NASA / FAA eVTOL Crashworthiness Workshop Series: Virtual Meeting #4:

NASA Revolutionary Vertical Lift Technology (RVLT) Project – NASA Crashworthiness Research Overview

April 13, 2021

Justin Littell Ph.D.
Research Aerospace Engineer
Structural Dynamics Branch
NASA Langley Research Center
Justin.D.Littell@nasa.gov

Jacob Putnam
Research Aerospace Engineer
Structural Dynamics Branch
NASA Langley Research Center
Jacob.B.Putnam@nasa.gov

Introduction – NASA RVLT Project
Impact Dynamics / Crash Safety Task

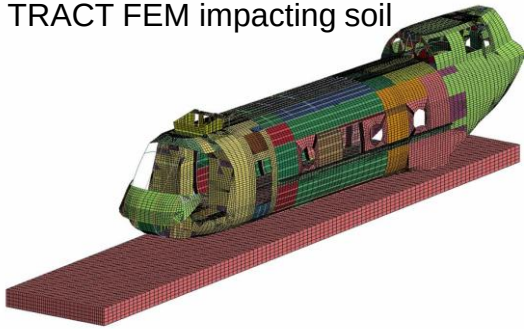
- **Task Objective:** *"To improve the crashworthiness and impact safety of UAM vehicle and provide data to simplify the certification process. Efforts will include development of validated computational models of these vehicles, as well as other impacting bodies such as birds and drones. Efforts will also focus on developing and evaluating energy absorbing and crush properties of emerging and non-traditional composite materials and processes. Finally, occupant protection will be addressed using computational models and physical assets as it pertains to all rotorcraft environments*."
- **Problem Statement:** "*There currently is a lack of data for requirements regarding the crashworthy performance of UAM vehicles and impact loads generated by a bird strike . To address this technology gap, NASA will develop test guidelines, adopt modeling methodologies demonstrating capability for 'certification by analysis', acquire vehicle and occupant data on full-scale representative vehicles, and provide data/guidance to consensus standards organizations and the UAM community."*

- 4 Main focus points
  - The investigation of occupant injury using physical and computational assets
  - The development of energy absorbing technology
  - The generation of data from sub- and full-scale crash test data
  - The execution of advanced finite element modelling techniques

RVLT Historical Testing / Research Examples

- RVLT (and predecessors) have been conducting crash research for 20+ years at LaRC
  - Dynamic performance of composites
    - ACAP – large composite rotorcraft prototype
    - SARAP – composite fuselage prototype
  - Occupant protection
    - F28 vertical and full-scale crash testing
    - Transport Rotorcraft Aircraft Crash Testbed (TRACT 1&2)
    - ATD vertical drop testing
    - Advanced ATD research
  - Energy absorbing concepts development
    - MD-500 with Deployable Energy Absorber concept
    - TRACT 2 crushable “conusoid” subfloor
  - Advanced computational simulation efforts
    - Full-scale aircraft development
    - Terrain replication
    - ATD evaluations

TRACT FEM impacting soil



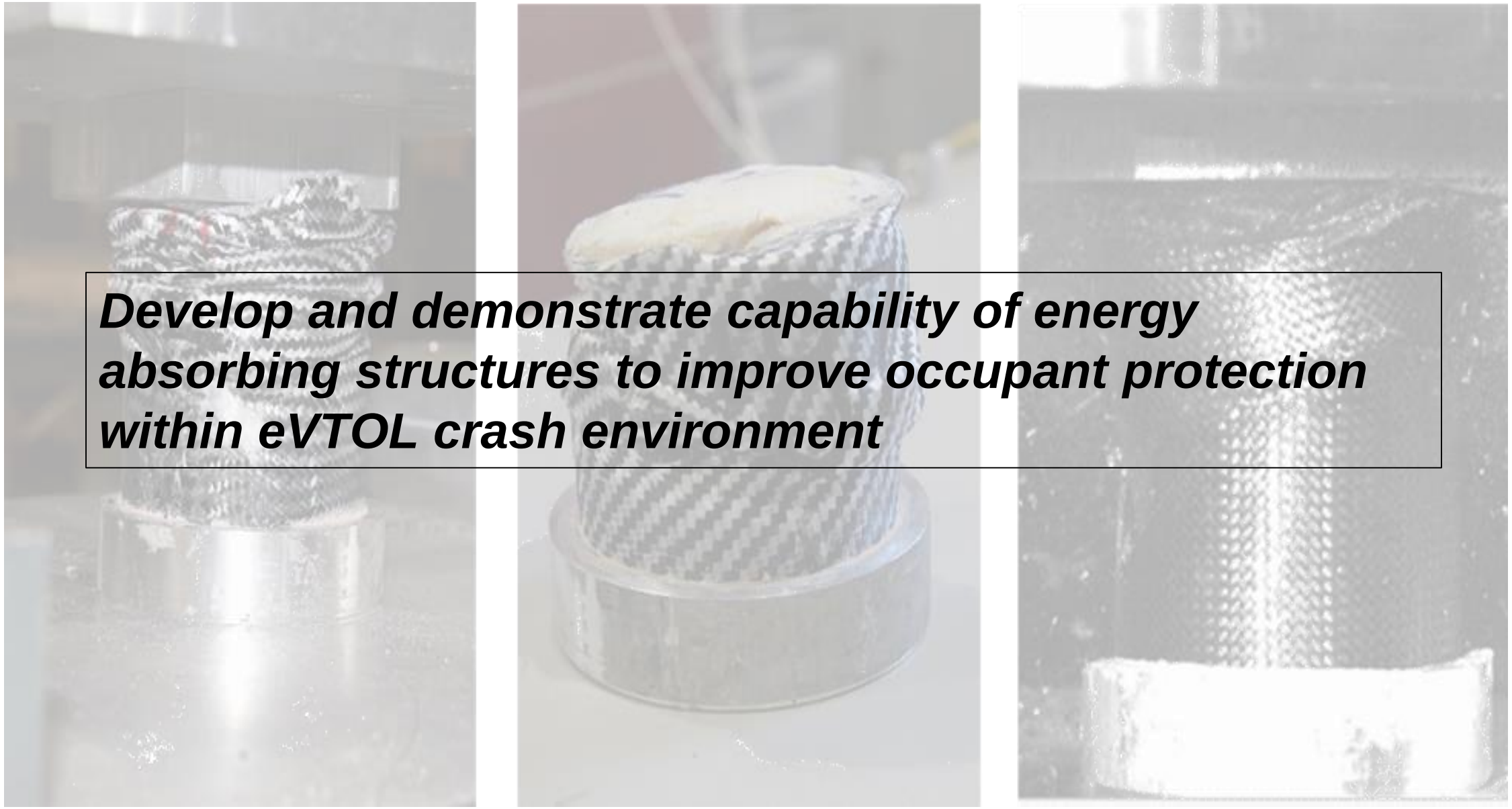
TRACT “conusoid” subfloor

Current/Upcoming eVTOL RVLT Crashworthiness Research

- Energy Absorbing (EA) concept development of landing gear components, subfloor components and seat components
- Seating system testing under eVTOL loading conditions
- Anthropomorphic Test Device (ATD) investigations, along with ATD and human model evaluation under eVTOL impact conditions
- LS-DYNA implementation of a fully characterized MAT 213 developmental composite material model capable of simulating deformation, damage and failure
- Full-scale crash testing of eVTOL representative reference vehicle cabin sections

- NASA Announcement of Collaboration addendum

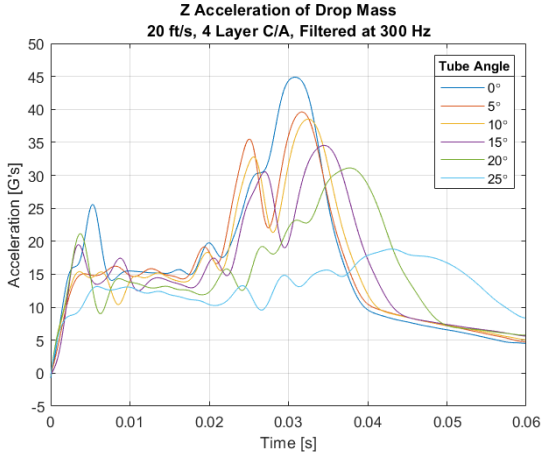
Energy Absorbing Concept Development - Goal

