FAA-NIAR-BETA eVTOL Battery Drop Test Results BD23A-01

| NIAR AVET and BETA Technologies | November 5th 2024 |

Contact email: luis.gomez@wichita.edu & gerardo.olivares@wichita.edu

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NIAR-AVET 50 ft. Battery Drop Test

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

Battery Drop Test R&D Program - FAA

FAA Program Scope

- 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 AAM battery packs and its 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 the 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.
    - Dynamic Structural Performance of Battery Packs
    - Effectiveness of Energy Absorption UAM Composite Structures
    - Identify Thermal environment post-test (Fire Protection, Temperatures,..etc)
    - Conceptual design and virtual testing (simulation) of a surrounding composite 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 for the construction of the cabin floor provide shielding during emergency landing situations?
  - Collaboration with a AAM OEM providing actual batteries
  - Develop material for the FAA to define future tests requirements and MoC.

AAM Crashworthiness: Battery Drop Test

FAA Program 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.)

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

NIAR AVET Digital Engineering Methods Internal R&D

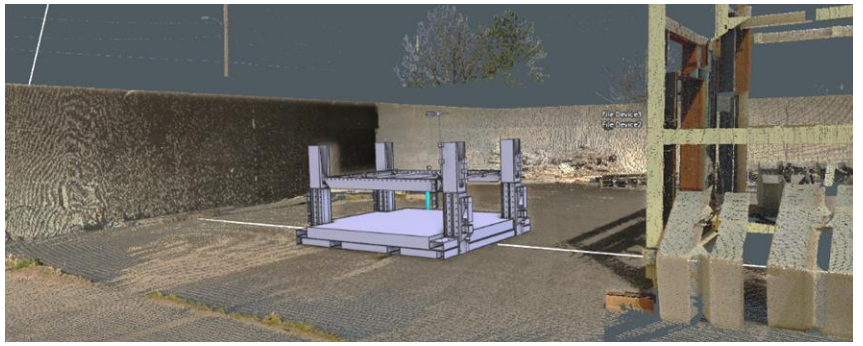
Battery Drop Testing

R&D Battery Crashworthiness

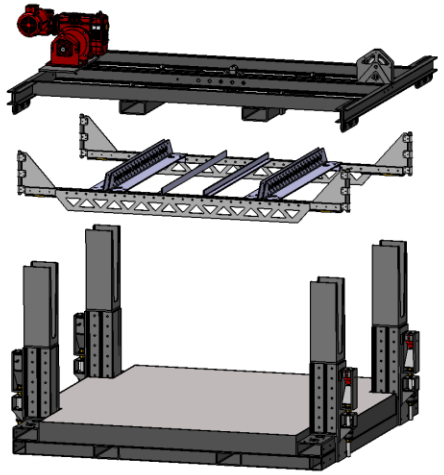
- The site is ready for testing.
- Trial Testing with dummy weight - completed.
- Hardware and Instrumentation checks- completed.
- The first Battery test was completed Fall 2022.
- Coordination of R&D efforts with NASA - ongoing
- Industry collaboration for future test articles – ongoing
  - Several conducted already

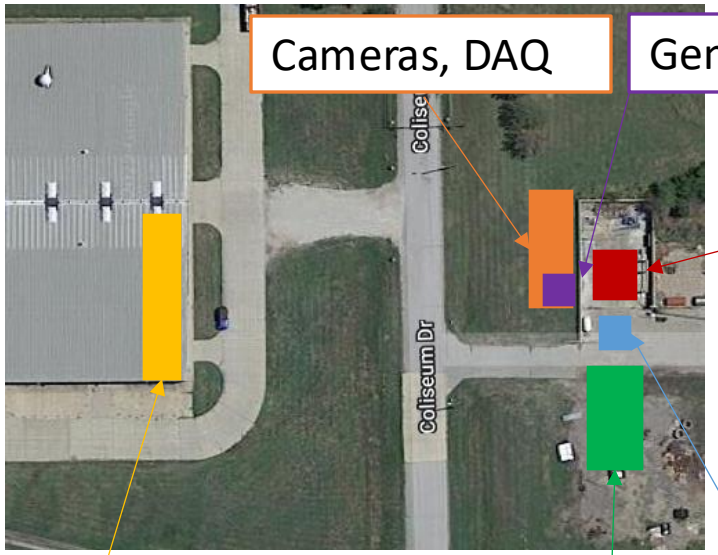
Battery Drop Test Setup

FAA UAM Crashworthiness Update



- Drop Test Site Layout
  - Drop Fixtures/Impact Area
    - Lifting Beam
    - Drop Frame
    - Impact Pad
    - Energy Absorbers and Guidewire Mounts
  - Dunk Tank
    - 1,000 gallon concrete tank

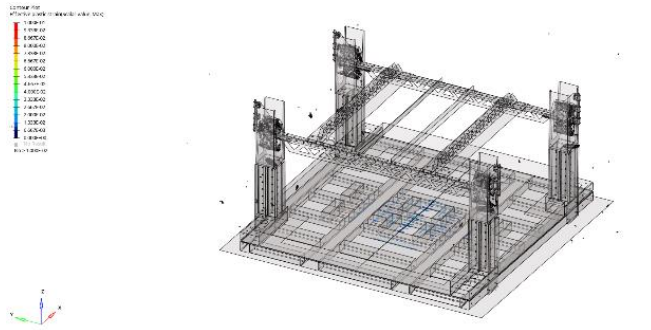


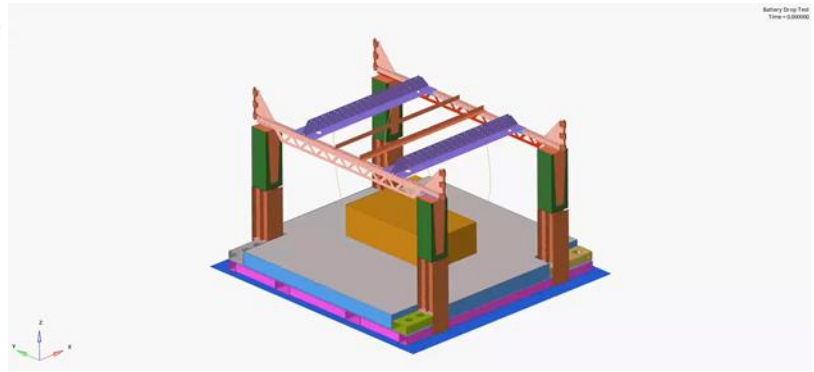


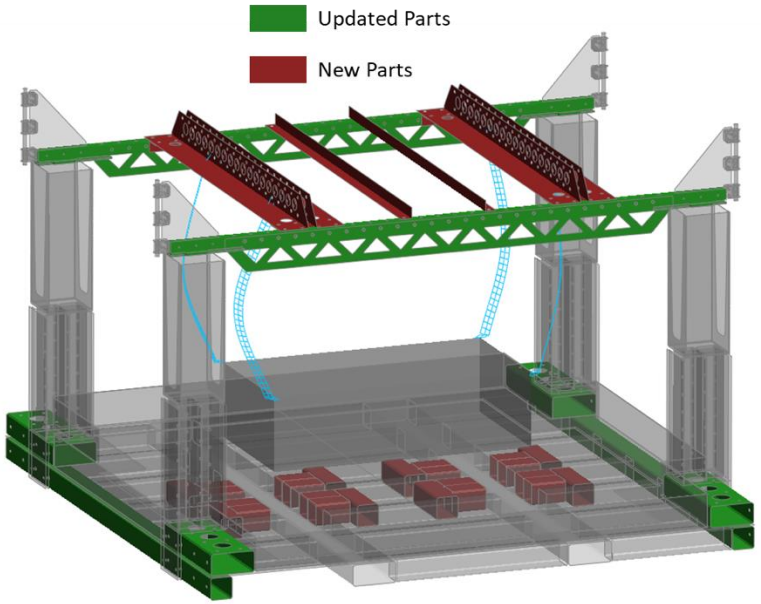
Battery Drop Test Setup

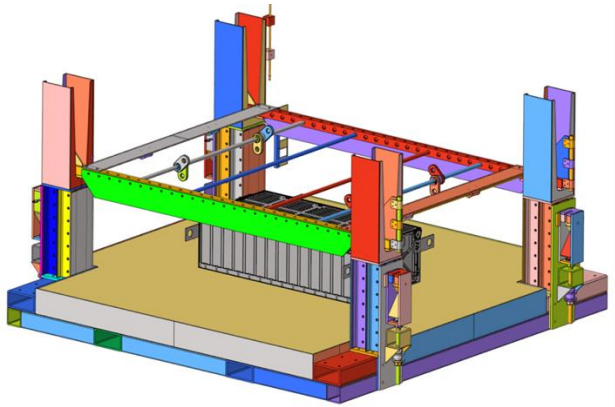
Digital Engineering – Drop Test Fixture Virtual Design & Testing

- Drop Fixture Analysis
  - Minimal plastic strain in center of impact pad from rigid mass used for the test article

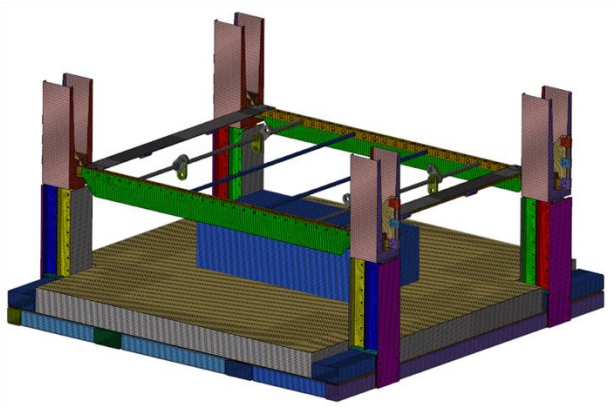








Geometry

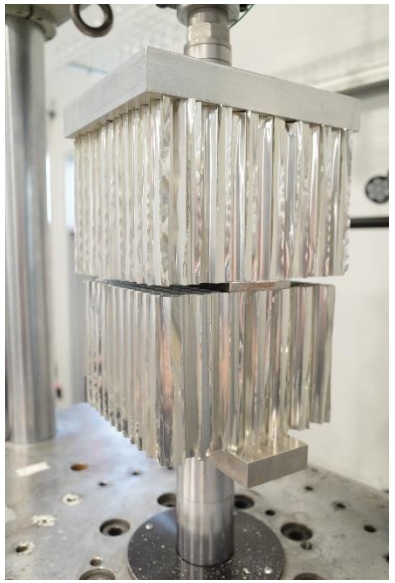


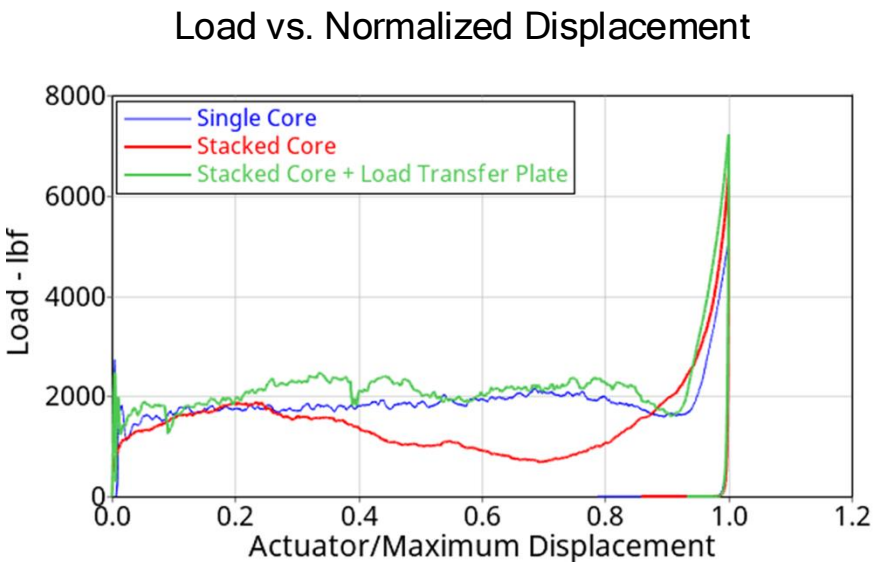
Mesh

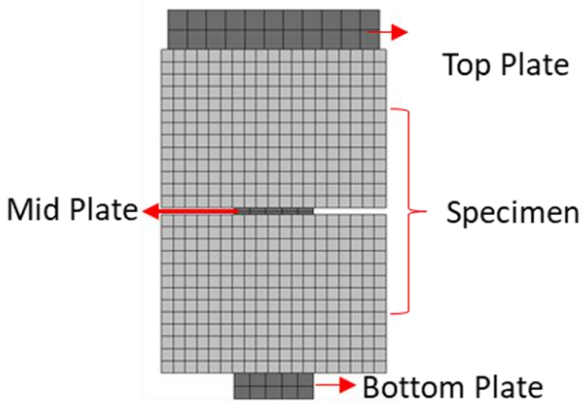
Building Block Testing and Validation

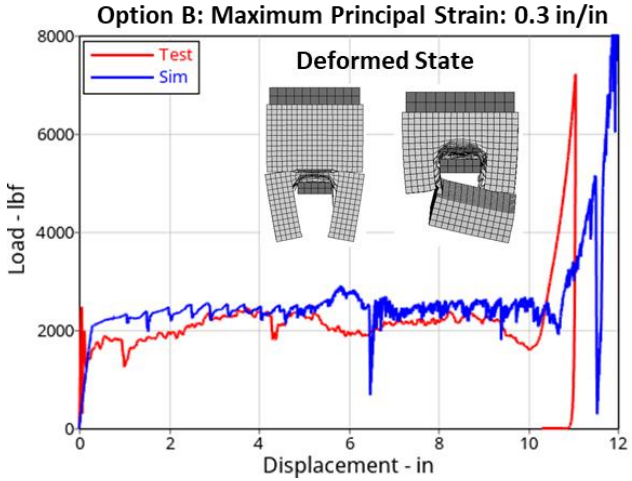
Digital Engineering – Drop Test Fixture Virtual Design & Testing

- Drop Fixture: design process incorporated the use of FEA tools to highlight potential weaknesses as well as the overall performance of the drop fixture design.
- Leveraged NIAR testing capabilities to enhance material modelling fidelity.



