An Overview of the NASA Lift+Cruise eVTOL Crash Test

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Introduction – NASA RVLT Project
Impact Dynamics / Crash Safety Task

- **Task Objective:** *"To improve the crashworthiness and impact safety of Urban Air Mobility (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."*

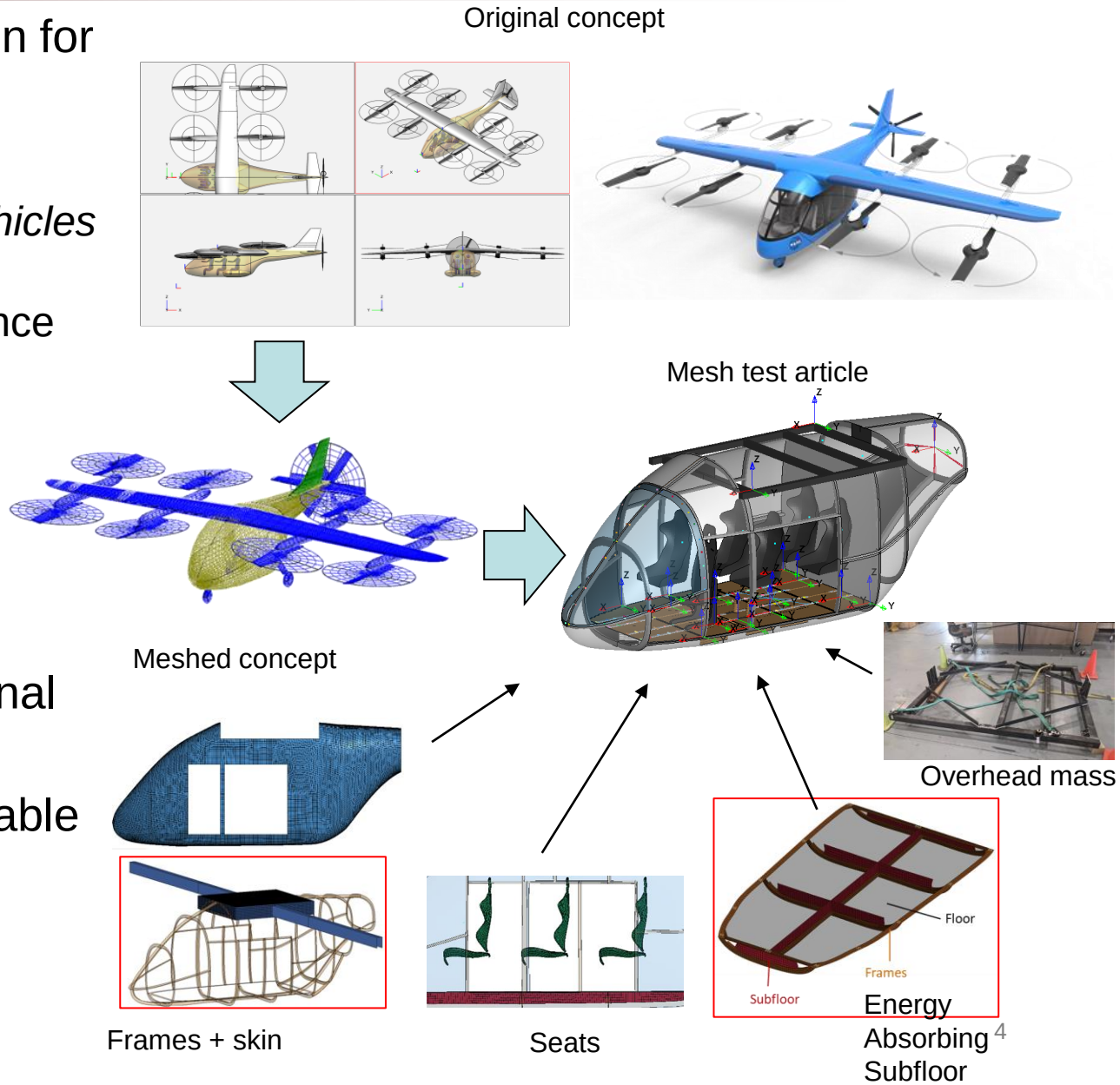
- 4 Main focus points
  - The investigation of occupant injury using physical and computational assets
  - The development of energy absorbing technology
  - The generation of data from sub- and full-scale crash test data
  - The execution of advanced finite element modelling techniques

Lift + Cruise Full-Scale Crash Test Objectives

1. Generate data on generic electric Vertical Take-off and Landing (eVTOL) vehicle design under crash conditions to inform regulation development
2. Generate data for the use in validation of computer modelling efforts
3. Generate data from onboard Anthropomorphic Test Devices (ATDs, a.k.a. crash test dummies) for the evaluation of injury
4. Generate data on experimental energy absorbing component designs

