NIAR Wichita State University
National Institute for Aviation Research

Integrated Safety for eVTOL Crashworthiness : From Conceptual Design to Certification

| Gerardo Olivares Ph.D. | Director Crashworthiness and AVET Laboratories| April 13th 2021|

NASA-FAA eVTOL Crashworthiness Workshop # 4

Agenda

Integrated Safety for eVTOL Crashworthiness

- Introduction to eVTOL Integrated Safety Approach
  - eVTOL Safety Challenges
  - Integrated Safety Concept
- Digital Engineering Methods from Conceptual Design to Certification
- Overview FAA Funded Research Programs :
  - FAA-JAMS Crashworthiness
  - FAA-ASSURE AAM/UAM
- Conclusions

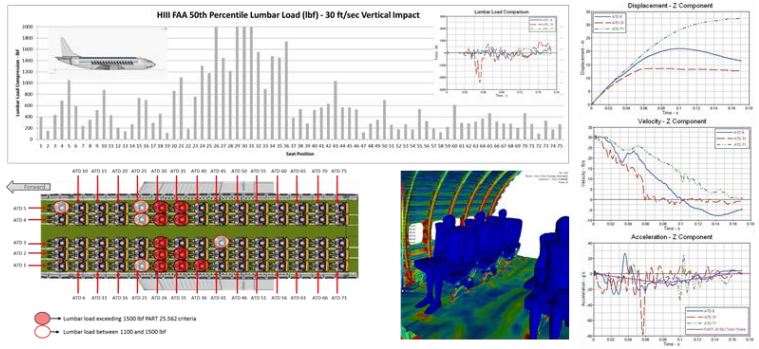
Introduction to eVTOL Integrated Safety Approach

Integrated Safety for eVTOL Crashworthiness

Aerospace Safety

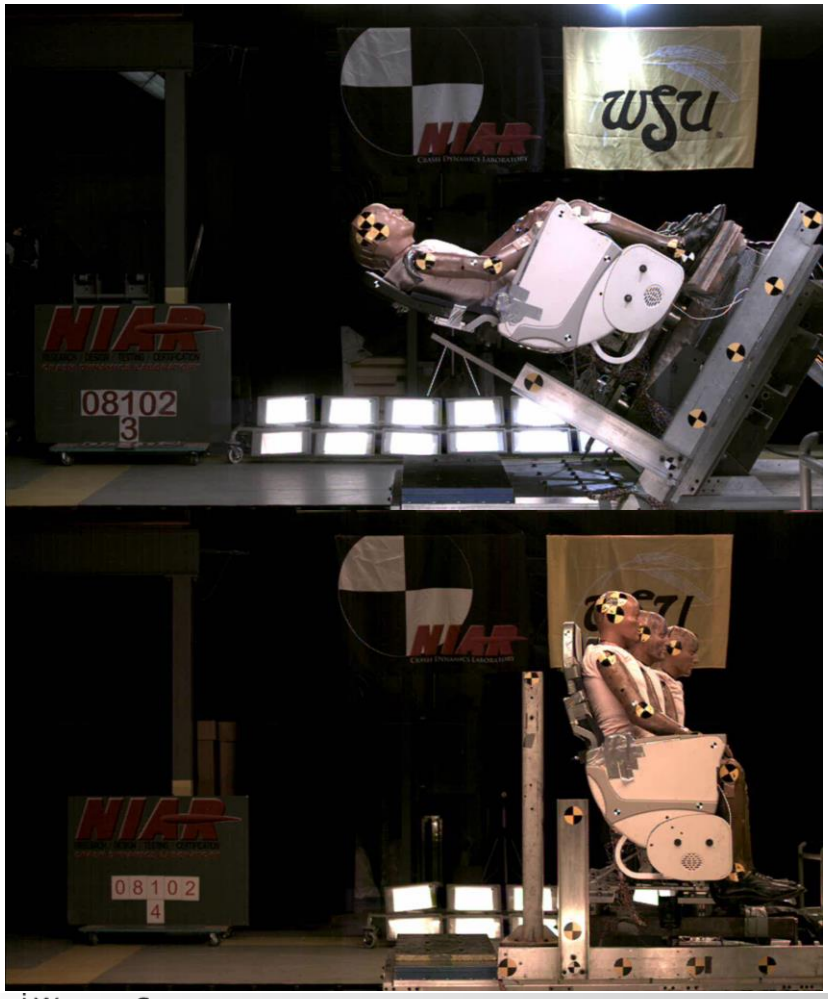
Non-Integrated vs. Integrated Safety

- Structural design for airplane safety combines **airworthiness** and **crashworthiness** design objectives to varying degrees.
- **Airworthiness** design objectives pertain to the ability of the airframe to withstand design loads, or to maintain safety of flight of the airplane relative to the operational environment.
- **Crashworthiness** design objectives pertain to safety of the occupants relative to the airplane.
- **Occupant Safety** must be an integral part of the overall technical and management processes associated with the design, development and operation of Urban Air Transport Systems. Nowadays the crashworthiness design for aerospace applications under 14 CFR *.561 and *.562 only addresses the dynamic response of the seat and restraint system during emergency landing conditions. In order to improve the survivability rate of occupants an **integrated safety approach** is required.



14CFR *.562 Dynamic Test Requirements

Non-Integrated vs. Integrated Safety



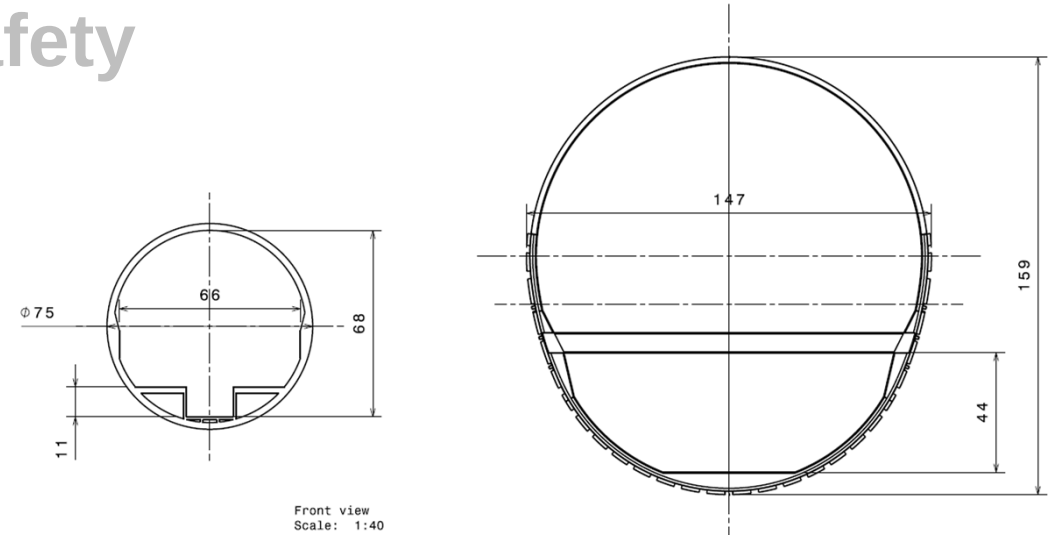
DYNAMIC TEST REQUIREMENTS	PART 23	PART 25	PART 27
TEST 1			
Test Velocity – ft/sec	31 (9.5 m/sec)	35 (10.7 m/sec)	30 (9.2 m/sec)
Seat Pitch Angle – Degrees	60	60	60
Seat Yaw Angle – Degrees	0	0	0
Peak Deceleration – G's	19/15	14	30
Time to Peak – sec	0.05/0.06	0.08	0.031
Floor Deformation - Degrees	None	None	10 Pitch/10 Roll
TEST 2			
Test Velocity – ft/sec	42 (12.8 m/sec)	44 (13.4 m/sec)	42 (12.8 m/sec)
Seat Pitch Angle – Degrees	0	0	0
Seat Yaw Angle – Degrees	±10	±10	±10
Peak Deceleration – G's	26/21	16	18.4
Time to Peak – sec	0.05/0.06	0.09	0.071
Floor Deformation - Degrees	10 Pitch/10 Roll	10 Pitch/10 Roll	10 Pitch/10 Roll
COMPLIANCE CRITERIA			
HIC	1000	1000	1000
Lumbar Load – lbf	1500 (6675 N)	1500 (6675 N)	1500 (6675 N)
Strap Loads – lbf	1750[1]/2000[2] (7787N[1]/8900N[2])	1750[1]/2000[2] (7787N[1]/8900N[2])	1750[1]/2000[2] (7787N[1]/8900N[2])
Femur Loads – lbf	N/A	2250	N/A

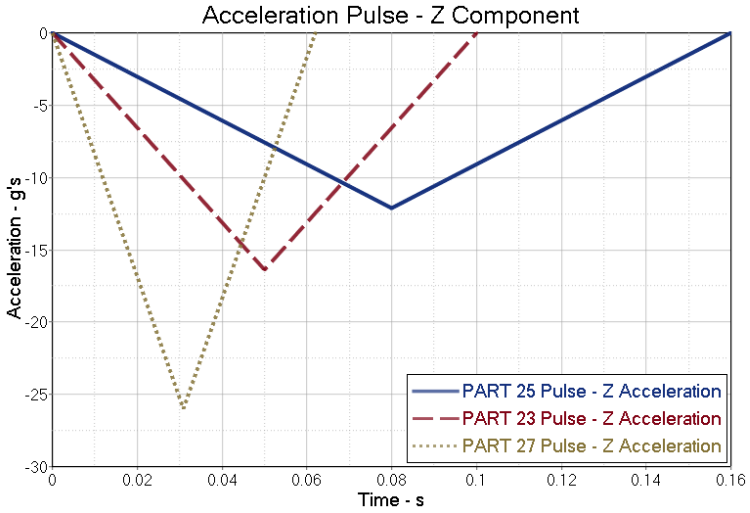
[1] –Passenger [2] - Pilot

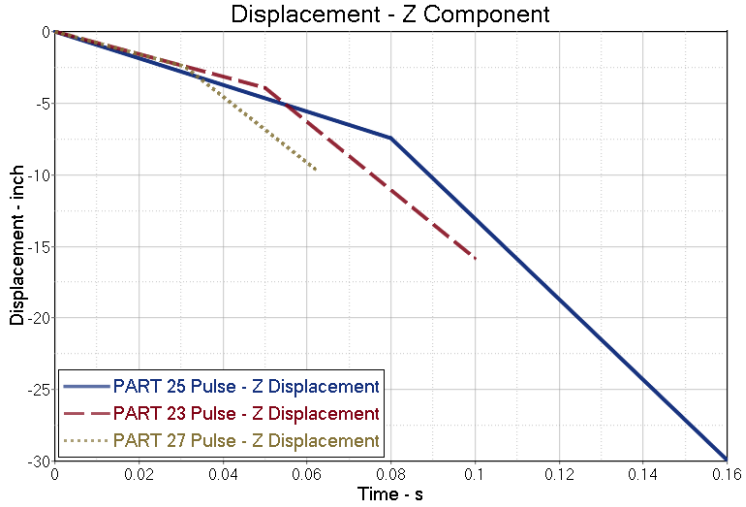
14 CFR *.562 Pulses Crush Requirements

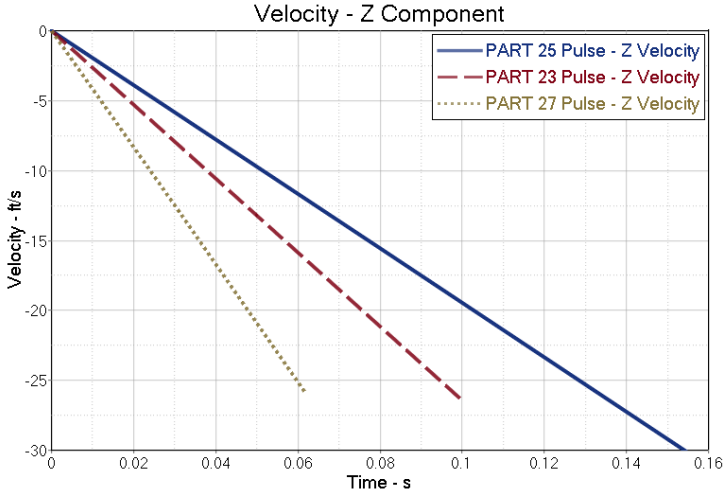
Non-Integrated vs. Integrated Safety

Test I	PART 25	PART 23	PART 27
Time to Peak (s)	0.08	0.05	0.031
Peak - Acceleration Pulse (g's)	14	19	30
Peak - Z Acceleration (g's)	12.1	16.4	26.0
Peak - Z Velocity (ft/s)	31.2	26.5	25.9
Peak - Z Displacement (inch)	30.3	16.2	9.6





