eVTOL Crashworthiness Results and Findings from a 50ft Battery Drop Test

Federal Aviation Administration

Presented by:

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Wichita State University

Joint Centers of Excellence for Advanced Materials

JAMS Technical Review

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A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

CECAM center of excellence for composites and advanced materials

Agenda

- Digital Engineering Design, Construction, Instrumentation, and Design Validation – AVET 50ft Drop Tower
- Pre-Test Analysis: Battery Model 50 ft. Drop Test Evaluation
- eVTOL Battery 50 ft. Drop Test Results: BD23A-01
- Future Work

All the Battery Data presented in this document is Proprietary to Beta Technologies

Research Team

- **Lead Principal Investigator** – Gerardo Olivares, NIAR AVET
- **Primary Researchers** – Luis Gomez, Robert Huculak, Marcus Pyles, Luis Daniel Castillo, Harjinder Singh, Akhil Bhasin, Aswini Kona Ravi
- **Student Researchers** – Preet Jaswal, Brady Martin, Khadija Ouajjani, Max Kinney
- **FAA Technical Monitor:** Dave Stanley
- **FAA Sponsors**: Cindy Ashforth, Joseph, Pellettiere
- **Industry Partnerships/Other Collaborations** – Beta Technologies

Battery Drop Test R&D Program - FAA

- **Occupant Safety must be an integral part of the overall technical and management processes associated with the design, development, and operation of AAM transport systems.**
- **To guarantee occupant safety, it is necessary to evaluate and analyze the performance and behavior of the complete vehicle (seats, batteries, and the surrounding composite airframe structure) during an emergency landing event (structural, thermal, and electrical).**
- **NIAR will evaluate the crashworthiness performance of UAM battery packs and their surrounding structure during a free fall of 50 ft based on 14 CFR § 27.952 and EASA MOC SC-VTOL 2:**
  - Crashworthiness via drop testing is currently regulated for fuel cells and fuel tanks. Due to the prevalence of fuel tanks and the novelty of battery systems in aircraft, EASA has adopted these fuel tank drop test requirements for use with battery systems as a starting point. The FAA is also pursuing this path while simultaneously researching more permanent methods.
  - Drop testing of fuel systems requires a 50ft drop of a nearly filled fuel system onto a flat, non-deforming surface. After the drop, the fuel system is monitored for leakage or fire. Similarly, a battery system should be critically charged and dropped from at least 50ft, then be monitored for leakage of gas or fluids, as well as fire or explosion.
- **This test program and simulation studies will provide information regarding the items relevant to FAA and Industry:**
  - **Primary Objective: identify the behavior (Structural, Thermal, and Electrical) of the battery pack during emergency landing conditions and how its performance will impact the selection of composite materials for the construction of an Airframe capable of providing an adequate level of safety to the passengers.**
  - Structural performance of the battery and evaluation of load transfer into the cabin and rest of the UAM composite airframe structure.
  - Thermal performance of the battery and risk of thermal runaway/explosion. Is thermal shielding required and will current composite and advanced materials used for the construction of the fuselage be acceptable for this use?
  - Electrical performance of the battery and risk of high-voltage discharge to the surrounding AAM structure, occupants or first response personnel. Can Advanced materials used to construct the cabin floor provide shielding during emergency landing situations?
  - Collaboration with a UAM OEM providing actual batteries
  - Develop material for the FAA to define future test requirements and MoC.

Battery Drop Test – Tasks

- **Task 1 :**
  - Literature review for battery testing standards and requirements
  - Literature review aerospace composites material behavior when exposed to severe electrical-thermal-fire environments
- **Task 2 – Develop a test plan and test objectives for evaluating AAM battery crashworthiness**
- **Task 3 – Design and manufacture drop test fixture**
- **Task 4 – 50 foot battery drop test, identification of structural (EA) and thermal requirements for the selection of composite materials to be used in AAM applications**
  - Task 4.1 – Identify structural and thermal requirements for Battery Surrounding Structure (Material Selection, Energy Absorbing requirements ..etc.)

Battery Drop Test – Key Updates

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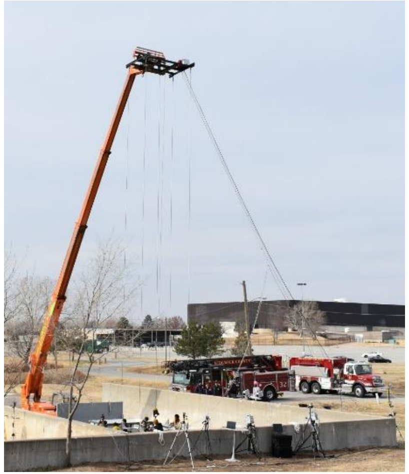
- Test fixture design using numerical analysis – Completed.
- Trial testing with dummy weight – Completed.
- Hardware and instrumentation checks – Completed.
- The first battery test is scheduled for Fall 2022 – Completed.
- Coordination of R&D efforts with NASA – Ongoing.
- Industry collaboration for future test articles – Ongoing.

Digital Engineering Design, Construction, Instrumentation, and Design Validation – AVET 50ft Drop Tower

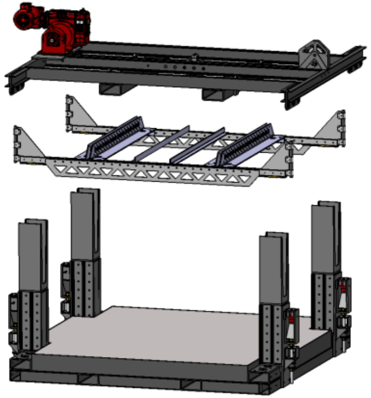
NIAR AVET Digital Engineering Methods Internal R&D

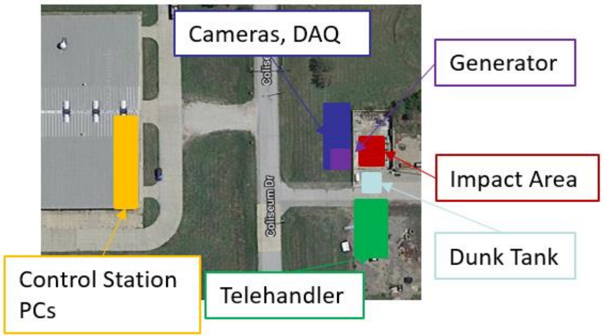
Battery Drop Test Overview

- **Out-door semi-enclosed test site**
- **Test Apparatus**
  - Lifting Beam
  - Drop Frame
  - Impact Pad
  - Energy Absorbers and Guidewire Mounts
- **Post-drop thermal runaway**
  - 1,000 gallon concrete dunk tank
  - Fire trucks on stand-by
- **Nominal impact height: 50 feet**
- **Nominal impact velocity: 56.718 ft/s**



Test Apparatus

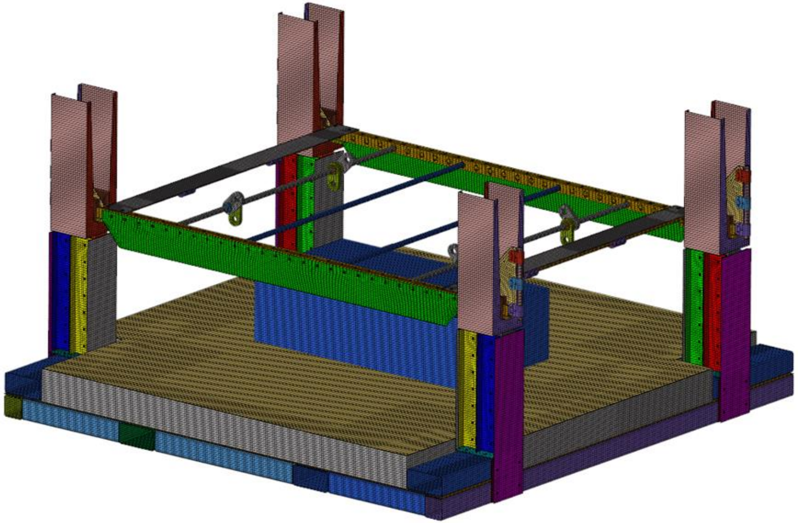




Dunk Tank

Pre-Test Analysis Overview

- Preliminary numerical analysis to design the test fixture, identify any shortcomings and improve the fixture design
- Battery pack modeled as a rigid structure with representative mass
- Preliminary analysis was used to determine the following -
  - Drop test fixture consisted of aluminum honeycomb as energy absorbers
    - Coupon-level testing was conducted to obtain the crushing response
  - Deformations of the various components in the drop test fixture
  - Deformation of the concrete impact pad