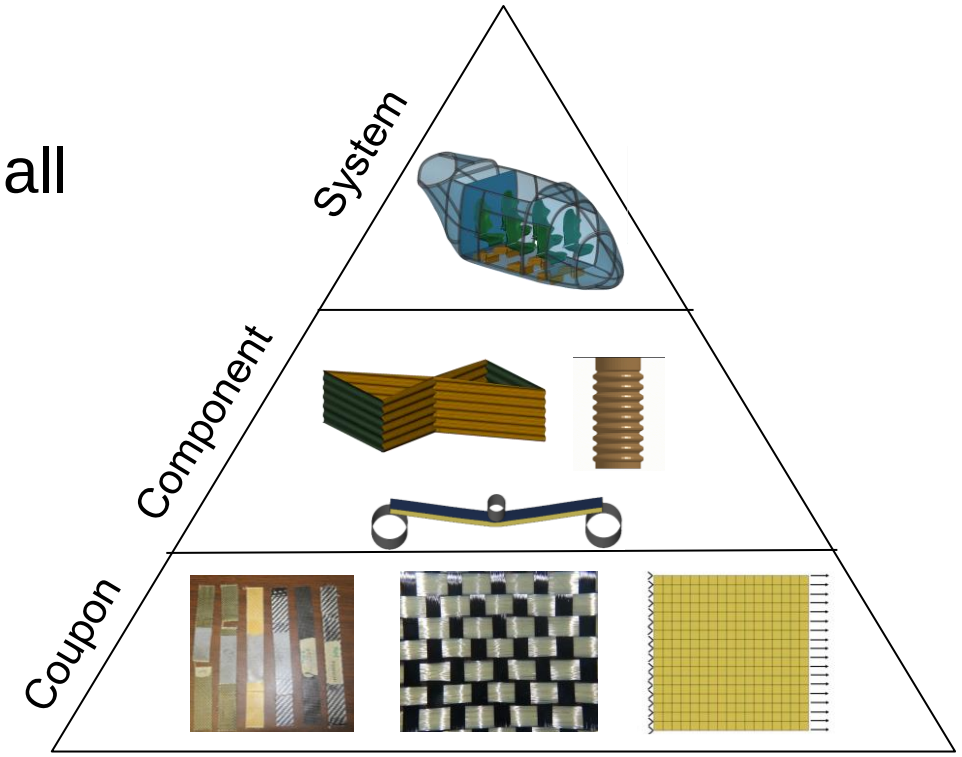
Lift + Cruise Main Features

- NASA Lift + Cruise (L+C) concept vehicle chosen for full-scale test campaign
- Reference
  - Silva et al. *VTOL Urban Air Mobility Concept Vehicles for Technology Development.* 2018 Aviation Technology Integration and Operations Conference
- Development of systems
  - Airframe structural configuration
  - Ballast and overhead mass
  - Rigid and energy attenuating seats
  - Energy attenuating subfloor
- Test article primarily designed using computational simulations
- Structural components sized to maintain survivable volume under load
    - 12 g static vertical load
    - 30 ft/s dynamic vertical impact



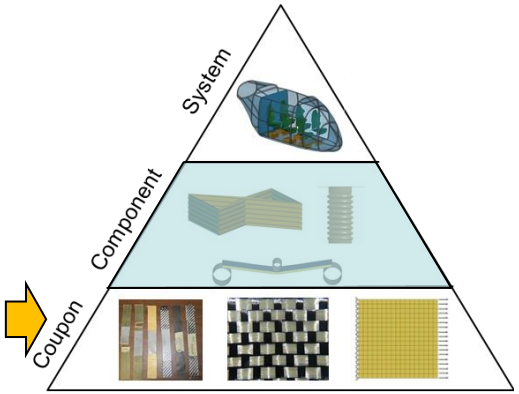
Lift + Cruise Development Overview

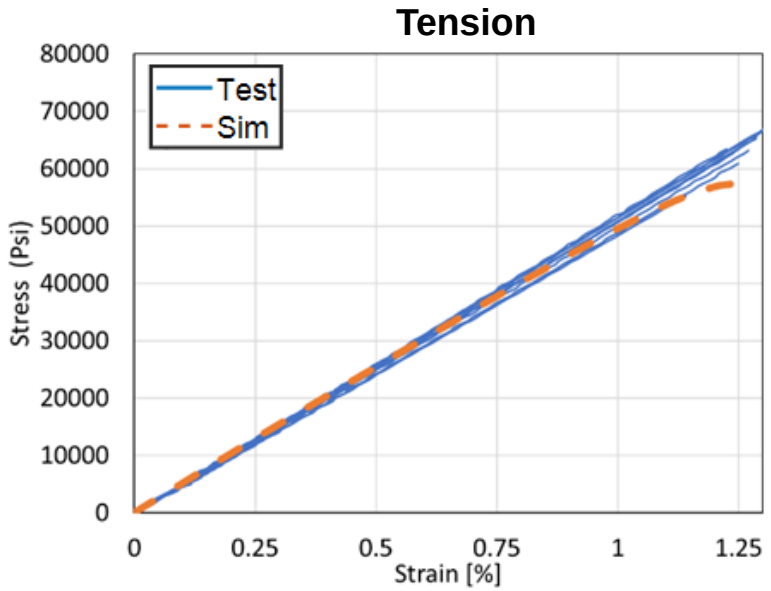
- Lift + Cruise test article model developed using standard building block method
  - Single physics coupon testing conducted for all materials (external and internal structure)
  - Subsystem testing conducted for internal structural components (no external structure subsystem available)
  - System level integration conducted to match external structure assembly and internal component integration
- *Limitation: No subsystem testing of external structure conducted*