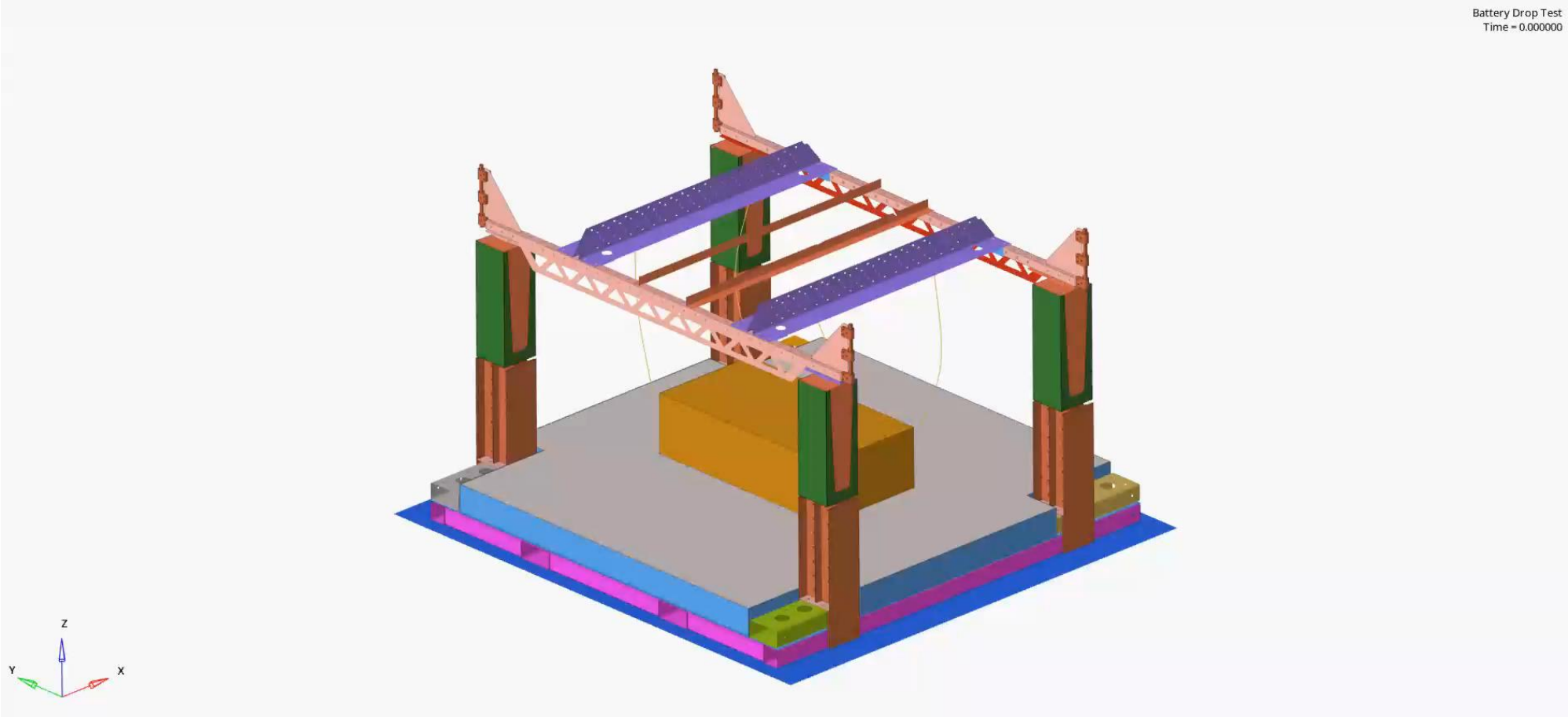






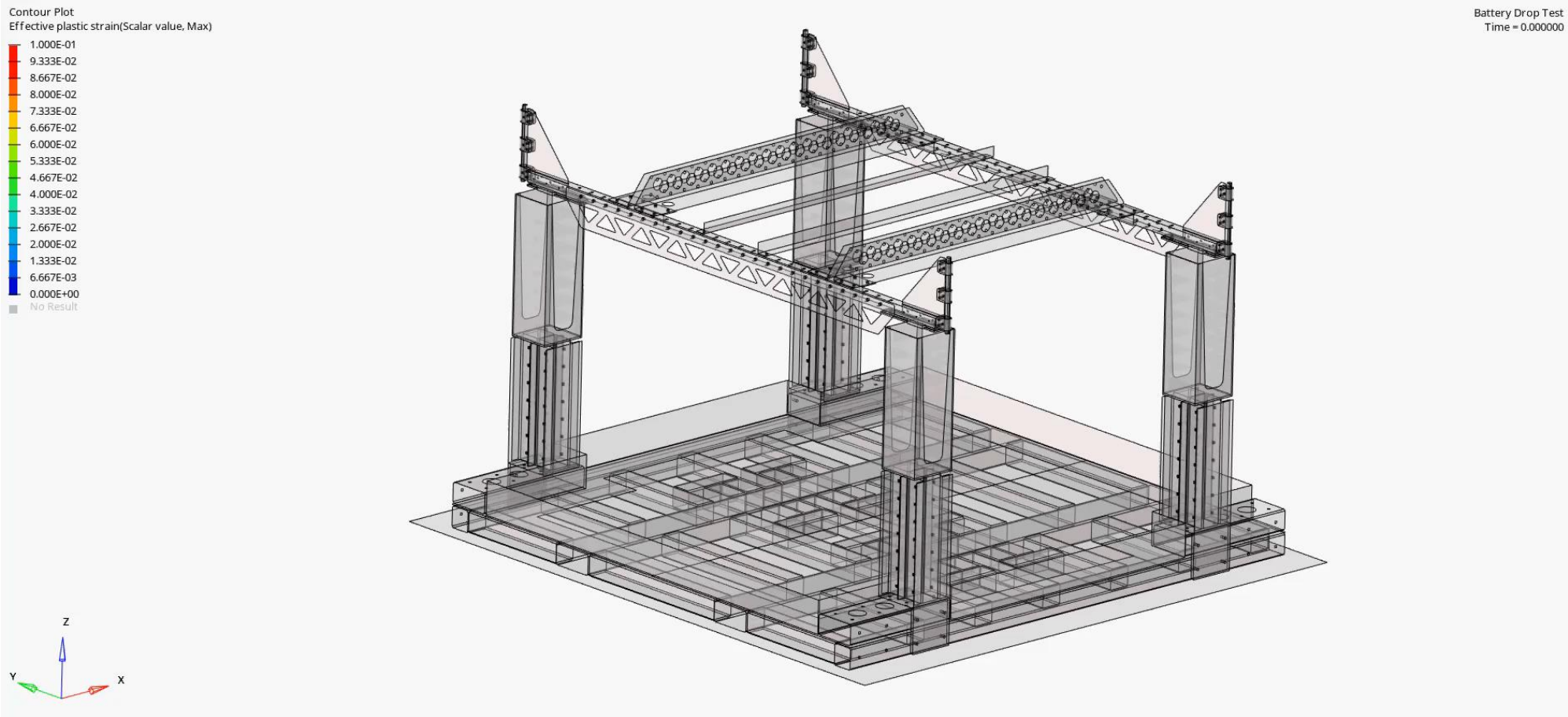
Simulation Video

Digital Engineering – Drop Test Fixture Virtual Testing



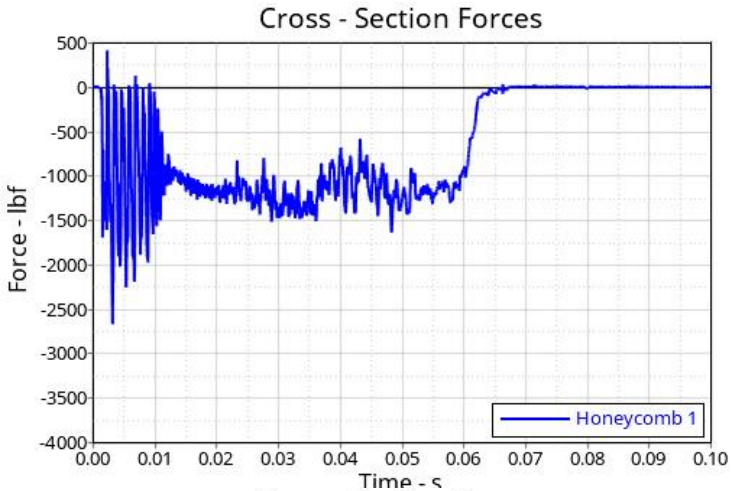
Effective Plastic Strain – Video

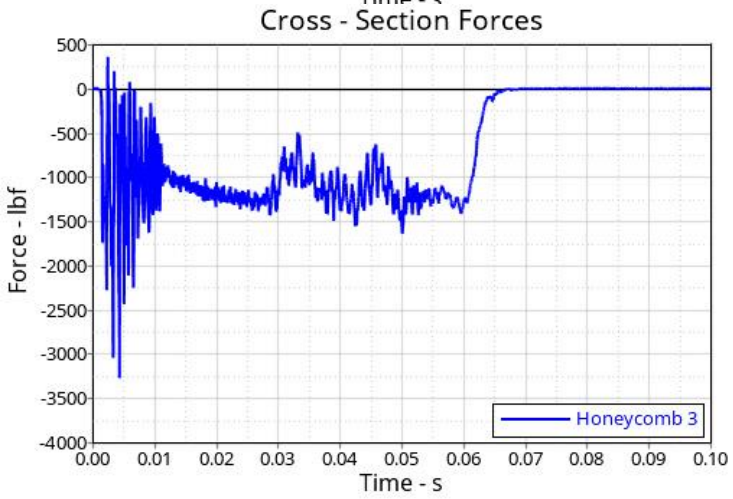
Battery Drop Test

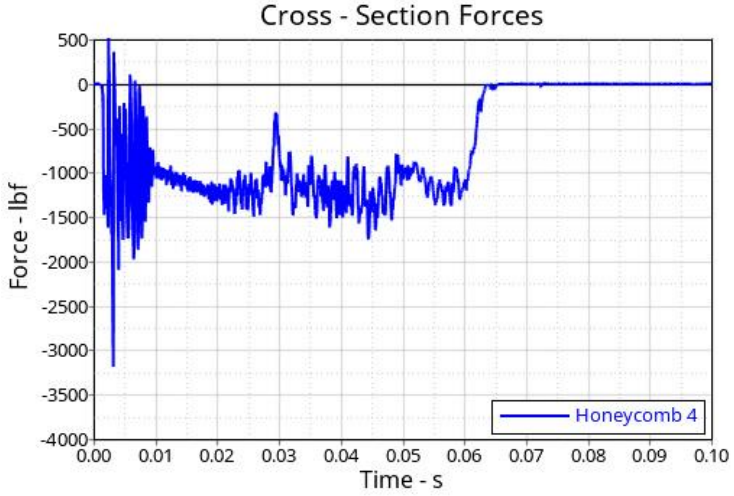


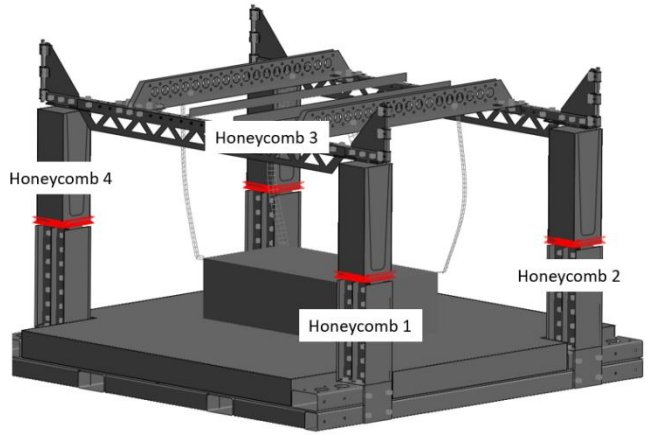
Cross-Section Forces – Honeycomb

Battery Drop Test





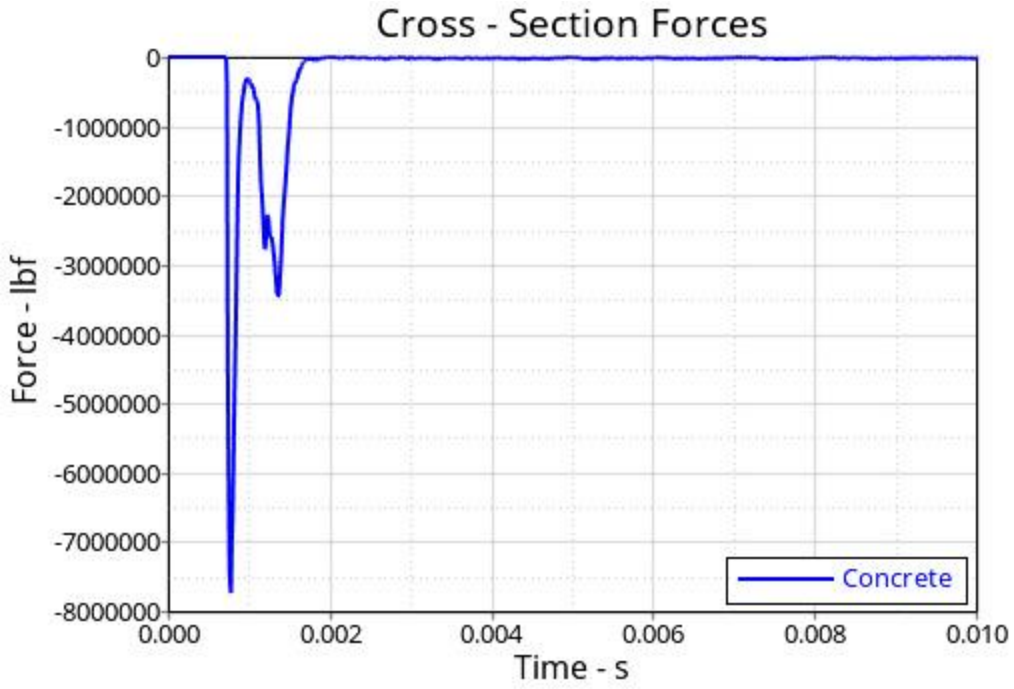


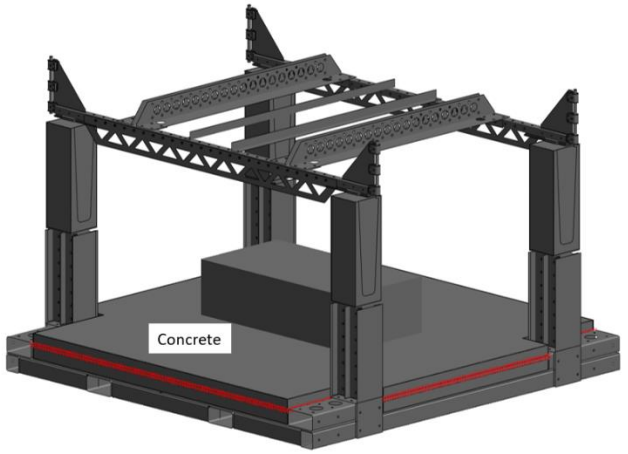


*No filter has been used to plot time history plots.

Cross-Section Forces – Concrete

Battery Drop Test

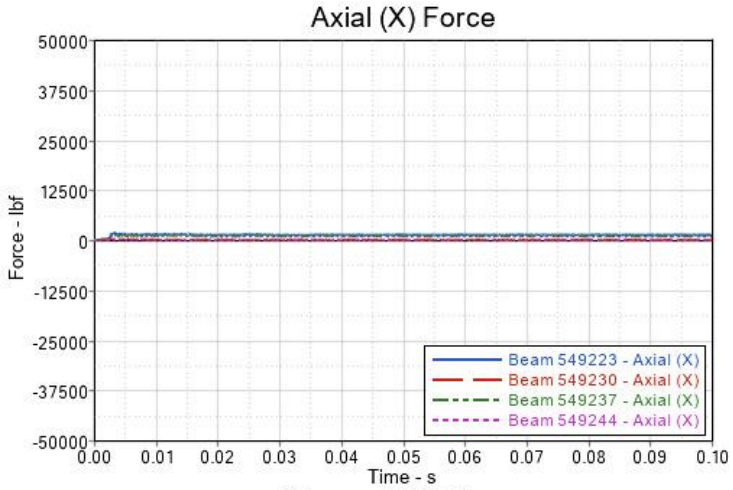


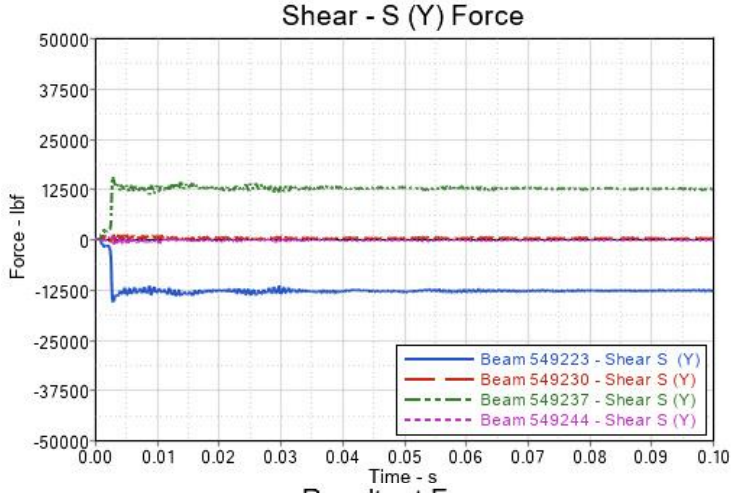


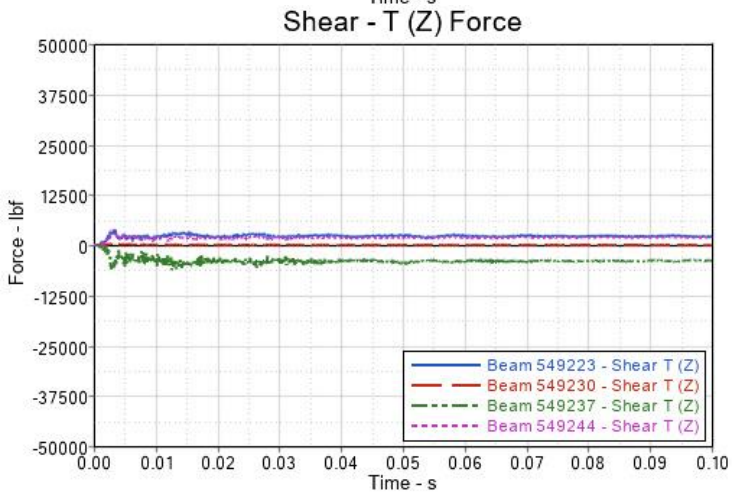
*No filter has been used to plot time history plots.