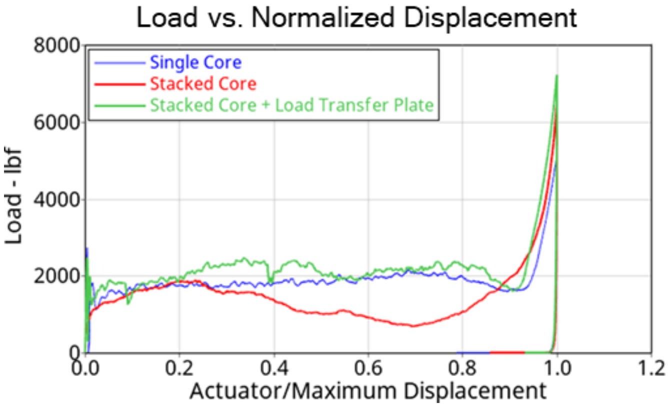


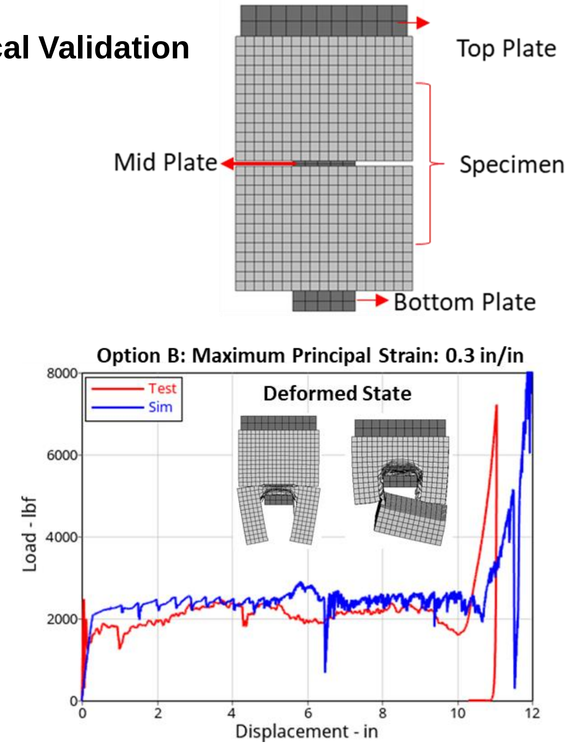
Numerical Model

Energy Absorber Testing & Validation

Numerical Validation

Aluminum Honeycomb Testing





Pre-Test Analysis: Kinematics

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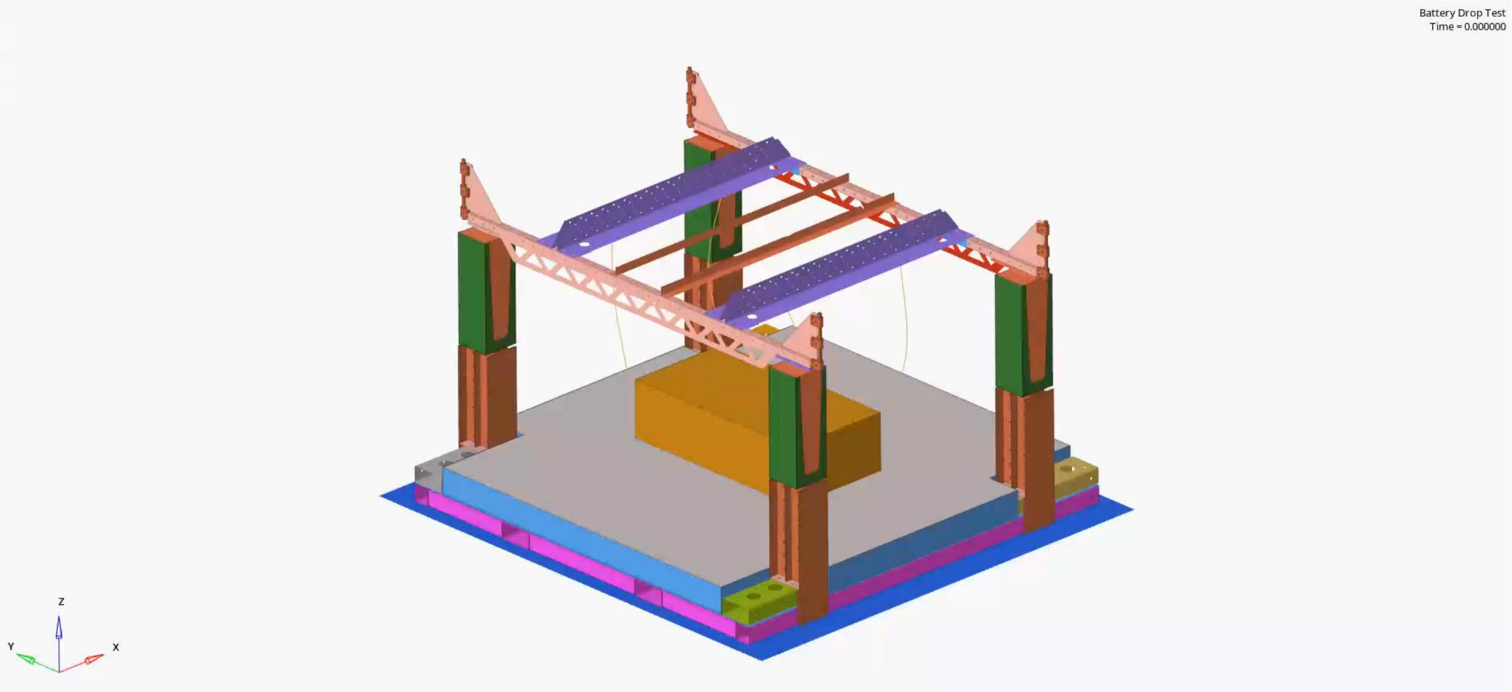
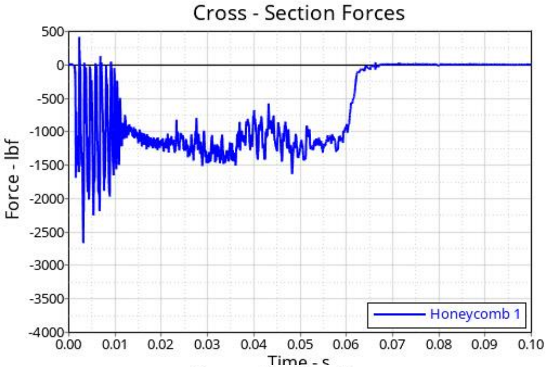
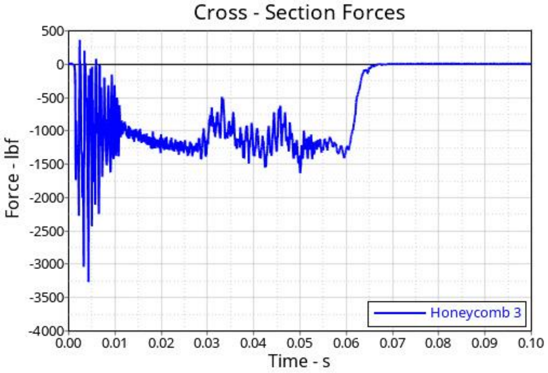
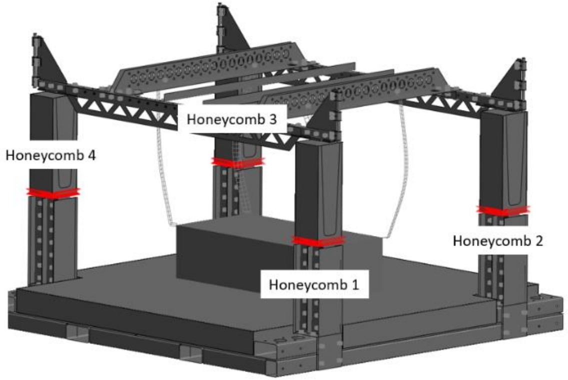


