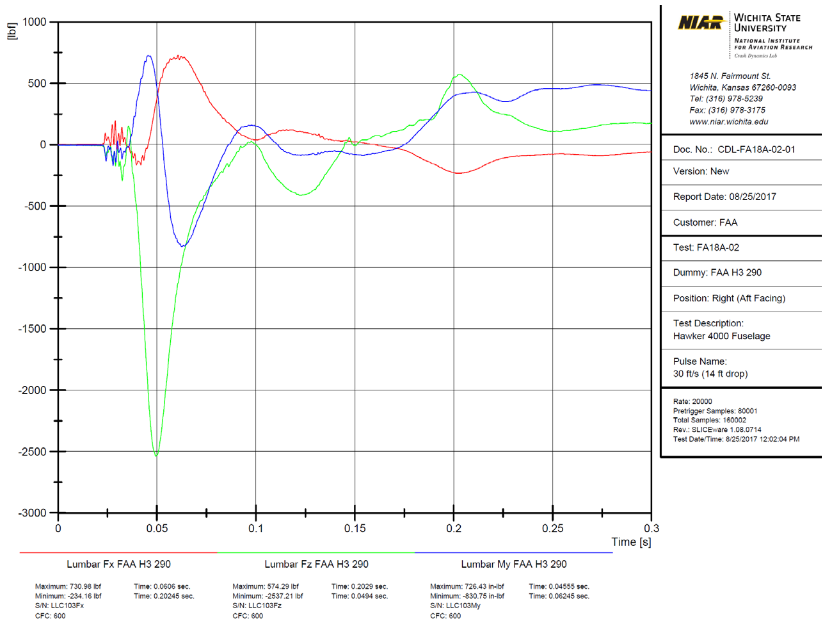




Lumbar Load – HII vs. FAA HIII

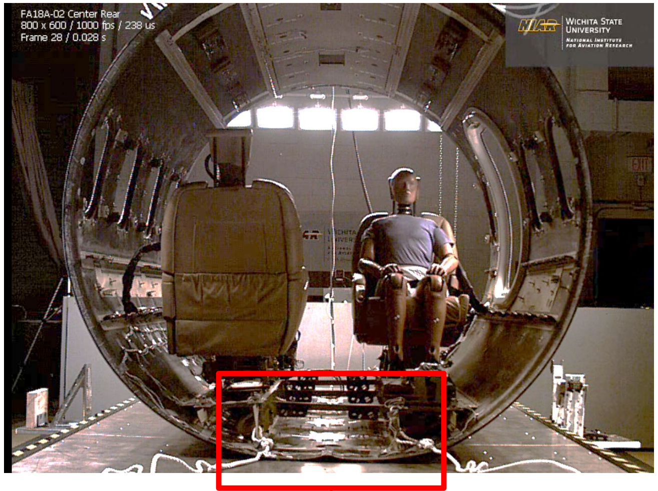
NIAR Drop Test – Hawker 4000

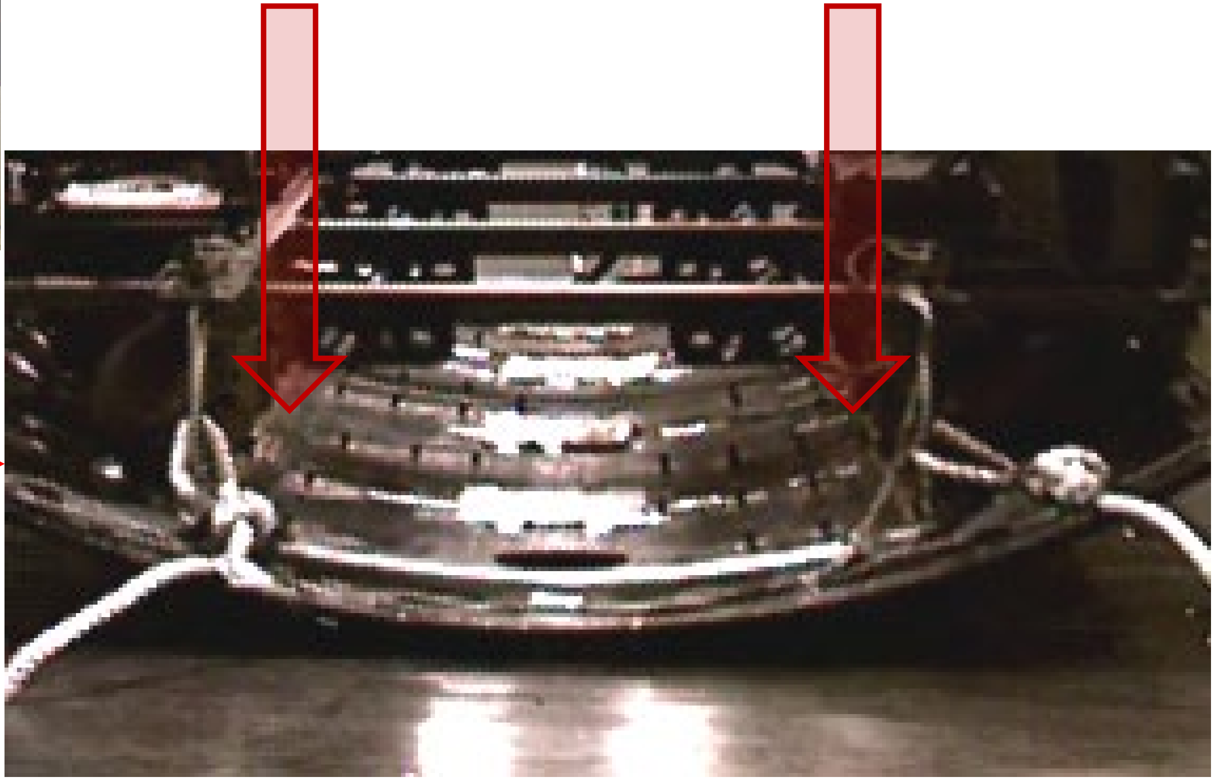




Lumbar Loads: 2500 lbs for both the HII and FAA HIII

Structural Failures Fuselage Structure