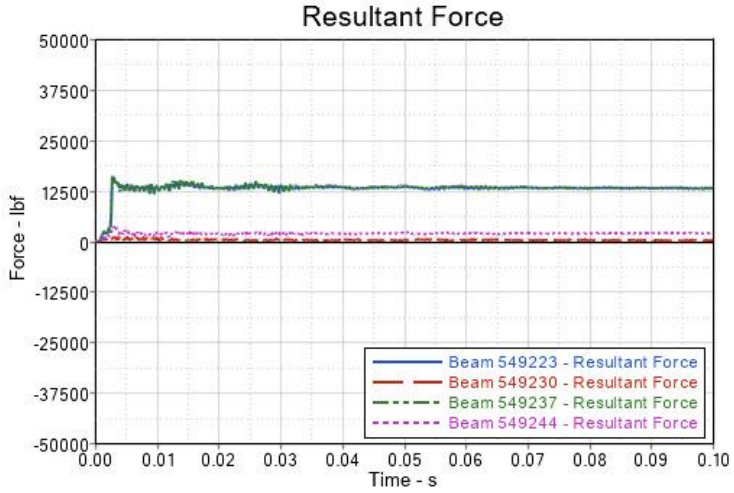
Fastener Forces

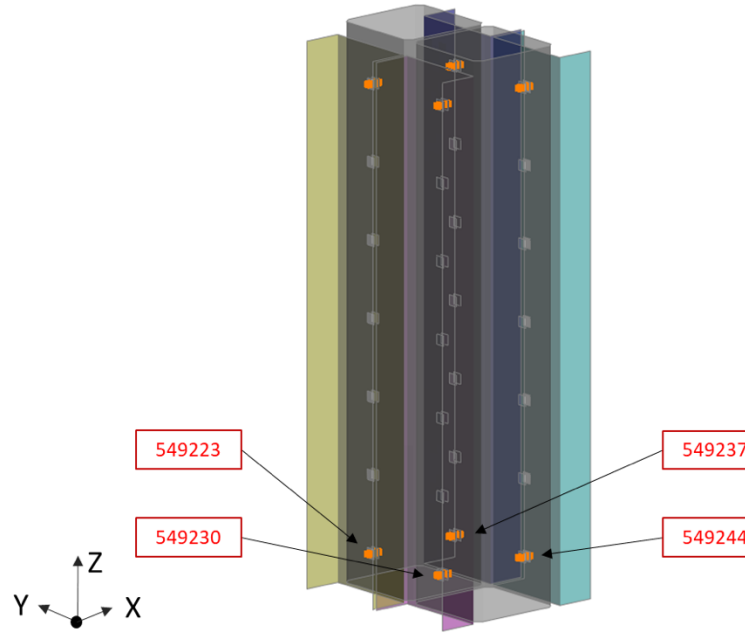
Battery Drop Test











*No failure allowable were defined.

Battery Drop Test Setup

FAA UAM Crashworthiness Update

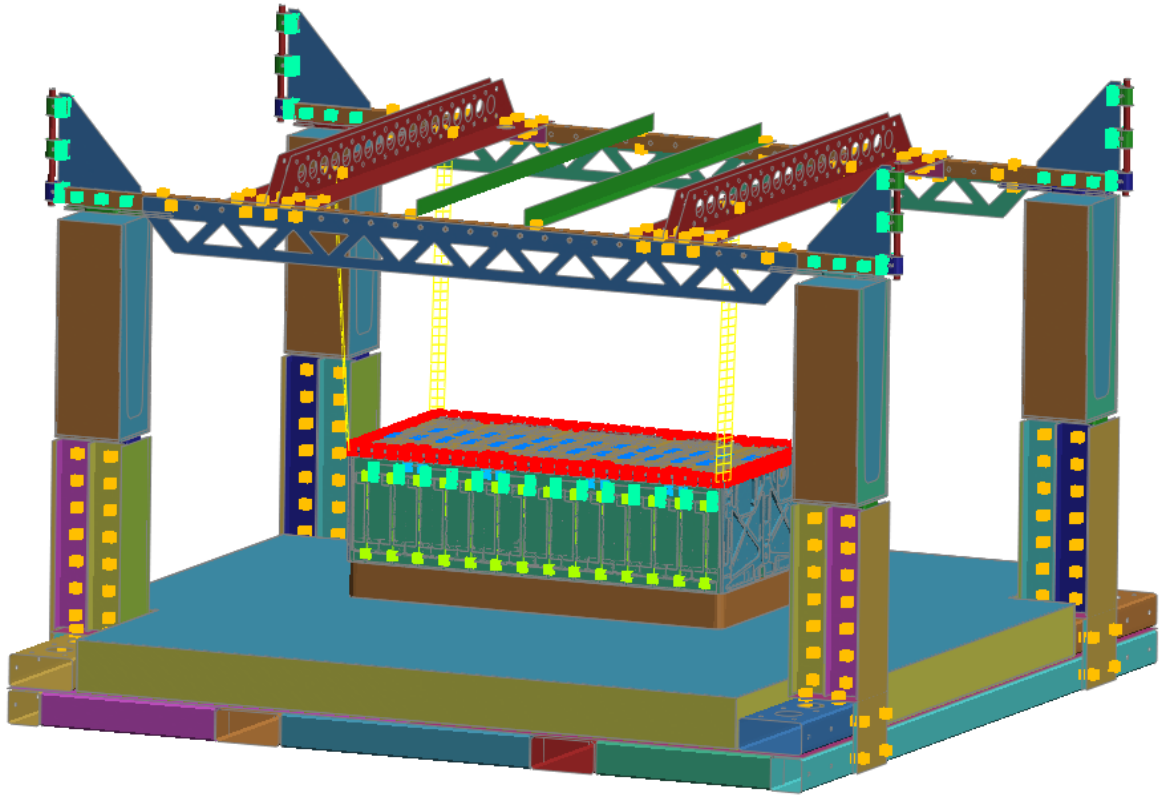
- Successful drop test with dummy payload
- Allowed further improvement and calibration of FE models based on actual test system response

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

NIAR AVET Digital Engineering Methods Internal R&D

FE Model Setup

Battery Drop Test



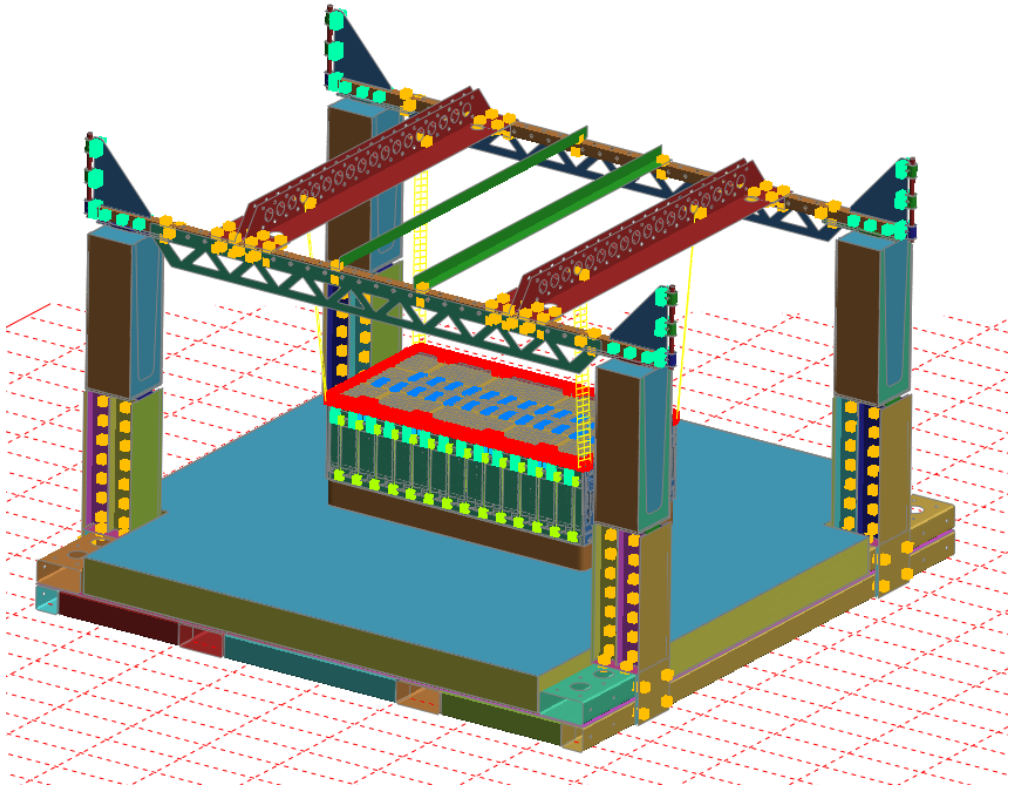
*Initial Velocity of Drop Frame and Battery: 16.8 m/s

Total numbers of Elements : - 17,261,689
Total numbers of nodes :- 21,590,503

Boundary Conditions

Battery Drop Test

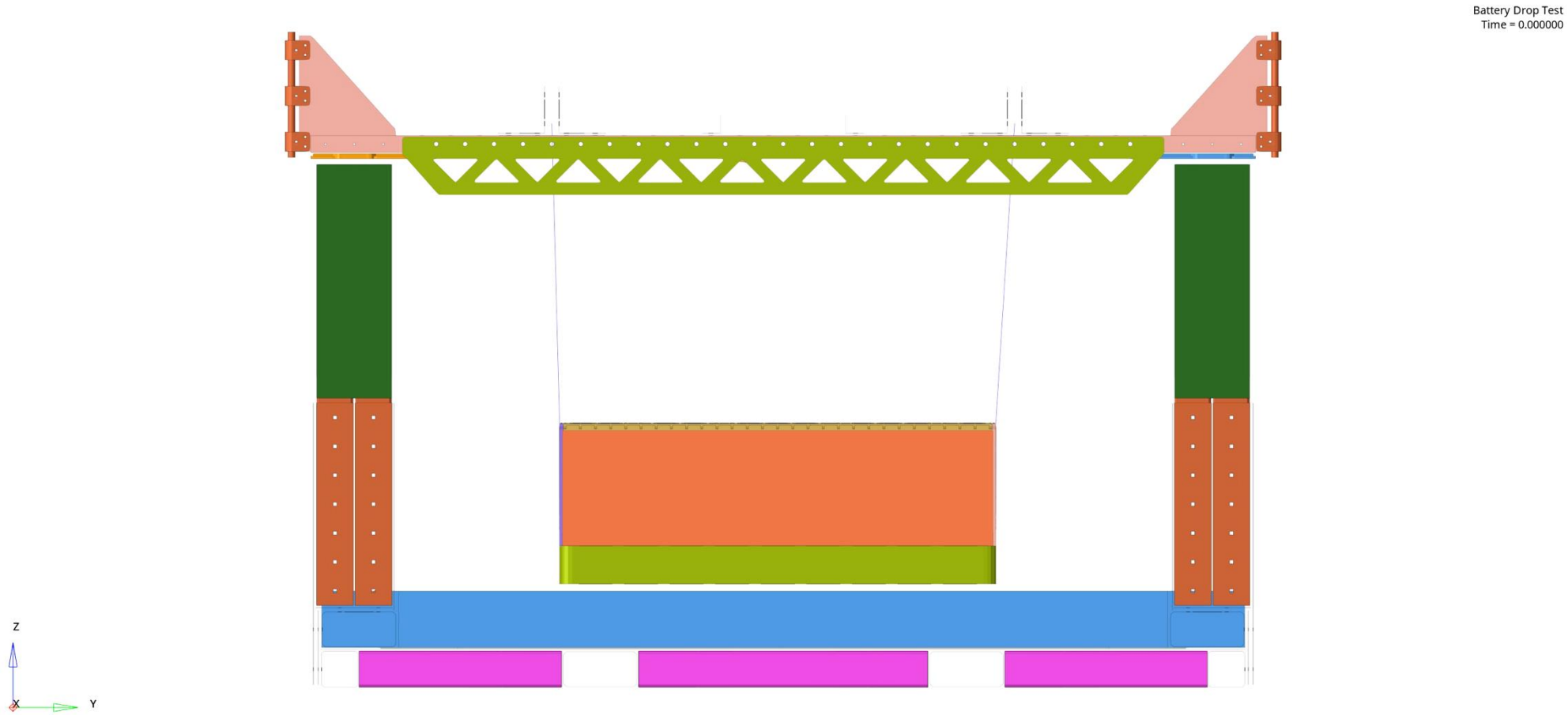
Gravity is applied to the entire model.



**A rigid Wall is used as a boundary condition at bottom of the entire fixture (represented by red dotted lines).

Simulation Video

Battery Drop Test



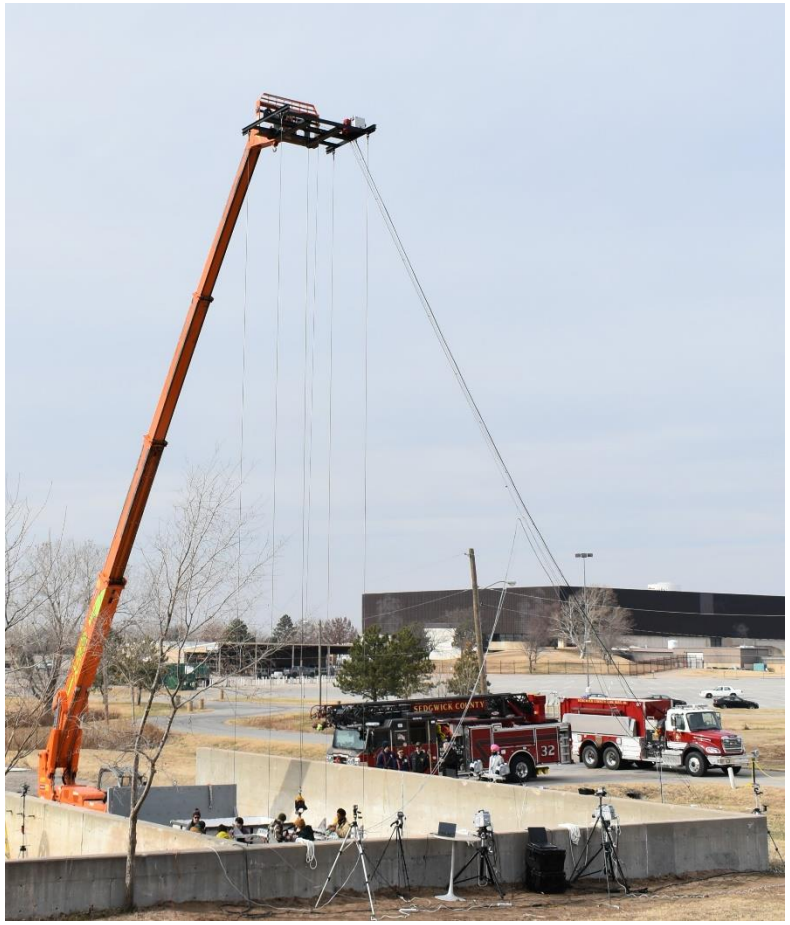
eVTOL Battery 50 ft. Drop Test - BD23A-01 – Results Analysis