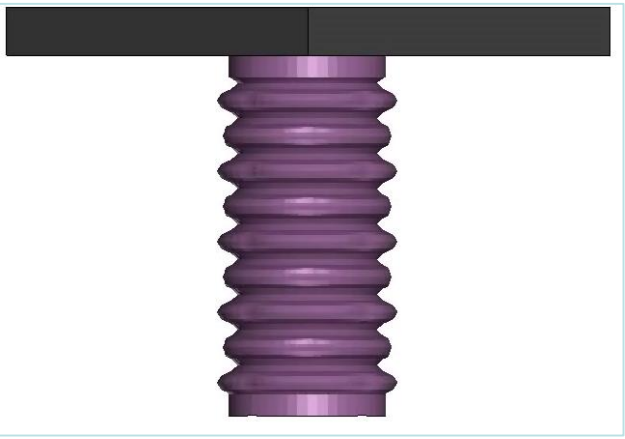


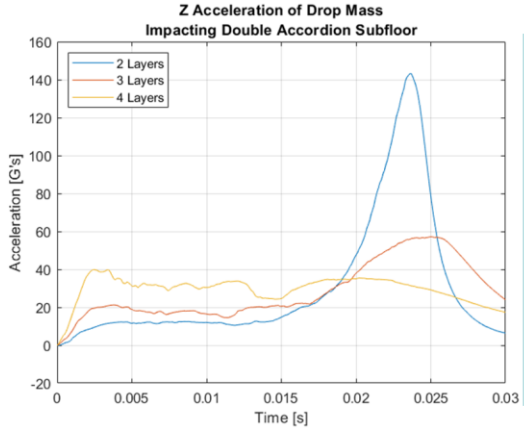
Develop and demonstrate capability of energy absorbing structures to improve occupant protection within eVTOL crash environment

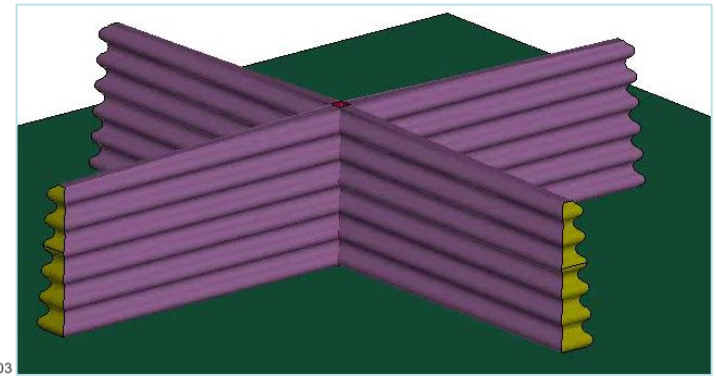
Energy Absorbing (EA) Concept Development - Subcomponents

- Carbon Aramid composite structures under evaluation for EA capability
  - Effects of geometry and layup studied through simulation
- Crush tube designs
  - Identify geometric concepts
  - Quantify design capabilities
  - Optimize performance
- Subfloor designs
  - Lessons learned in crush tube development implemented within subfloor structures