NDT Test Results – Post-Impact Inspection

Equipment: Olympus BondMaster 600

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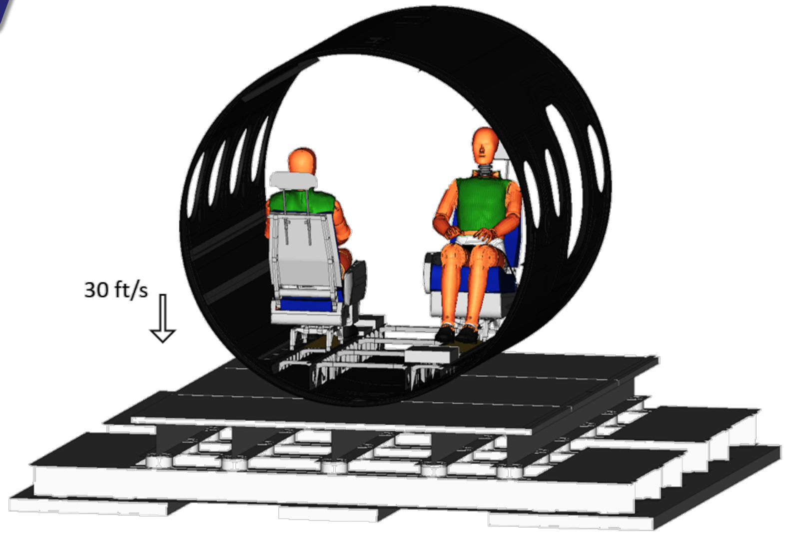
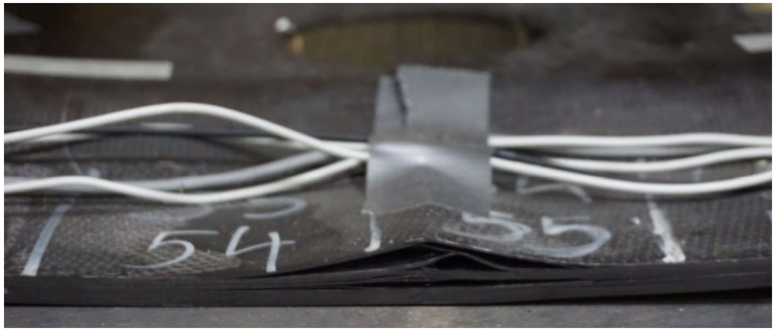
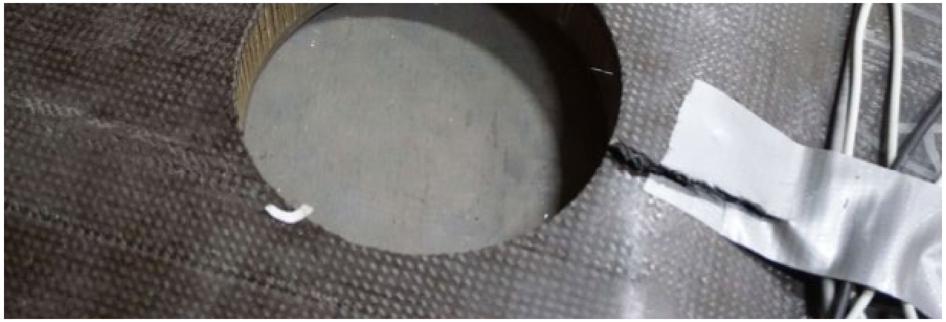
CBA Modeling Methodology