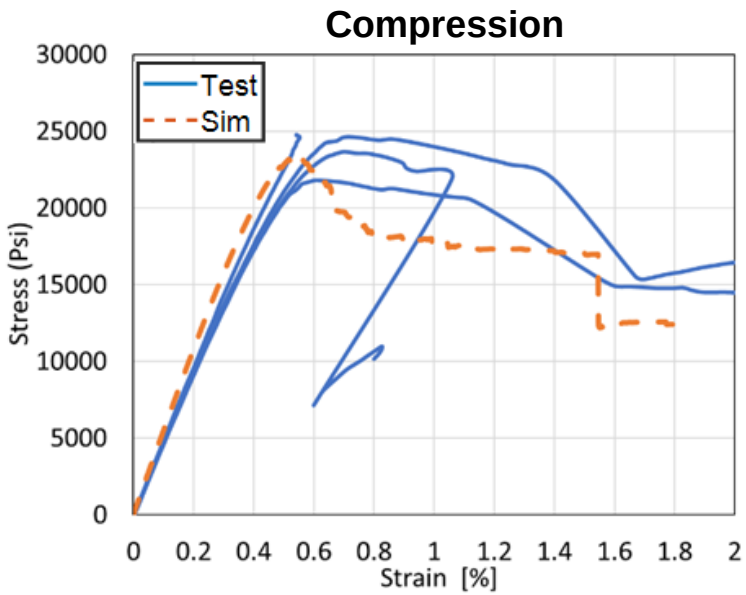


Lift + Cruise Structural Model – Material Characterization

- Samples of Carbon Composite (C/C) material used in L+C external structure acquired
  - Samples included skin and frame layups which were fabricated using same curing methodology
- Laminated composite fabric material model generated from static tension and compression test data

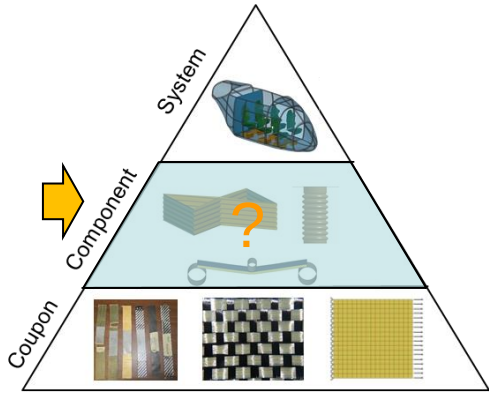


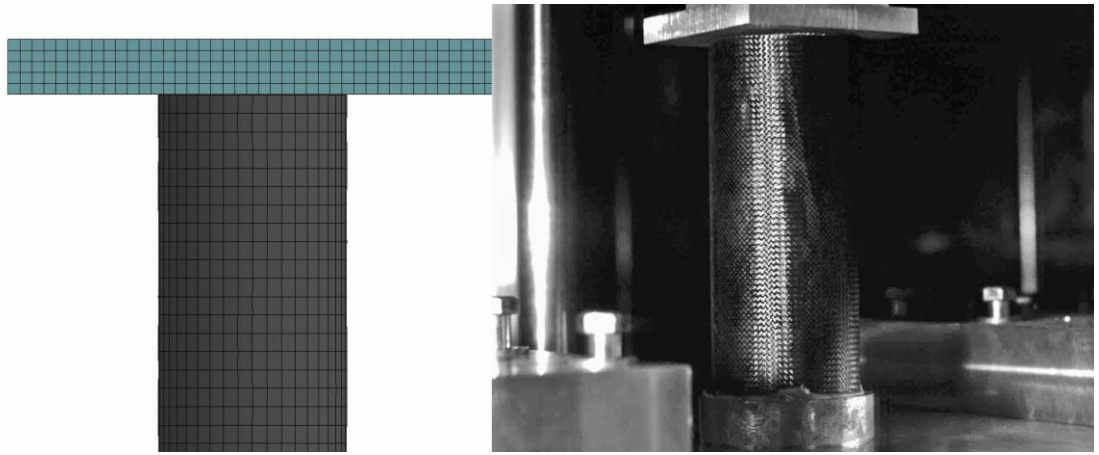


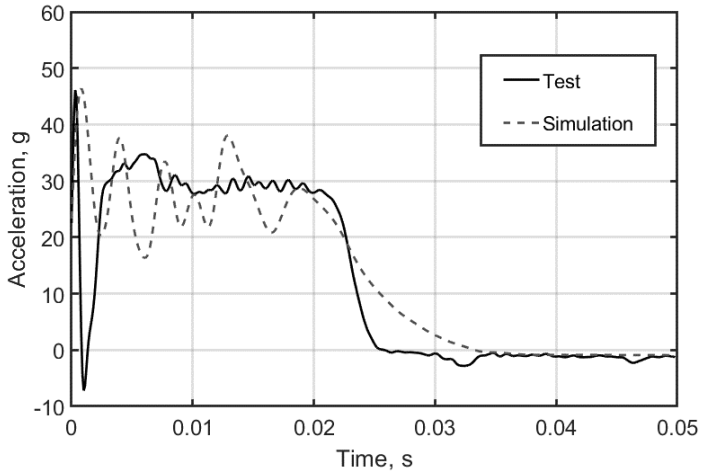


Lift + Cruise Structural Model – Subsystem Characterization

- No subsystem specimens of external structure available for characterization under representative dynamic loads
- Damage and failure parameters of material model defined from previously conducted crush tube testing of C/C material using different resin system
  - *Assumption: Material parameters applicable to L+C structure under higher energy loading conditions*