NIAR AVET Digital Engineering Methods Internal R&D

Test Results Analysis

AVET Drop Test BD23A-01

- Test Videos
  - High Speed Kinematics
  - Thermography
- Test Signals
  - Accelerometers
  - High Voltage Signals
  - Thermocouples
  - Drop Velocity
  - Impact Orientation
- Damage Documentation
  - General Impact Damage
  - Batteries Deformation



Data Acquisition Systems

AVET Drop Test BD23A-01

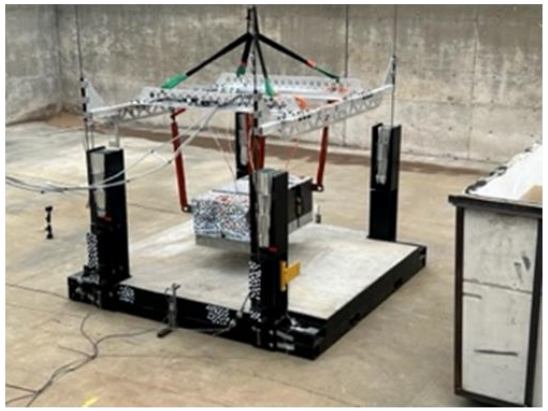
- Dynamic DAQ
  - -4 seconds to 30 minutes (or longer)
    - 100-500 sps static recording rate
    - Up to 200,000 sps recording on trigger
  - Requires trigger input to one channel
- Monitoring DAQ
  - -4 seconds to 30 minutes; 100-500 sps
  - Can start new logging file after 30 minutes without major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

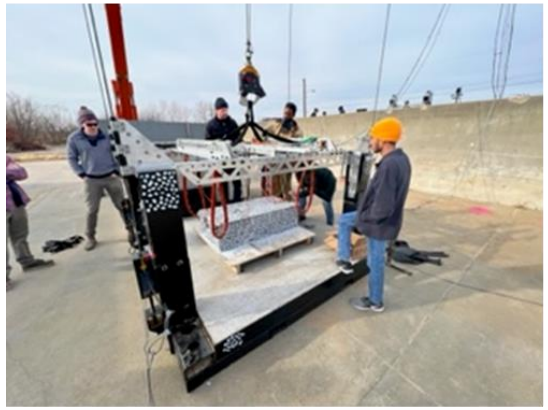
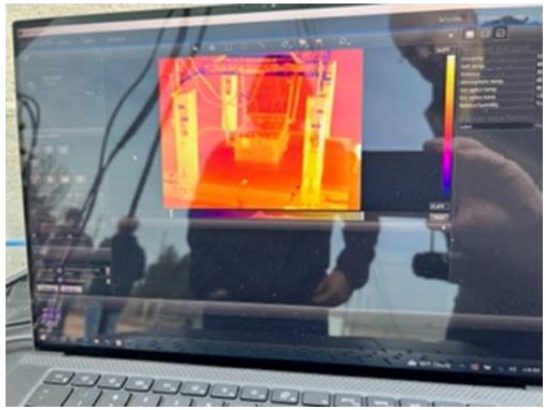
		Channel Allocation		
Channel #	Description	Dynamic DAQ	Monitoring DAQ	High Speed DAQ
1	HV+, HV- [Vb]	X		
2	HV-, Chassis [V1]	X		
3	HV+, Chassis [V2]	X		
4	HV-, Chassis with Resistor [V1']	X		
5	HV+, Chassis with Resistor [V2']	X		
6	Distance Sensor	X		
7	Trigger Input	X		
8	Thermocouple 1		X	
9	Thermocouple 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

Test Setup – Pre Test

AVET Drop Test BD23A-01



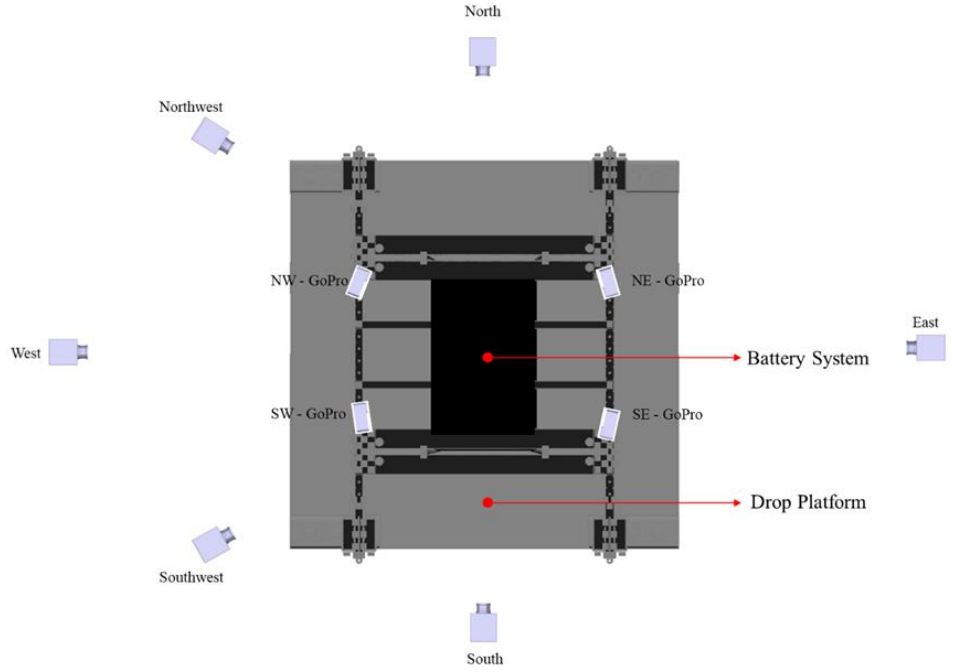


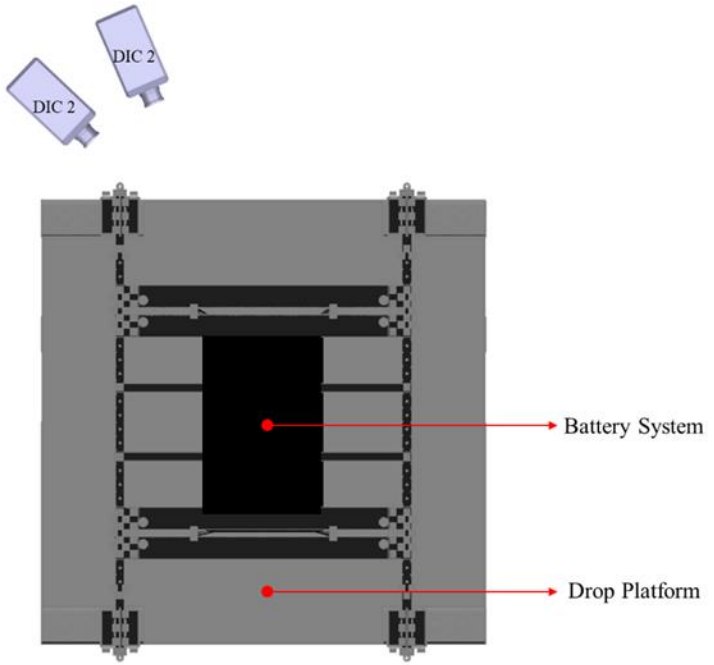



High Speed Video and Thermal Cameras

AVET Drop Test BD23A-01

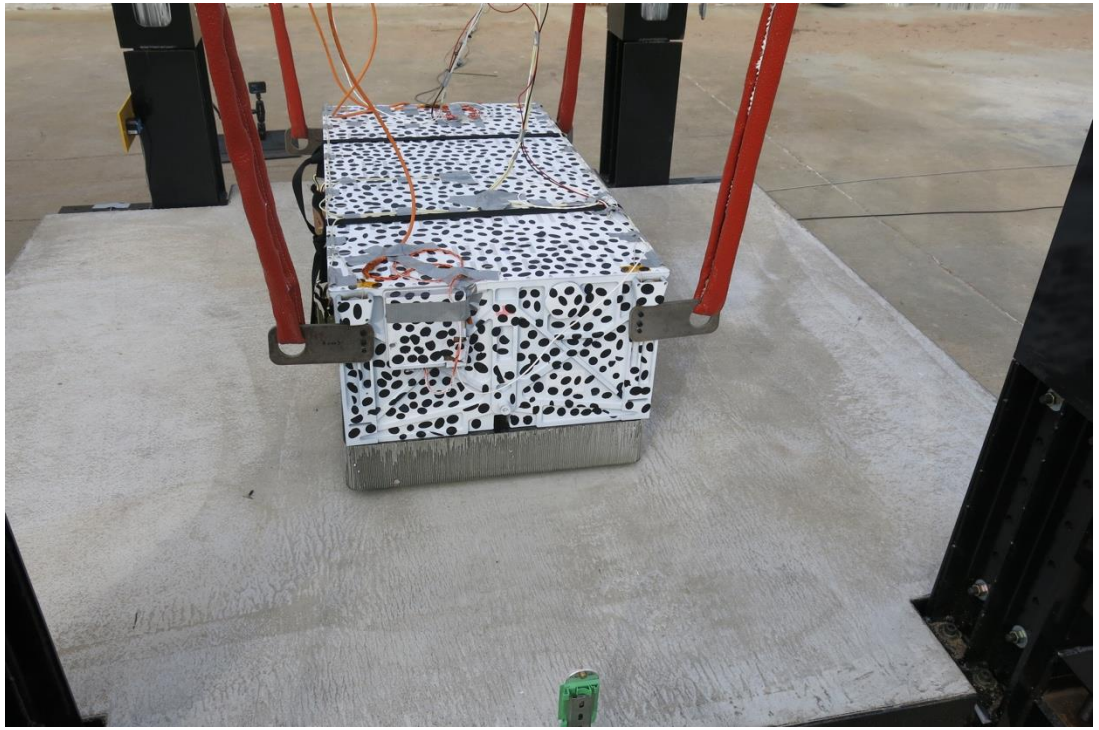
- High Speed Cameras from different angles
- Low-speed Thermal Camera
- High Speed DIC Stereo Set