- **Internal NIAR-KART R&D Full Scale Modeling**
- **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:** Vertical Impact Velocity Survibability Study





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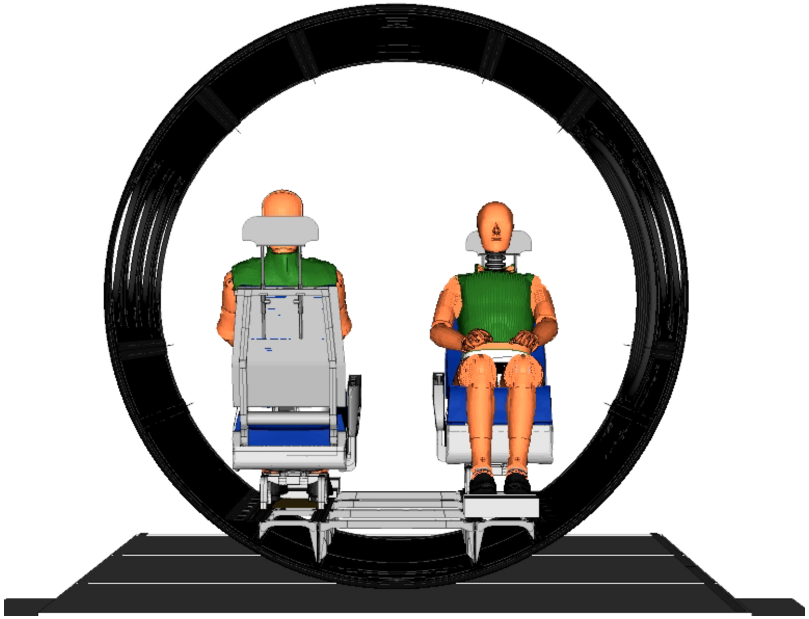
Kinematics Comparison

NIAR Drop Test – Hawker 4000

Simulation
Time = 0.000000



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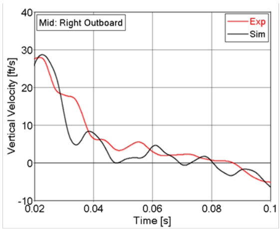
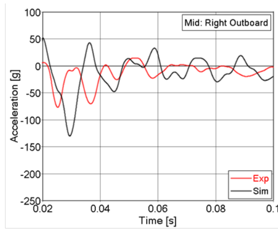
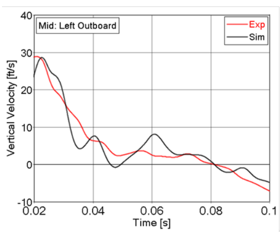
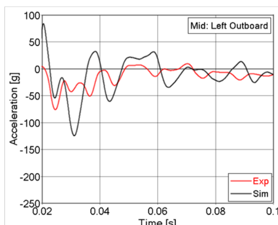
FEA Model Validation