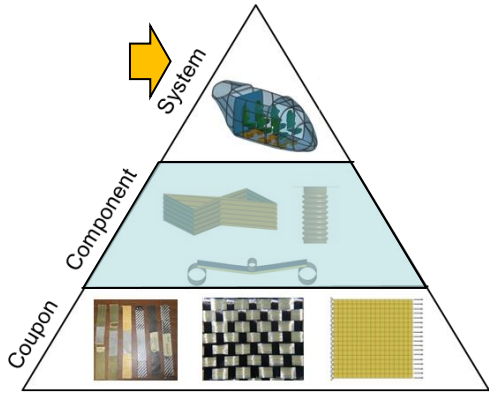




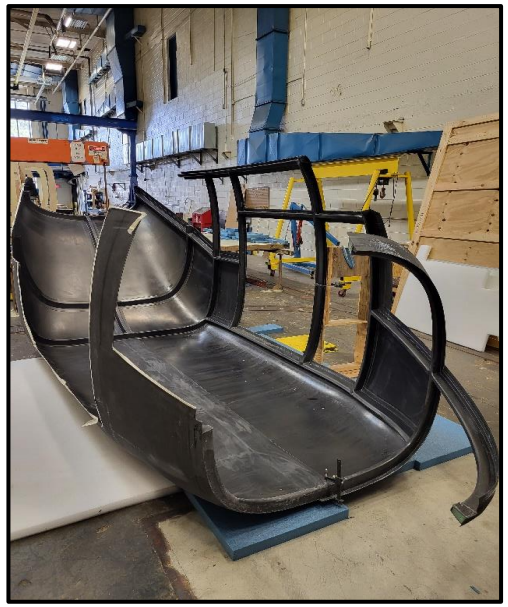


Lift + Cruise Structural Model – Top Level Assembly

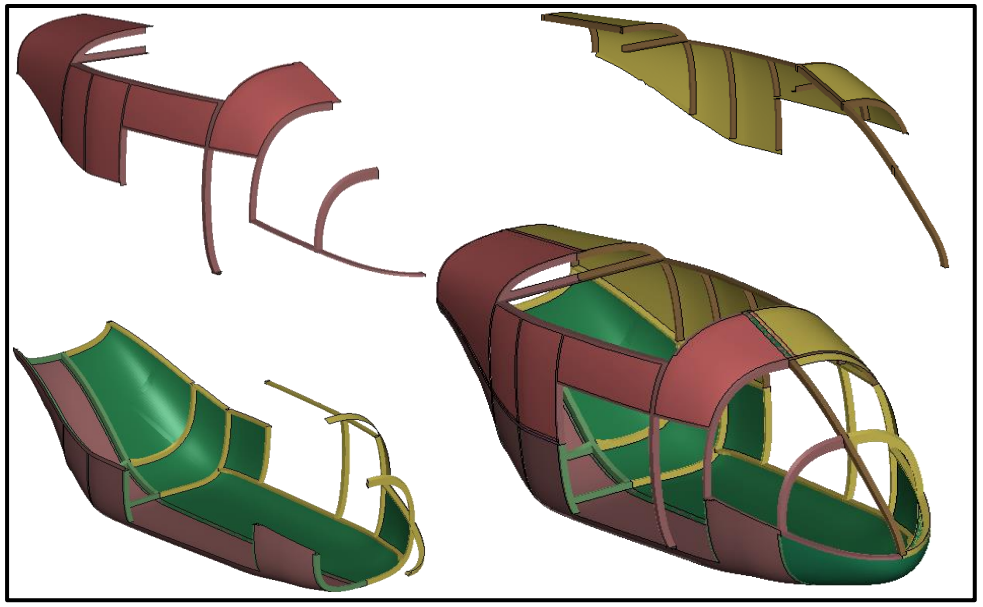
- Finite element model (FEM) generated to match geometry and assembly specifications of L+C test article
- Test article fabricated in four sections and bonded with lap joints: FEM parts generated to match each section



Test Article Assembly



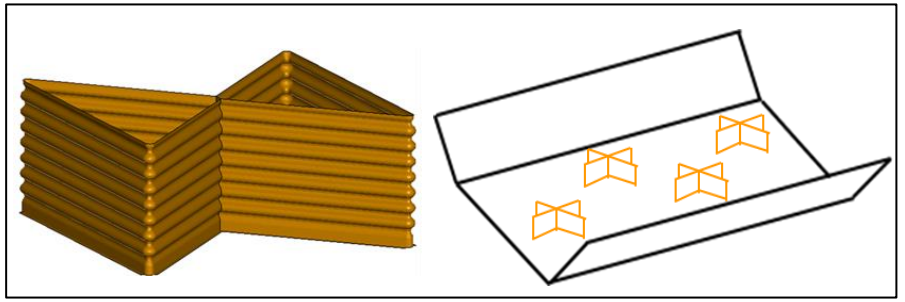
FEM Assembly



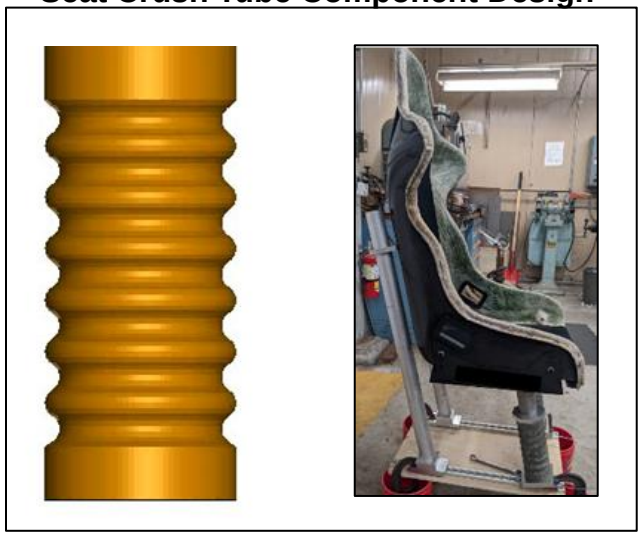
Internal Structure – Energy Absorbing Component Background