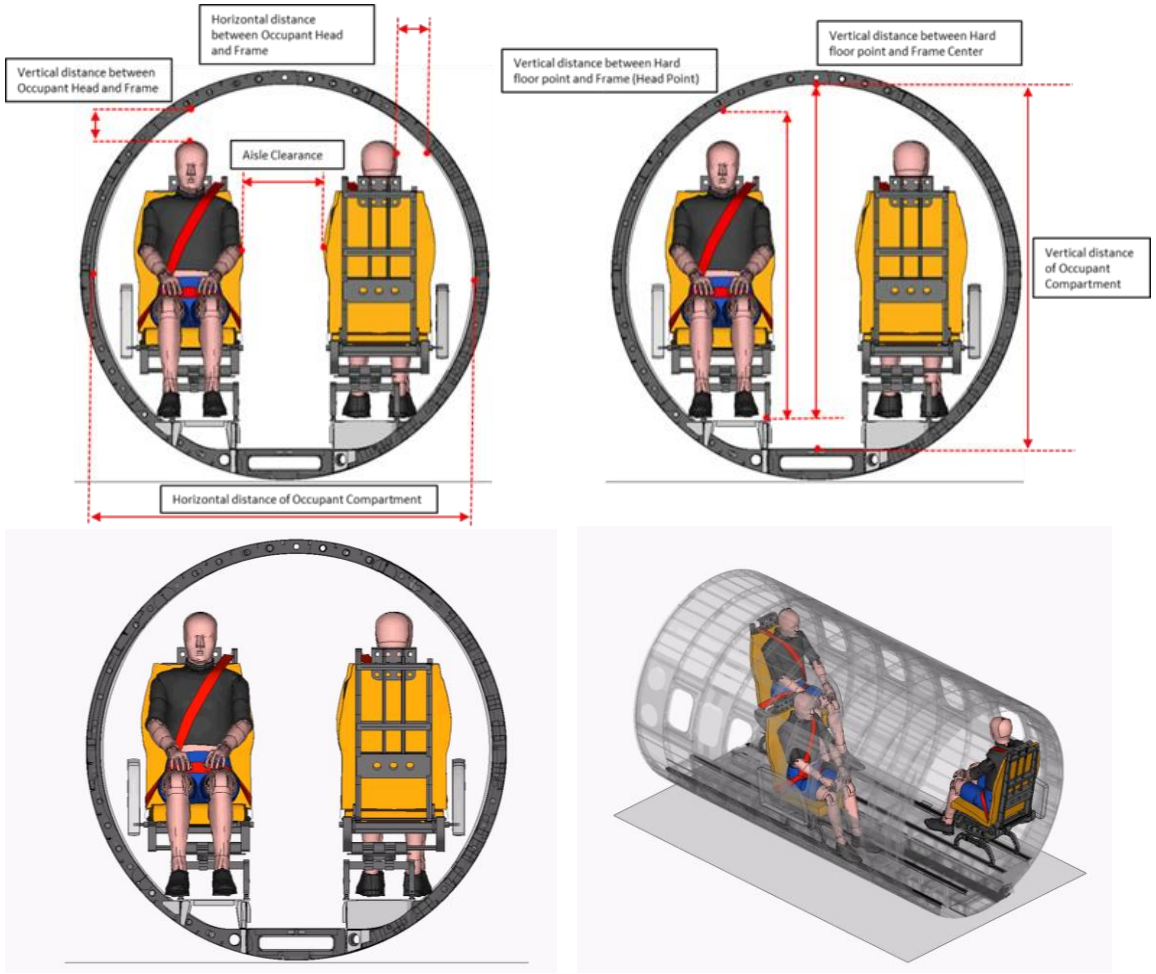




Aerospace Safety Criteria

Integrated Safety for eVTOL Crashworthiness

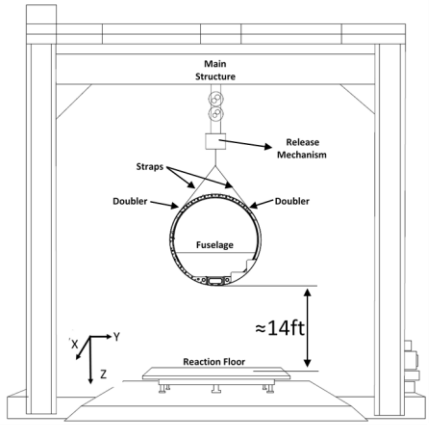
- Maintain Survivable Volume
  - Overall Survivable Space Dimensional Check (Peak during Dynamic Event and Post Test Deformations)
  - Avoid Occupant to Interior Structure Contacts during impact
- Maintain Deceleration Loads to Occupants
  - Injury Criteria Limits per 14 CFR *.562 :
    - 1500 lbf, HIC 1000, Shoulder Strap Loads….
- Retention Items of Mass
  - Interior items of mass per 14 CFR *.561
  - Occupants and Seat Structures supported throughout the crash event (14 CFR *.562)
- Maintain Egress Paths
  - Maintain Aisle Distance (if applicable)
  - Evaluate Plastic deformations of the supporting structure near the exit door
  - Floor Warping
  - Floor Beam Failures – Reduced Strength to support passenger weight

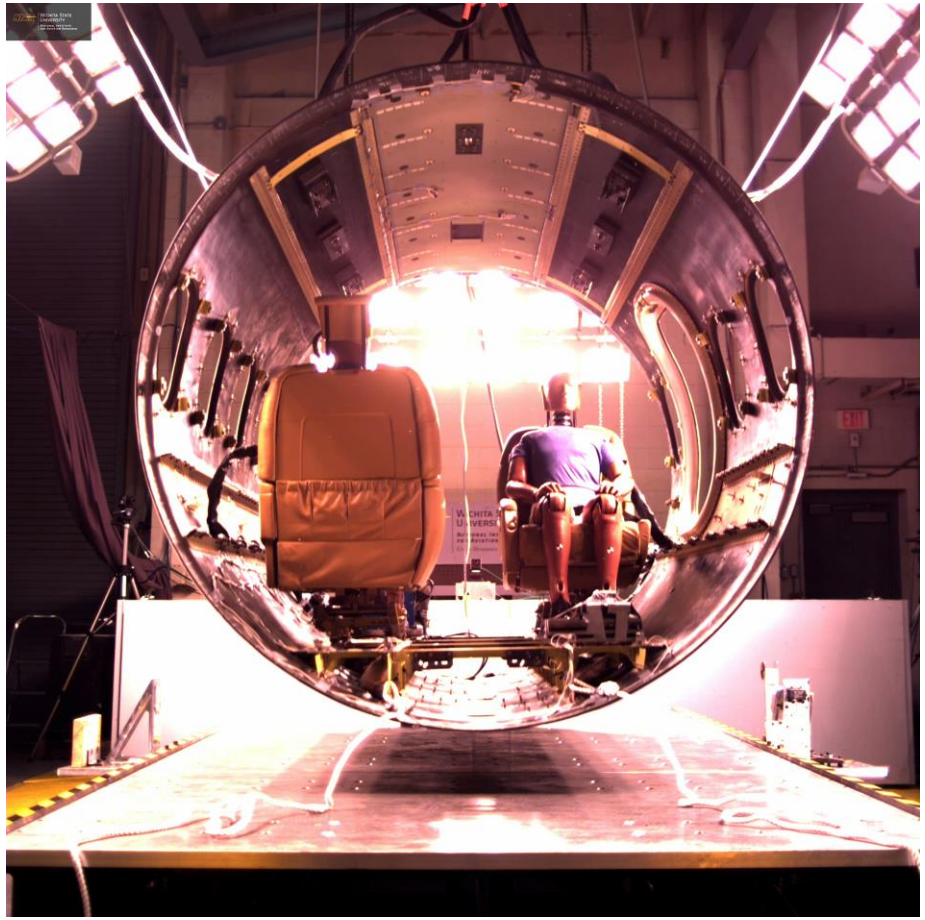


Non-Integrated Safety

Example Aerospace Non-Integrated Safety Development

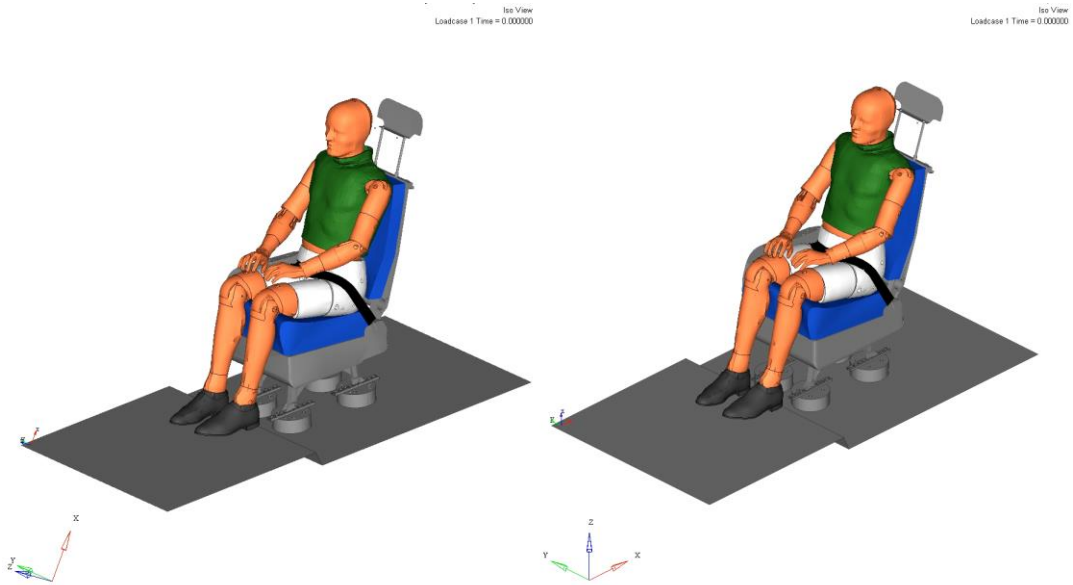
- **Drop velocity:** 30 ft./sec
- Composite Fuselage Certified under 14 CFR Part 25 - **Airworthiness**
- Dynamic Certified Seats per 14 CFR 25.561 and 562 – **Emergency Landing Conditions**

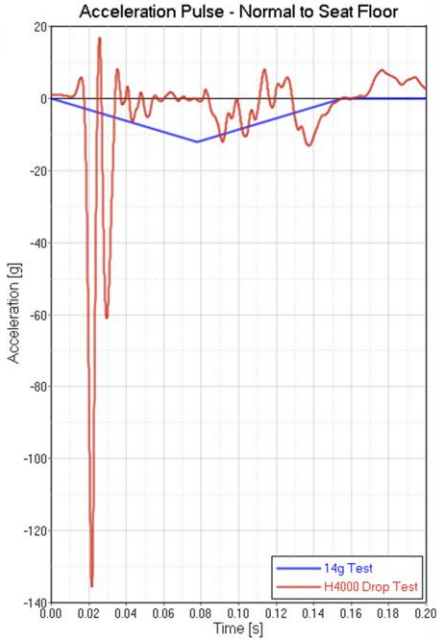


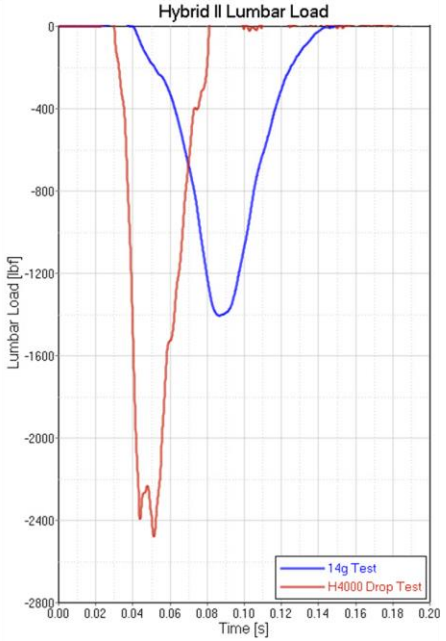


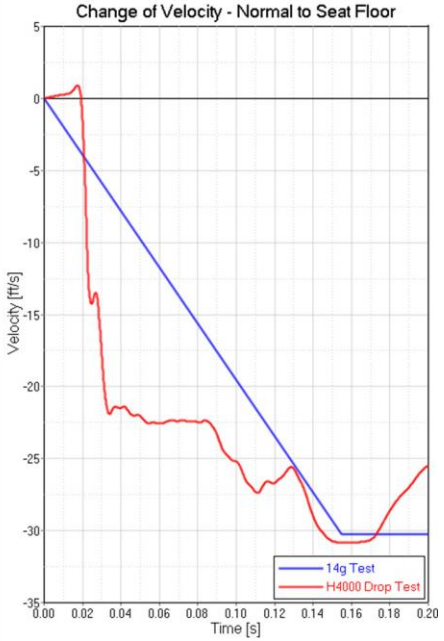
Non-Integrated Safety “Real World” Issues

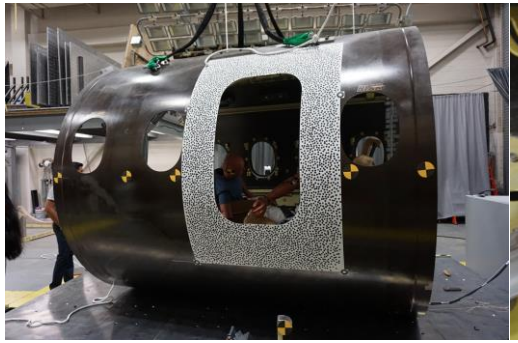
Example Aerospace Non-Integrated Safety Development