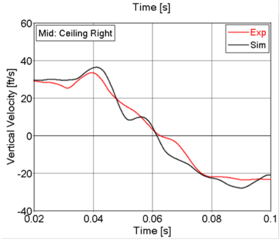
NIAR Drop Test – Hawker 4000

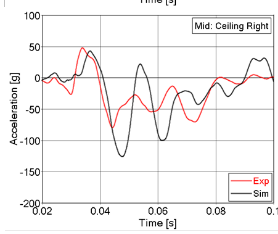


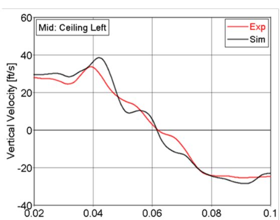


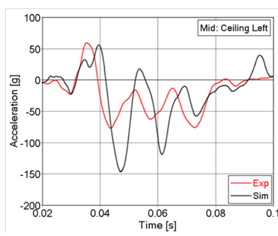


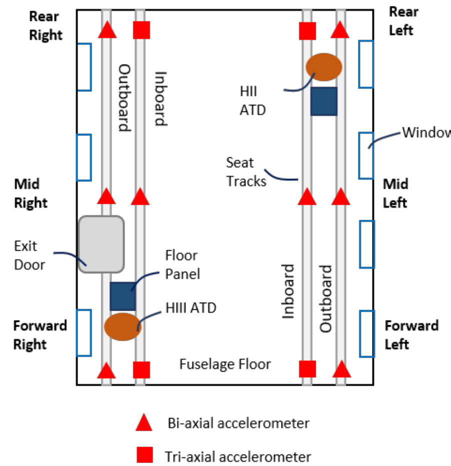


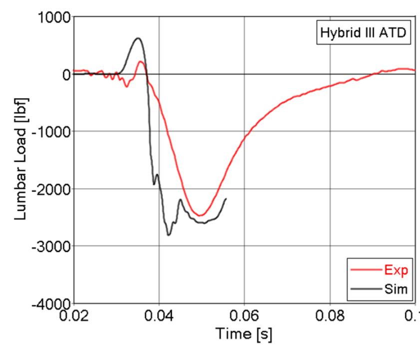




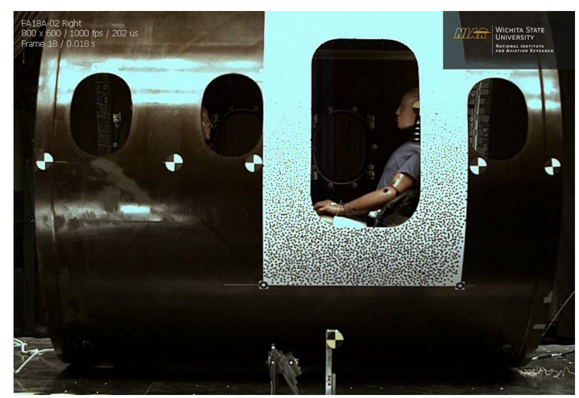








Note: The seat used for analysis is a representative business jet seat but not the actual model used for testing



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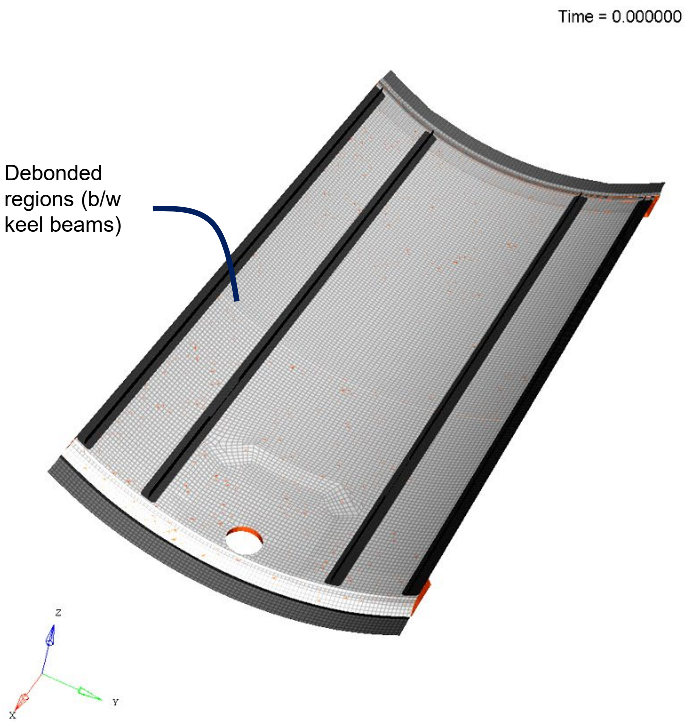
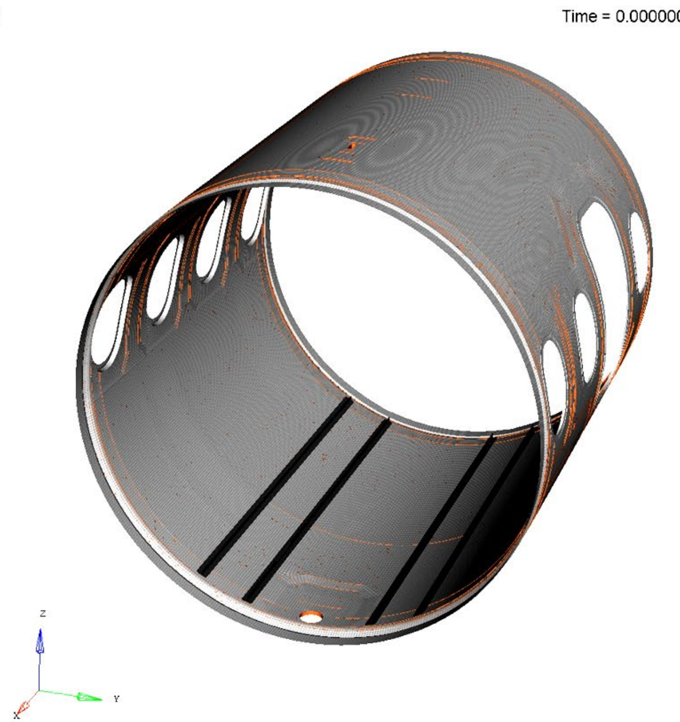
FE Model Structural Failure Mechanisms