- Energy absorbing component development focused on two areas
  - Material – ductility and weight : Carbon Aramid (C/K)
  - Geometry – crush efficiency and directional robustness
- Subfloor geometry designed for modular application, independent from vehicle structure
  - Layout optimization specific to design requirements
    - Space, weight, and occupant-based optimization
- Seat energy absorbers designed using lightweight composite crush tubes
  - Wall geometry optimized to improve crush efficiency
  - Scalable to occupant and impact load requirements

Modular Subfloor Component Design

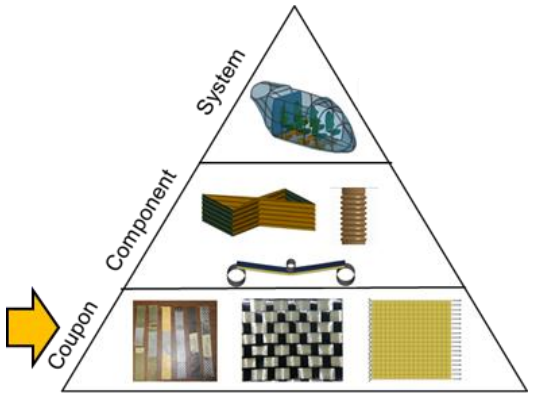


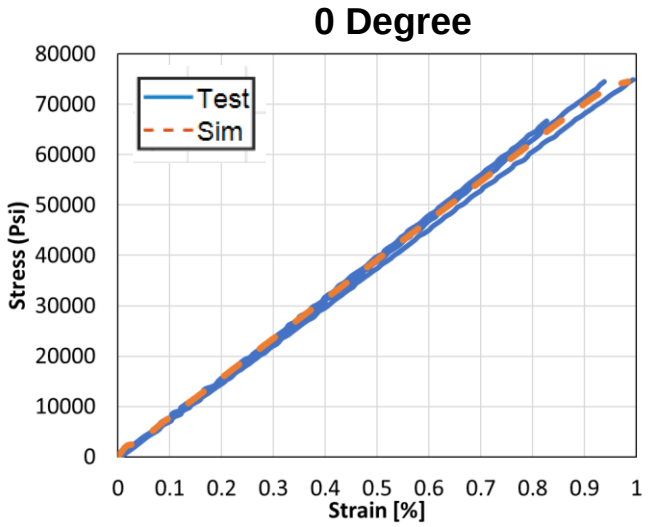
Seat Crush Tube Component Design

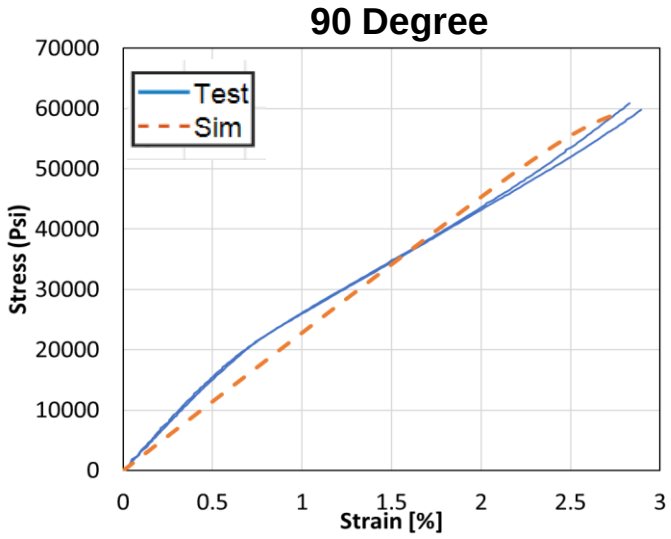


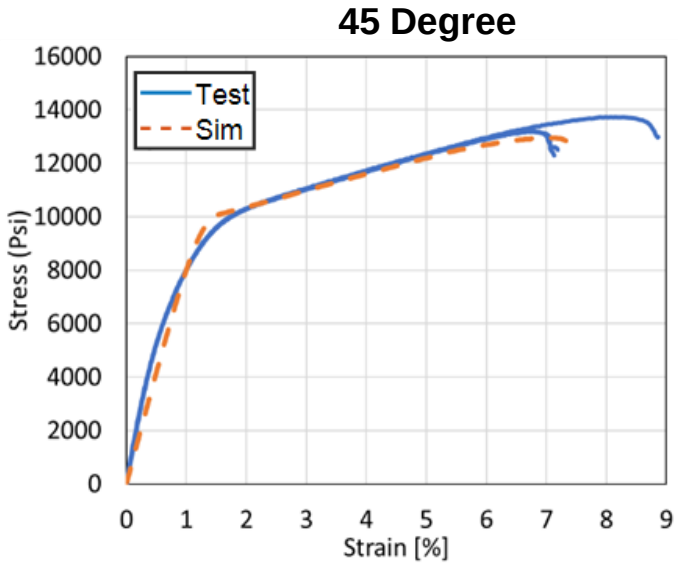
Internal Structure – Material Characterization

- Subfloor and energy absorbing (EA) seat components fabricated from woven (C/K) hybrid composite
  - Extensive coupon and component level characterization conducted previously using C/K fabric
- New resin system used in L+C component fabrication characterized through coupon tests