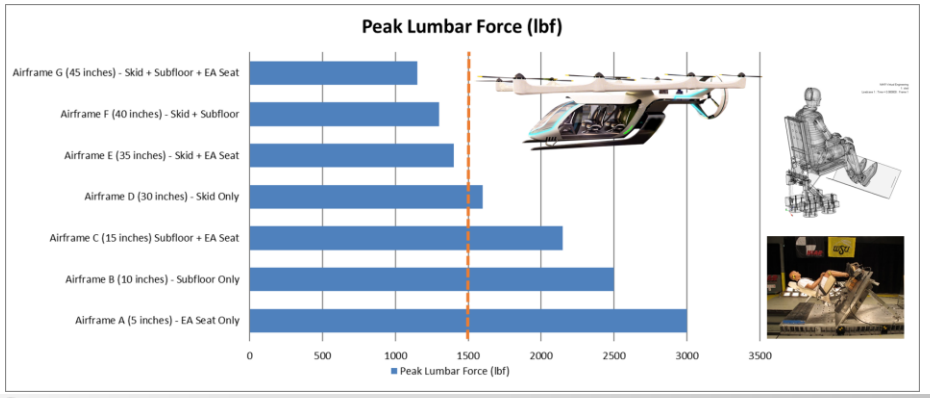


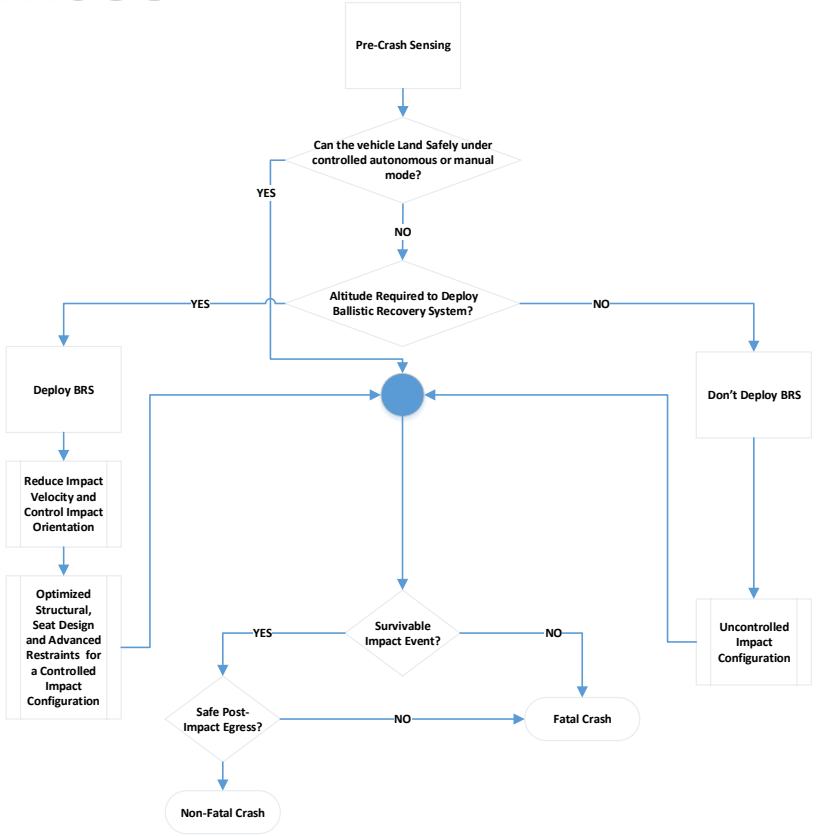


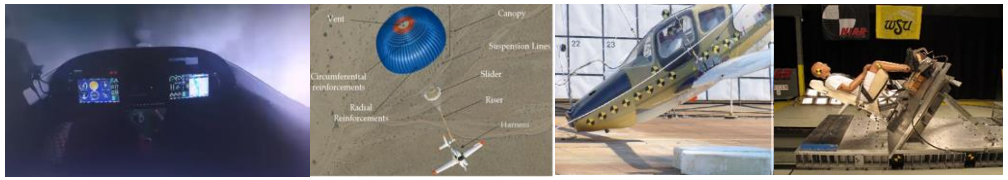
Aerospace Integrated Safety

Integrated Safety for eVTOL Crashworthiness

- Occupant safety must be an integral part of the overall technical and management processes associated with the design, development and operation of eVTOL Urban Air Transport systems.
- The different elements that constitute the integrated safety concept approach are:
  - Pre-crash: Event Recognition.
  - Control Impact Velocity and Attitude: Distributed Propulsion System Redundancy, Parachute Ballistic Recovery Systems, Retro Rockets ..etc..
  - Integration of Landing Gear-Airframe Crashworthy Structure, Deployable Energy Absorbing Systems (Vehicle Airbags, Structural EA Devices..etc.)
  - High-energy Absorbing Seats, and Advanced Restraints.
  - Post-crash: Battery Fire Suppression, and Egress
- Energy Absorbing Landing/Take off Sites
- The implementation of Pre-Crash, Active Safety Systems can prevent or mitigate the outcome of eVTOL crashes. The autonomous nature of eVTOL Urban Air Transport systems could potentially provide a significant effect in the reduction of fatalities caused by human error (75 % of the cases for GA fixed wing aircraft).



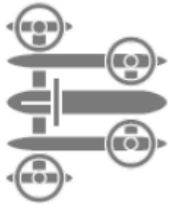




UAM Architectures

Integrated Safety for eVTOL Crashworthiness





Multicopters	Quadcopters	Hybrid	Tilt Rotor	Fixed Wing Ducted Vectored Thrust
VTOL	VTOL	VTOL or VTOL & CTOL	VTOL or VTOL & CTOL	VTOL or VTOL & CTOL
Skid System	Skid System	Skid System or LG	Skid System or LG	Skid System or LG





Key Hazards and Risk Severity

Integrated Safety for eVTOL Crashworthiness

Risk Severity= Probability x Consequence
High, Medium, Low




Hazard Description	Multirotor	DEP Powered Lift	Powered Lift	Fixed Wing
Battery Thermal Runaway	High	High	High	High
Battery Energy Uncertainty	High	High	Medium	Medium
Common Mode Power Failure (Low-/High-Altitude)	High/High	High/Medium	Medium/Medium	Medium/ Medium
Fly-By-Wire System Failure	High	High*	Low**	Low
High-Level Autonomy Failure	High	High	High	High
Bird Strike	Medium	Medium	Medium	Medium

*Including Tilt-Lift vehicles **Except Tilt-Lift vehicles

Battery Thermal Runaway

	Extremely Improbable	Extremely Remote	Remote	Probable
Catastrophic			All	
Hazardous				
Major				
Minor				
Negligible				

M - Multirotor
D - DEP Powered Lift
R - Rotorcraft
F - Fixed Wing

Battery Energy Uncertainty

	Extremely Improbable	Extremely Remote	Remote	Probable
Catastrophic		D_{Low}, M_{All}		
Hazardous		D_{High}, F_{All}, R_{All}		
Major				
Minor				
Negligible				

M - Multirotor
D - DEP Powered Lift
R - Rotorcraft
F - Fixed Wing

Subscripts indicate Low, High, or All altitudes.

Common Power System Failure

	Extremely Improbable	Extremely Remote	Remote	Probable
Catastrophic	F_{Low}	D_{Low}, M_{All}		
Hazardous		D_{High}, F_{High}, R_{All}		
Major				
Minor				
Negligible				

M - Multirotor
D - DEP Powered Lift
R - Rotorcraft
F - Fixed Wing

Subscripts indicate Low, High, or All altitudes.

Fly-B-Wire System Failure

	Extremely Improbable	Extremely Remote	Remote	Probable
Catastrophic			All_{FBW}	
Hazardous				
Major				
Minor				
Negligible	F_{conv}, R_{conv}			

M - Multirotor
D - DEP Powered Lift
R – Rotorcraft (except Tilt-Lift)
F - Fixed Wing

Subscripts indicate Fly-By-Wire (FBW) or Conventional (Conv) control systems.

Bird Strike

	Extremely Improbable	Extremely Remote	Remote	Probable
Catastrophic				
Hazardous		$All_{Cockpit}$		
Major				
Minor		All_{Prop}		
Negligible				

M - Multirotor
D - DEP Powered Lift
R - Rotorcraft
F - Fixed Wing

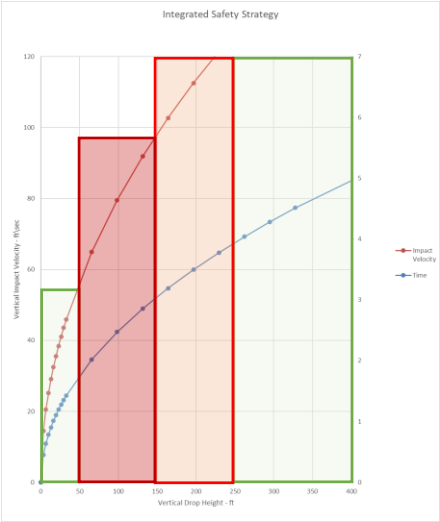
Subscripts indicate bird strike on the Cockpit or on a Propulsor.

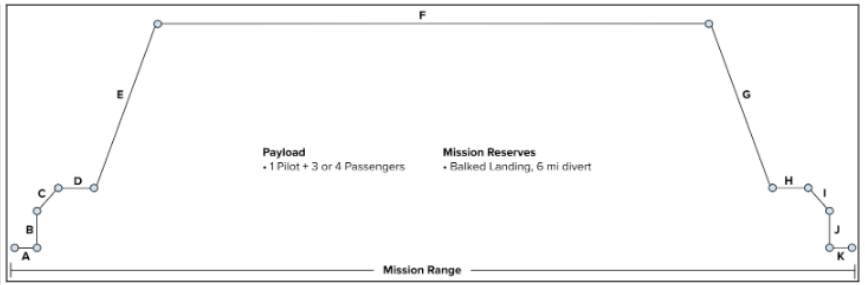
Reference: C. Courtin and J. Hansman, Safety Considerations in Emerging Electric Aircraft Architectures, Report No ICAT-2018-07, MIT ICAT, June 2018

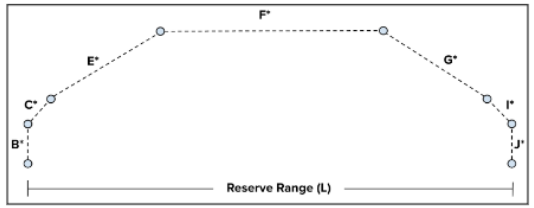
Integrated Safety - Typical Mission Profile

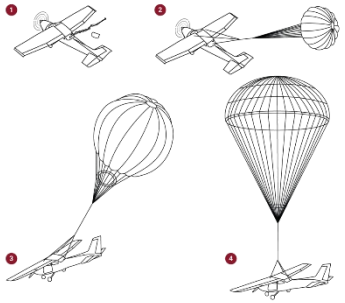
Integrated Safety for eVTOL Crashworthiness

- Hover Climb (B) and Hover Descent (J):
  - **Distributed Propulsion:** Reduce Impact Velocity
  - **Aircraft Systems:** EA Seat, Advanced Restraints, EA Airframe, EA Skid/Landing Gear System, Deployable Energy Absorbing Devices
  - **Take-off & Landing Site:** Energy Absorbing Sites
  - **Impact Parameters:**
    - Max. AGL Altitude: 50 ft (15 m)
    - Max. Vertical Impact Velocity: 56.7 ft/s (17.3 m/s)
    - Max. Horizontal Impact Velocity: ~ 0 ft/s (0 m/s)
    - Max. Time: 1.75 s
- Transition Climb (C) and Transition Descent (I):
  - **Distributed Propulsion:** Reduce Impact Velocity
  - **Aircraft Systems:** EA Seat, Advanced Restraints, EA Airframe, EA Skid/Landing Gear System, Deployable Energy Absorbing Devices
  - **Take-off & Landing Site:** Energy Absorbing Sites
  - **Ballistic Recovery System (10% Efficiency up to 150ft, 50 % Efficiency up to 250 ft, ~ 100% Efficiency 250 ft plus) [Note these are estimates]**
  - **Impact Parameters:**
    - Max. AGL Altitude: 300 ft (91.5 m)
    - Max. Vertical Impact Velocity: 139 ft/s (42.3 m/s)
    - Max. Horizontal Impact Velocity: 1.2*Vstall
    - Min. Time: 4.3 s
- Accel + Climb (E), Decel + Descent (G), Cruise (F)
  - **Distributed Propulsion:** Reduce Impact Velocity
  - **Aircraft Systems:** EA Seat, Advanced Restraints, EA Airframe, EA Skid/Landing Gear System, Deployable Energy Absorbing Devices
  - **Ballistic Recovery System**
  - **Impact Parameters:**
    - AGL Altitude: 1500 ft (457 m)
    - Max. Vertical Impact Velocity: 310 ft/s (94 m/s)
    - Max. Horizontal Impact Velocity: 220 ft/s (67 m/s)
    - Min. Time: 9.69 s









Picture Source: BRS Website

	Segment	Distance (mi)	Vertical Speed (ft/min)	Horizontal Speed (mph)	AGL Ending Altitude (ft)
A	Ground Taxi	No Distance Credit	0	3	0
B	Hover Climb		0 to 500	0	50
C	Transition + Climb	Sizing I Repeated 60 I 25	500	0 to 1.2*Vstall	300
D	Departure Terminal Procedures		0	1.2*Vstall	300
E	Accel + Climb		500	1.2*Vstall to 150	1500
F	Cruise		0	150	1500
G	Decel + Descend		500	150 to 1.2*Vstall	300
H	Arrival Terminal Procedures		500	1.2*Vstall	300
I	Transition + Descend		500 to 300	1.2*Vstall to 0	50
J	Hover Descend	No Distance Credit	300 to 0	0	0
K	Ground Taxi		0	3	0
L	Reserves	Balked Landing, 6 mi divert at 500 feet AGL			

Reference: UberAir Vehicle Requirements and Missions Document

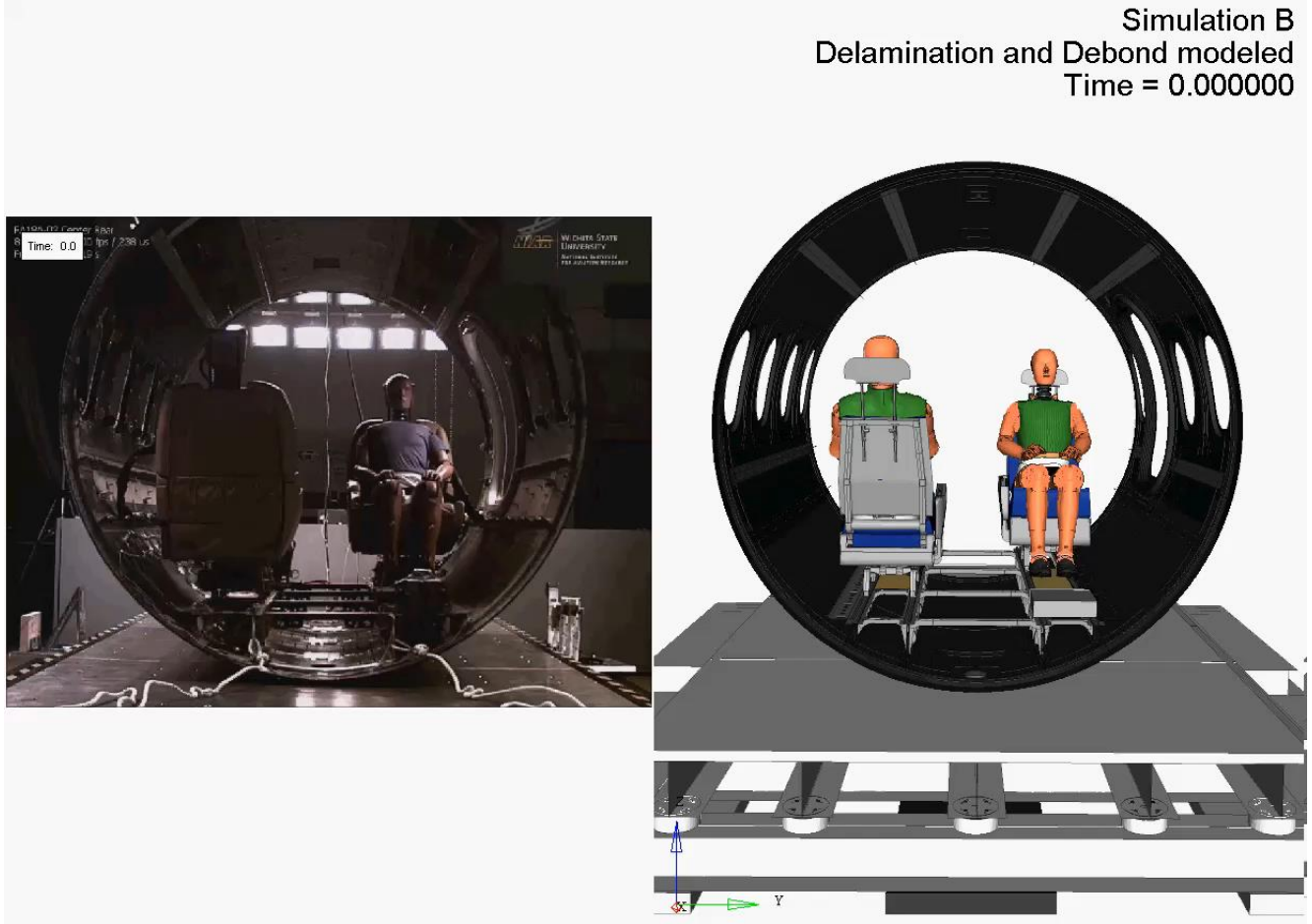
Digital Engineering Methods from Conceptual Design to Certification