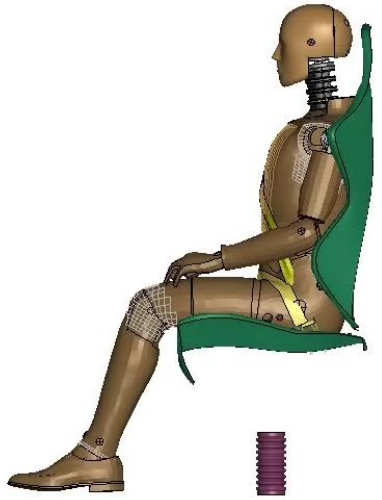


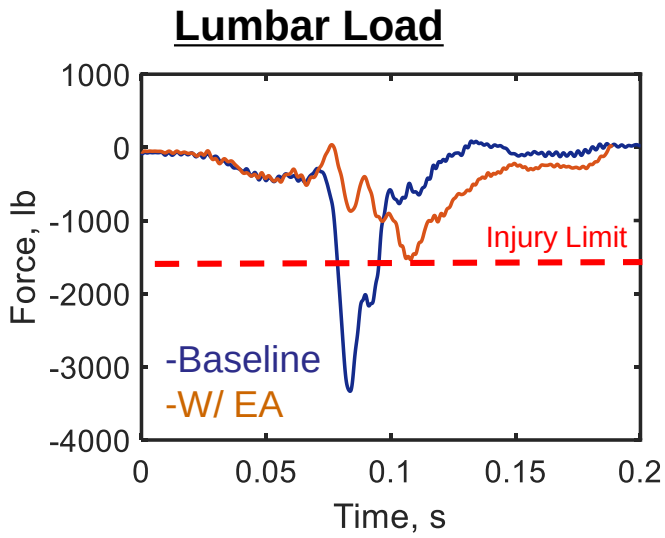


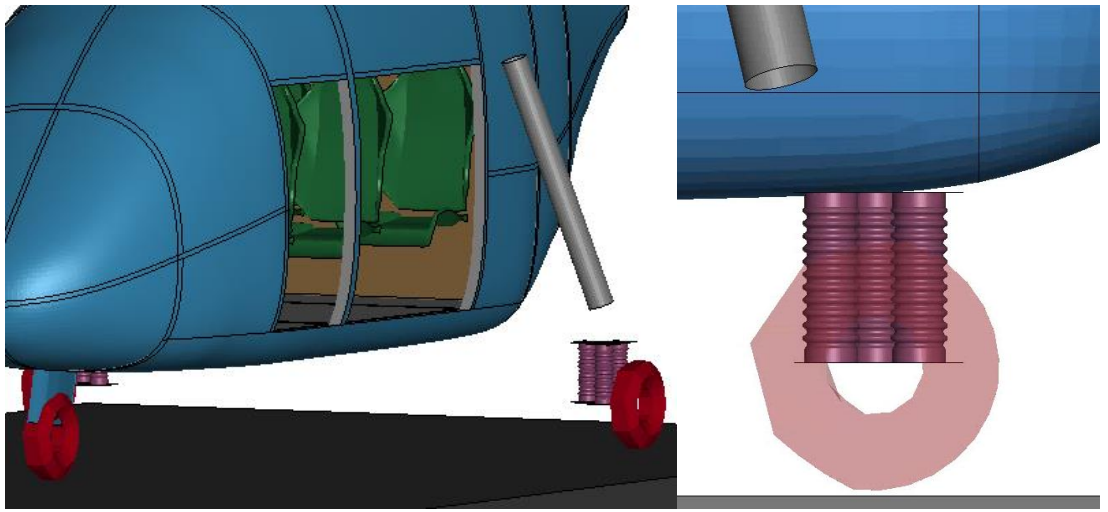


Energy Absorbing Concept Development - Components

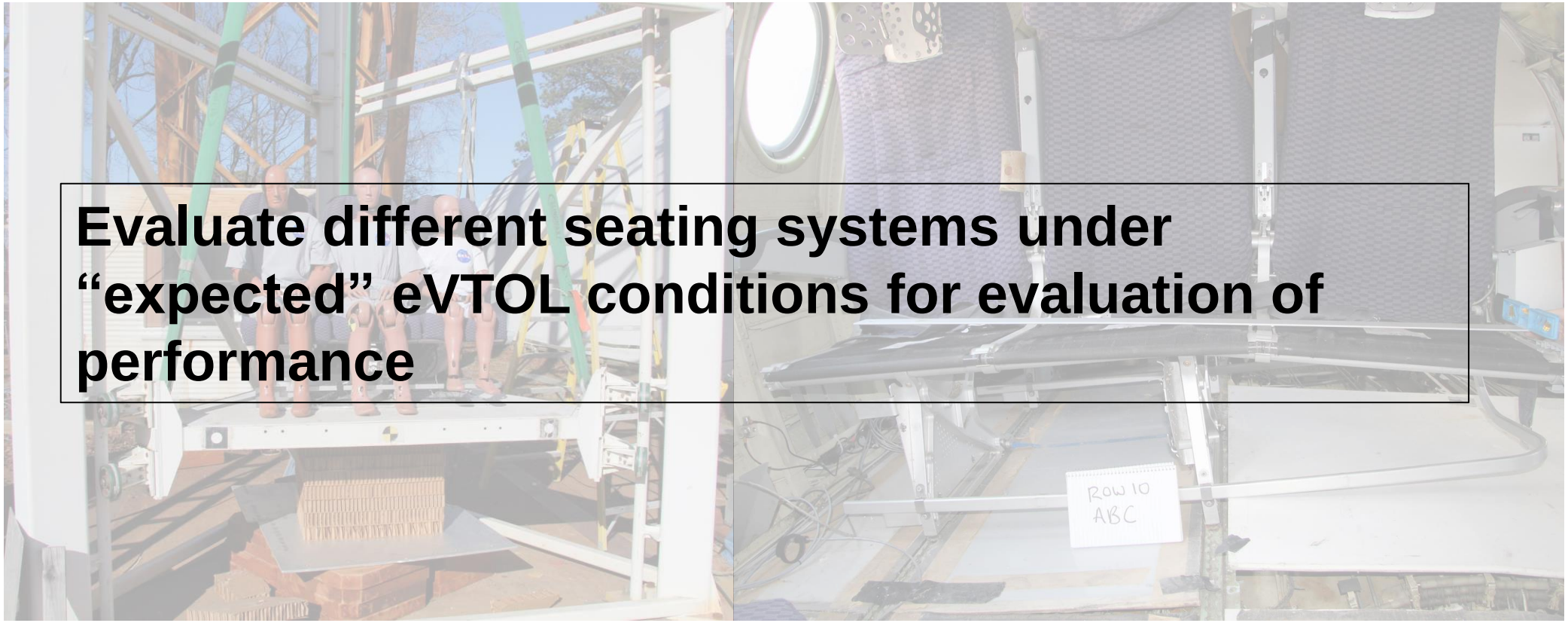
- EA components currently under development based on design concept study
  - Integrated into full vehicle design for testing
- Seat stroke mechanisms
  - Crush tube integrated into seat load path
  - Simple and lightweight
  - Robust to vehicle design
- Landing gear designs
  - Crush tube integrated into landing gear struts
  - Variety of design concepts currently under consideration
  - Vehicle specific







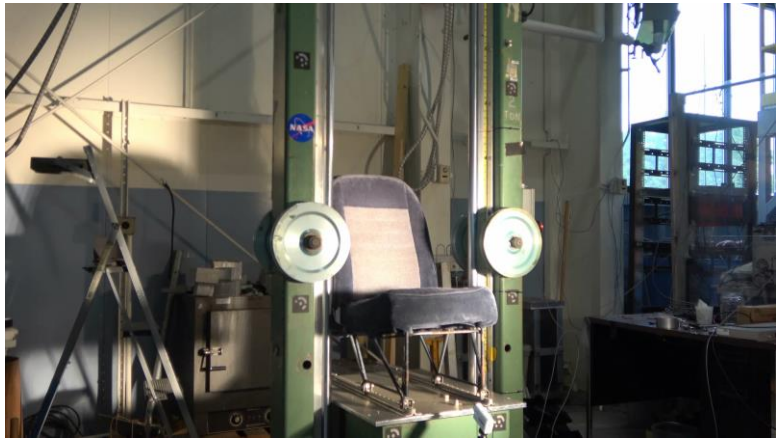
Seat investigations - Goal

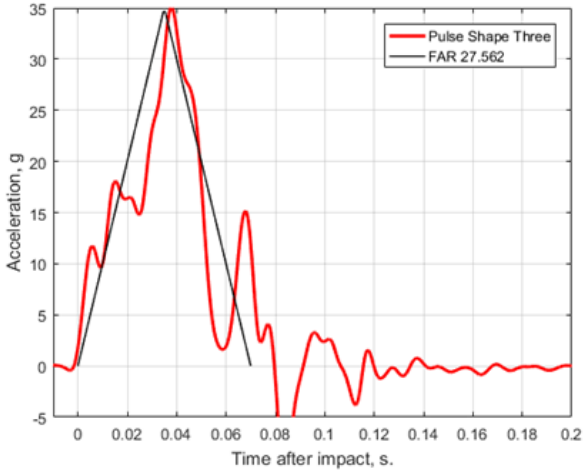


Evaluate different seating systems under “expected” eVTOL conditions for evaluation of performance

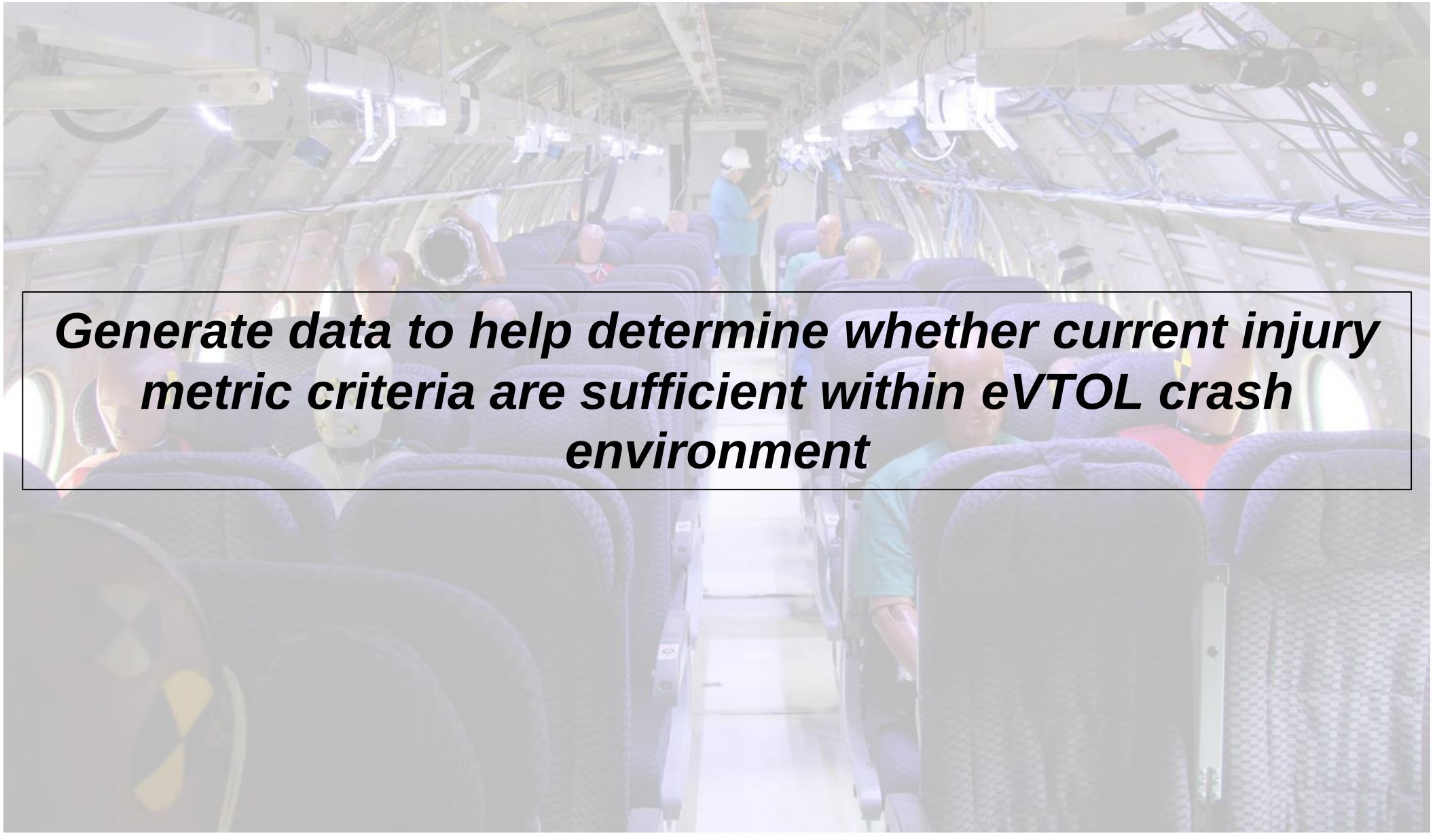
Seat investigations - Full-Scale Crash and Drop Testing