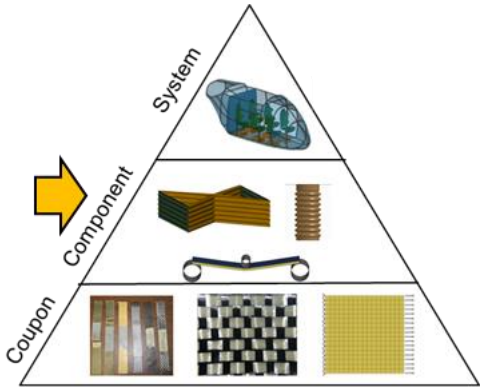




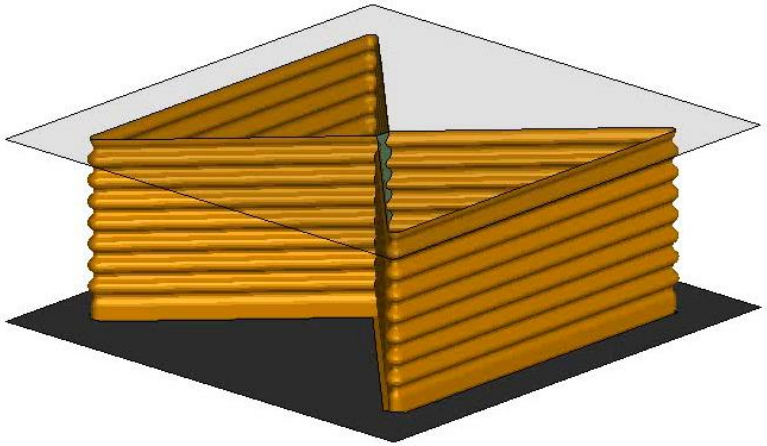


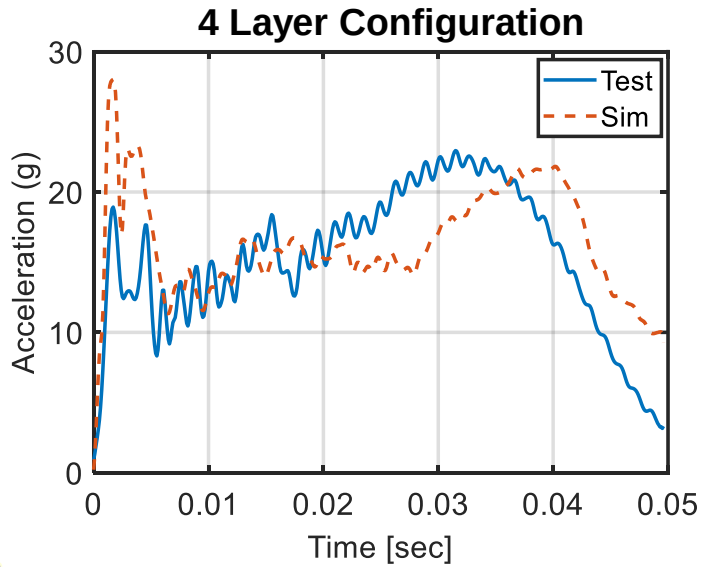
Internal Structure: Subfloor – Component Testing

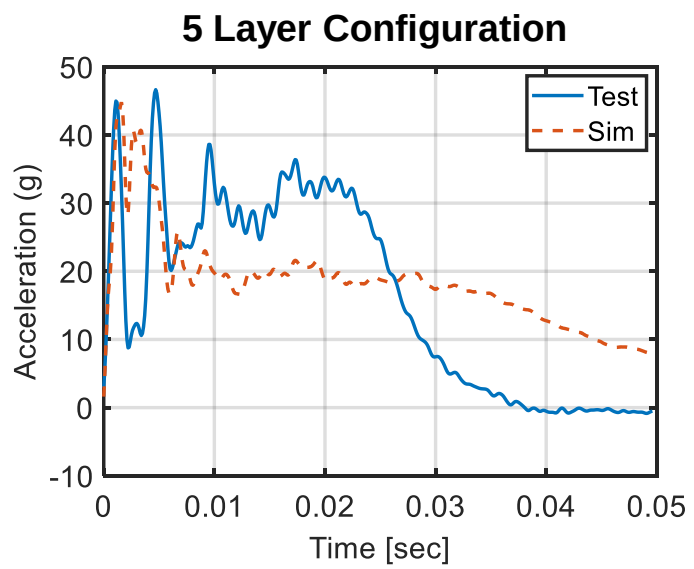
- Subfloor design: Self supported accordion cruciform
  - Proto-type design previously characterized[1]
  - Dynamic impact tests conducted to verify damage response prediction of component FEM



175 lb. mass: 22 ft/s impact



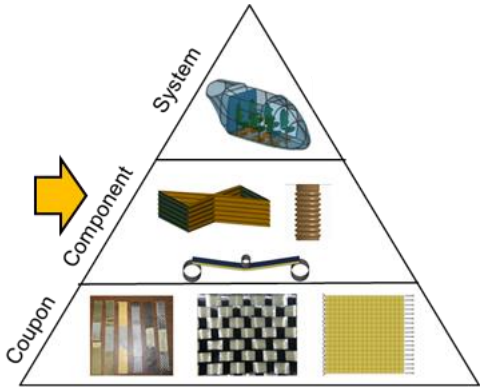




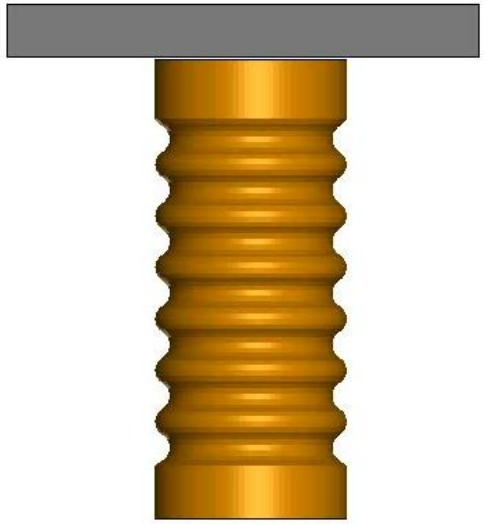
[1]Putnam, J.B. et al. "Development and Analysis of Energy Absorbing Subfloor Concepts to Improve eVTOL Crashworthiness." Proceedings from the Vertical Flight Society 78 Forum. Ft. Worth TX. May 10-12, 2022