Integrated Safety for eVTOL Crashworthiness

Engineering and Certification Methods

Integrated Safety for eVTOL Crashworthiness

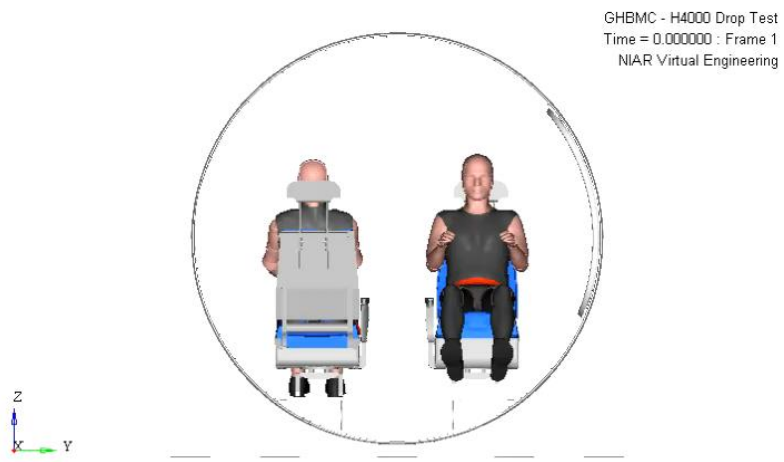
- 1 – Experimental – with physical ATDs:
  - High Cost and Time.
  - Difficulties optimizing the system through physical prototypes.
  - Difficult to quantify the Energy Absorbing capabilities of the individual crashworthy design features.
  - Deterministic approach: Reduced to one single impact configuration.
  - Current ATD's (HII and FAA HIII) will not capture real world eVTOL occupants injury mechanisms.
- 2 – Digital Engineering: Computational supported by the building block approach - with Virtual ATDs:
  - High Cost of entry: validated methods and tools.
  - Reduced development and Certification cycles.
  - Non-deterministic approach: Optimized solutions for multiple impact conditions and occupant sizes. Robust Design.
  - Virtual ATD's (HII and FAA HIII) will not capture real world eVTOL occupants injury mechanisms.

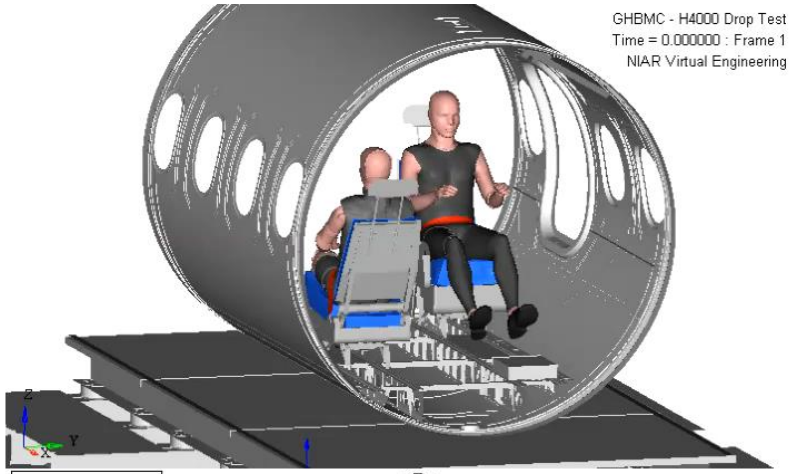


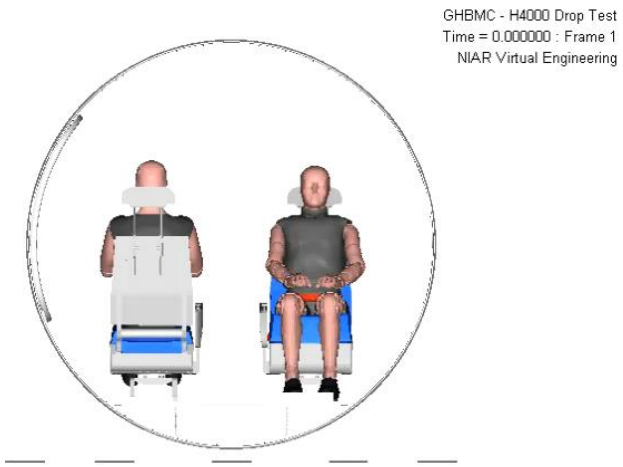
Engineering and Certification Methods

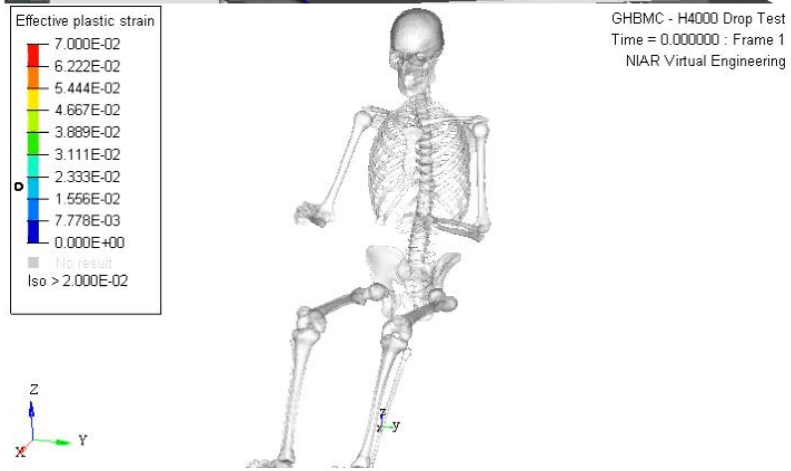
Integrated Safety for eVTOL Crashworthiness

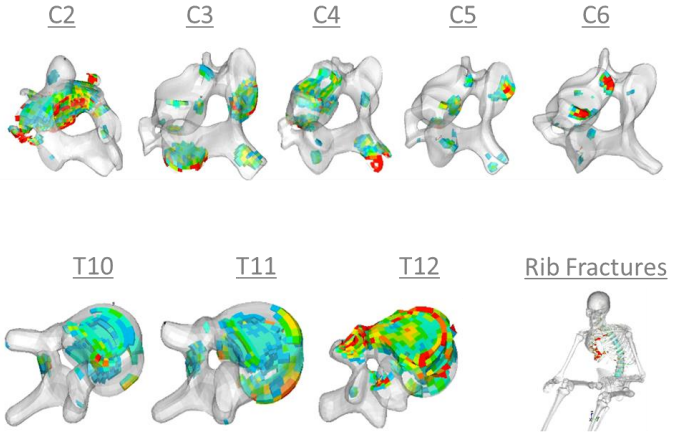
- 3 – Digital Engineering: Computational supported by the building block approach - with Virtual Human Body Models:
  - High Cost of entry: validated methods and tools.
  - Reduced development and Certification cycles.
  - Non-deterministic approach: Optimized solutions for multiple impact conditions and occupant sizes. Robust Design.
  - Virtual Human Body models will capture real world eVTOL occupants injury mechanisms. Further V&V research is required to evaluate Human body models for non-conventional seating arrangements and aerospace loading applications











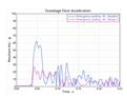
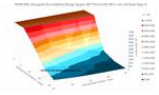
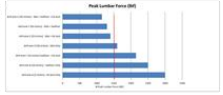
Conceptual Design Process

Urban Air eVTOL Integrated Safety Conceptual Design Methods

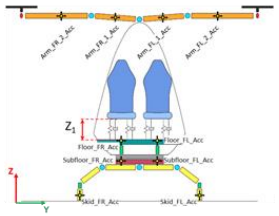
1. Define Design Specifications and Performance Requirements
2. Define Design Space
3. NIAR Initial Integrated Safety Calculator
4. Multibody Integrated Safety Optimization Process
5. Integrated Safety Airframe and Safety Systems Optimized Solution
6. Sanity Check with NIAR Integrated Safety Analytical Calculations
7. Check that the optimum solution meets the Design Requirements
8. Final Conceptual Design

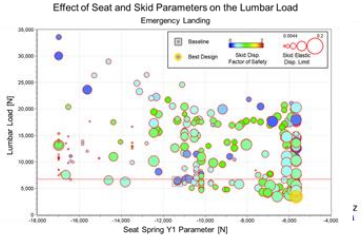
System	Seat Track Peak Acceleration Initial Pulse [g]	Seat Track Time Duration Initial Pulse [ms]	Seat Track Avg. Acceleration Initial Pulse [g]	Maximum Stroke [in]	Eff. Maximum Stroke* [in]	Δv Initial Pulse [ft/s]	Eq. Linear Stiffness** [lbf/in]	Mass [lb]	Peak Lumbar Force non-EA Seat [lbf]
Seat [Z_1]	83.9	22	41.9	8.00	4.00	30	3.57E+03	170.0	3500
Floor [Z_2]	56.8	33	28.4	11.81	5.91	30	1.35E+04	1407.5	2250
Skid System [Z_3]	28.0	67	14.0	24.00	12.00	30	1.11E+04	4743.9	1450
Baseline Design Prediction	56.8	**33**			**9.91**				**2250**

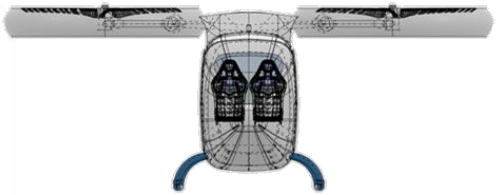
* 50% EA Efficiency
**Peak Pulse Only

- NIAR ISSC: NIAR Integrated Safety Sizing Calculator



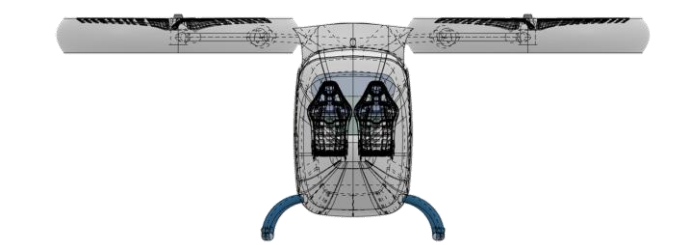


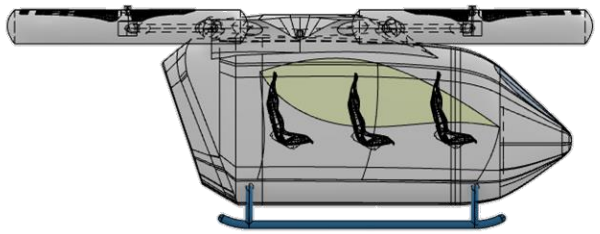



eVTOL Design Specifications

Urban Air eVTOL Integrated Safety Conceptual Design Methods

- **MTOW:** 4850 lbs. (2200 kg)
- **Powerplant:** Ducted Electric
- **Battery System :** Sub floor
- **Configurations:**
  - 4 Occupants + Luggage
  - 6 Occupants (no Luggage)
  - Piloted or Autonomous Flight
- **Structural Dynamic Design Performance Requirements:**
  - Landing Gear/Skid Reserve Energy Absorption [Hard Landing]:
    - Impact Velocity: 10.22 ft/s [3.12 m/s]
    - The structure must withstand this test without introducing permanent deformations
  - Crashworthiness [Emergency Landing Requirements]:
    - A change in downward velocity of no less than 30 ft/s [9.1 m/s]
    - Injury Criteria per 14CFR *.562



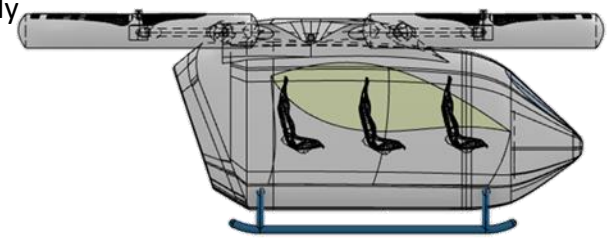


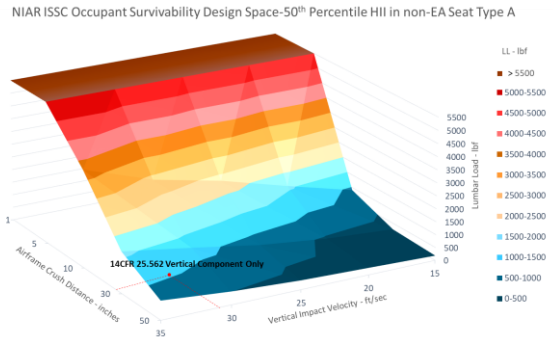
Initial Sizing Calculations – NIAR ISSC

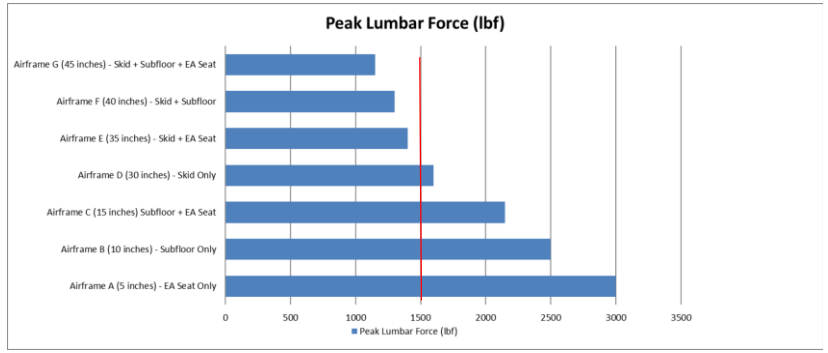
Urban Air eVTOL Integrated Safety Conceptual Design Methods

Configuration	Seat Track Peak Acceleration Initial Pulse [g]	Seat Track Time Duration Initial Pulse (ms)	Seat Track Avg. Acceleration Initial Pulse (g)	Maximum Stroke [in]	Eff. Maximum Stroke* [in]	Δv Initial Pulse [ft/s]	Eq. Linear Stiffness** [lbf/in]	Mass [lb]	Peak Lumbar Force Seat Type A [lbf]
Seat [Z_1]	83.9	22	41.9	8.00	4.00	30	3.57E+03	170.0	3500
Floor [Z_2]	56.8	33	28.4	11.81	5.91	30	1.35E+04	1407.5	2250
Skid System [Z_3]	28.0	67	14.0	24.00	12.00	30	1.11E+04	4743.9	**800**
Baseline Design Prediction	**56.8**	**33**			**9.91**				**2250**