- Testing Conditions
  - Drop testing includes conditions: Current requirements, full scale test/simulation results
  - Full scale testing included conditions defined in test matrix
- Combination of rigid, in-house developed EA, others
  - *Still being defined*
  - Will utilize various occupant sizes, types and builds





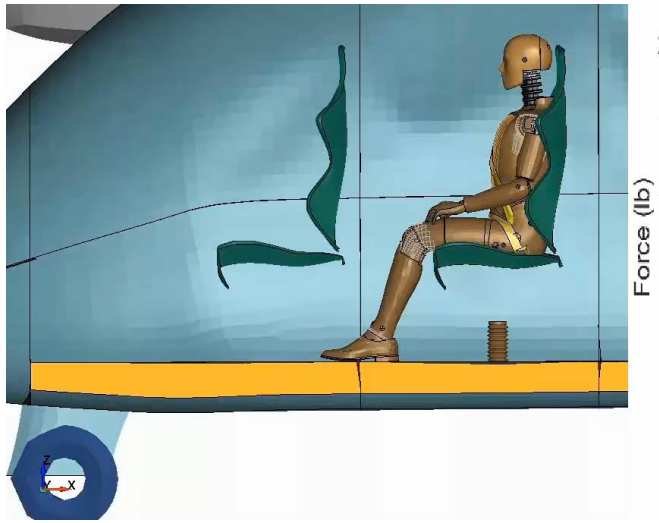
Occupant Analysis - Goal

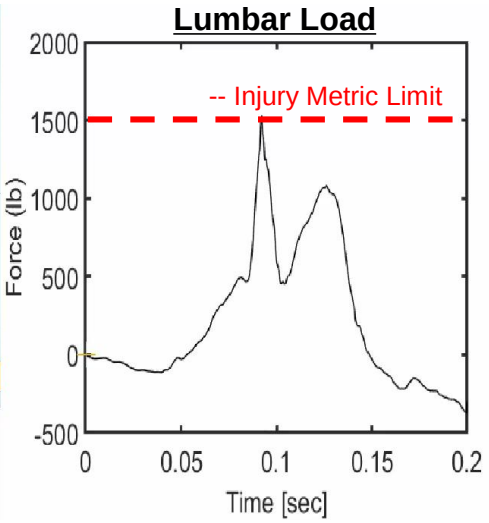


Generate data to help determine whether current injury metric criteria are sufficient within eVTOL crash environment

Occupant Analysis – Anthropomorphic Test Devices (ATDs)

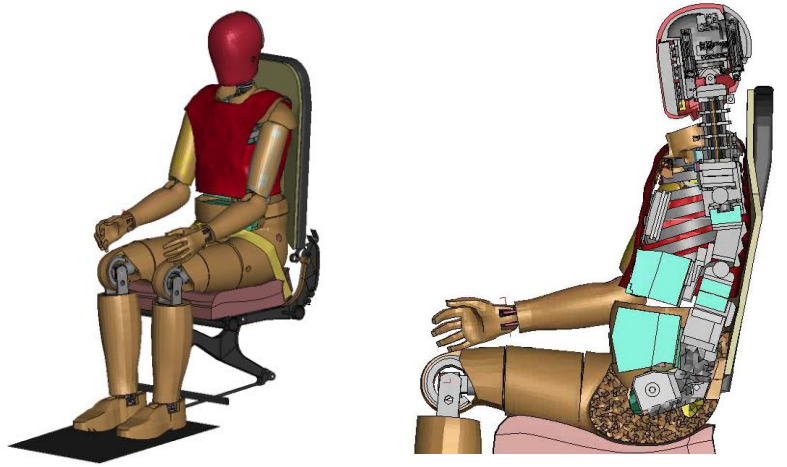
- Evaluate occupant injury risk within eVTOL vehicle design w/ respect to current certification limits
  - Validation predicted of injury metric response against full scale test data
  - Demonstrate use of ATD FEM to quantify occupant safety across crash environment





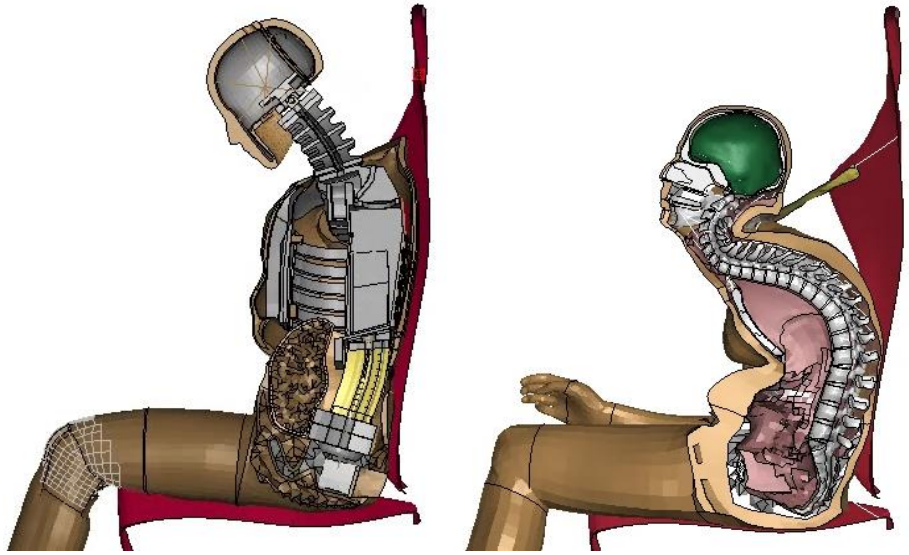
- Evaluate capability of advanced ATD designs to predict injury within the eVTOL crash environment
  - Identify potential benefits over standard (Hybrid III) configuration

Test Device for Human Occupant Restraint (THOR)