Honeycomb: Cross-Section Force

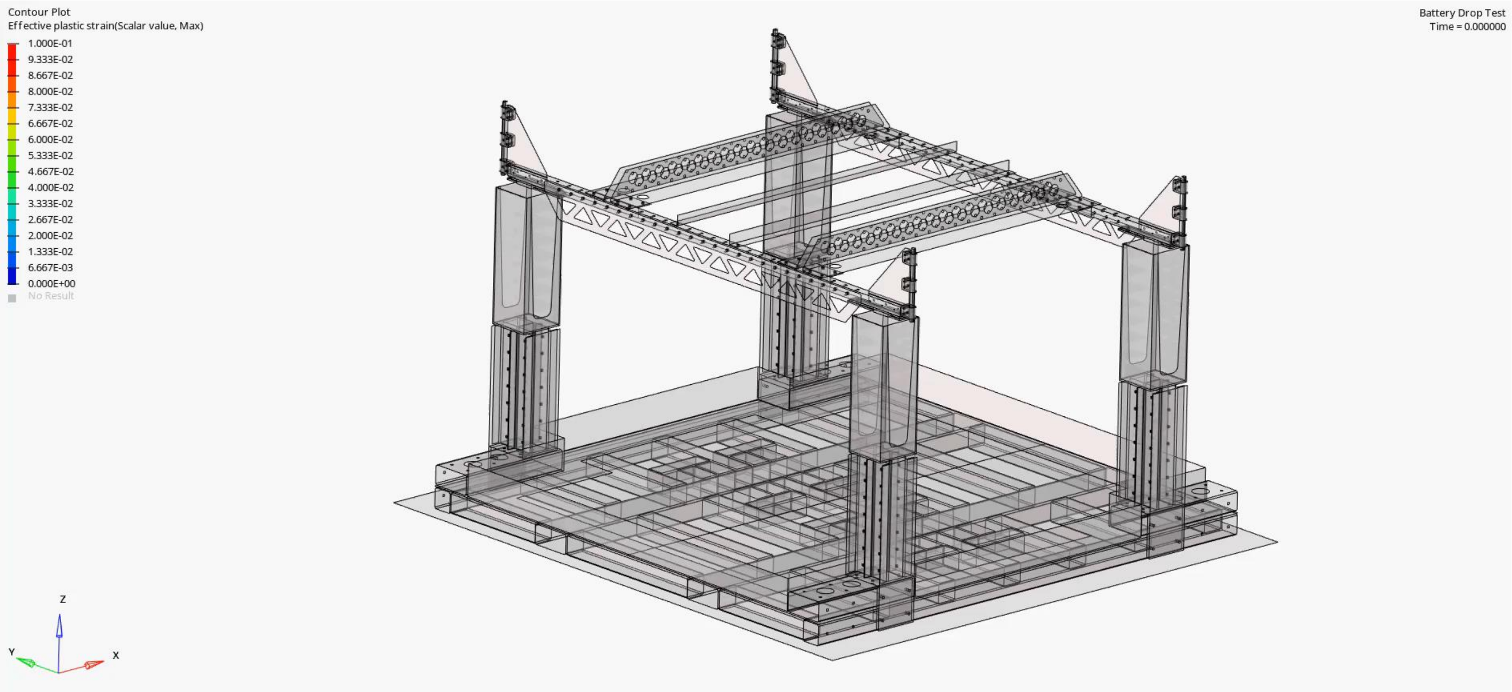






*No filter has been used to plot time history plots.

Kinematics: Effective Plastic Strain



Battery Drop Test – Trials

- Successful drop test with a dummy payload
- Allowed further improvement and calibration of FE models based on actual test system response
- Dummy payload weight: 250 lbs. and 800 lbs.

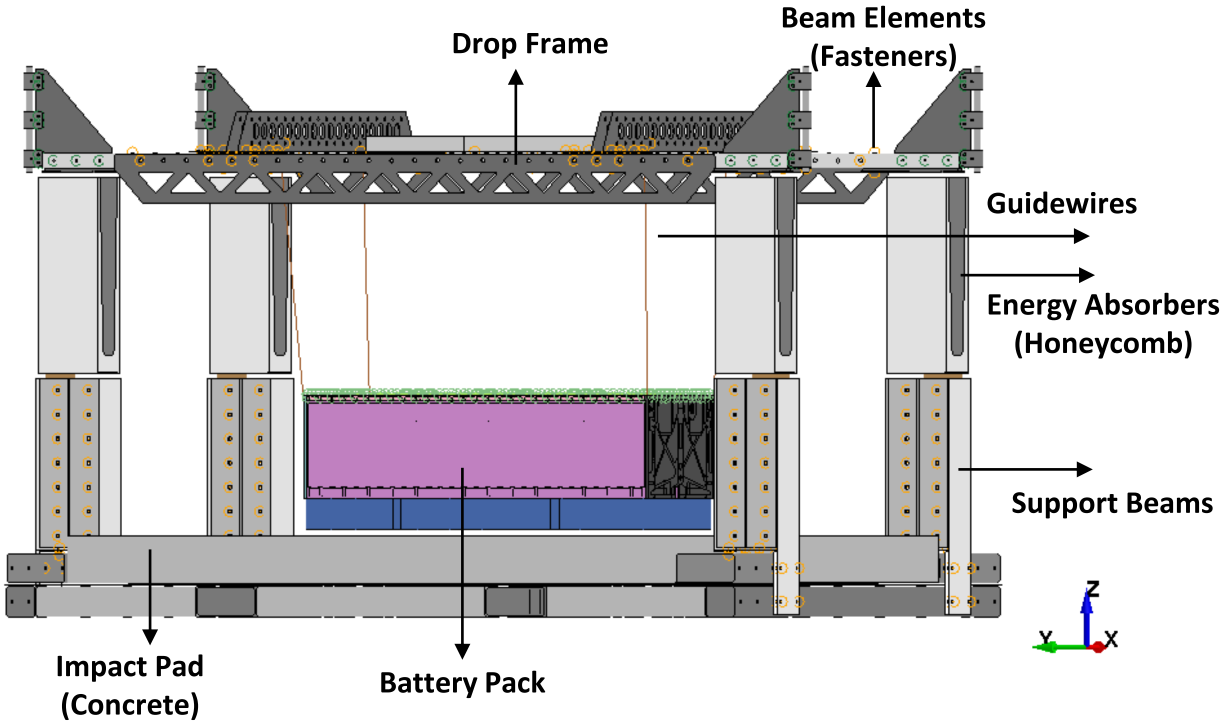
Pre-Test Analysis: Battery Model 50 ft. Drop Test Evaluation