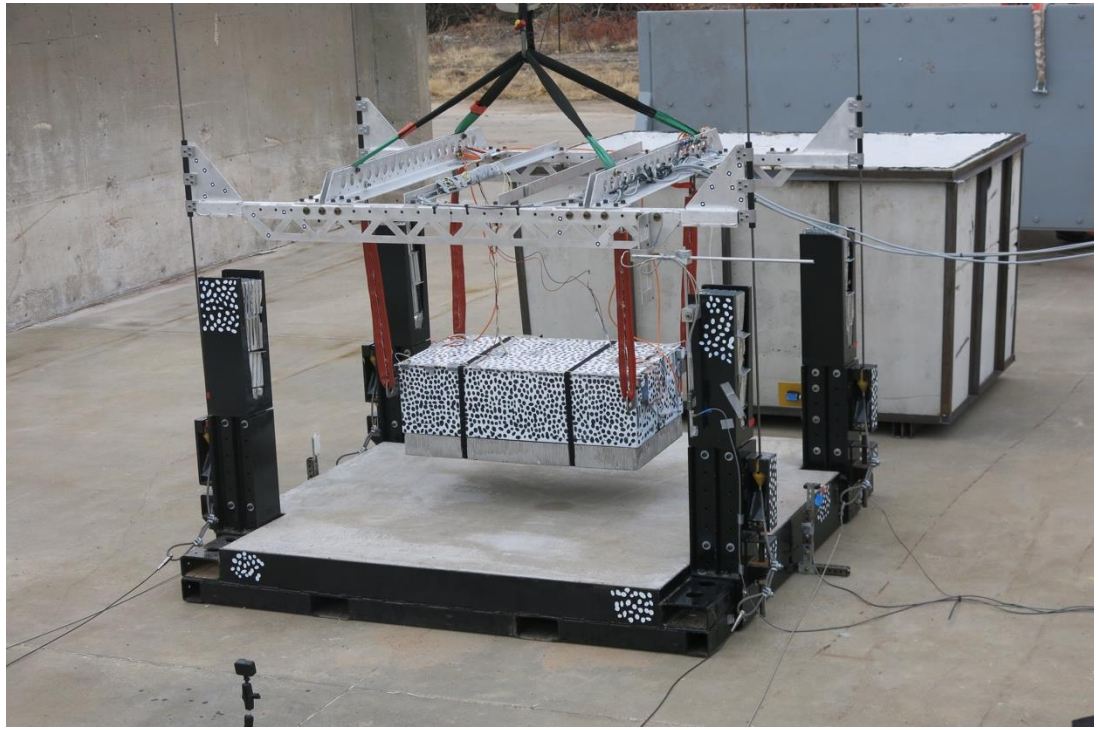




Test Setup – Pre Test

AVET Drop Test BD23A-01



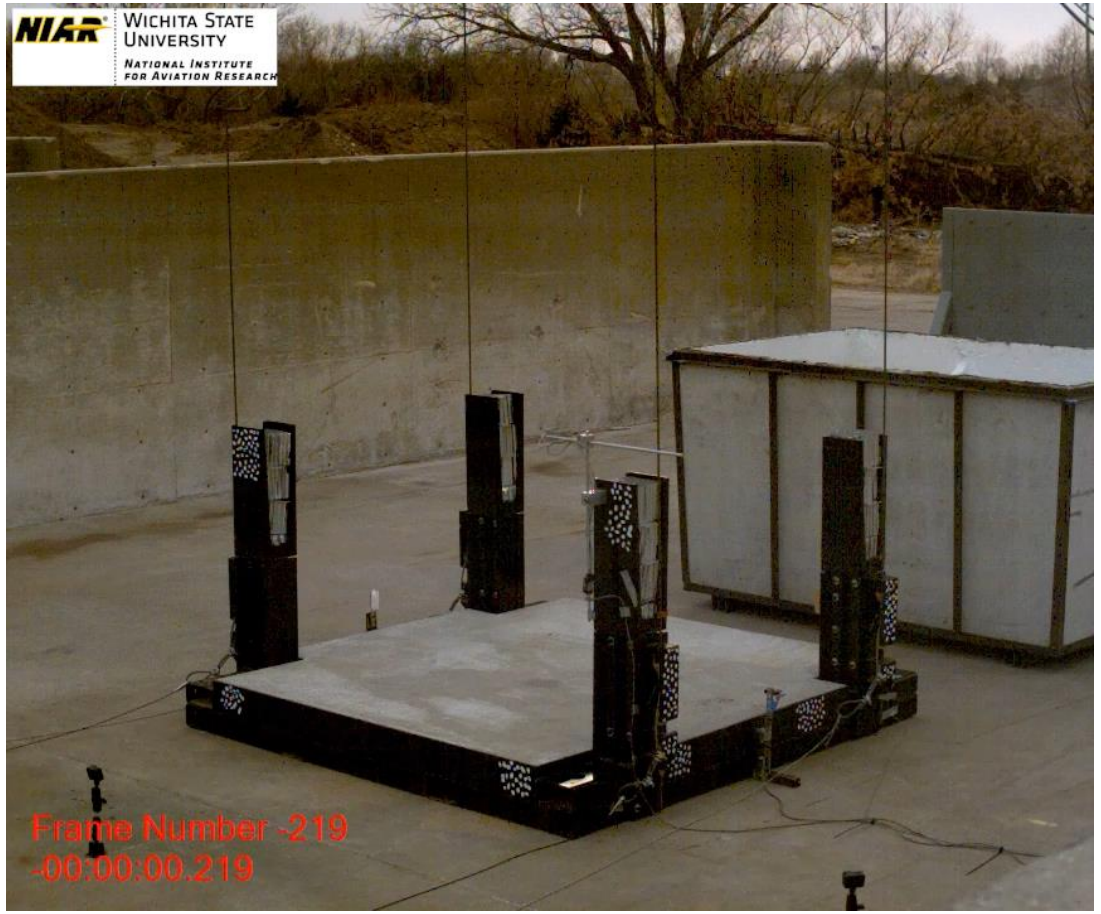


High Speed Video

AVET Drop Test BD23A-01

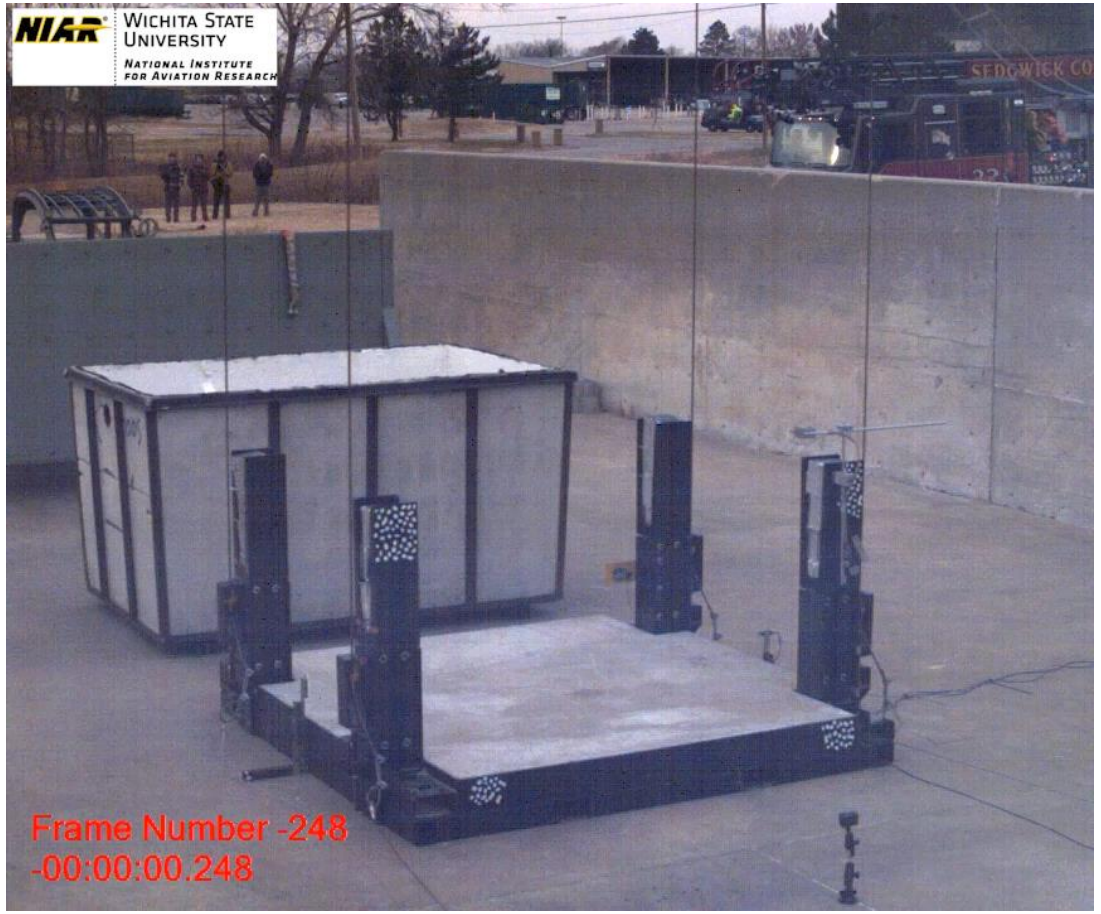
High Speed Video

AVET Drop Test BD23A-01



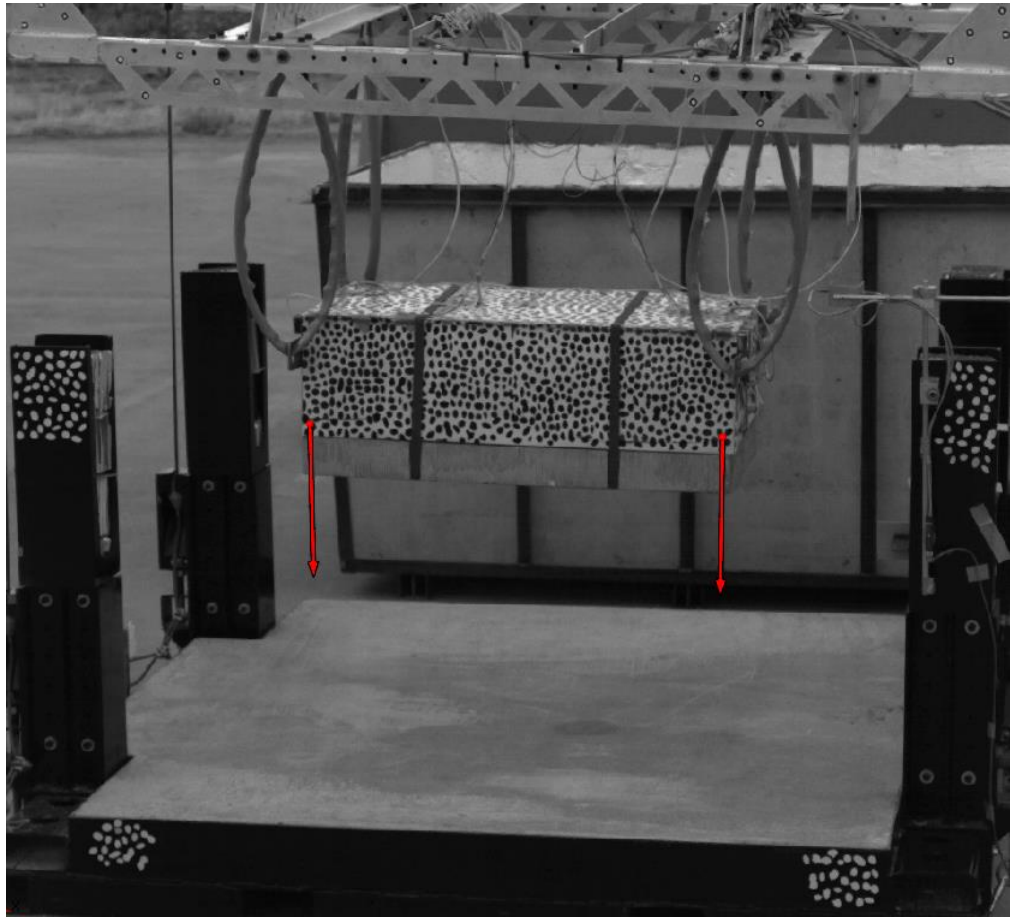
High Speed Video

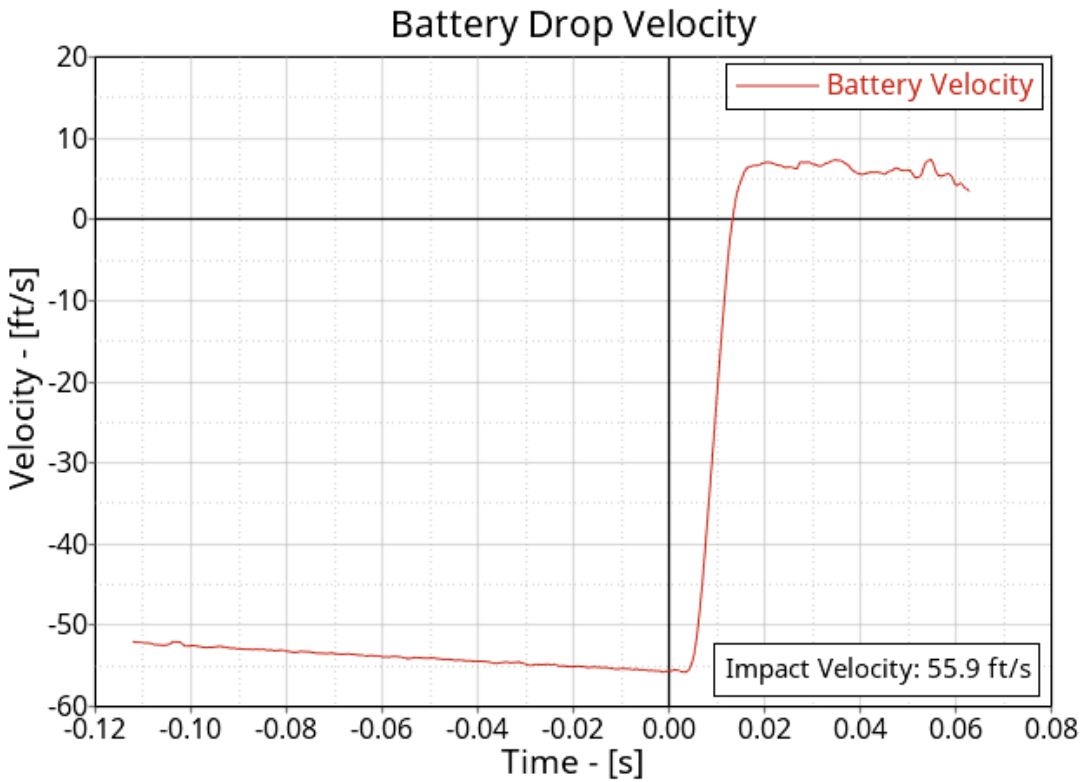
AVET Drop Test BD23A-01



Drop Velocity

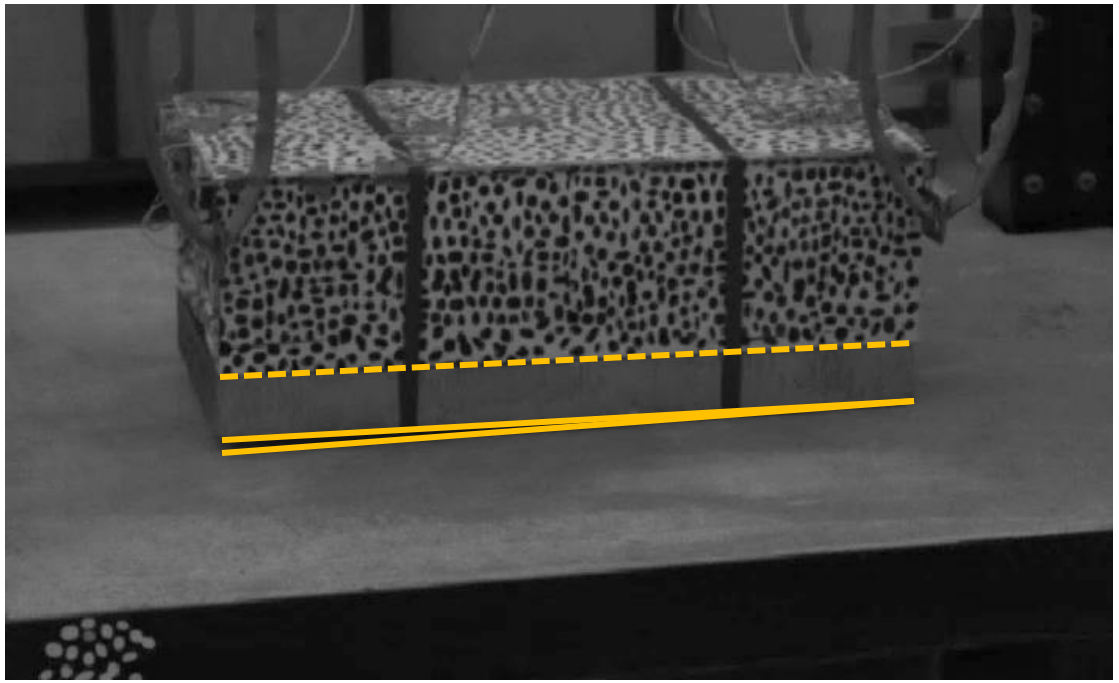
Full Scale Battery Drop Test Preliminary Test Results