* 50% EA Efficiency
**Peak Pulse Only





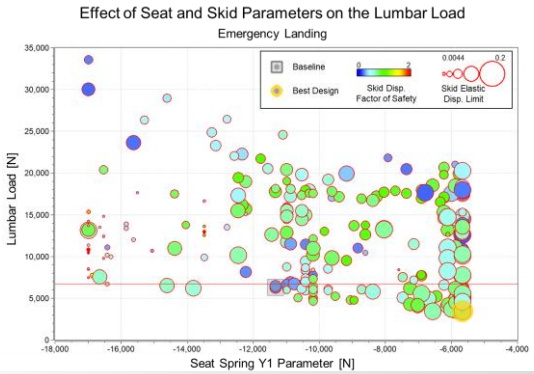


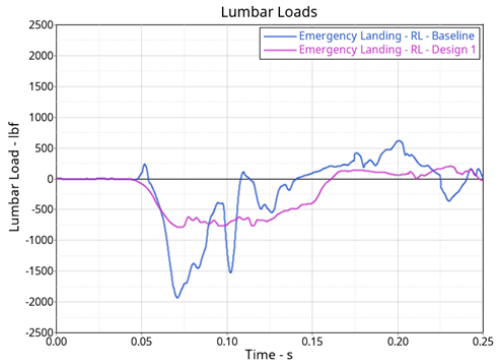
- NIAR ISSC: NIAR Integrated Safety Sizing Calculator

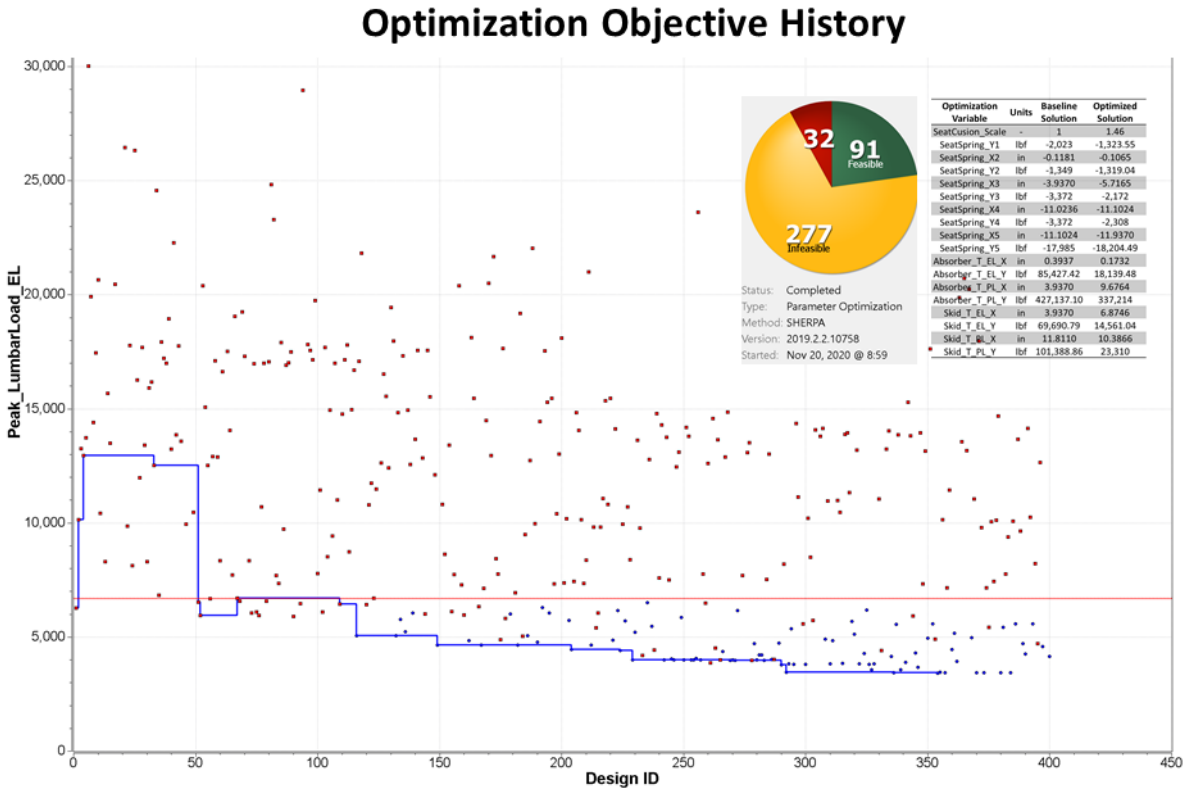
eVTOL Optimization - Sizing Study

Urban Air eVTOL Integrated Safety Conceptual Design Methods

- **18 Design Variables :**
  - Seat Foam Dynamic Characteristic Curves: [1 Variable: Force Scaling Factor]
  - Seat EA Profile: [9 Variables: 5 Force Levels, 4 Displacement Levels]
  - Floor System: [4 Variables: 2 Crush Distance, 2 Crush Force]
  - Skid Systems: [4 Variables: 2 Crush Distance, 2 Crush Force]
- **Monitoring Output Variables:** Occupant Injury, Structural, Accelerations
- **Objective Function:**
  - **<u>Minimize Lumbar Load for Emergency Landing Condition (EL)</u>**
  - **Design Constraints:**
    - Not to exceed the Elastic Limit for the Seat, Floor, and Skid System during Hard Landing Condition (HL)
    - Not to exceed injury criteria to passengers for HL and EL Conditions
- **Reduction of 64% on the Lumbar Load for the Emergency Landing Condition:**
  - Reduction from 2,194 lbf to 778 lbf
  - Design meets all constraints for EL and HL



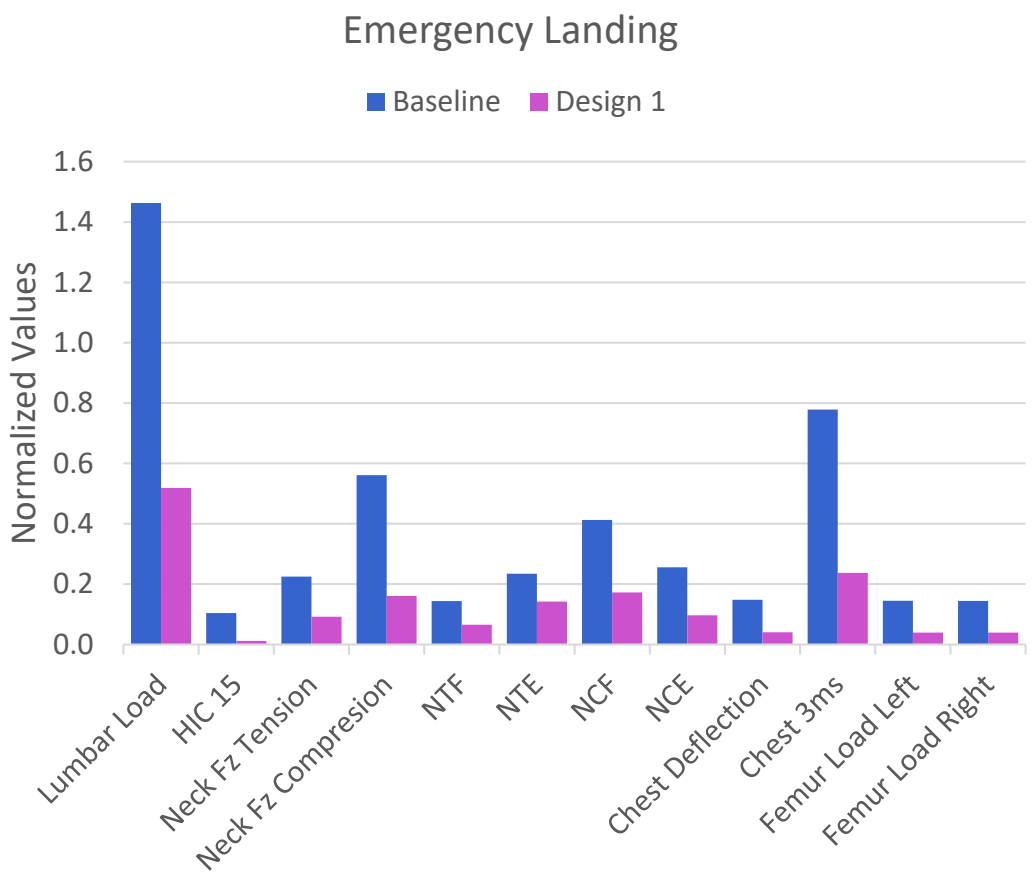




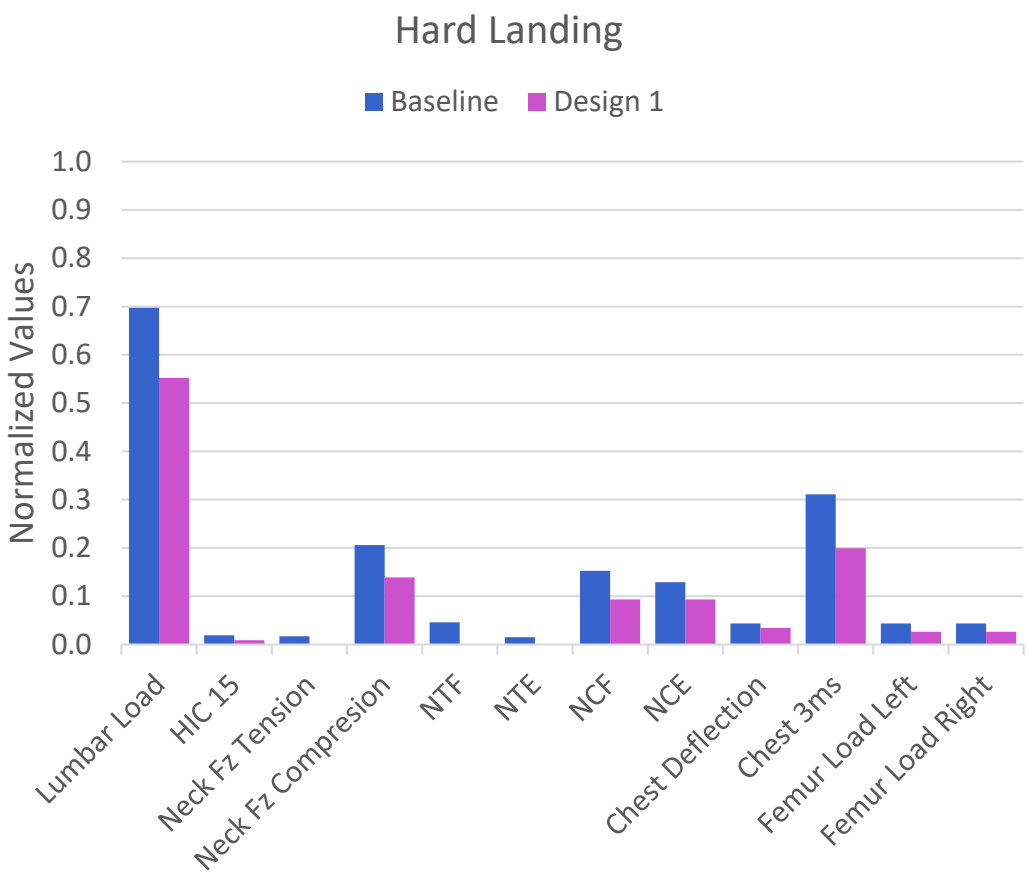
Optimization Variable	Units	Baseline Solution	Optimized Solution
SeatCusion_Scale	-	1	1.46
SeatSpring_Y1	lbf	-2,023	-1,323.55
SeatSpring_X2	in	-0.1181	-0.1065
SeatSpring_Y2	lbf	-1,349	-1,319.04
SeatSpring_X3	in	-3.9370	-5.7165
SeatSpring_Y3	lbf	-3,372	-2,172
SeatSpring_X4	in	-11.0236	-11.1024
SeatSpring_Y4	lbf	-3,372	-2,308
SeatSpring_X5	in	-11.1024	-11.9370
SeatSpring_Y5	lbf	-17,985	-18,204.49
Absorber_T_EL_X	in	0.3937	0.1732
Absorber_T_EL_Y	lbf	85,427.42	18,139.48
Absorber_T_PL_X	in	3.9370	9.6764
Absorber_T_PL_Y	lbf	427,137.10	337,214
Skid_T_EL_X	in	3.9370	6.8746
Skid_T_EL_Y	lbf	69,690.79	14,561.04
Skid_T_PL_X	in	11.8110	10.3866
Skid_T_PL_Y	lbf	101,388.86	23,310

Injury Criteria Summary

Design 1 – Optimization Results



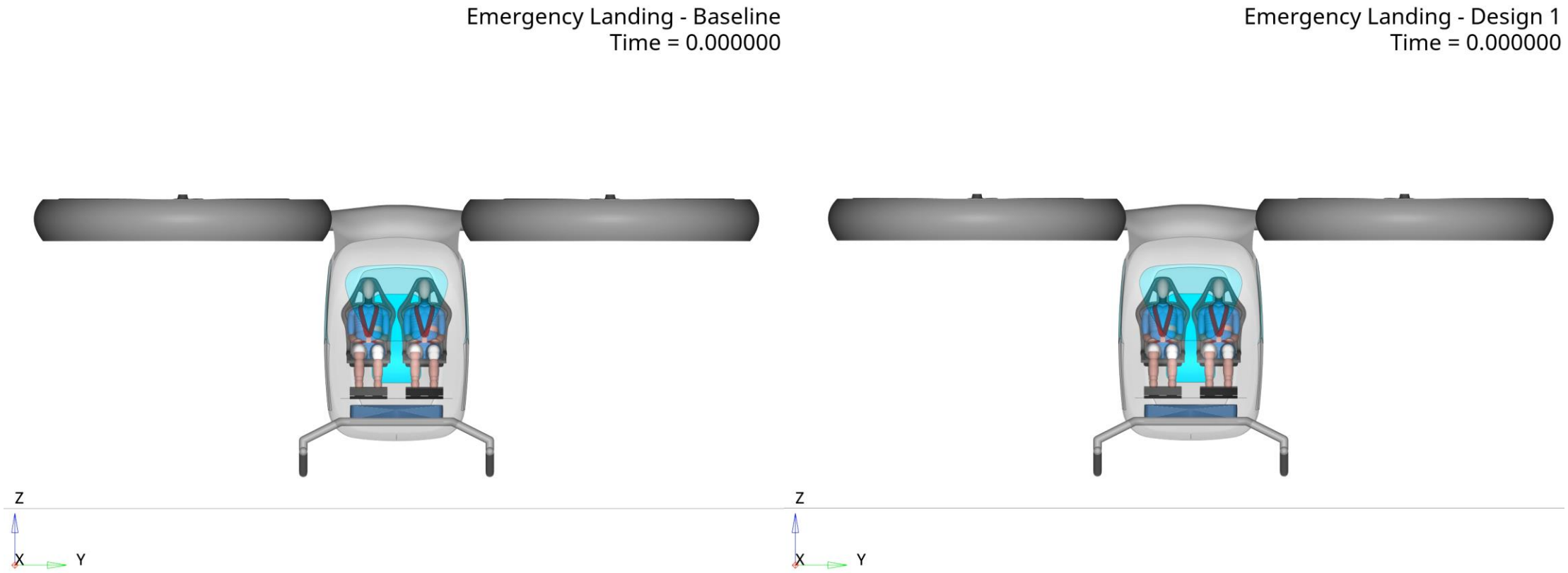
* Normalized with 14 CFR *.562, and FMVSS208 Limits