NIAR AVET Digital Engineering Methods Internal R&D

Numerical Model Description

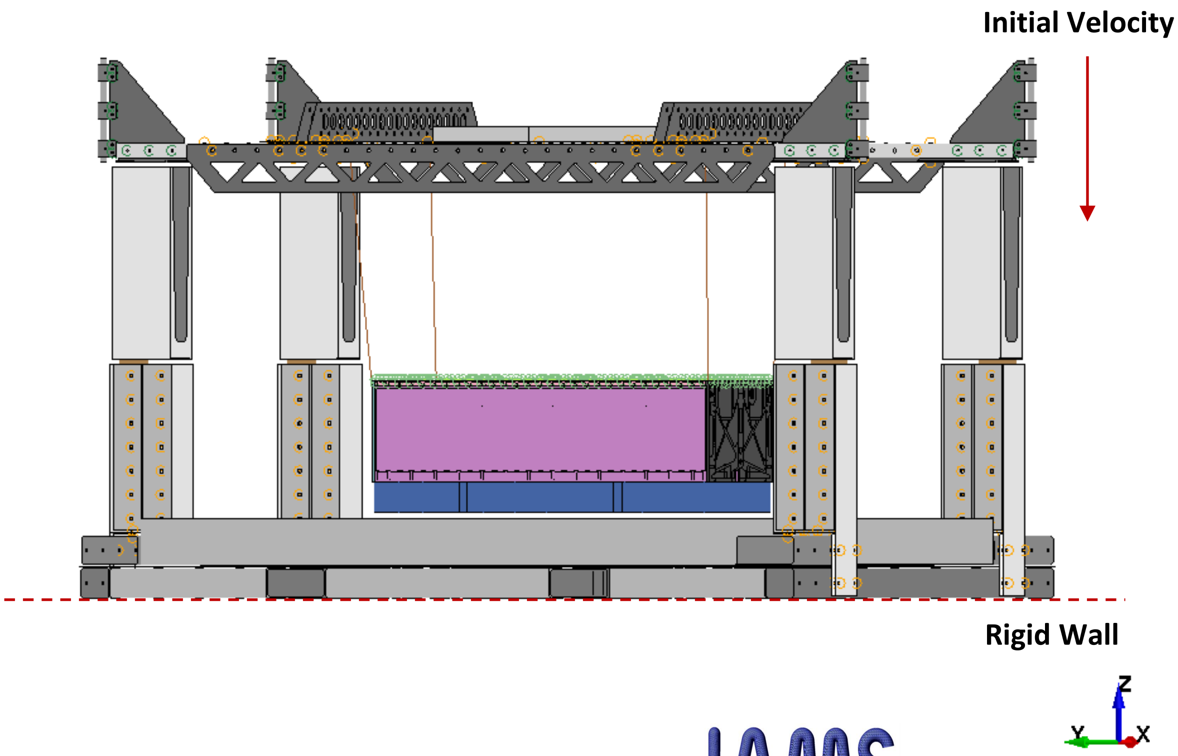
- Numerical model was generated similar to the physical setup
- Battery pack modeled in detail
- Pre-processors: Altair Hyperworks and Meta Ansa
- Solver: LS-Dyna

Total number of Elements: 17,261,689
Total number of Nodes: 21,590,503

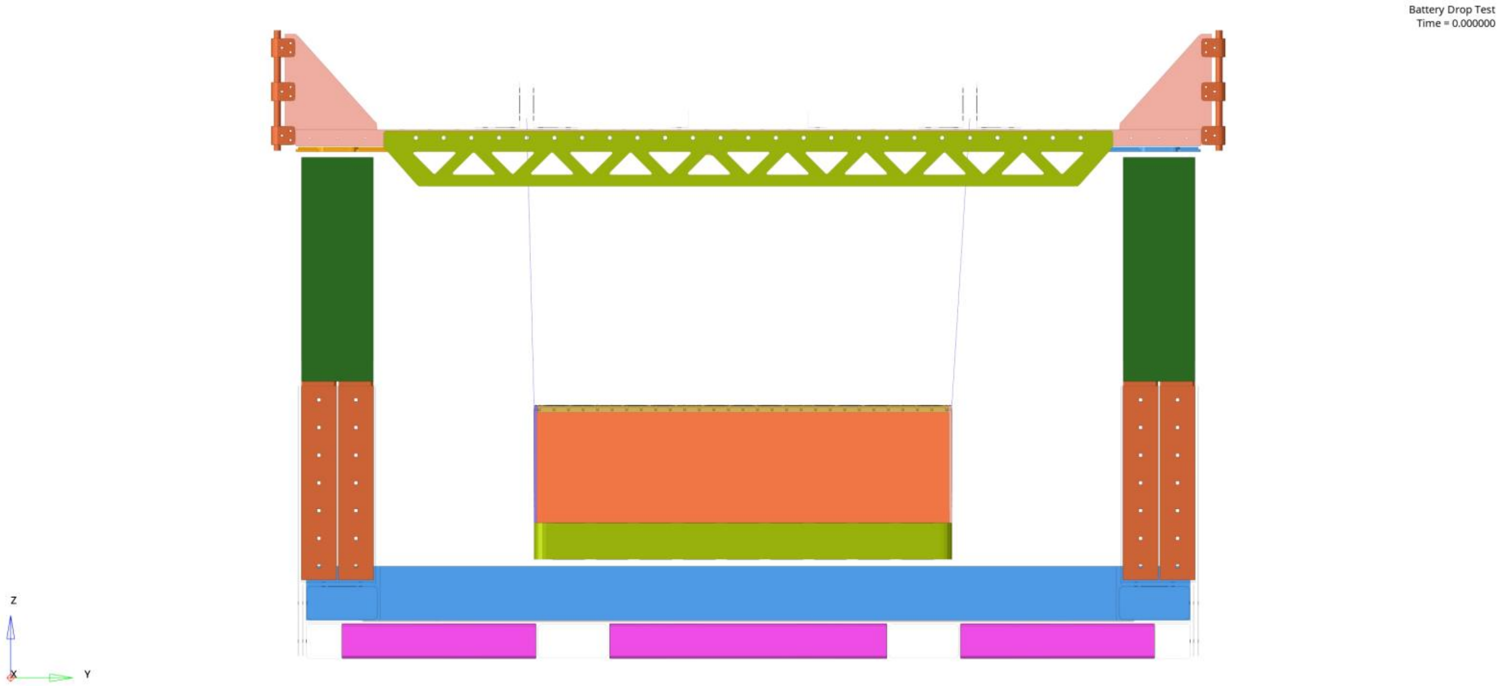


Numerical Model Description

- Drop velocity of frame and battery: 16.8 m/s [55.1 ft/s]
- LS-Dyna *Rigid wall acts as boundary condition at the bottom of the test setup simulating the ground
- Gravity applied to the entire model



Simulation Kinematics



eVTOL Battery 50 ft. Drop Test Results: BD23A-01

NIAR AVET Digital Engineering Methods Internal R&D

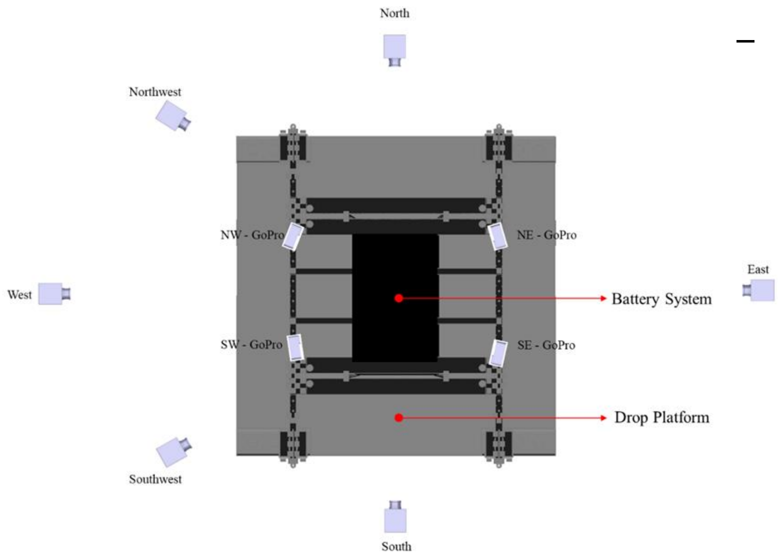
Test Article Overview

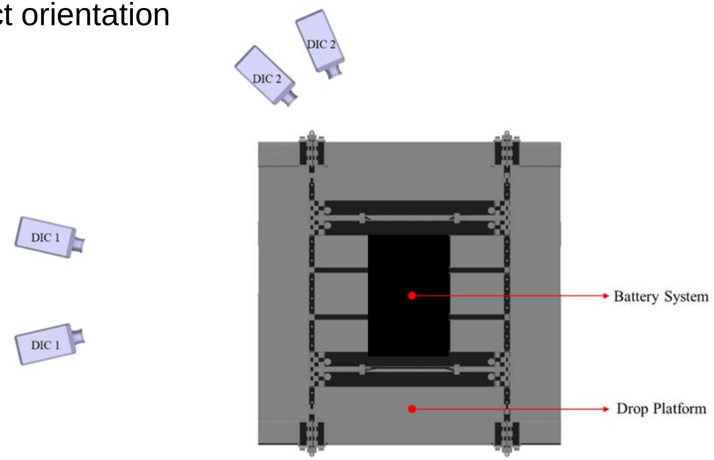
- Representative AAM battery pack without surrounding structure
- Battery charged to the most critical condition expected during a crash event
- Drop orientation of the battery pack to represent a typical installation in the aircraft
- Battery pack was painted with a random speckle pattern to compute deformations using DIC