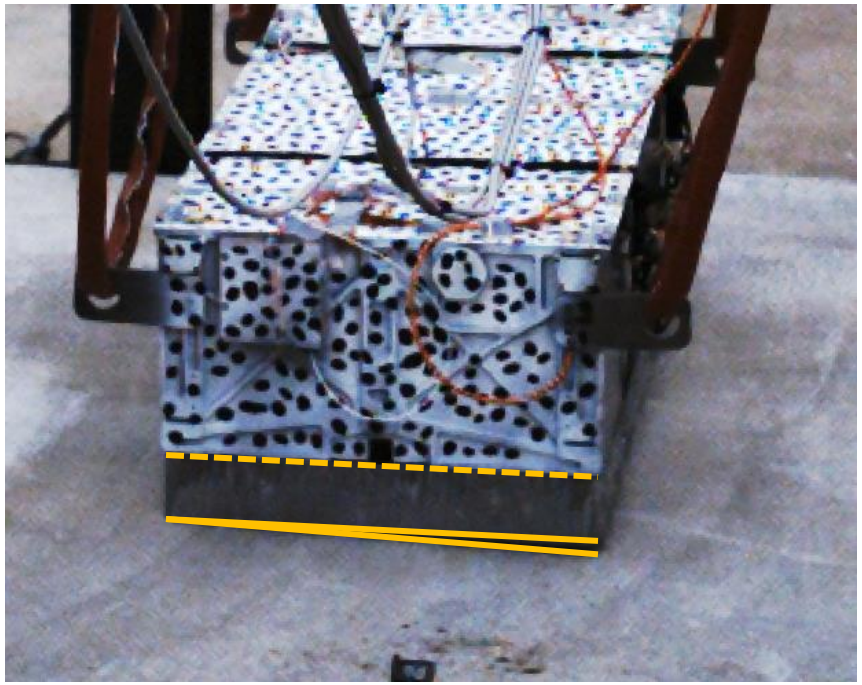


Impact Orientation

Full Scale Battery Drop Test Preliminary Test Data



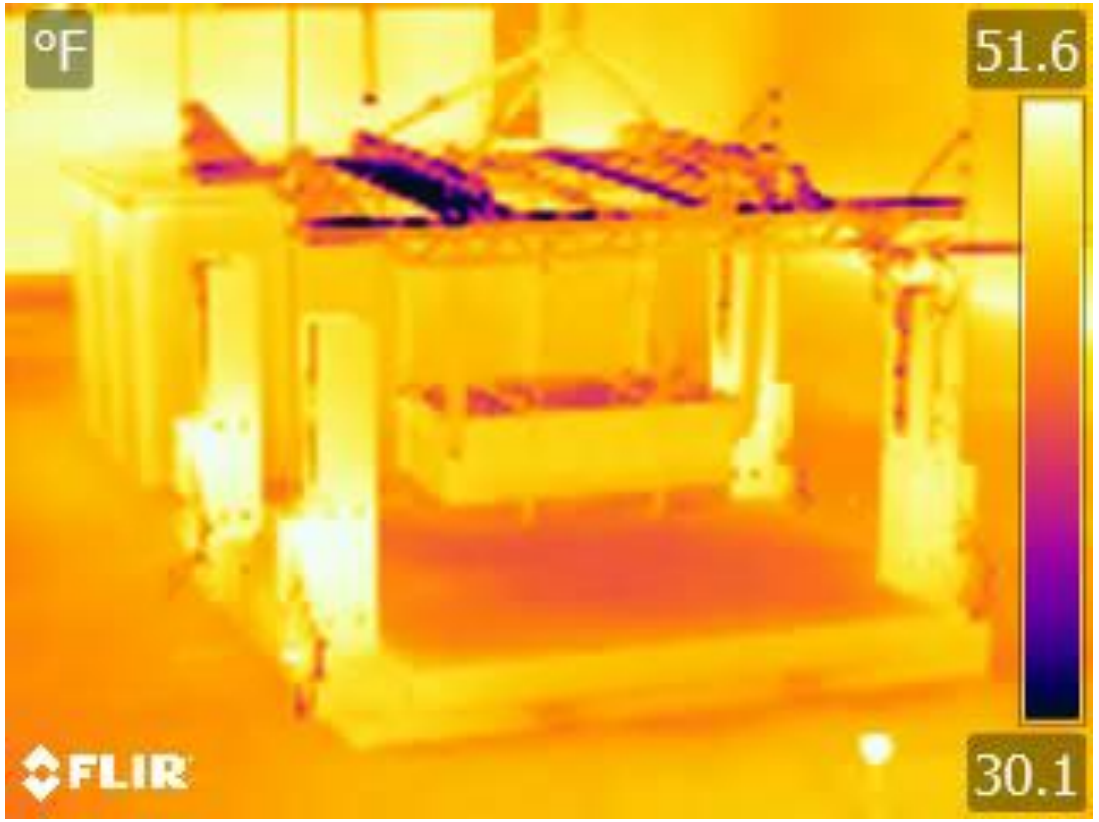
- Impact Angle 2.18°

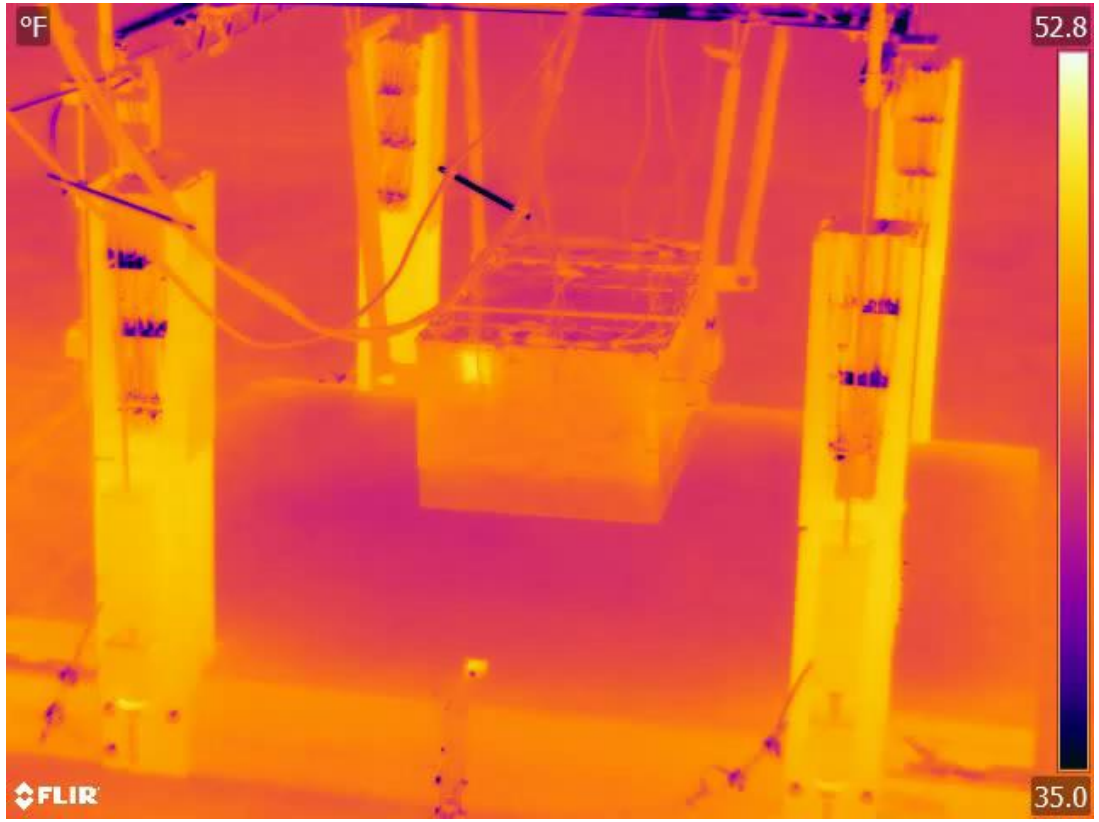


- Impact Angle 0.99°

Thermal Cameras

FAA Battery Drop Test

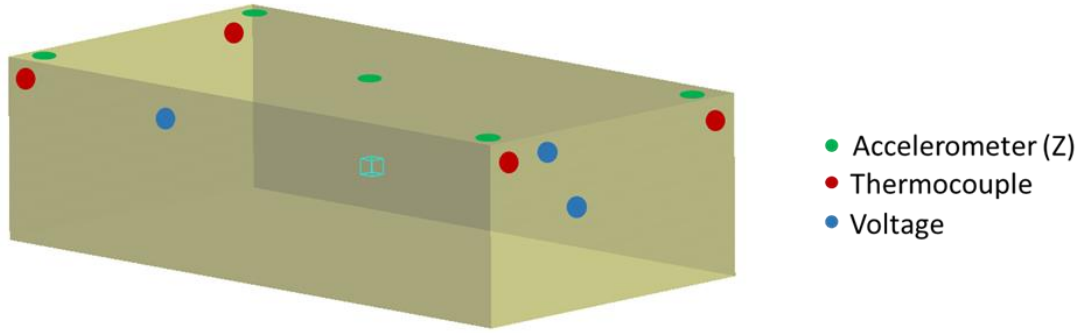




Data Channels

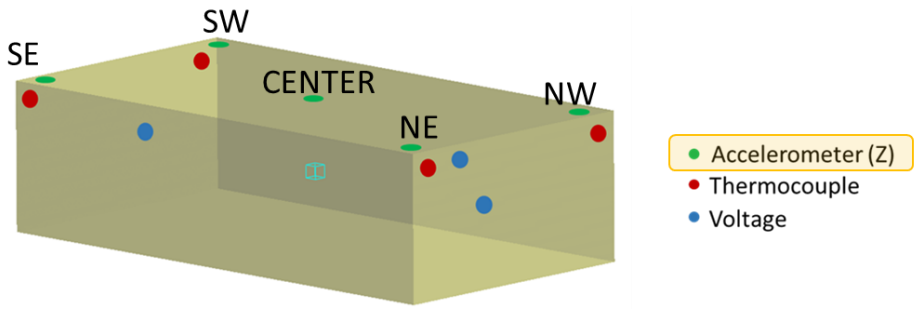
Full Scale Battery Drop Test Data

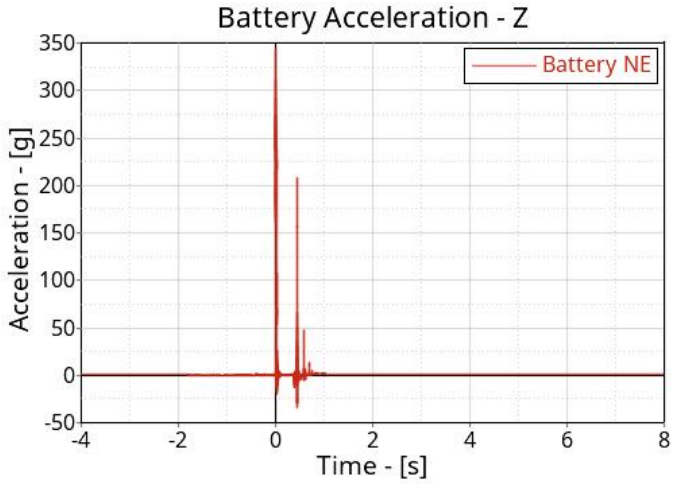
- High Speed Data
  - 5x Accelerometers
  - 5x High Voltage Readings
  - 1x Velocity Gate
- Temperature Monitoring
  - 4x Thermocouples
- Digital Image Correlation
  - Drop Velocity
  - Impact Orientation