* Normalized with 14 CFR *.562, and FMVSS208 Limits

Kinematics – Baseline vs. Optimized

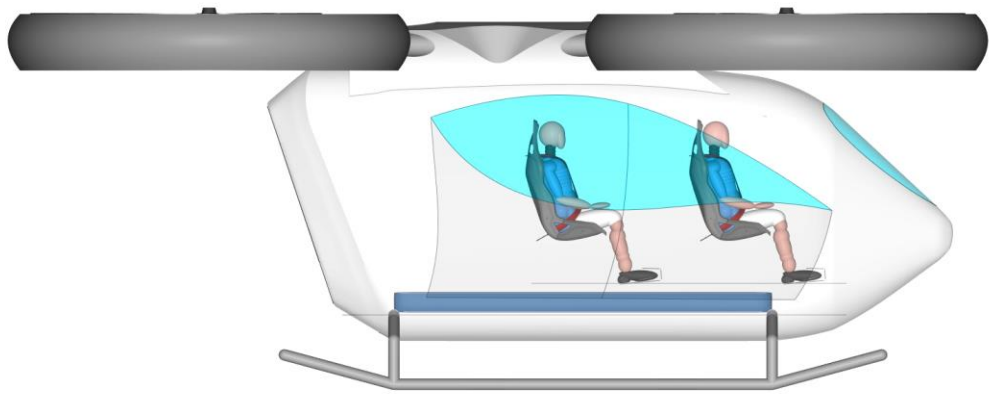
Emergency Landing Results



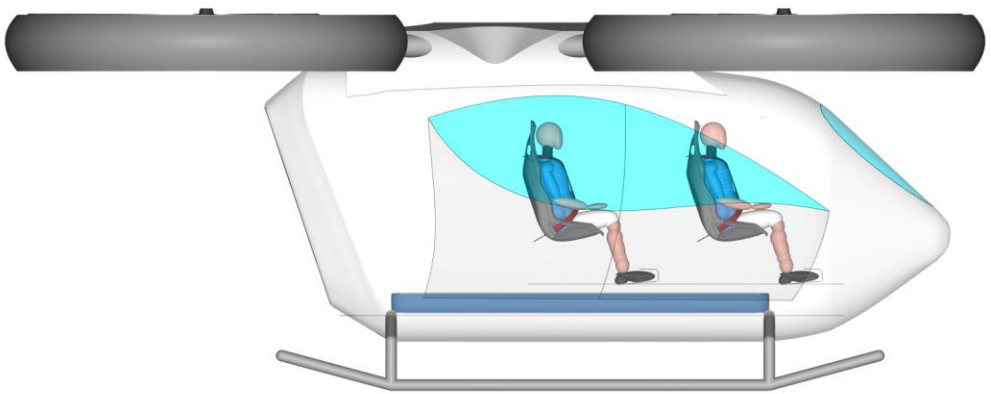
Kinematics – Baseline vs. Optimized

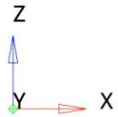
Emergency Landing Results

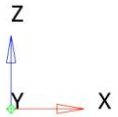
Emergency Landing - Baseline
Time = 0.000000



Emergency Landing - Design 1
Time = 0.000000





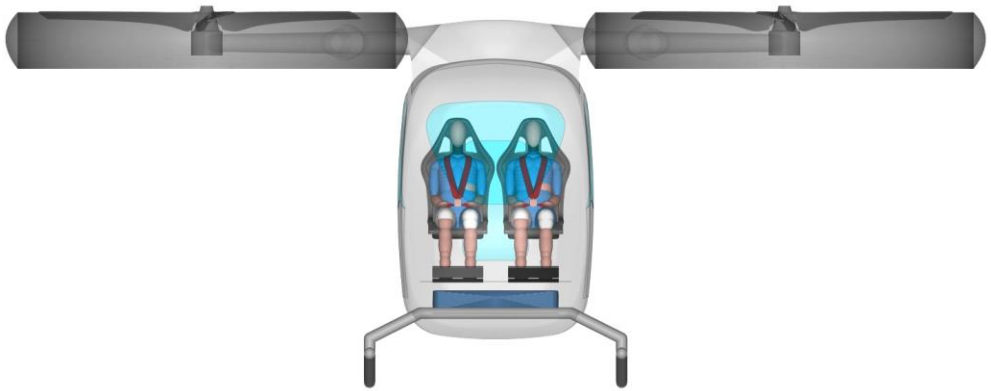


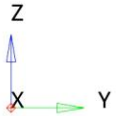
Kinematics – Baseline vs. Optimized

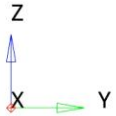
Hard Landing Results

Hard Landing - Baseline
Time = 0.000000

Hard Landing - Design 1
Time = 0.000000



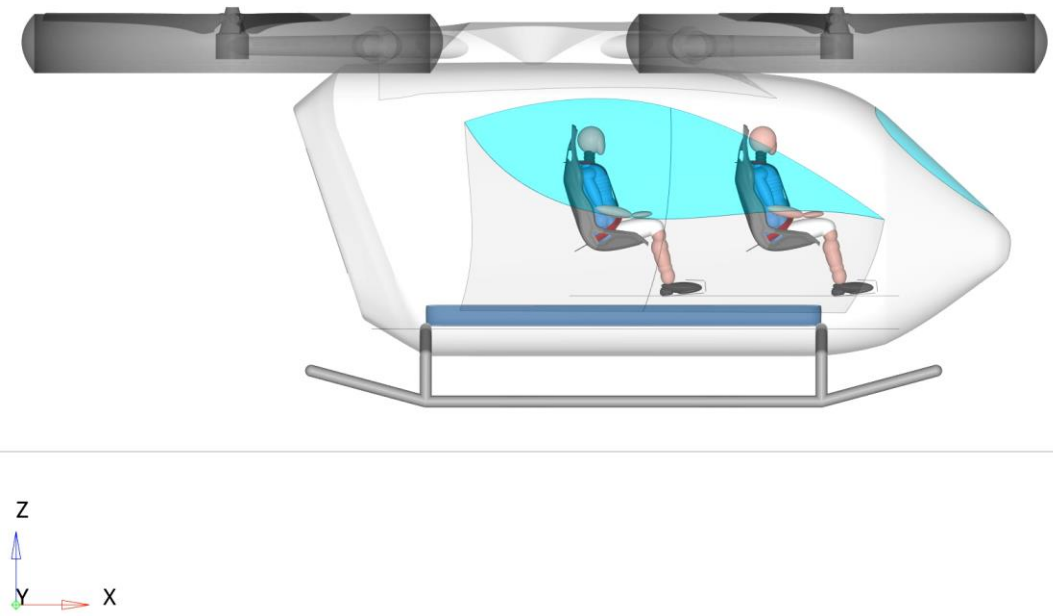




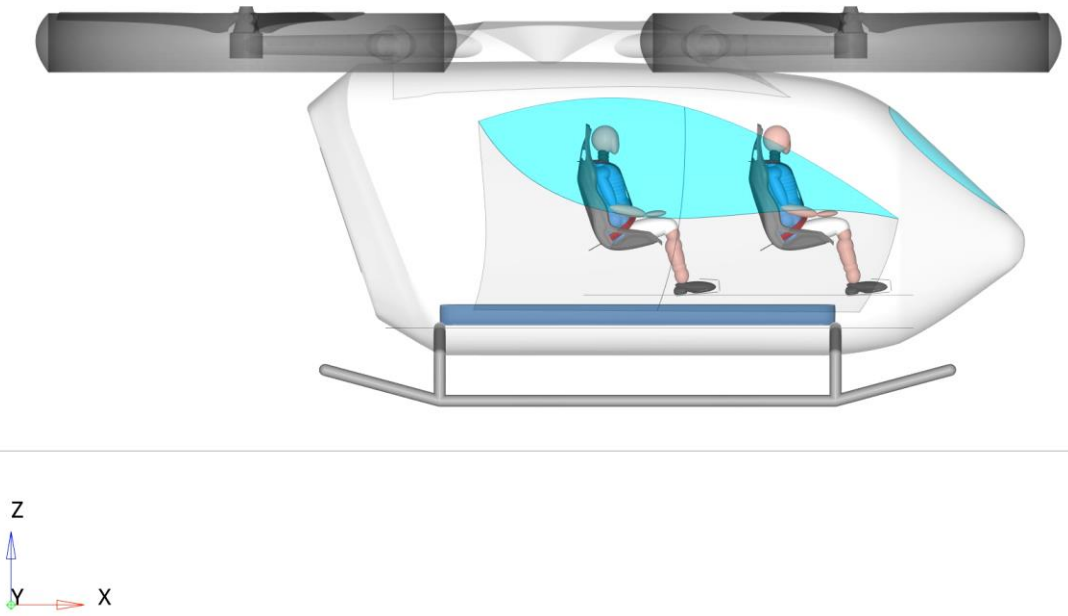
Kinematics – Baseline vs. Optimized

Hard Landing Results

Hard Landing - Baseline
Time = 0.000000



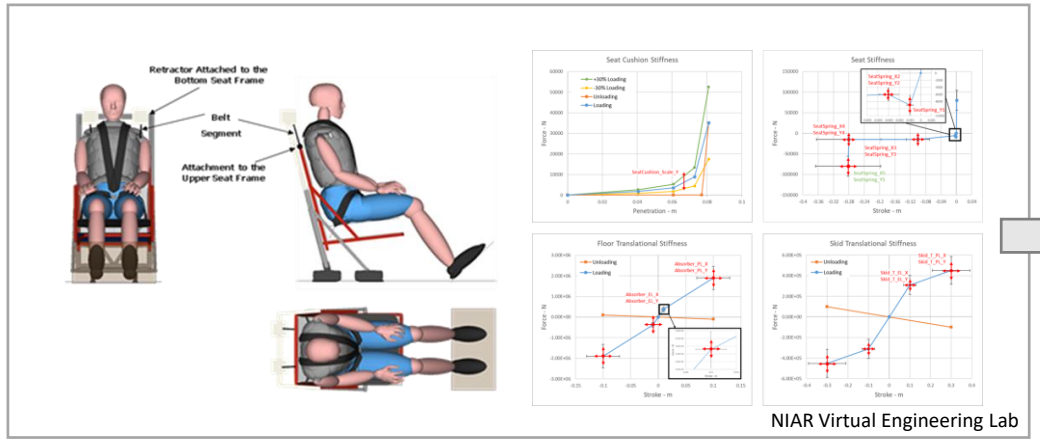
Hard Landing - Design 1
Time = 0.000000



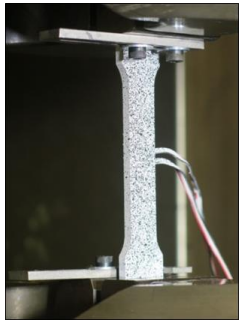
EA Seat Design

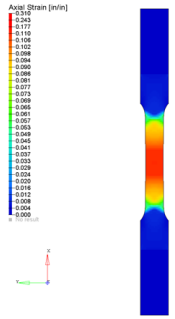
eVTOL Integrated Safety

1. **Detail Conceptual Design Specifications** based on Multibody Model Optimization results.
2. **Virtual Engineering Design – NIAR Building Block Methodologies:** Coupon and Component Level Testing.
3. **Detail Conceptual Design FEA Proof of Concept Virtual Testing.**
4. **Prototype Full Scale Testing.**