Pre-Test Image: Mounted Battery Pack

Test Data Overview

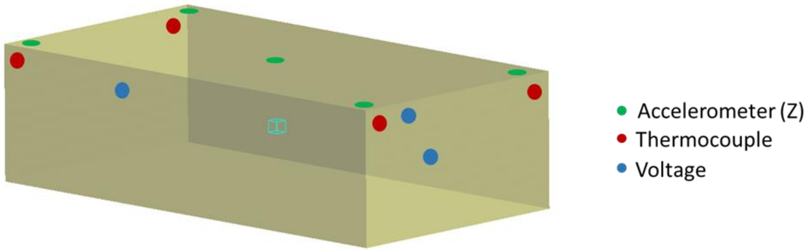
- **Test Videos**
  - High-speed cameras
  - Thermography
  - High-speed DIC stereo set
- **Test Signals**
  - Accelerometers
  - High voltage signals
  - Thermocouples
  - Drop velocity
  - Impact orientation
- **Damage Documentation**
  - General impact damage
  - Batteries deformation





Overview of Data Channels

- **High-Speed Data**
  - 5x Accelerometers
  - 5x High Voltage Readings
  - 1x Velocity Gate
- **Temperature Monitoring**
  - 4x Thermocouples
- **Digital Image Correlation**
  - Drop Velocity
  - Impact Orientation



Data Acquisition Systems

- **Dynamic DAQ**
  - -4 seconds to 30 minutes (or longer)
    - 100-500 sps static recording rate
    - Up to 200,000 sps recording on trigger
  - Requires trigger input to one channel
- **Monitoring DAQ**
  - -4 seconds to 30 minutes; 100-500 sps
  - Can start a new logging file after 30 minutes without a major interruption in data
- **High-Speed DAQ**
  - -4 seconds to +8 seconds; 20,000 sps
- **Industry Partner PMU 1 and 2 for additional monitoring**

Channel Allocation

Channel #	Description	Dynamic DAQ	Monitoring DAQ	High Speed DAQ
1	HV+, HV- [Vb]	X		
2	HV-, Chassis [V1]	X		
3	HV+, Chassis [V2]	X		
4	HV-, Chassis with Resistor [V1']	X		
5	HV+, Chassis with Resistor [V2']	X		
6	Distance Sensor	X		
7	Trigger Input	X		
8	Thermocouple 1		X	
9	Thermocouple 2		X	
10	Thermocouple 3		X	
11	Thermocouple 4		X	
12	Battery Center Accel Z			X
13	Battery Corner 1 Accel Z			X
14	Battery Corner 2 Accel Z			X
15	Battery Corner 3 Accel Z			X
16	Battery Corner 4 Accel Z			X
17	Velocity Gate			X

High Speed Video - BD23A-01

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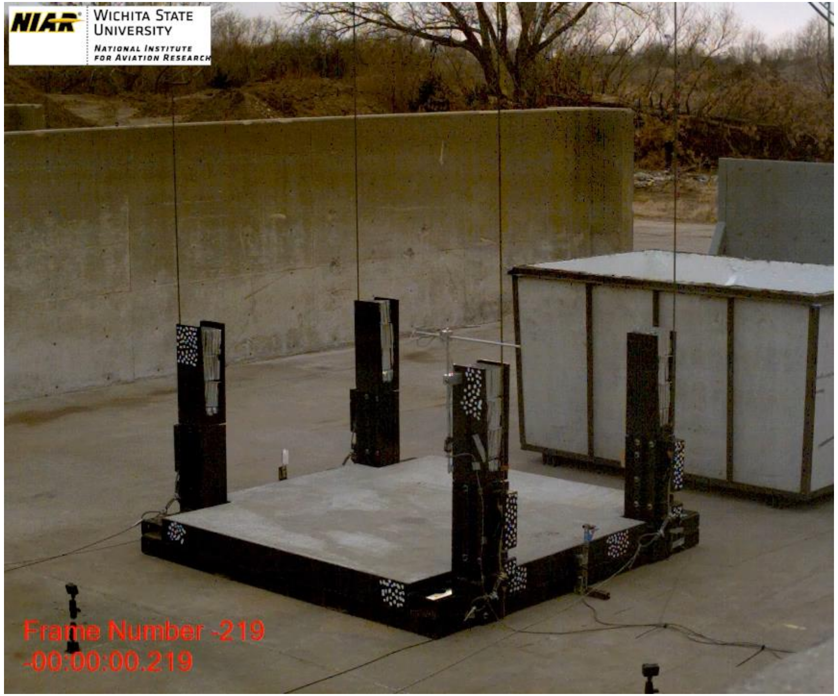
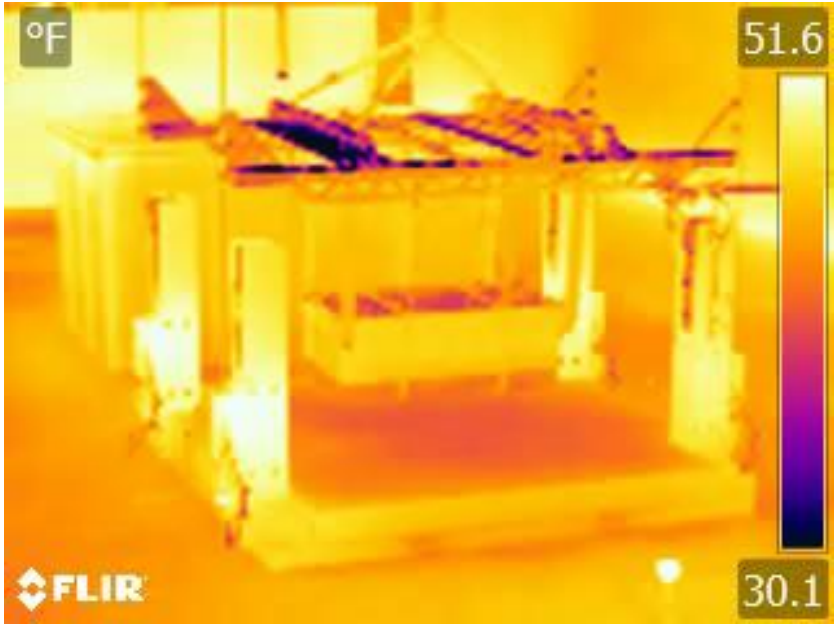
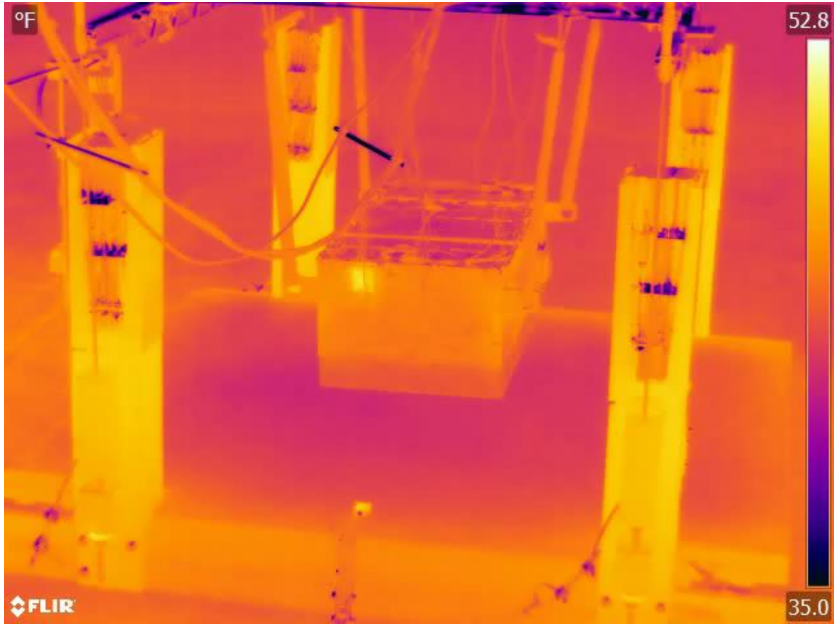
High Speed Video - BD23A-01