NIAR Drop Test – Hawker 4000





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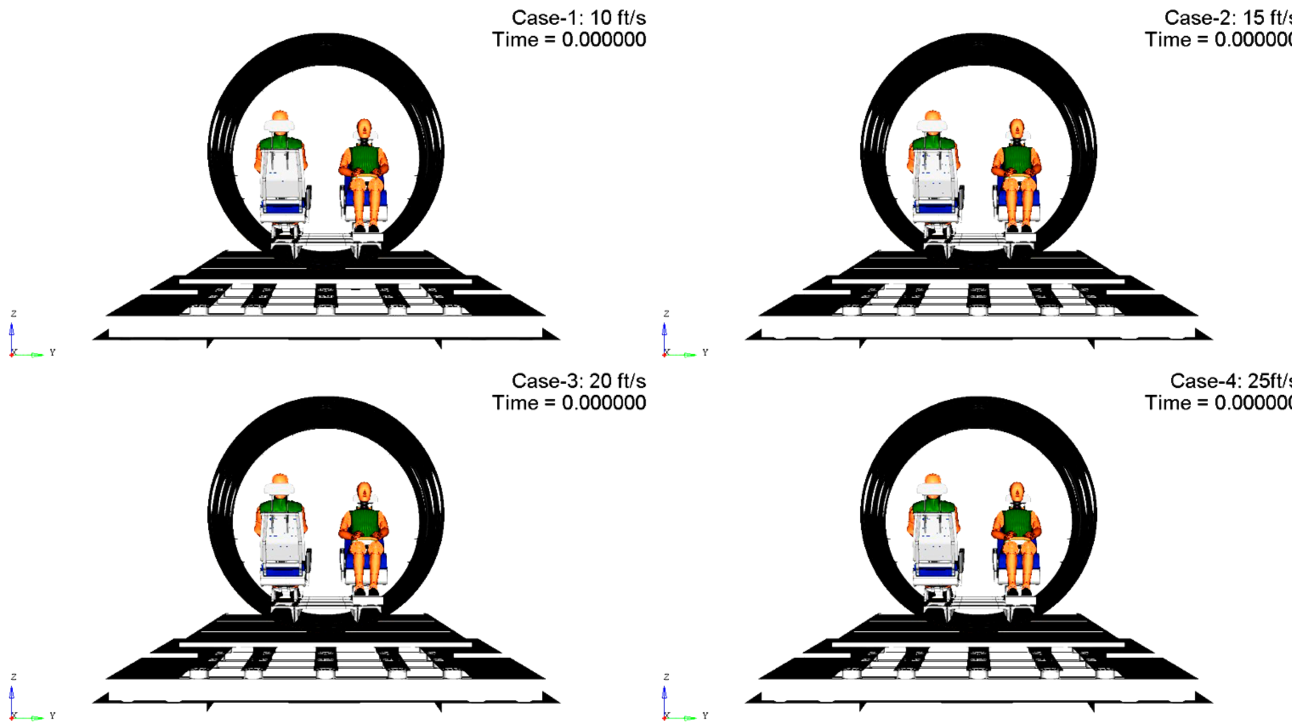
Parametric Study: Velocity Profiles