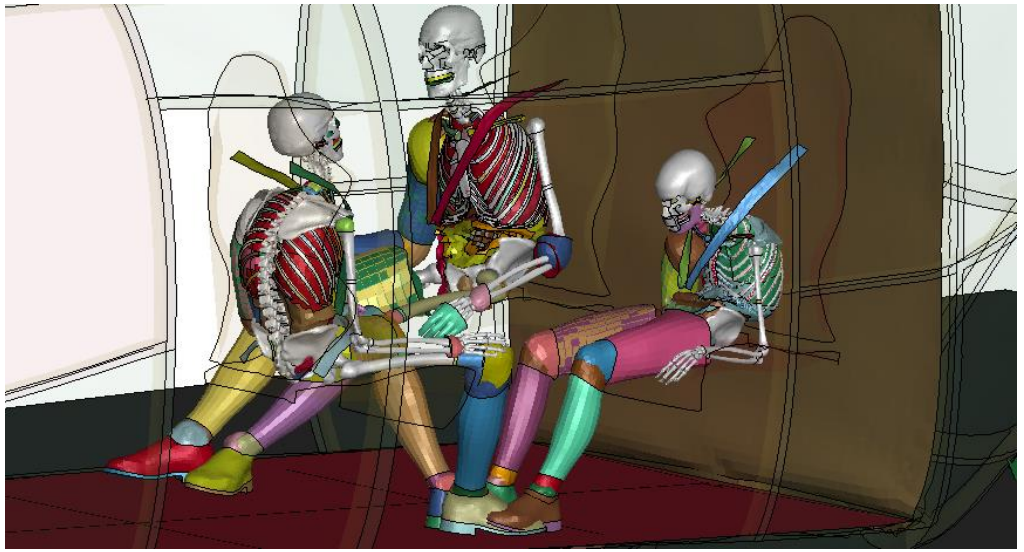


Occupant Analysis – Human Body Models

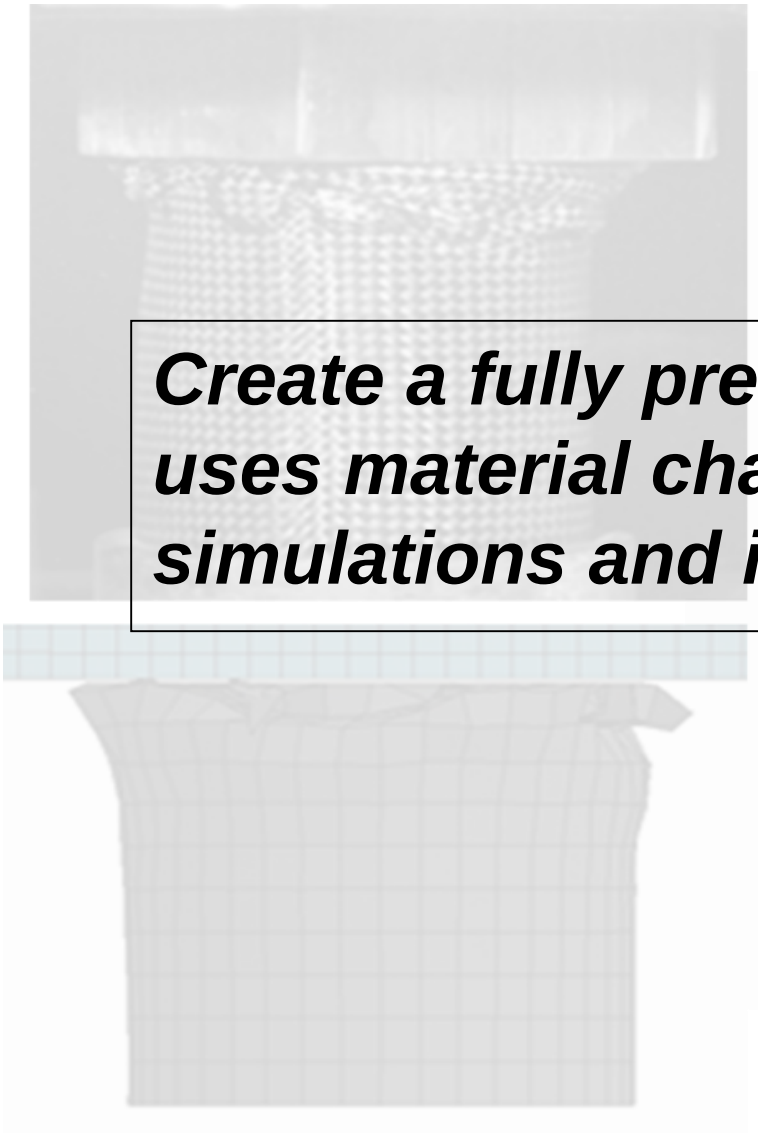
- Evaluate capability of human body models to supplement limitations of ATDs within eVTOL crash environments
  - Full body musculoskeletal injury risk prediction
  - Biofidelity under multi-axis loading
  - Effects of muscle activation (bracing)

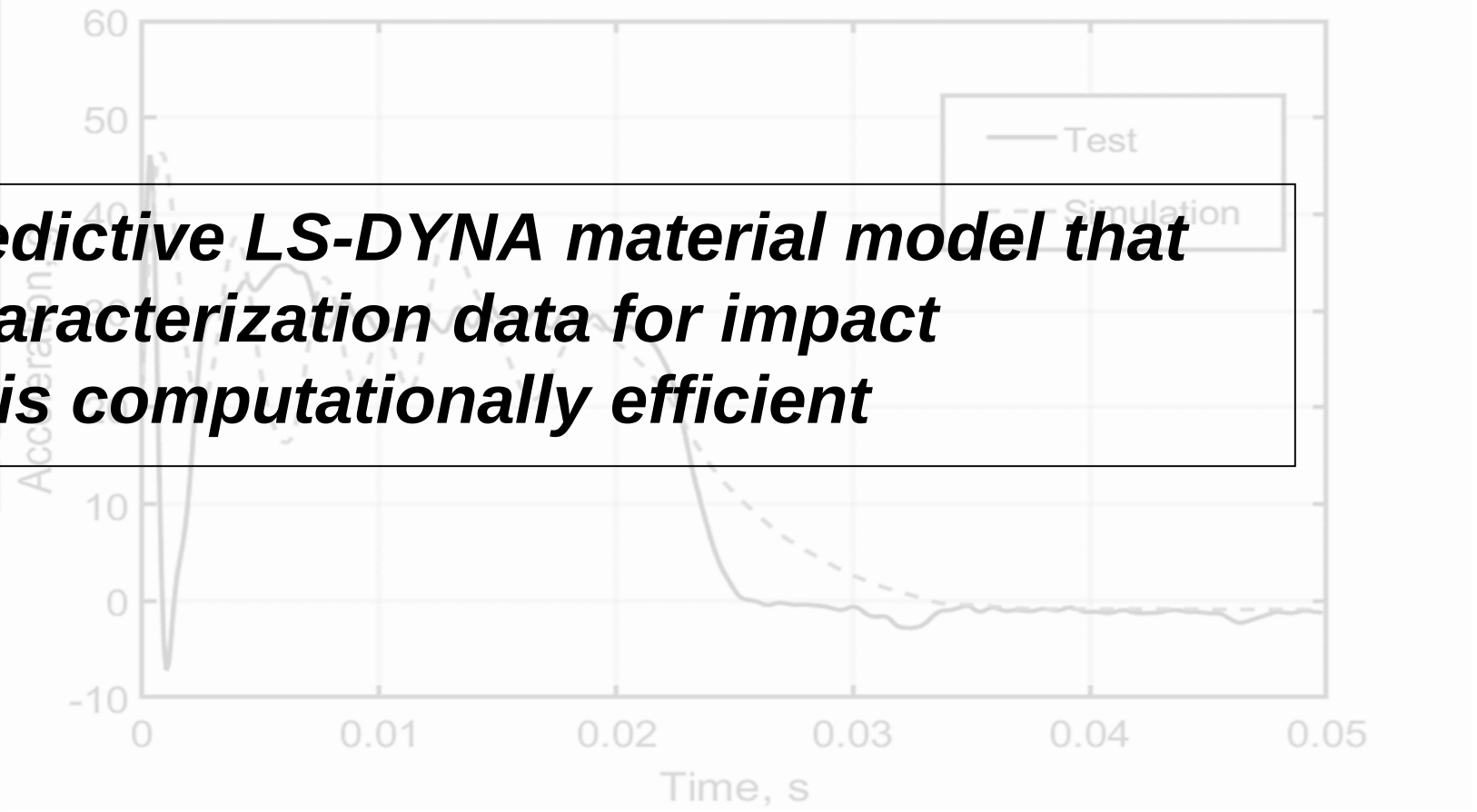


- Demonstrate use of human body models to characterize injury risk mechanisms within vehicle design
  - Verify low injury risk across “survivable” crash space (5^{th} – 95^{th} anthropometry)
  - Identify potential injury sources not captured under current ATD criteria



MAT 213 Composite Model Development - Goal





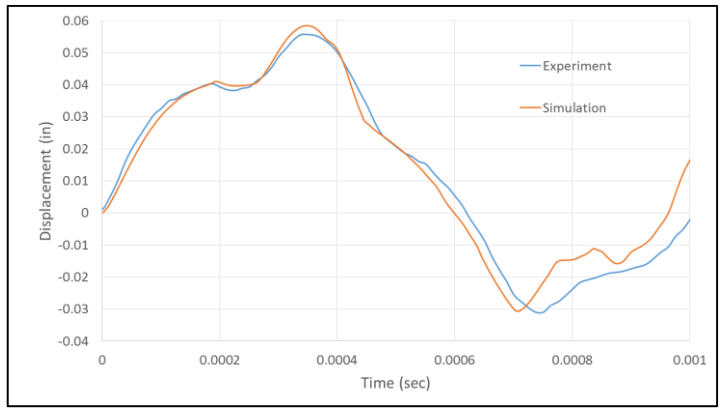
Create a fully predictive LS-DYNA material model that uses material characterization data for impact simulations and is computationally efficient