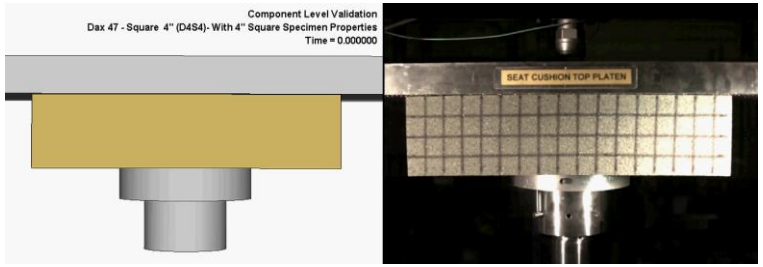


NIAR Virtual Engineering Lab

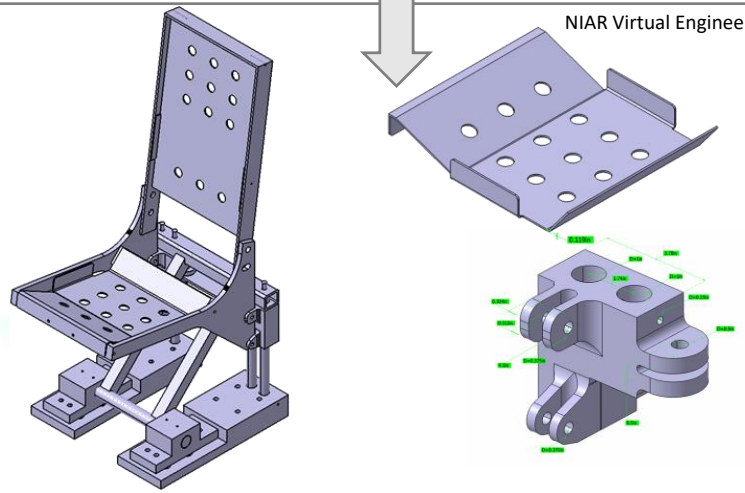


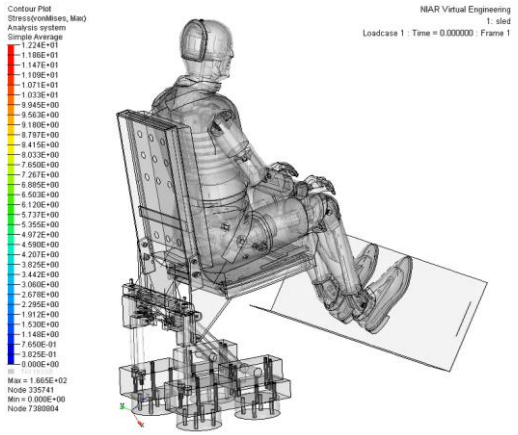


NIAR Building Block Testing Lab



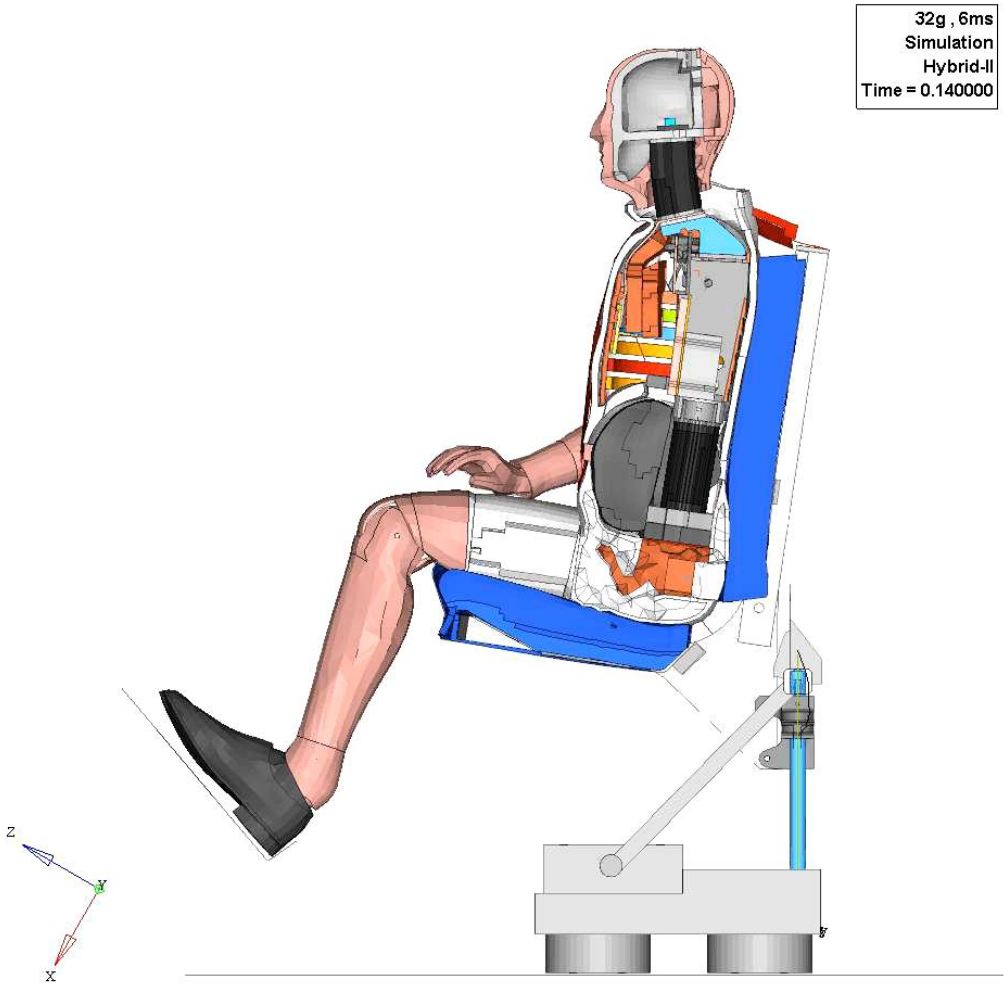
NIAR Virtual Engineering Lab

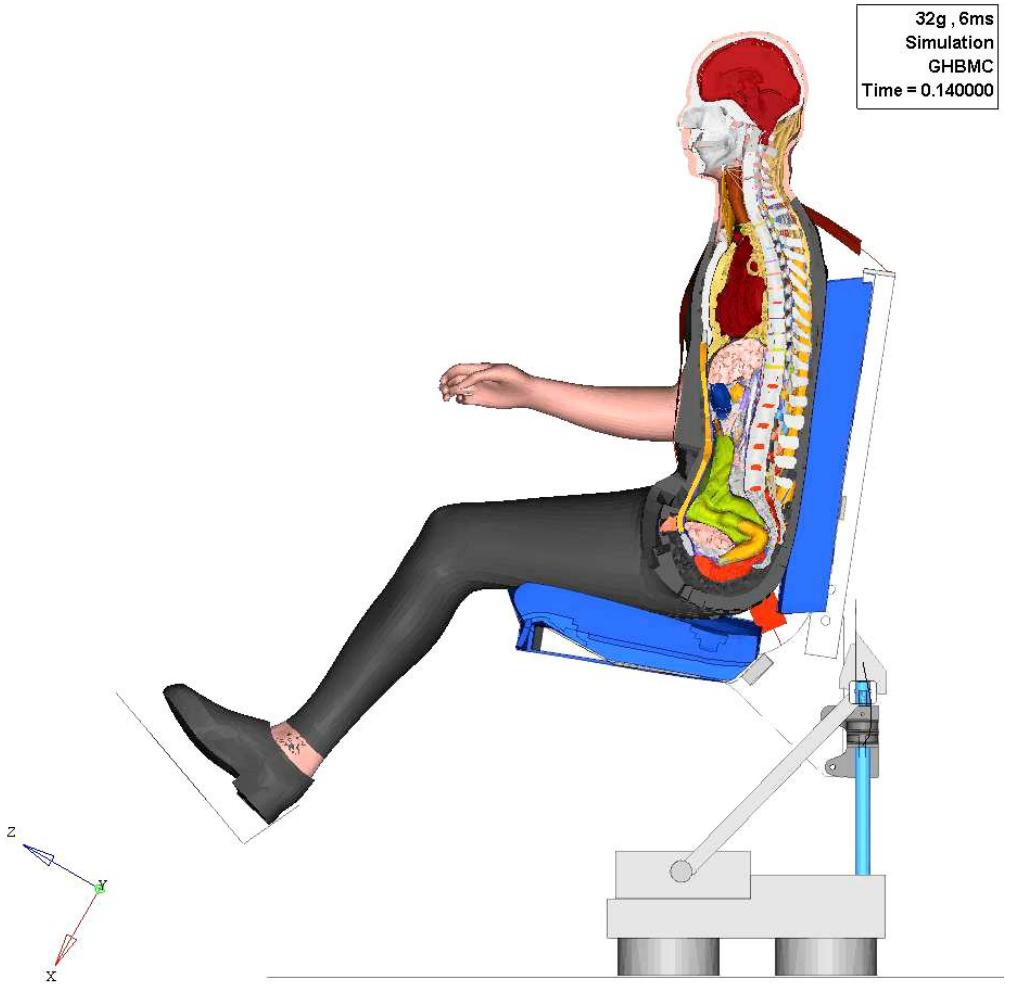




EA Seat Design Check HBM

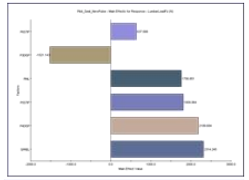
eVTOL Integrated Safety

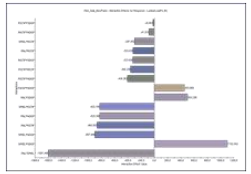




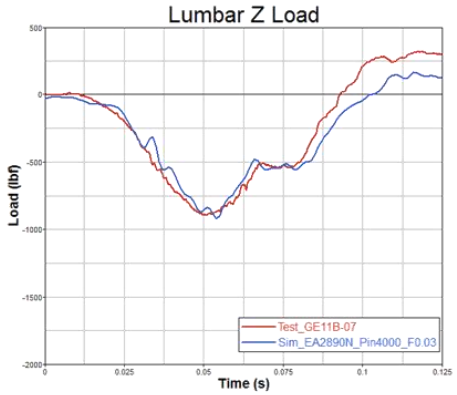
Seat Prototype Testing – Proof of Concept

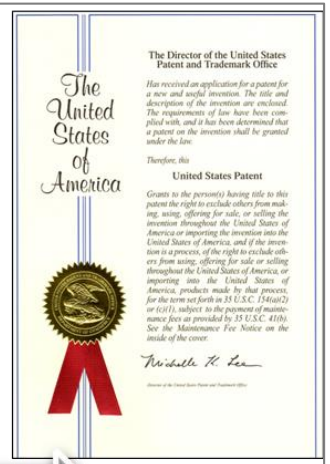
eVTOL Integrated Safety





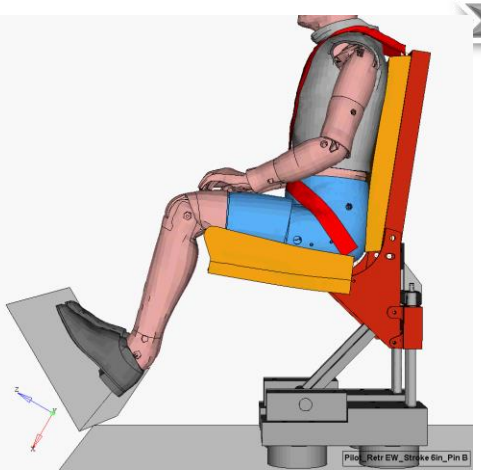
- 6 Month Development
- Concept to Proof Test
- Optimization Methods to cover 5th through 95th Percentile Occupants
- Over 5000 Simulations
- New EA Technology Development - US Patent 9,327,623
- 1st Prototype test meets the Design Requirements
- Lumbar Load Reduction from 2300 lbf down to 895 lbf

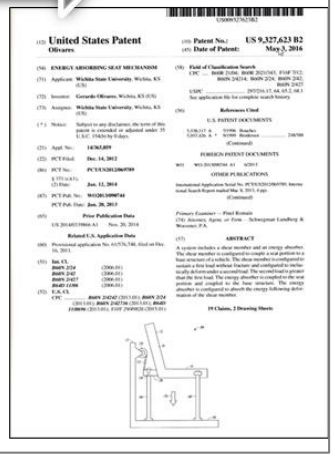




Planning
↓
Screening
↓
Model Generation
↓
Evaluation
↓
Optimization
↓
Verification

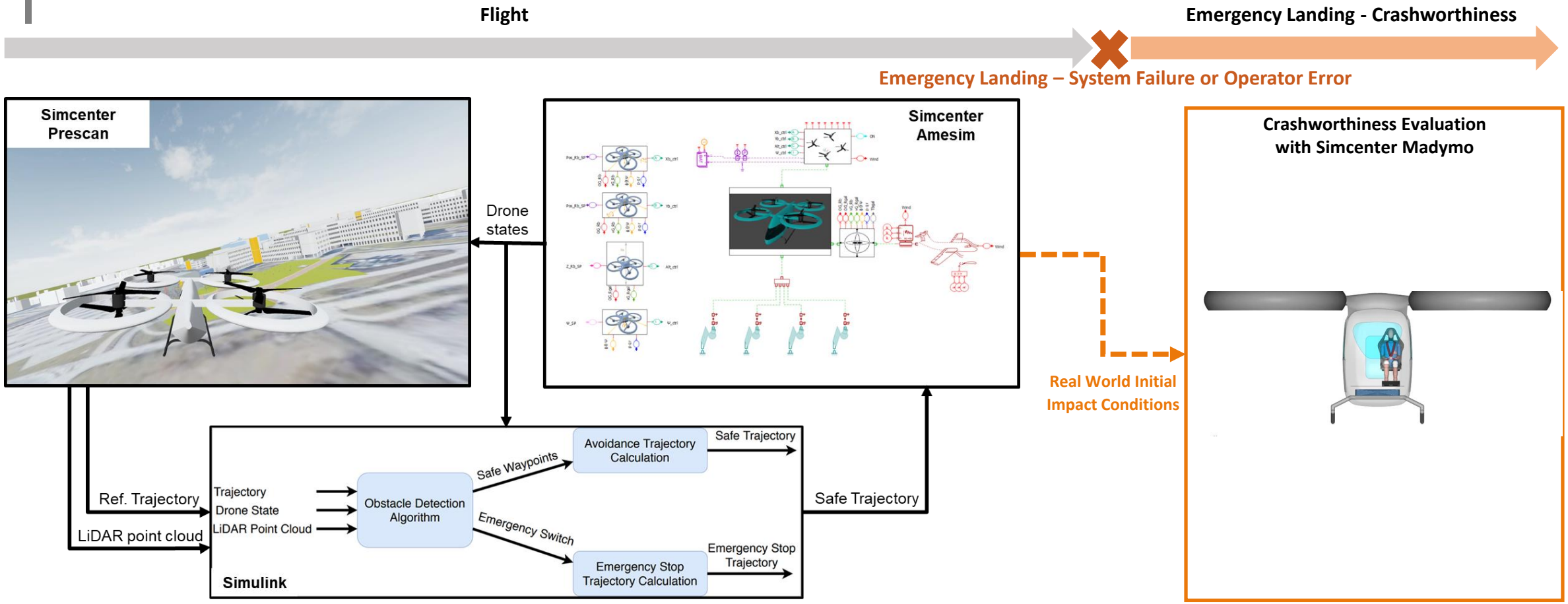
Product Design Specifications | Conceptual Design | Design and Validation | Prototype Testing