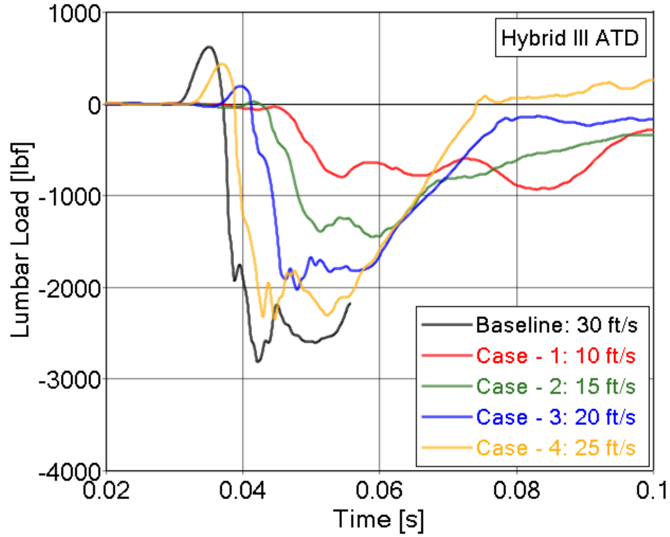
Hawker 4000 Drop Test Analysis

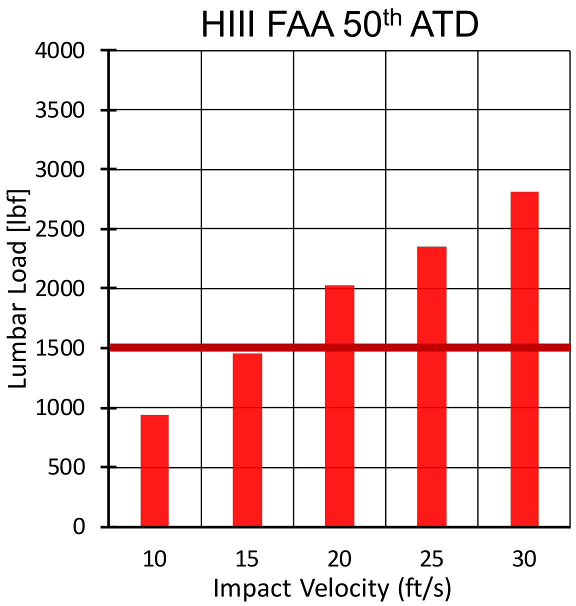
Velocity Parametric Study	
Case ID	**Description**
Case – 1	10 ft/s
Case – 2	15 ft/s
Case – 3	20 ft/s
Case – 4	25 ft/s
Baseline	30 ft/s



Lumbar Load Response – Hybrid III ATD

Parametric Study: Velocity Configurations





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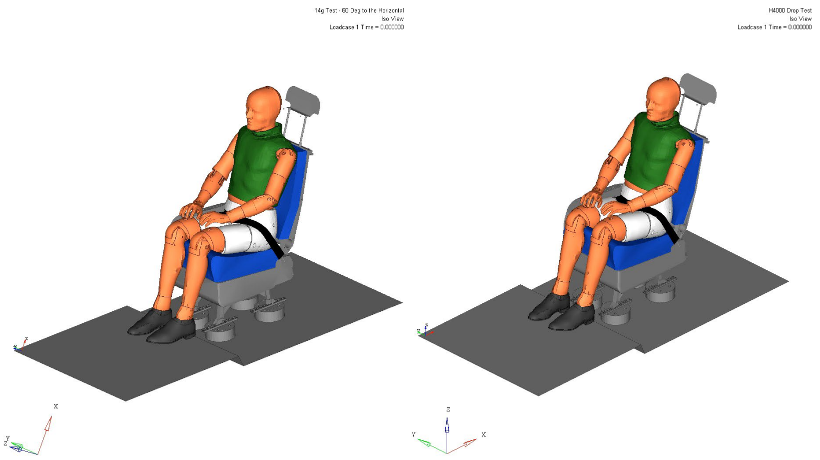
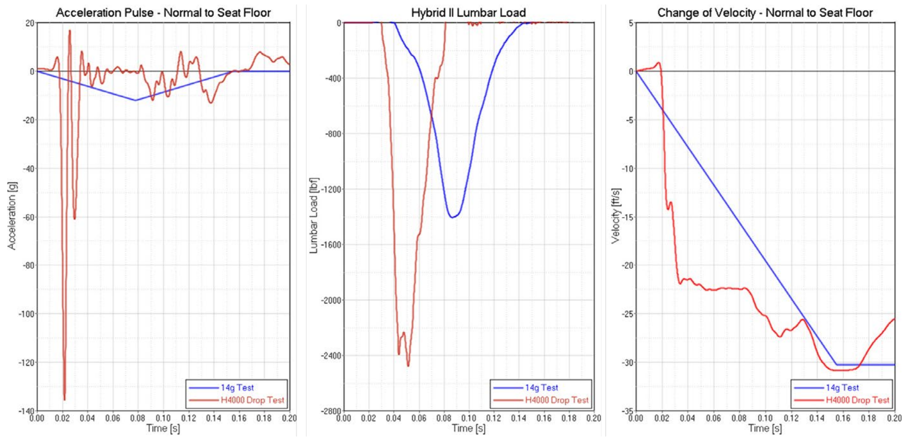
Non-Integrated vs. Integrated Safety