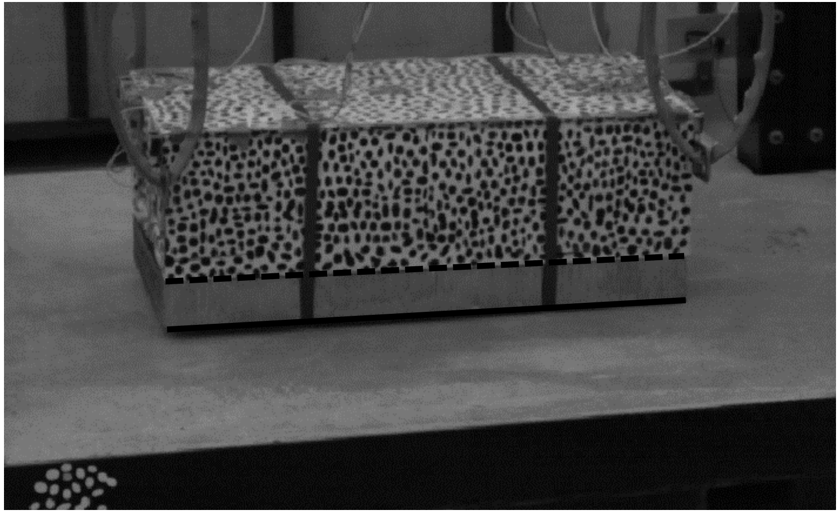
High Speed Video - BD23A-01

Thermal Camera Videos

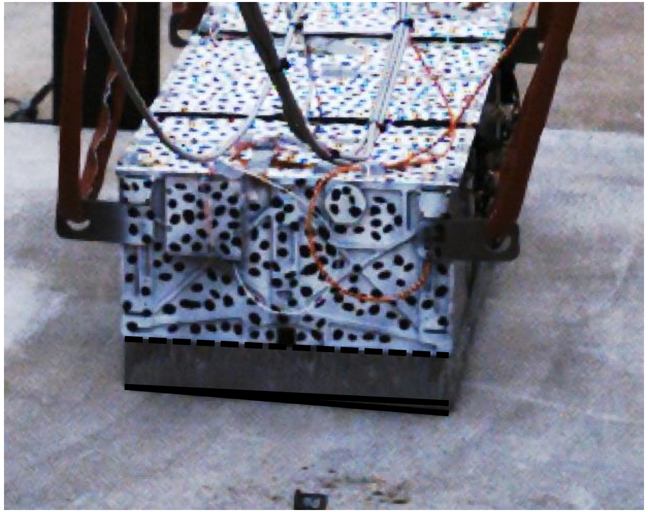




Impact Orientation

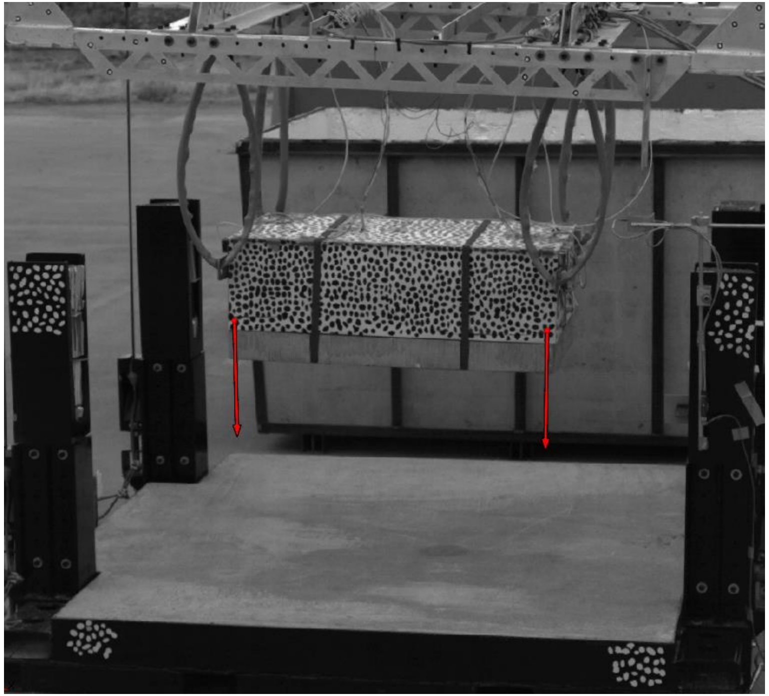


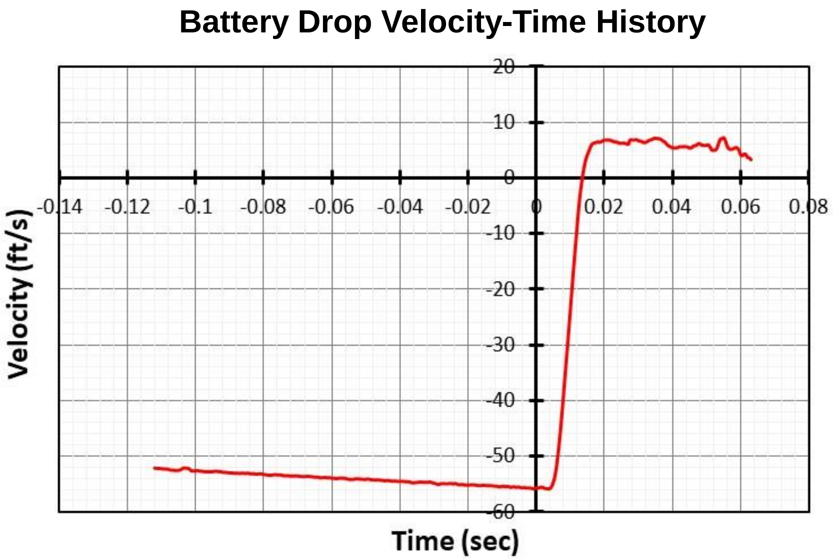
Pitch - Impact Angle 2.18°



Roll - Impact Angle 0.99°

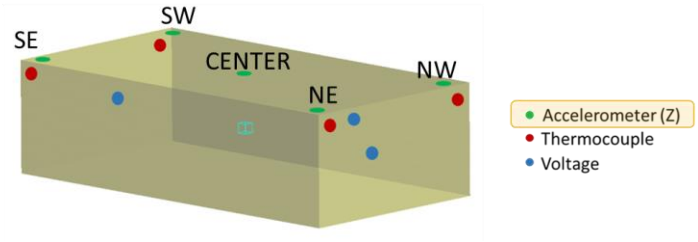
Battery Drop Velocity (DIC)

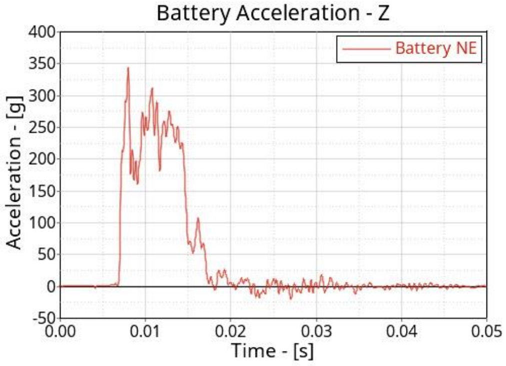


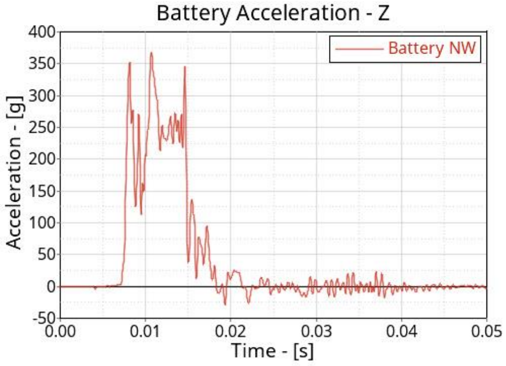


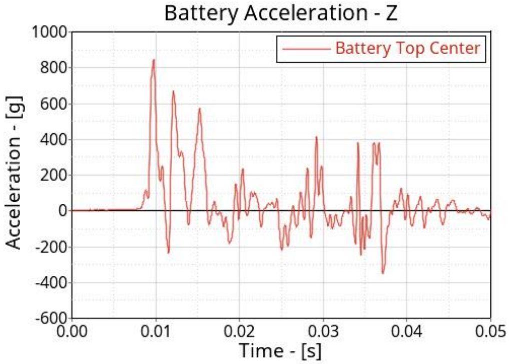
- **Recorded Impact Velocity: 55.9 ft/s**