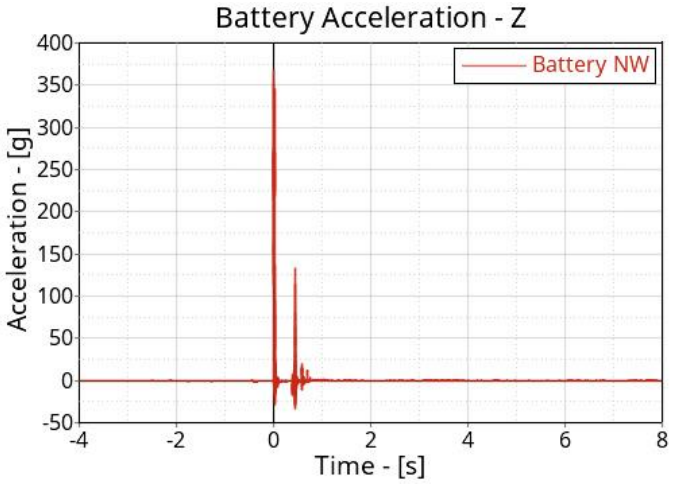


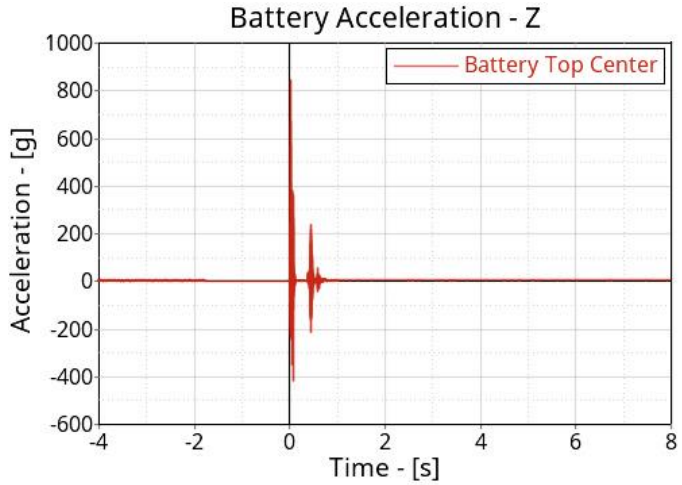
Accelerometers – Entire Recorded Time

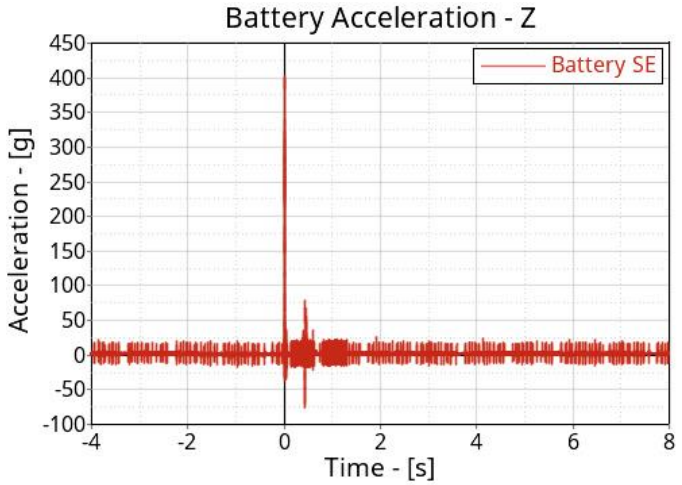
Full Scale Battery Drop Test Results

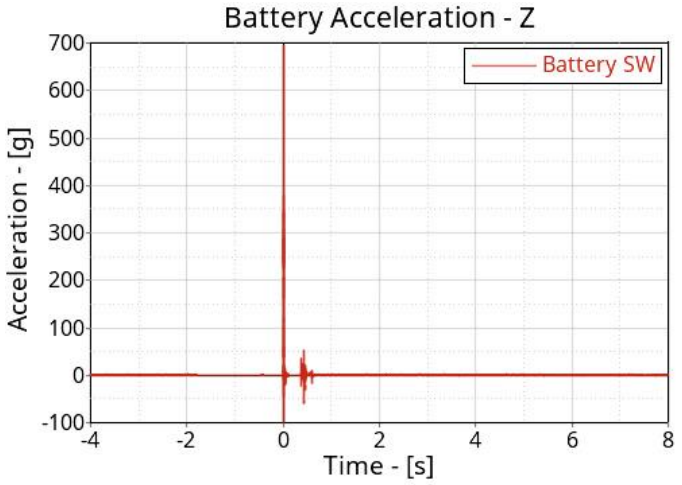






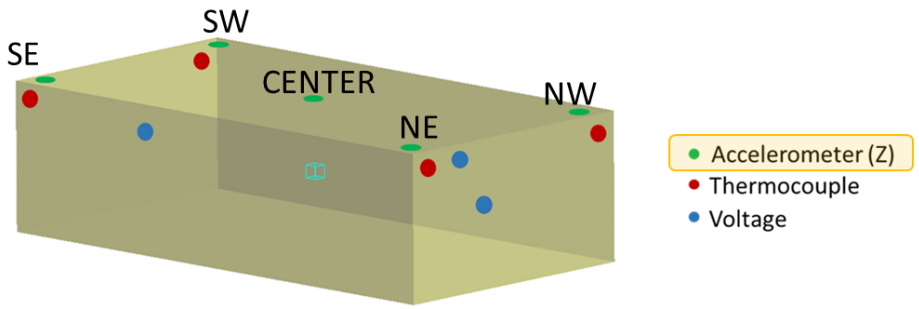


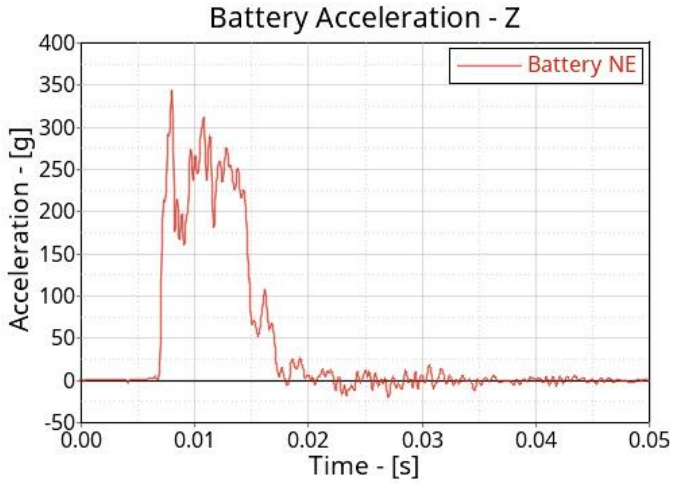


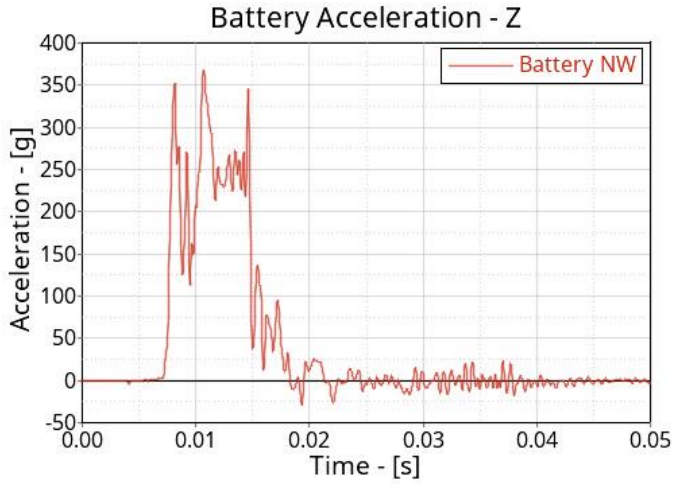


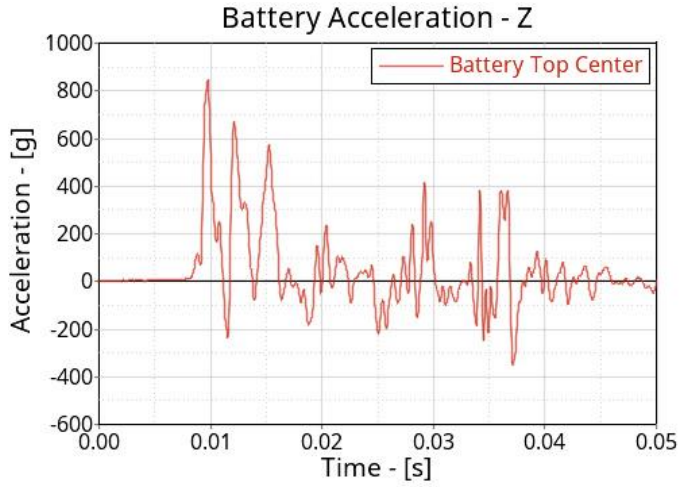
Accelerometers – Impact

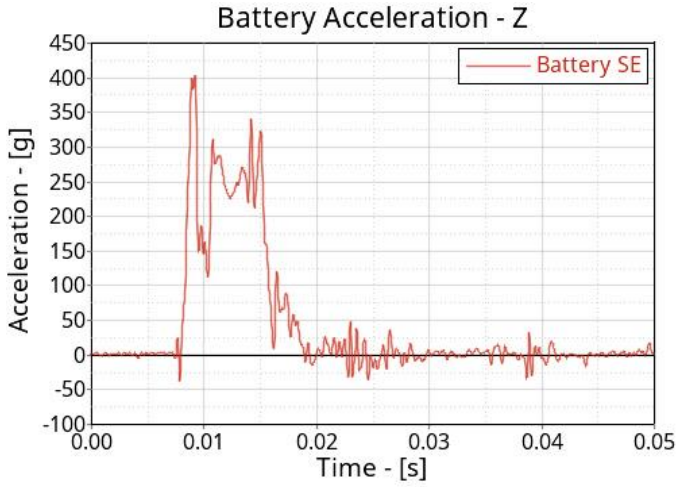
Full Scale Battery Drop Test Results

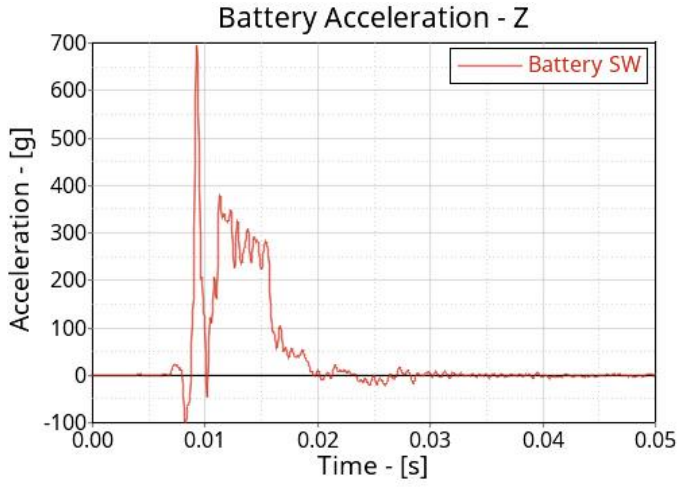






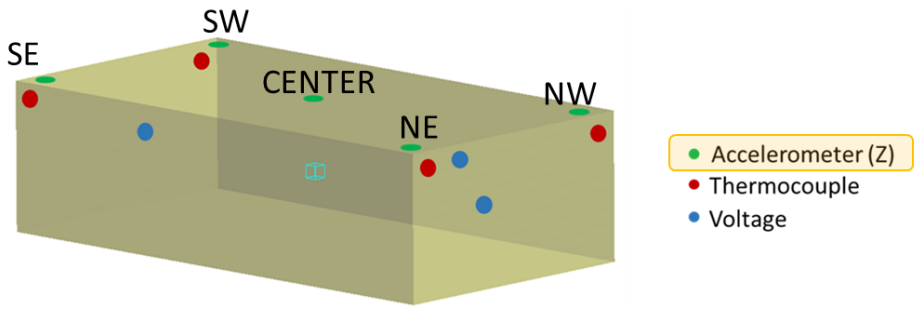


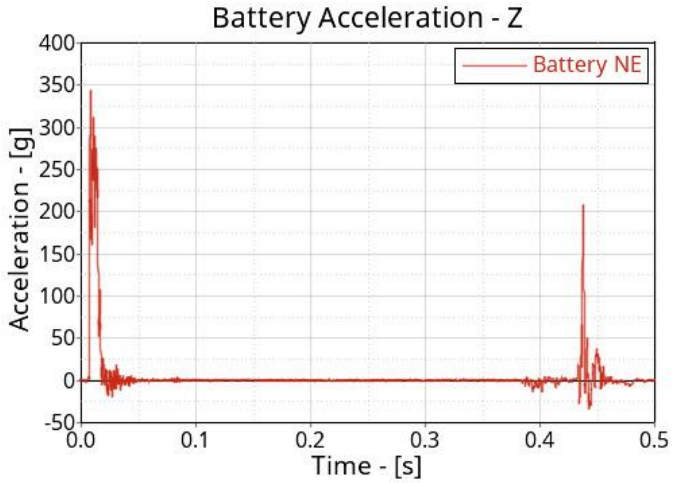


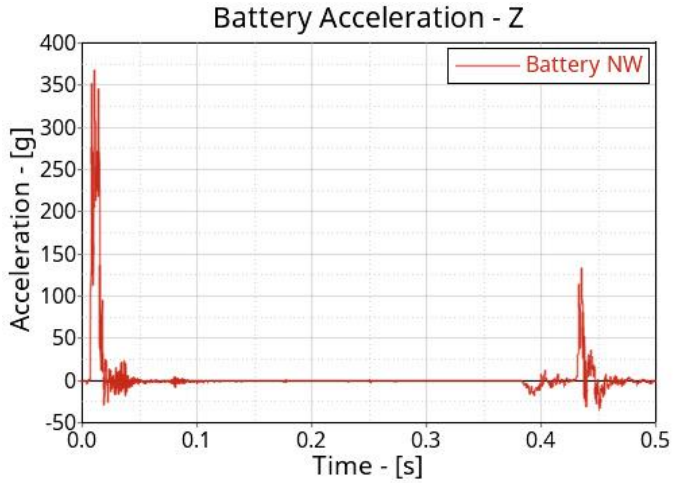


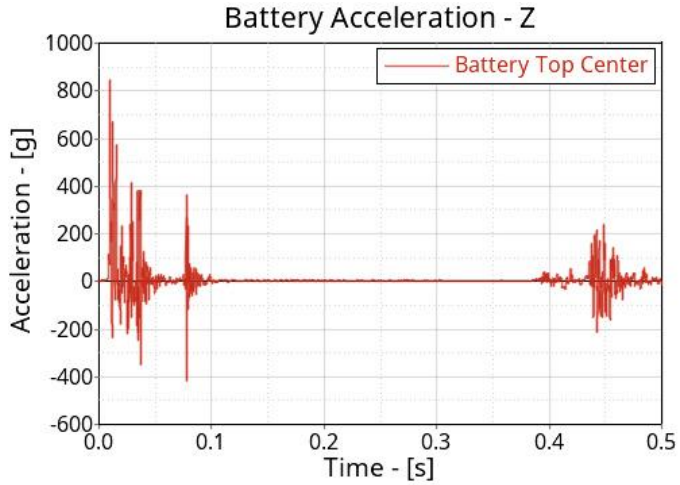
Accelerometers – Rebound

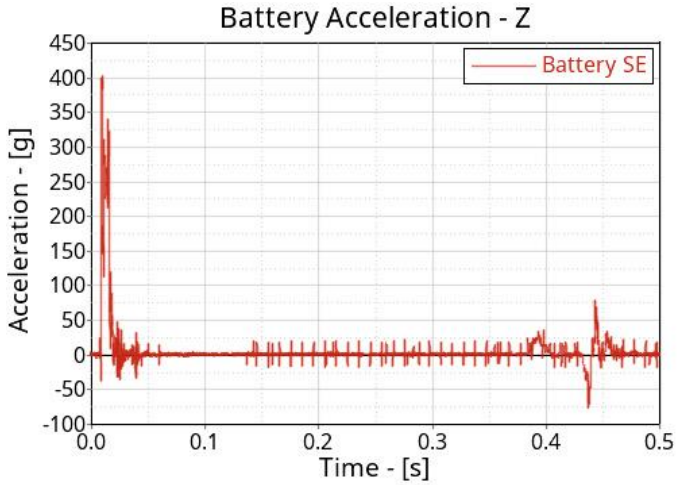
Full Scale Battery Drop Test Results

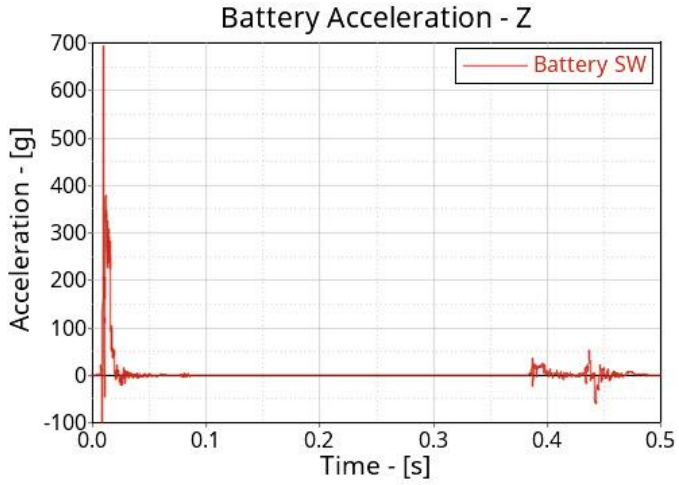






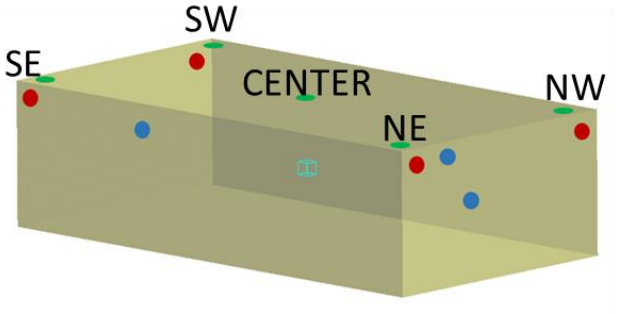


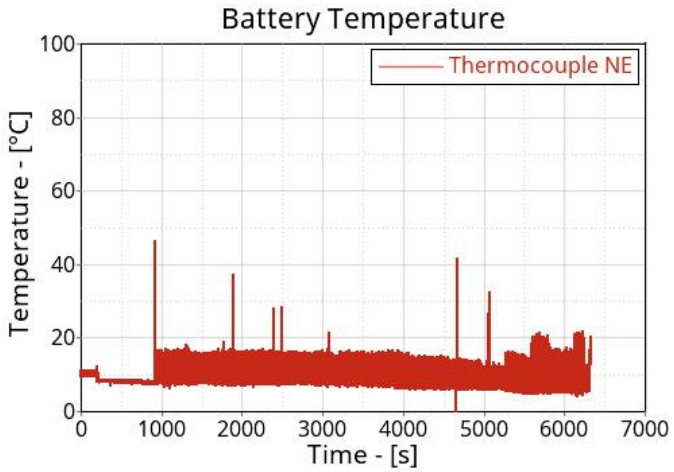


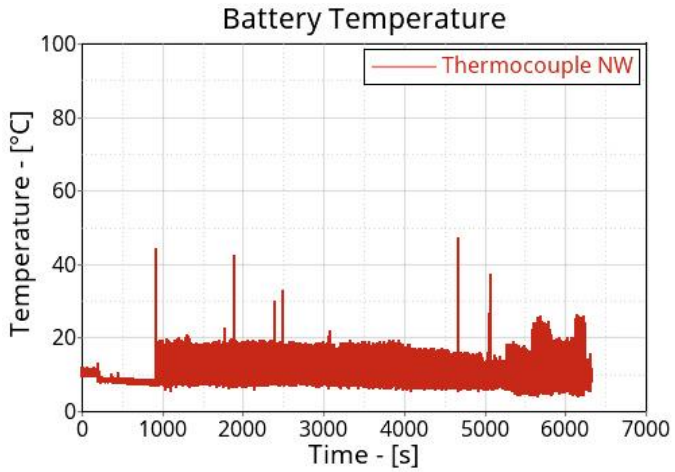


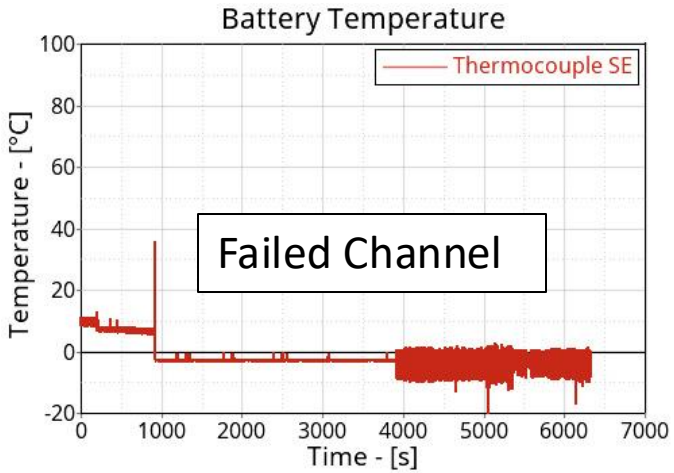
Thermocouple Readings – Module

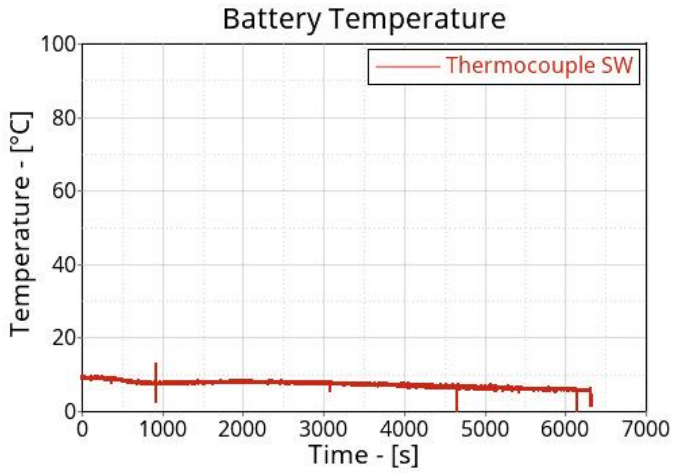
Full Scale Battery Drop Test Results





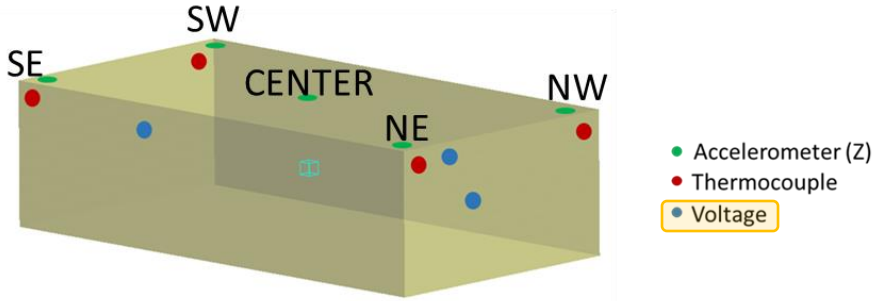


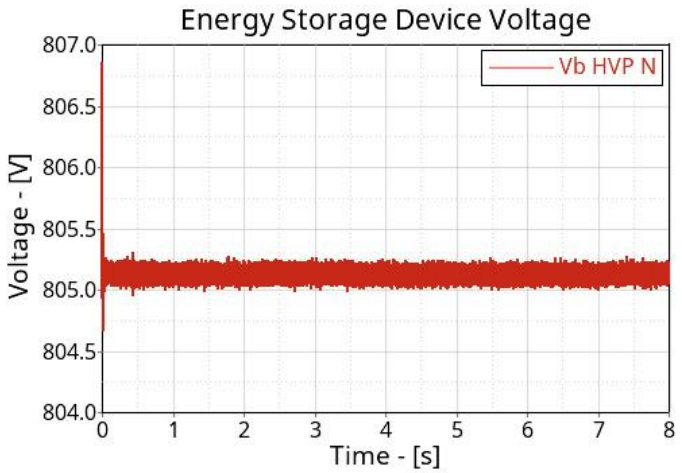


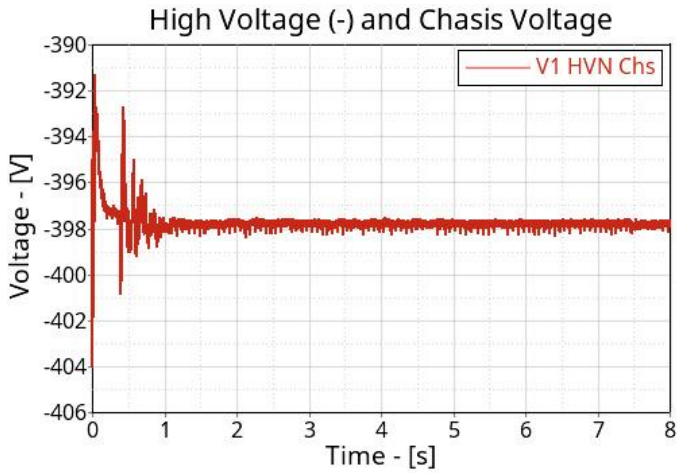


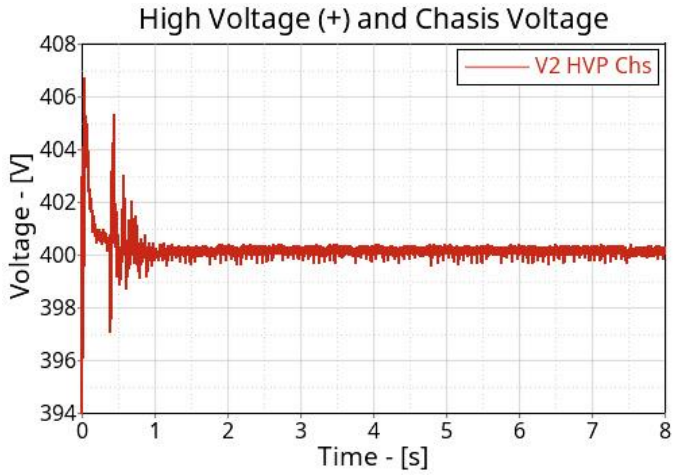
High Voltage Signals – Entire Recorded Time