NIAR Drop Test – Hawker 4000





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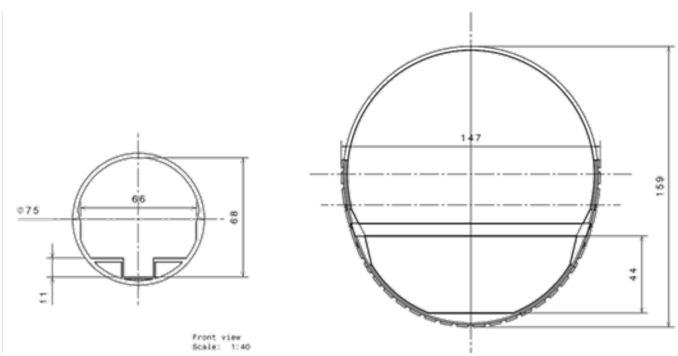
Conclusions

- A building block methodology has been developed to evaluate the crashworthiness response of metallic and composite airframes subjected to Emergency Landing Conditions
- Findings from this research have supported the ARAC Transport Airplane Crashworthiness and Ditching Working Group, SAE Seat Committee and CMH17 Working Group
- Not all aircraft configurations certified under 14 CFR 25 are capable of providing the same level of safety to passengers for a vertical ΔV of 30ft/s. Subfloor configurations with reduced crushable space (14 CFR 25 Business Jets) have shown survivability capabilities up to 18 ft./sec (for metallic, composite or hybrid airframe configurations)



Test I	PART 25
Time to Peak (s)	0.08
Peak - Acceleration Pulse (g's)	14
Peak - Z Acceleration (g's)	12.1
Peak - Z Velocity (ft/s)	31.2
Peak - Z Displacement (inch)	30.3

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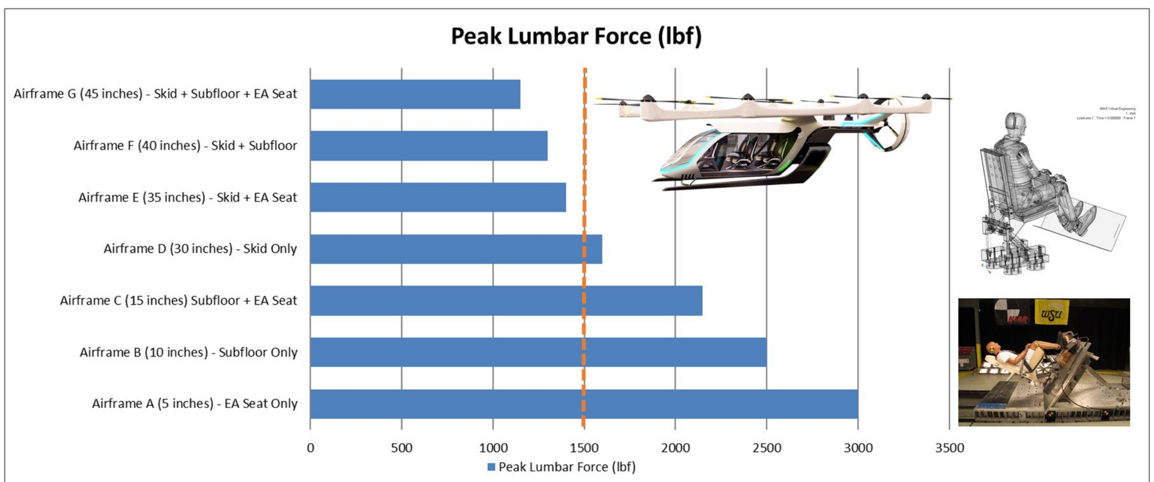
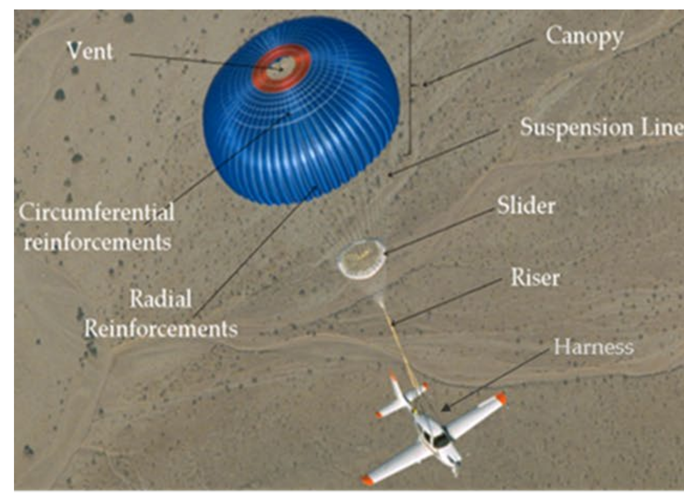
Conclusions (cont)