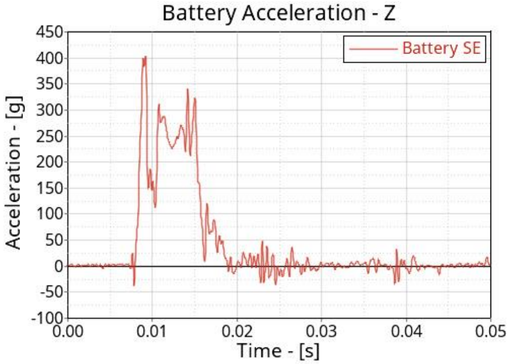
Accelerometers – Impact

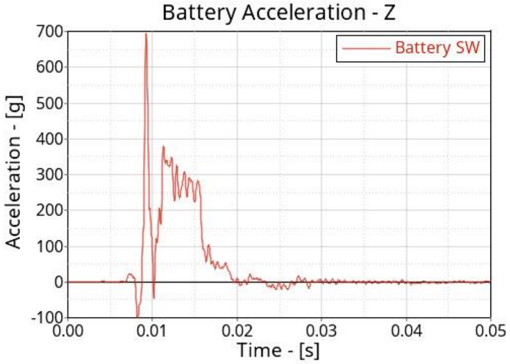




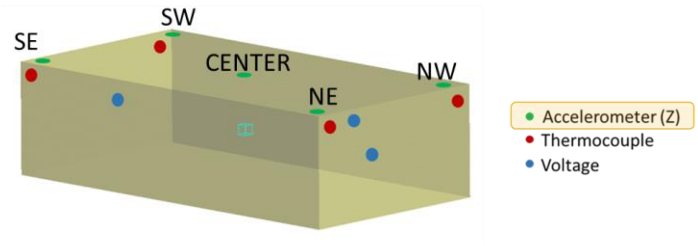


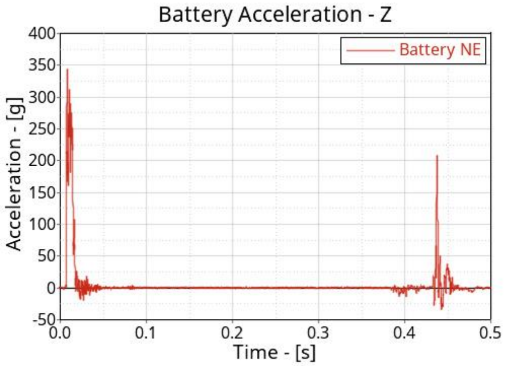


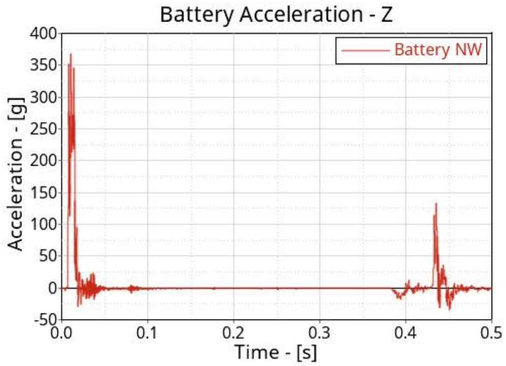


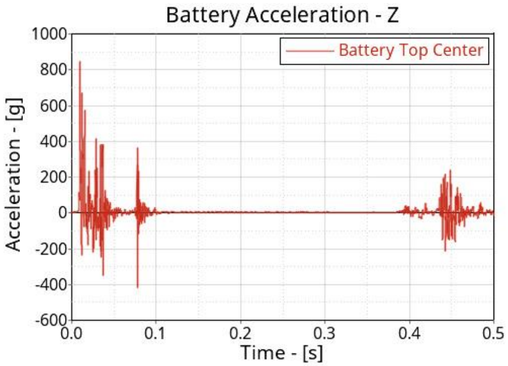


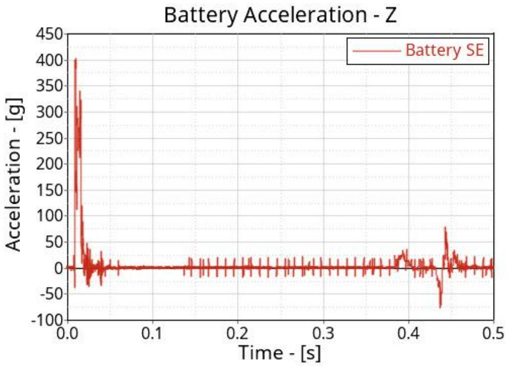
Accelerometers – Rebound

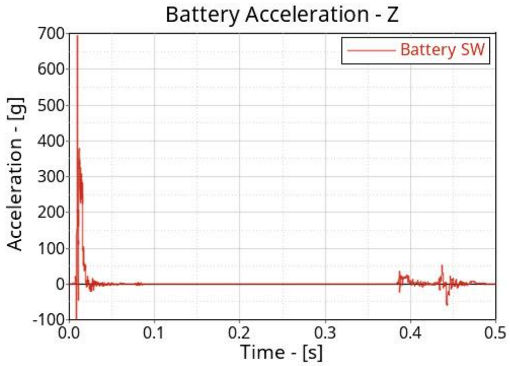




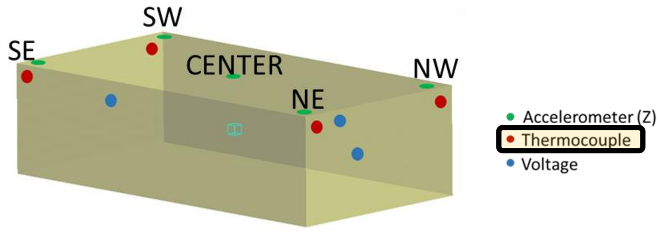


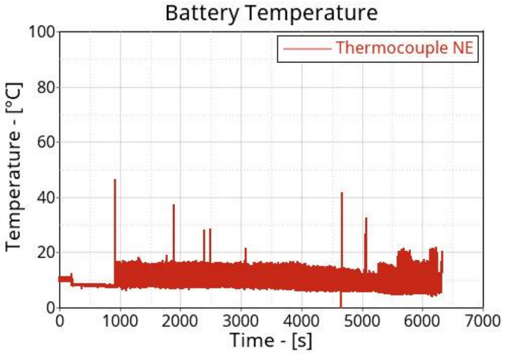


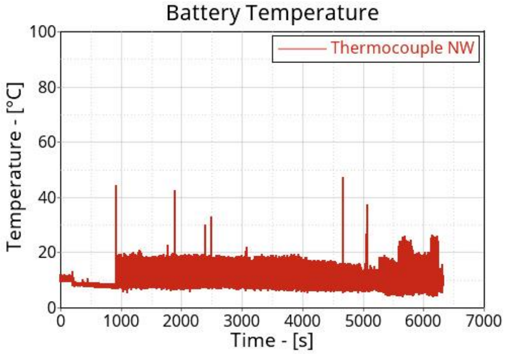


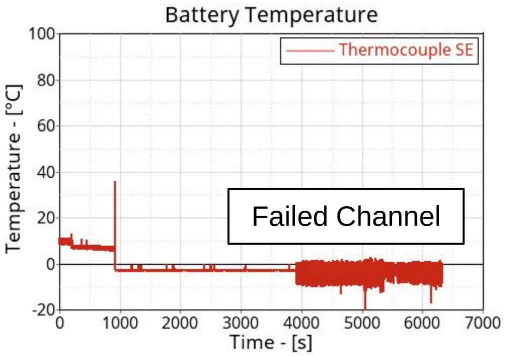


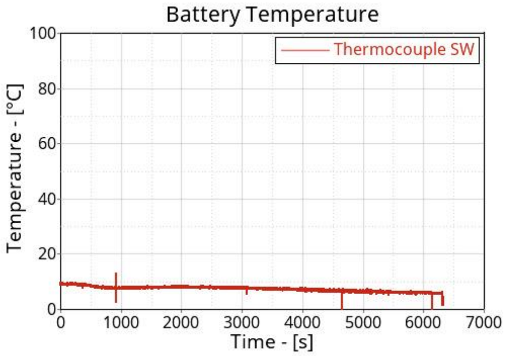
Thermocouple Readings – Module



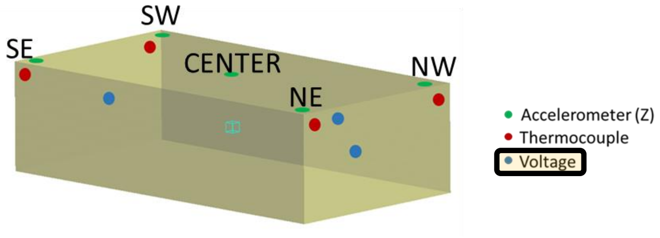


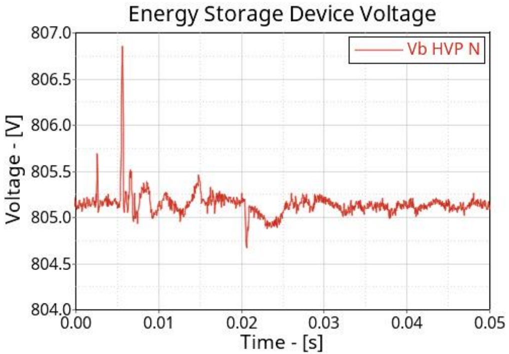


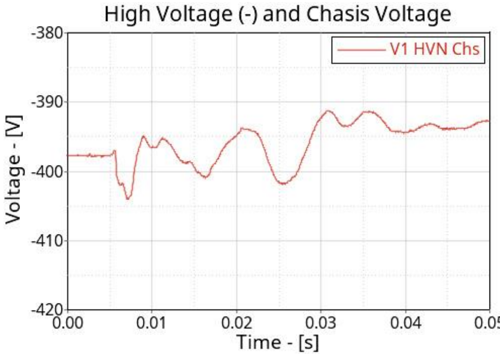


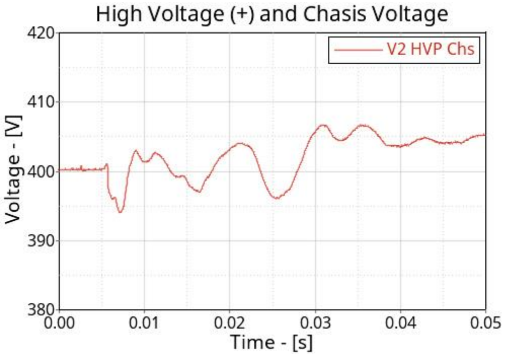


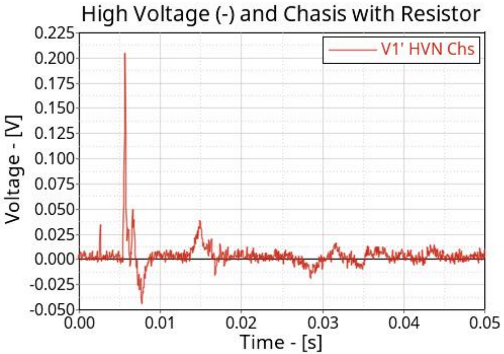
High Voltage Signals – Impact