Virtual Flight Testing

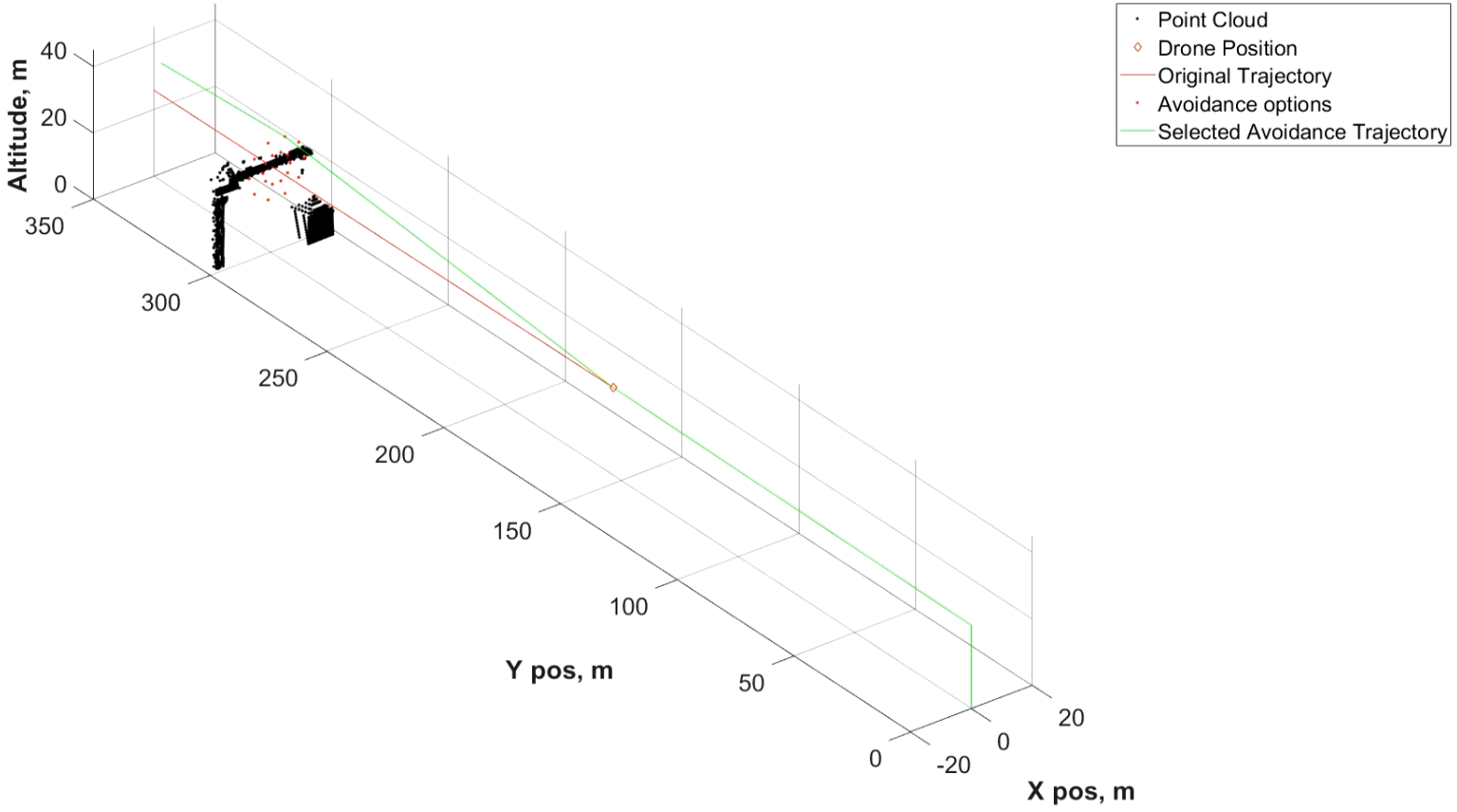
Integrated Safety for eVTOL Crashworthiness

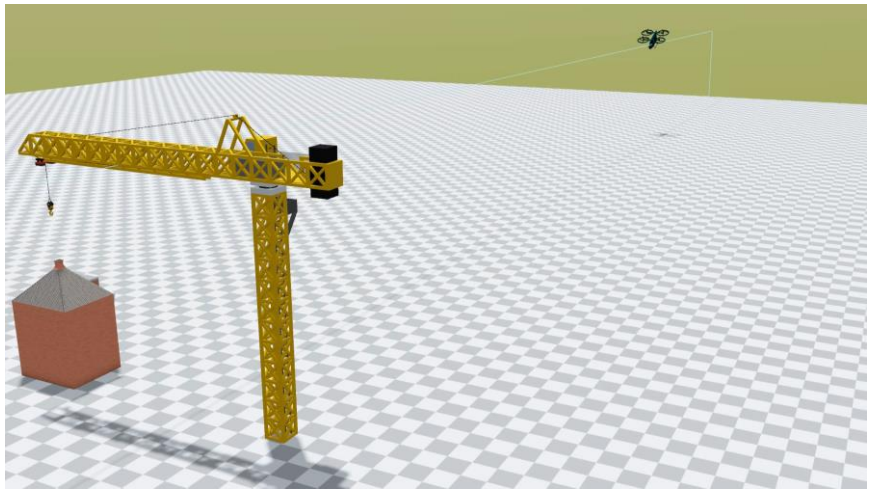


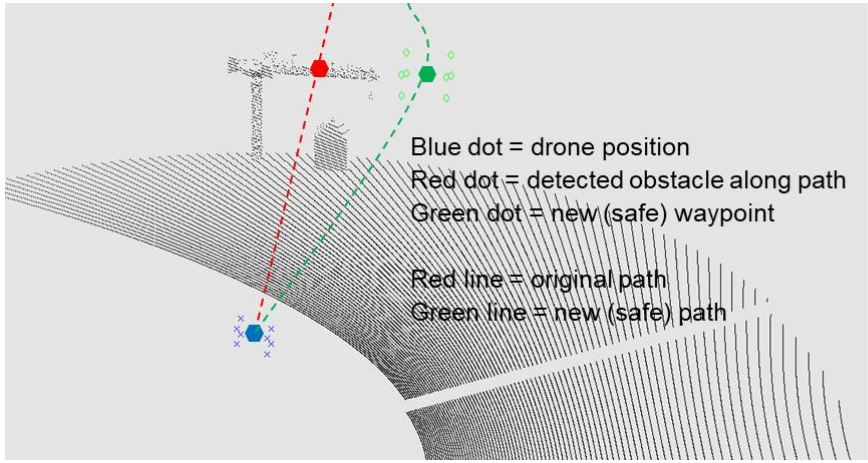
SIEMENS NIAR

Detect and Avoid Virtual Testing

Integrated Safety for eVTOL Crashworthiness





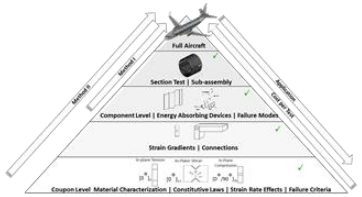


Overview FAA Funded R&D Programs

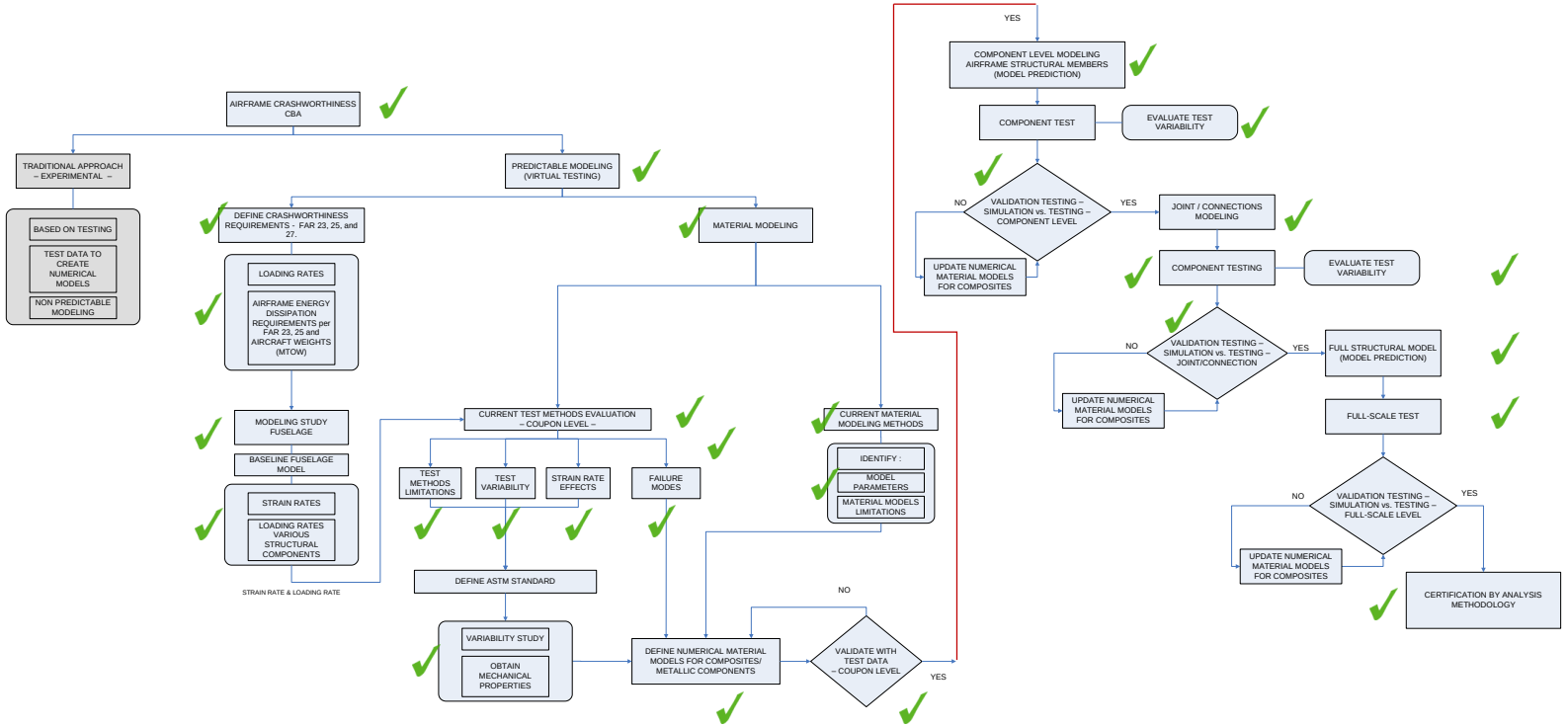
Integrated Safety for eVTOL Crashworthiness

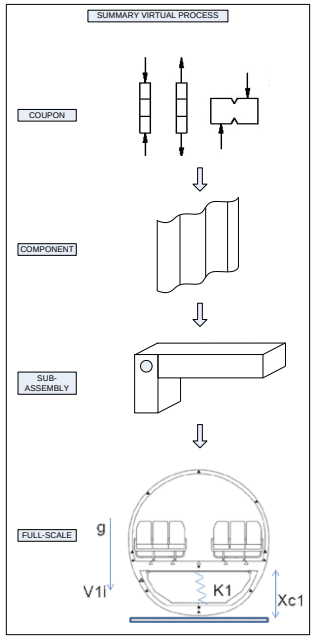
eVTOL Crashworthiness Research

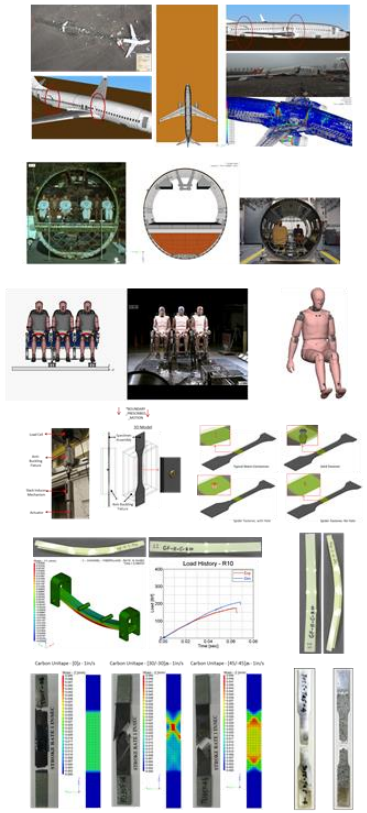
FAA JAMS COE Research



- Metallic Fuselage Drop Test (PMHS Injury Evaluations) – Ongoing
- Effects of Defects in the Energy Absorbing Capabilities of Composite Structures – Ongoing
- eVTOL Crashworthiness Methods – Pending Funding FY 2021



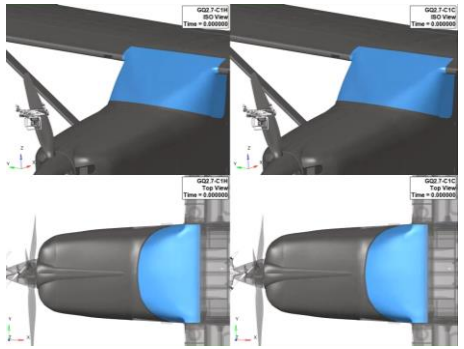




eVTOL UAM Research

FAA ASSURE COE Research

- **A36 Urban Air Mobility**: Safety Standards, Aircraft Certification and Impact on Market Feasibility and Growth Potentials
  - **Working Packages Overview:**
    - WP 1: Evaluation of UAM Market Potential: economic feasibly, potential size and growth, characteristics of population, and ground infrastructure.
    - WP 2: Airworthiness regulations and its applicability to UAM aircraft certification.
    - WP 3: Evaluation of UAM integration on the National Aerospace System – Air Traffic Control and Operations.
    - WP 4: Final Report and Recommendations for future research.
  - **Period of Performance:** 10/5/2020 to 7/1/2022
  - **Universities:** WSU– NIAR, Mississippi State University, Embry Riddle Aeronautical University, South Carolina State University
- **A47 sUAS Mid-Air Collision (MAC) Likelihood (14 CFR 23,25 ,27,and 29)**
- **A3, A16, A17: sUAS Airborne Collision Severity Studies (14 CFR 23,25 ,27,and 29)**



Conclusions

Aerospace Integrated Safety

- In order to successfully operate eVTOL vehicles, occupant safety must be an integral part of the overall technical and management processes associated with the design, development and operation of eVTOL Urban Air Transport systems.
- Current emergency landing conditions requirements specified in 14 CFR *.561 and *.562 do not provide the level of safety required for eVTOL vehicles.
- A successful implementation of the eVTOL market will require the development of Emergency Landing Standards and means of compliance (FAA, EASA, ASTM.. etc.) that address real world safety expectations.
- Emergency landing standards will need to be defined for eVTOL vehicles taking into consideration their unique design features and operation:
  - New and Novel Electric Distributed Propulsion Systems
  - New and Novel Vehicle Architectures
  - Non-conventional seating arrangements
  - Complex Urban environment operations (sharing airspace with other aircraft, sUAS, building infrastructure, people on the ground..etc..)
  - Mixed Modes of Transportation (Air and Ground)
  - Landing Sites crashworthiness design
  - Battery System Protection and post impact fire risk assessment
- 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.

Thank you for your attention.

NIAR Advanced Virtual Engineering and Testing Laboratories

| Gerardo Olivares Ph.D. | Director AVET Laboratories and Crashworthiness Research| gerardo.olivares@wichita.edu|