- The 14 CFR 25.562 dynamic seat requirements for business jets dynamic certified seats should be defined taking into consideration the reduced crushable subfloor space and reduced maximum vertical ∆V airframe/seat capabilities [compared to larger aircraft certified under 14 CFR 25 with 30 inches or more of crushable subfloor space]
- The use of simulation to support the development and certification process will enable the introduction of an integrated safety approach to aerospace crashworthiness, where the restrain system, seat and airframe can be optimized concurrently to improve the occupant survivability rates.
- The introduction of integrated safety will have a big impact in General Aviation and eVTOL Urban Air applications.
- Crashworthiness design needs to be implemented from the conceptual design stage of the vehicle, since the crashworthiness optimization of the various structural elements cannot be implemented once the design has been driven only by airworthiness requirements.

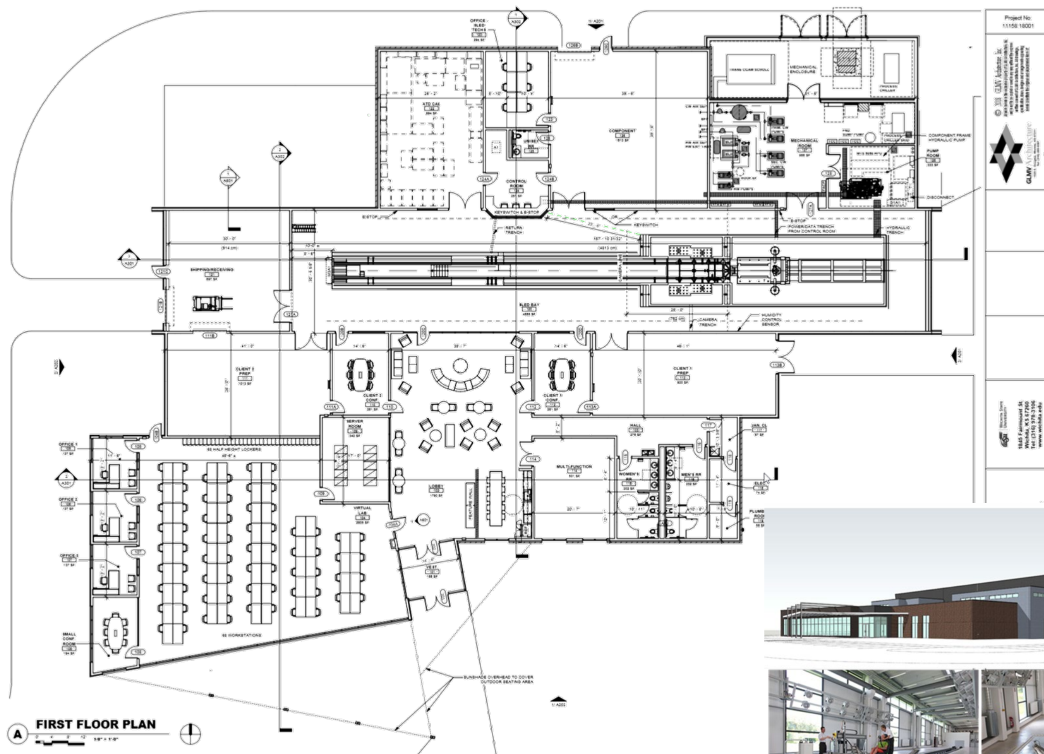




NIAR Aerospace Integrated Safety Center

Experimental and Computational Capabilities

- **November 2019**
- **State of the art aerospace crashworthiness research from coupon level to full scale testing**
- **Experimental Capabilities:**
  - **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**
- **Computational Capabilities:**
  - **Virtual Engineering Lab**
    - **Seat Development and CBA**
    - **Airframe Development and CBA**
  - **Virtual Flight Testing Lab**



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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, FAA CBA Workshops, SAE Seat Committee and CMH 17.
- Future needs
  - Address the effects of defects (damage/repair) on the dynamic response of crashworthy composite seat and airframe structures
  - Urban Air Transport Emergency Landing - Crashworthiness Certification Requirements and Protocols
  - General Aviation Crashworthiness Design Strategies – Composites Crashworthy Structures
  - Integrated Safety Concepts and Technology Demonstrators for GA and eVTOL Vehicles
  - Training of Industry and FAA personnel on the use of numerical tools to support the development and certification process

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