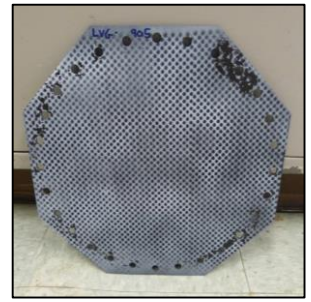
MAT 213 Composite Model Development

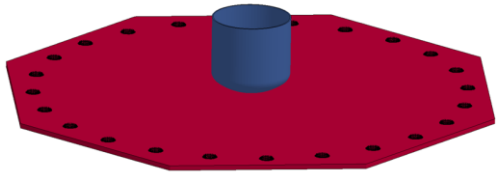
- *MAT_COMPOSITE_TABULATED_PLASTICITY_DAMAGE
- Current LS-DYNA material models have been found to have limitations in the modeling of impact in composites
  - Existing models usually require significant a priori knowledge of damage and failure responses on the structural scale
- New composite impact model being developed for implementation into LS-DYNA as MAT 213.
- Model has three modules
  - “Deformation”: Nonlinear loading and permanent deformation
  - “Damage”: Reduction of average modulus on unloading
  - “Failure”: Simulate end of stress-strain curve
- Model has generalized, tabulated input.
  - Avoid point wise properties and curve fitting
  - Input based on physically meaningful mechanical property tests.

MAT 213 Simulation Results

- Previous model validation efforts have focused on the ballistics impact problem

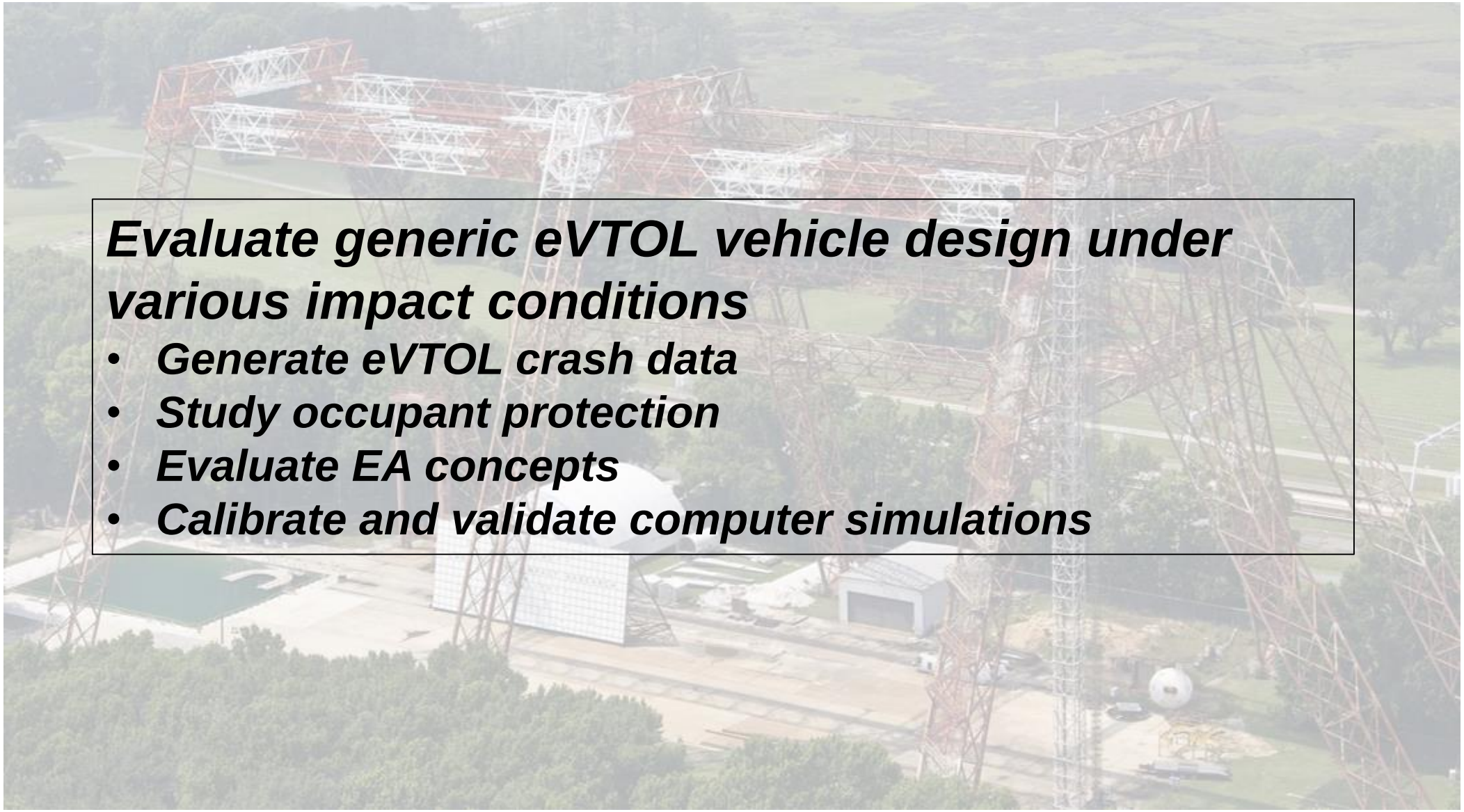






- Current and upcoming research will focus on the development of shell-based models for crushable structures
  - Traditional and Hybrid composite materials
  - Material characterization testing anticipated startup Summer 2021
    - Specifically, how to characterize damage and failure models to simulate failures in the “crush” problem