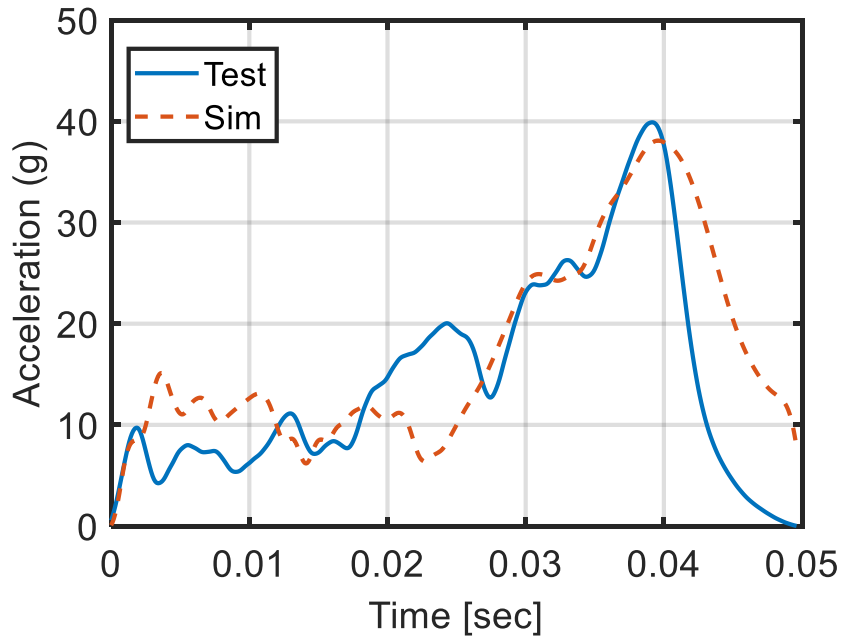
Internal Structure: Crush Tube – Component Testing

- Seat EA mechanism design: Accordion crush tube
  - Proto-type design previously characterized[2]
  - Dynamic impact tests conducted to verify damage response prediction of component FEM



100 lb. mass: 22 ft/s impact

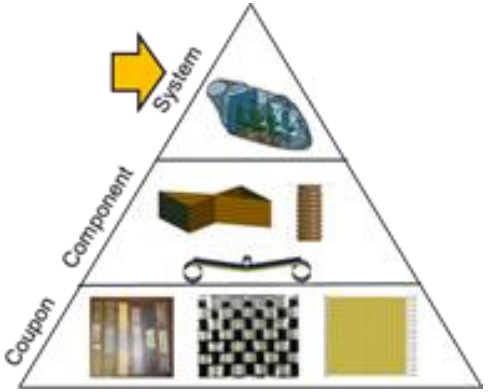




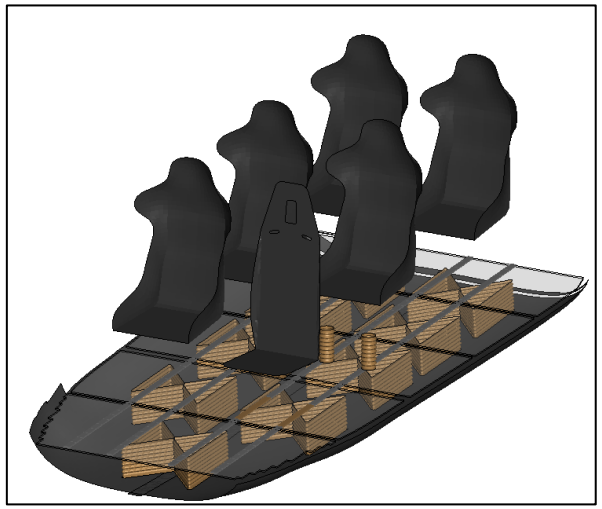
[2]Putnam, J.B. and Littell, J.D. "Crashworthiness of a Lift plus Cruise eVTOL Vehicle Design within Dynamic Loading Environments" Proceedings from the Vertical Flight Society 76 Forum. Virtual. 2020.

Complete L+C Test Article FEM Integration

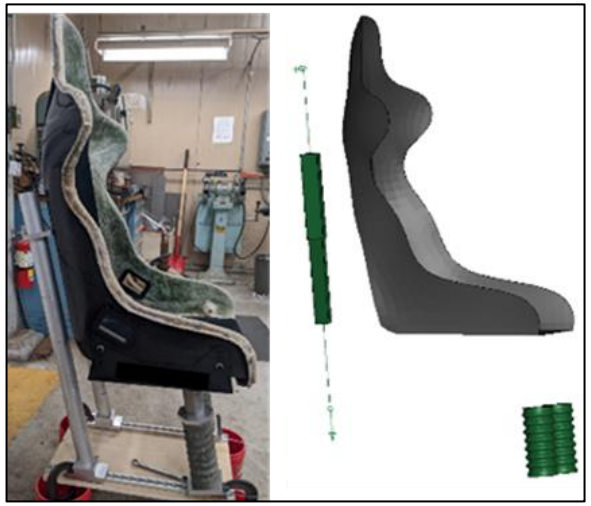
- Subfloor and seat component models integrated into L+C external structure
- Test components added to structure
  - Lifting hardware, fixed mass, instrumentation
- ATDs used in test represented as point masses