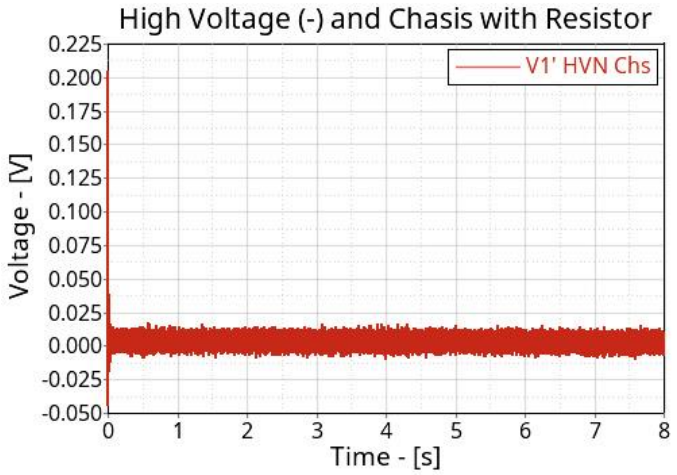
Full Scale Battery Drop Test Results

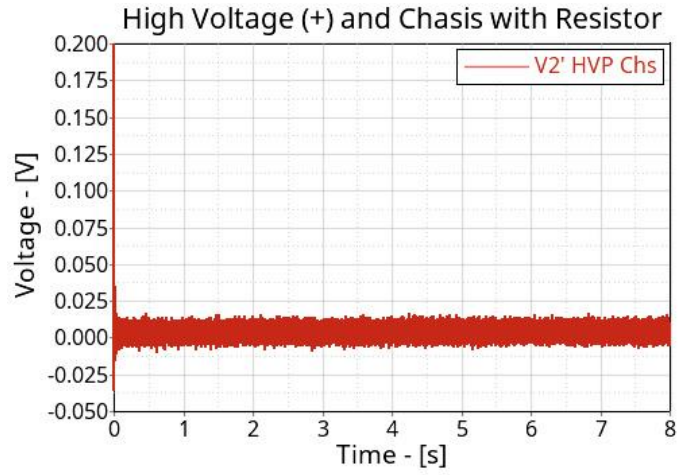






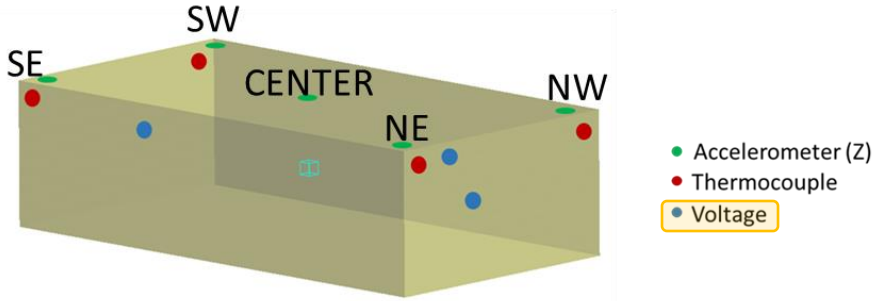


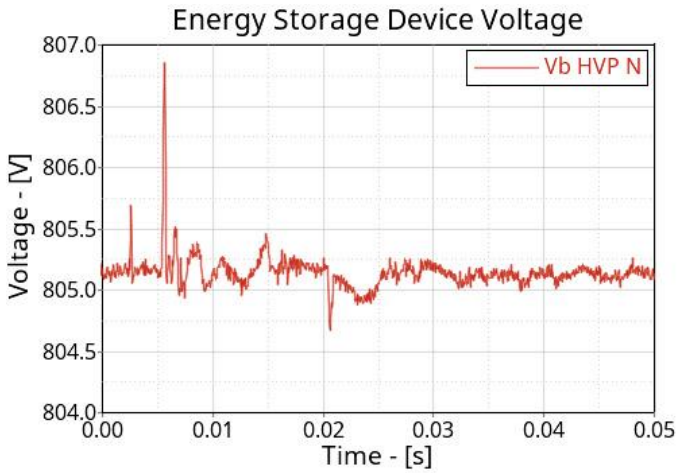


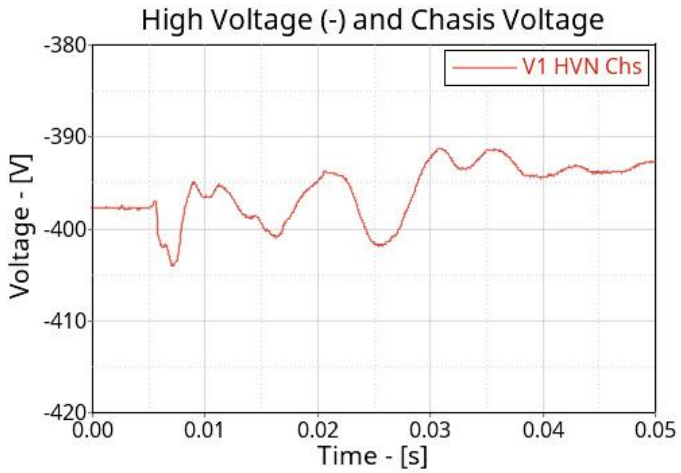


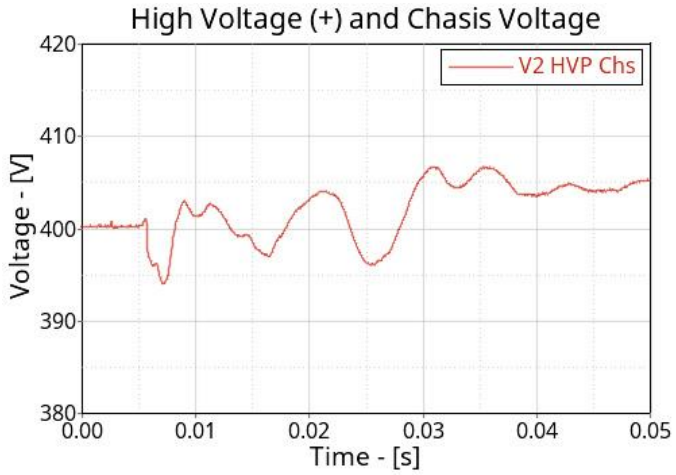
High Voltage Signals – Impact

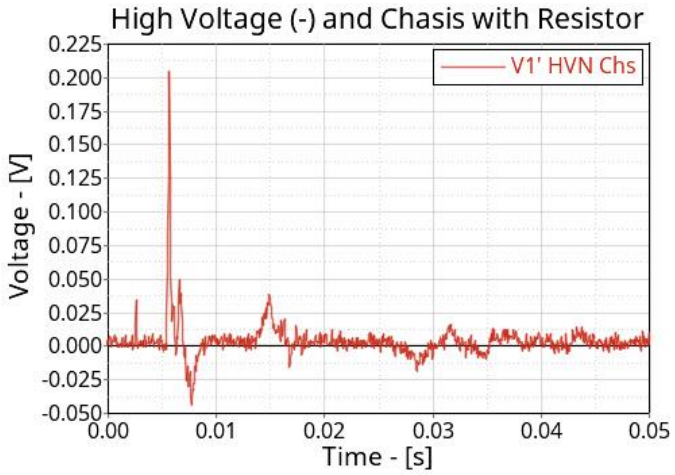
Full Scale Battery Drop Test Results

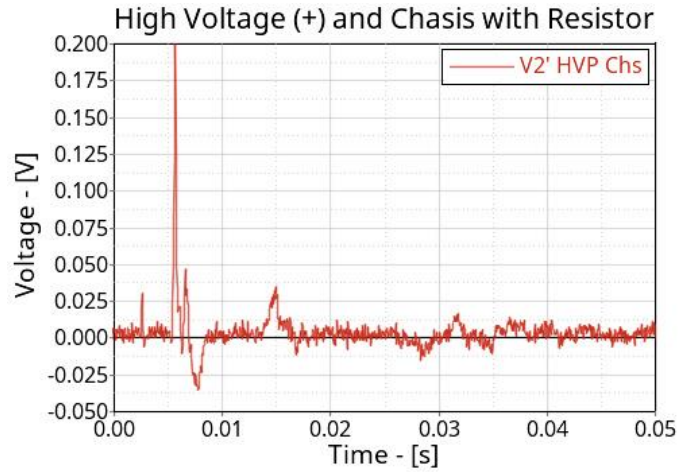






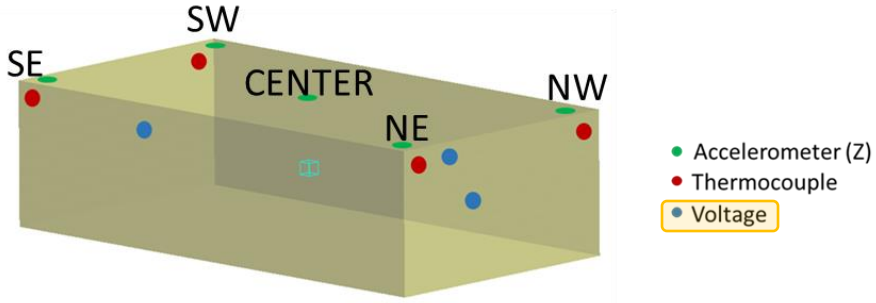


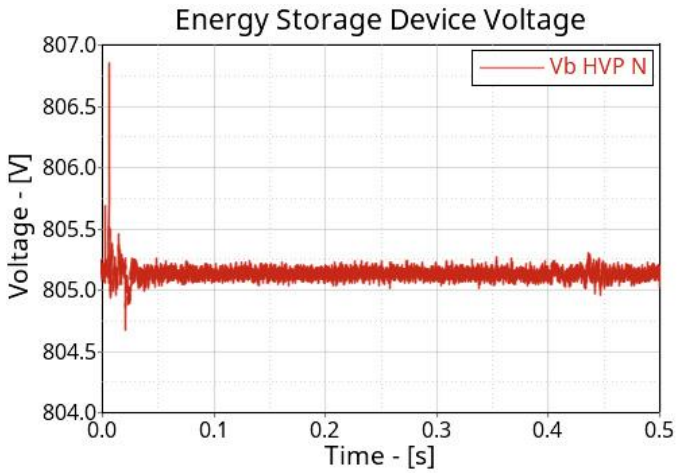


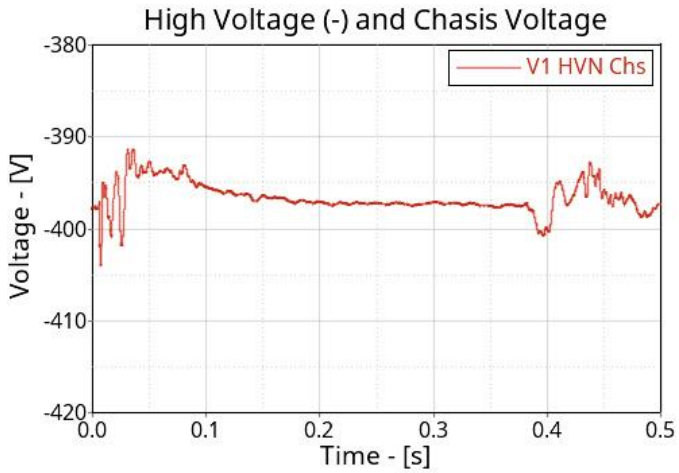


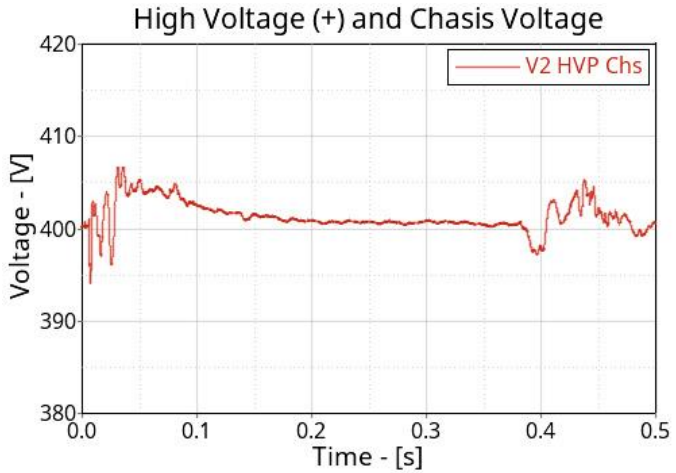
High Voltage Signals – Rebound

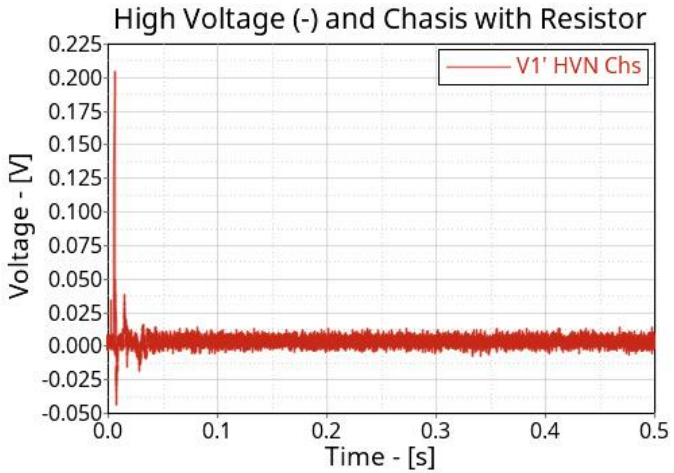
Full Scale Battery Drop Test Results

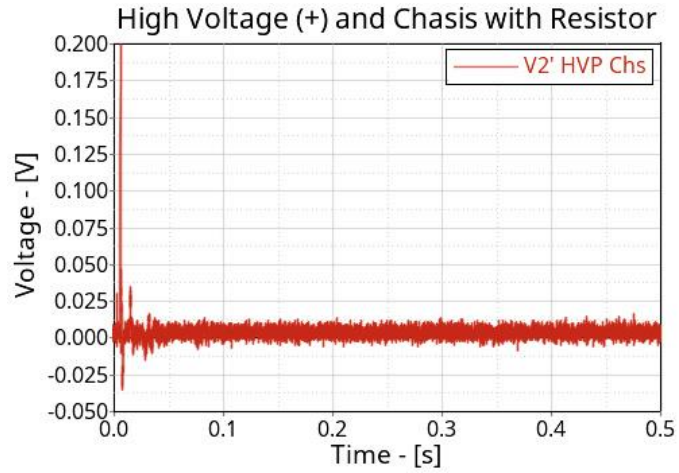












Research - Next Steps

NIAR-AVET 50 ft. Battery Drop Test

- Finalize Official FAA Report
- Continue to work with the FAA R&D to define next steps
- Continue to coordinate R&D Efforts with NASA Langley Battery Drop Test Project
- Continue working with AAM OEMS and Battery suppliers to test different battery architectures
- Continue developing and validating numerical methods to support the development and certification of AAM Battery Packs:
  - Analysis could play an important role in the future in developing and certifying variants of a certified design

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