Full-Scale Crash Testing - Goal

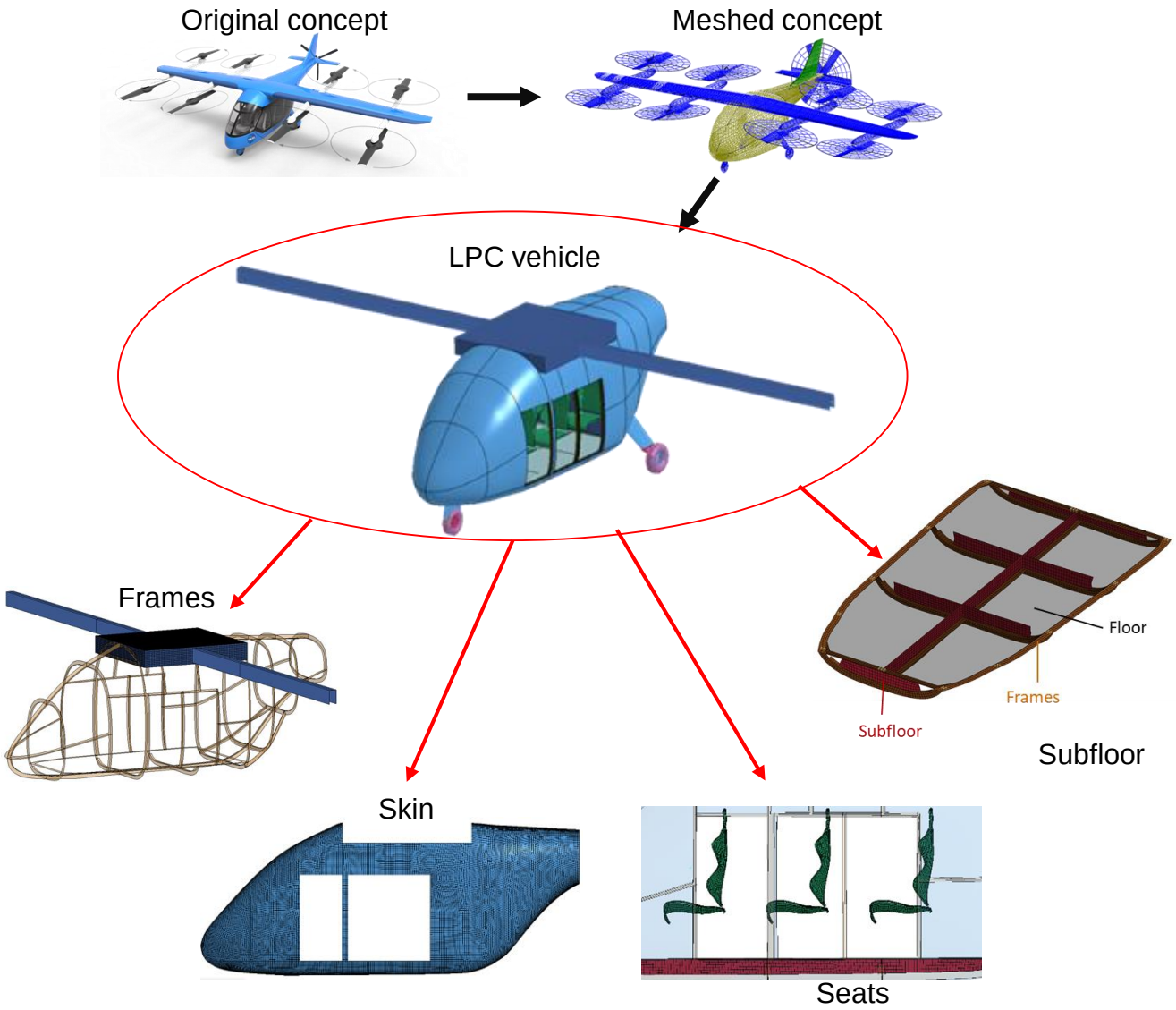


Evaluate generic eVTOL vehicle design under various impact conditions

- ***Generate eVTOL crash data***
- ***Study occupant protection***
- ***Evaluate EA concepts***
- ***Calibrate and validate computer simulations***

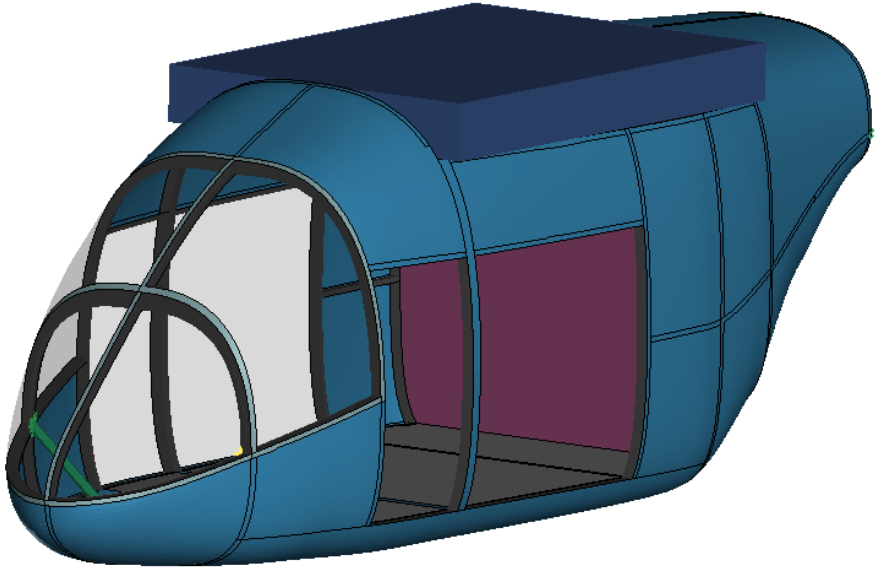
Full-Scale Crash Testing – Vehicle development

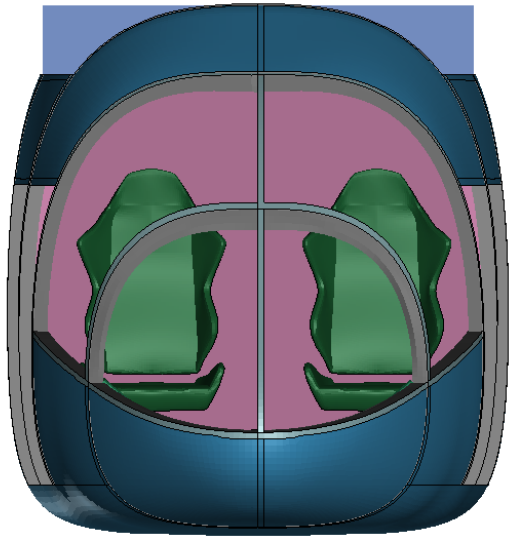
- NASA Lift + Cruise concept vehicle chosen for full-scale test campaign
- Design underway
  - Carbon fiber weave skin
  - Carbon fiber weave frames
  - Rigid overhead Wingbox area
  - Rigid and energy attenuating seats
  - In-house EA designs
    - Seat
    - Subfloor
    - Landing gear



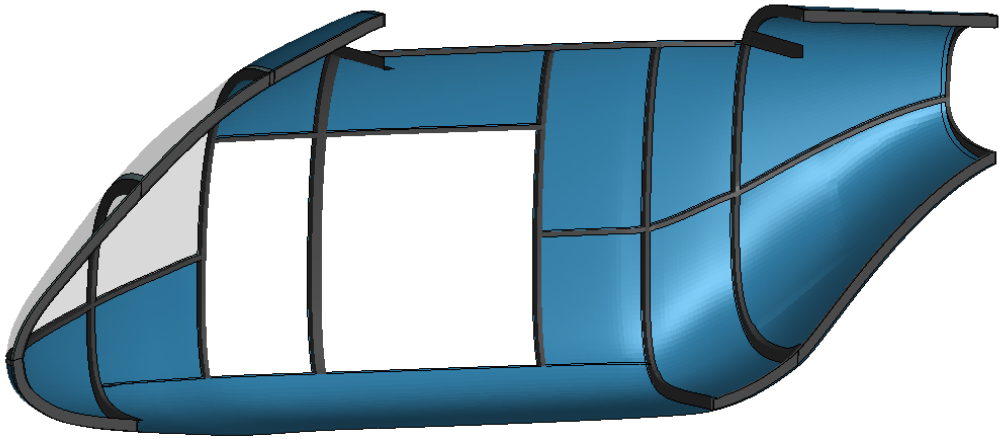
Full-Scale Crash Testing – Test Article

- Test Article Specifications
  - Dimensions: 18’x6’x7’
  - Weight: ~6000 lb
  - Seats: 6 passenger
  - Wing Type: High wing



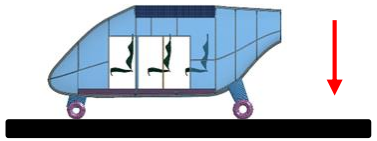


- Structural components sized to maintain survivable volume under load
  - 12g static vertical load
  - 30 ft/s dynamic vertical impact
  - Non-structural components replaced with mounted mass



Full-Scale Crash Testing – Test Matrix

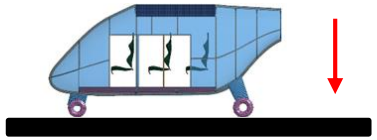
Test 1	Vz=Med	Vx=None
Concrete	Pitch = 0	Yaw = 0



Case: Case covers baseline and used for model validation

SF	LG	NG	WB
Base	Base	Base	Base

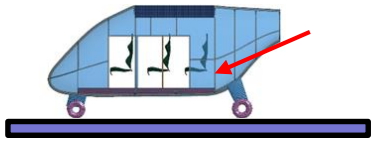
Test 2	Vz=Med	Vx=0
Concrete	Pitch = 0	Yaw = 0



Case: Performance of optimized EA mechanisms vs baseline. Model Validation

SF	LG	NG	WB
Opt	Opt	Base	Base

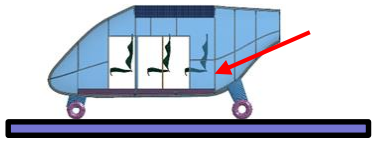
Test 3	Vz=Med	Vx=High
GUS	Pitch = 0	Yaw = 0



Case: Combined high horiz, validate horizontal into soil response (ASTM)

SF	LG	NG	WB
Base	Base	Base	Base

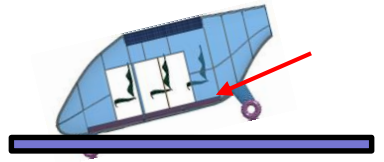
Test 4	Vz=Med	Vx=High
GUS	Pitch = 0	Yaw = 0