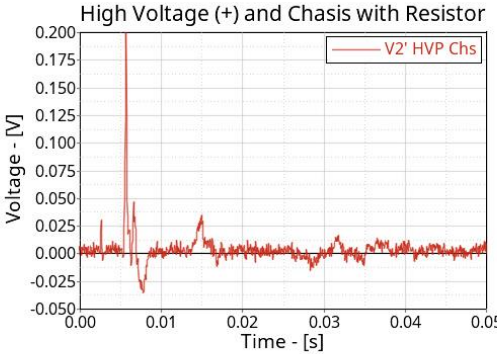




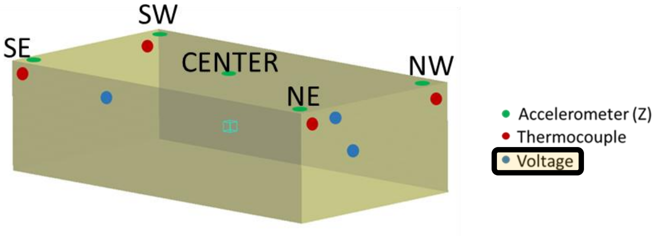


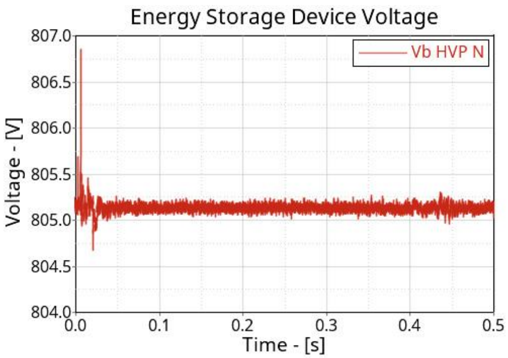


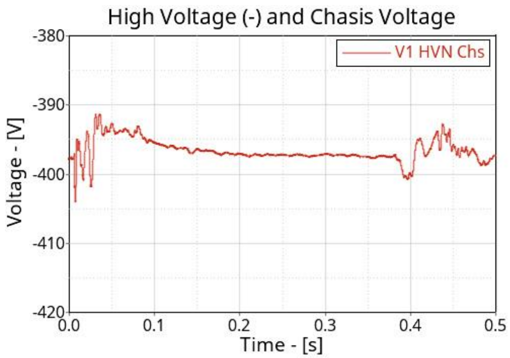


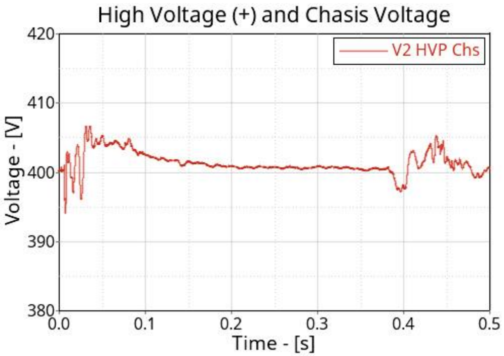


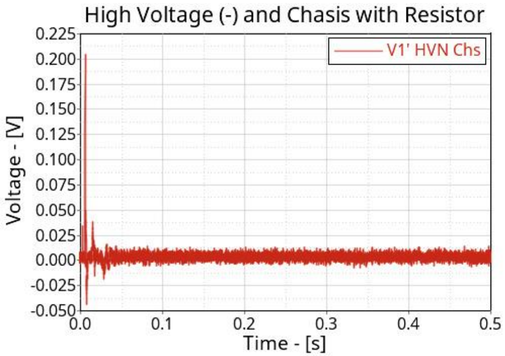
High Voltage Signals – Rebound

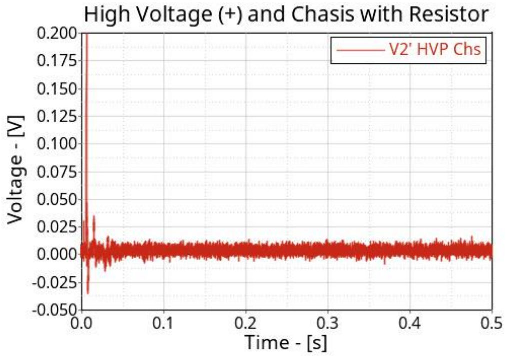












Ongoing and Future Activities

- **Finalize data analysis and test documentation**
- **Final report and documentation**
- **FAA R&D Group Meeting to define the next steps**
- **Coordinate R&D Efforts with NASA Langley Battery Drop Test Project**
- **Contact AAM OEMS to donate representative battery packs for future testing**
- **Continue developing and validating numerical methods to support the development and certification of AAM Battery Packs:**
  - Analysis will play an essential role in the future in developing and certifying variants of a certified design

Questions?