Case: Evaluate effectiveness of EA in multi-axis soil (ASTM)

SF	LG	NG	WB
Opt	Opt	Opt	Base

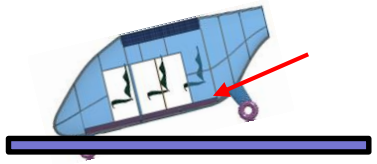
Test 5	Vz=Med	Vx=High
GUS	Pitch = Y	Yaw = 0



Case: Compare to test 3 for pitch effect

SF	LG	Nose	WB
Base	Base	Base	Base

Test 6	Vz=Med	Vx=High
GUS	Pitch = Y	Yaw = 0

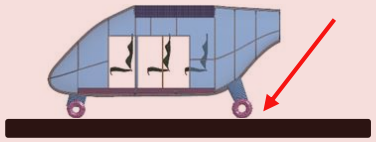


Case: Compare to test 5 for nose gear effect

SF	LG	Nose	WB
Base	Base	Opt	Base

Cases selected after modeling – Survivability envelope expansion

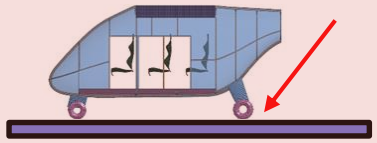
Test 7	Vz=High	Vx=High
Concrete	Pitch = 0	Yaw = 0



Case: Validation of predicted survivability boundary. Performed later to allow model calibration to earlier tests if needed before condition selection.

SF	LG	NG	WB
Opt	Opt	Opt	Base

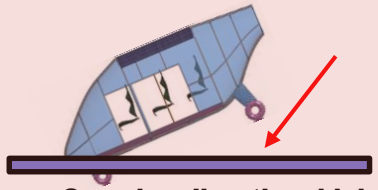
Test 8	Vz=High	Vx=High
GUS	Pitch = 0	Yaw = 0



Case: Repeat of 7 with GUS to quantify injury risk changes w/ soil impact.

SF	LG	NG	WB
Opt	Opt	Opt	Base

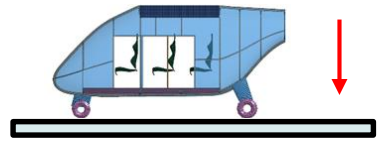
Test 9	Vz=High	Vx=High
Concrete	Pitch = Y	Yaw = Y



Case: Complex direction, high energy, soil – Bound analysis (interpolate in)

SF	LG	NG	WB
Opt	Opt	Base	Base

Test 10	Vz=Med	Vx=0
Water	Pitch = 0	Yaw =0

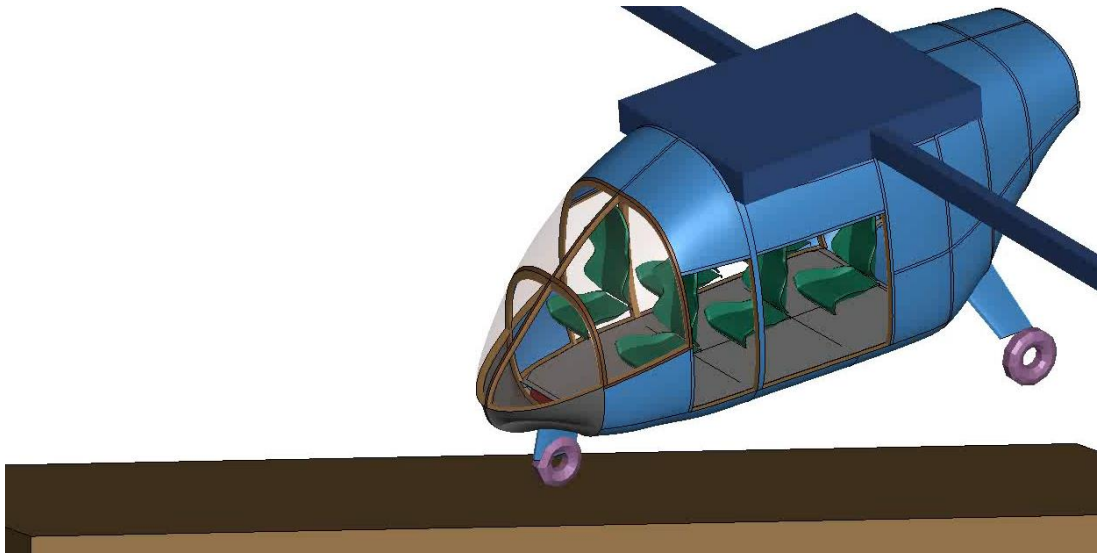


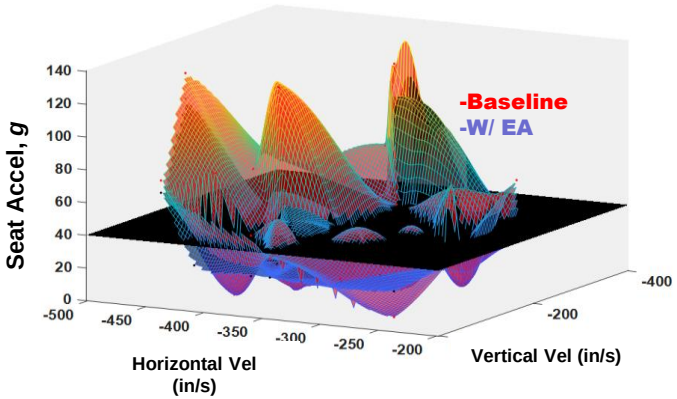
Case: Simple ditching condition

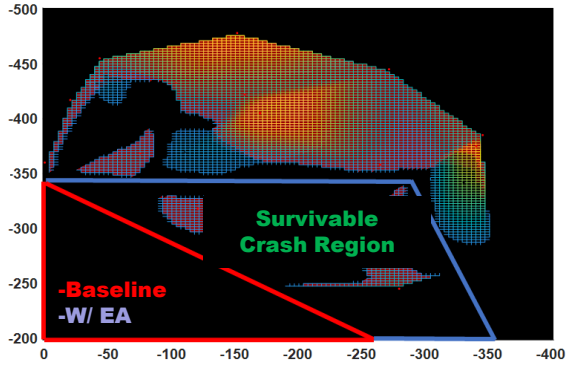
SF	LG	NG	WB
Base	Base/none	Base	Base

Full-Scale Crash Testing - Finite Element Modeling (FEM)

- Evaluate capability of FEM to predict vehicle crash response
  - Validation of composite structural models through full scale test data
  - Validation of EA mechanisms under multi-axis integrated loading environment
- Demonstrate analytical techniques for defining “survivable” crash space
  - Expansion of crashworthiness through EA mechanisms
  - Validation through enveloping test selection
- Extend the full-scale crash matrix by simulating additional cases







Research Summary

- Full-scale testing anticipated to occur starting FY23/FY24 timeframe, which utilizes all component level research identified herein
  - Energy absorbing mechanism robustness and efficiency
    - Component level design ongoing
  - Seat attenuation systems
    - Component level drop testing conducted parallel to full-scale efforts
  - ATD and human model evaluation
    - Occupant safety analysis
  - Composite material model validations
    - MAT 213 material model will be developed in parallel using component and full-scale test data
- Full-scale simulations performed using knowledge gained from the above full-scale and component level test data
  - Develop analysis methodologies for defining vehicle crashworthiness capability

Addendum – Announcement of Collaboration (ACO-3)

- Annex 7 – Crashworthiness Research and Testing Annex
- Released 2/24/21
- Closed 4/2/21
- Provides opportunities to partner with NASA under non-reimbursable Space Act Agreements to test eVTOL vehicle(s) under agreed upon impact scenario(s)

- Industry day video describing Annex 7
  - Overall ACO-3 description
    - https://www.youtube.com/watch?v=KK1mWhfs4tI
  - Annex 7
    - https://youtu.be/yo1KmZzdKB8
- ACO available on beta.sam
  - https://beta.sam.gov/opp/8894f0eae855449c99c606f522b817e4/view