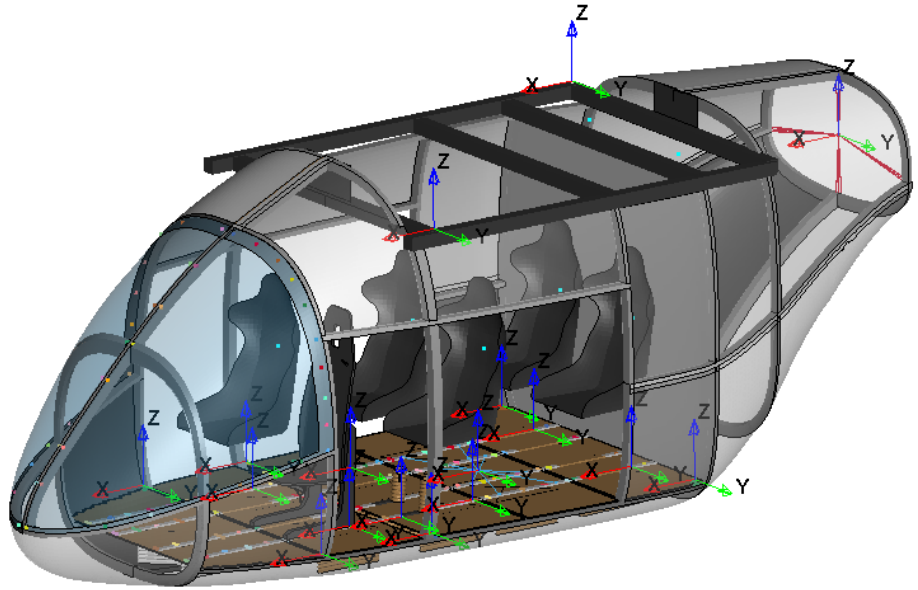


Subfloor/Floor/Seat Setup



NASA EA Seat





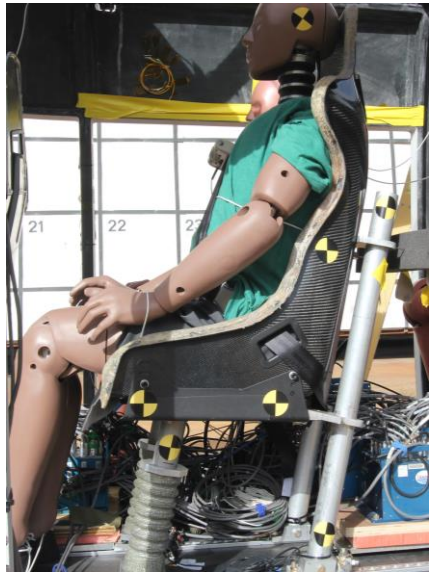
NASA Lift + Cruise As-Built Crash Test Article

- Utilized computational simulation results
- 6 ATDs of various sizes
- 3,450 lb total weight
- 164 data acquisition system (DAS) channels collected
- 10 high speed cameras used
- 4 onboard cameras used
- Port side speckle coated for use in digital image correlation
- 1 NASA developed EA Seat
- 9 NASA fabricated EA Subfloors

NASA Lift + Cruise As-Built Crash Test Article - ATD Layout

- Various size ATDs ranging from a 10 year old (YO) to a 95th percentile male seated in various configurations of seats
  - Mix of Hybrid II (H2) and Hybrid III (H3)
- Front row Commercial seat
- Middle row experiment rigid to EA seat comparison
- Rear row experiment on ATD size

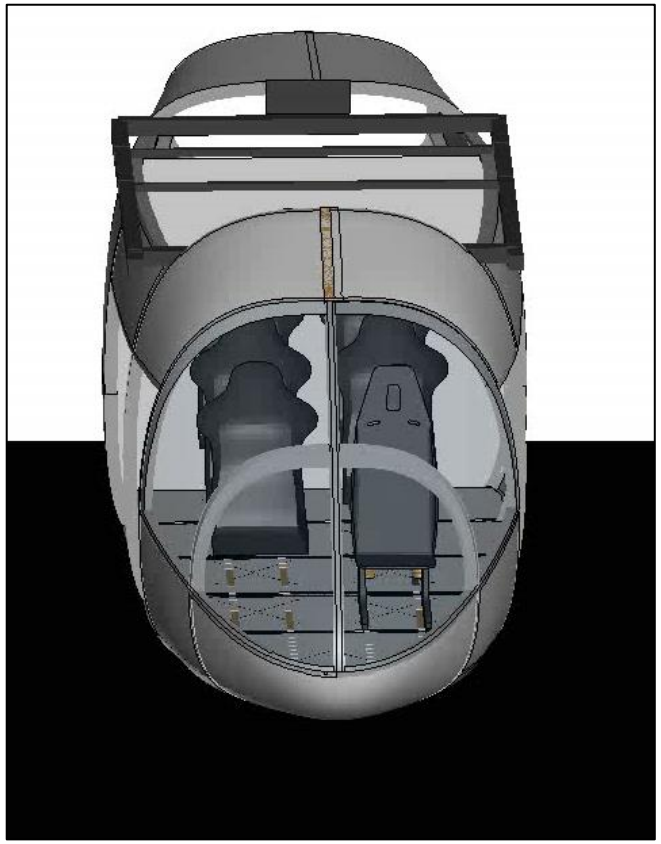
Front Row

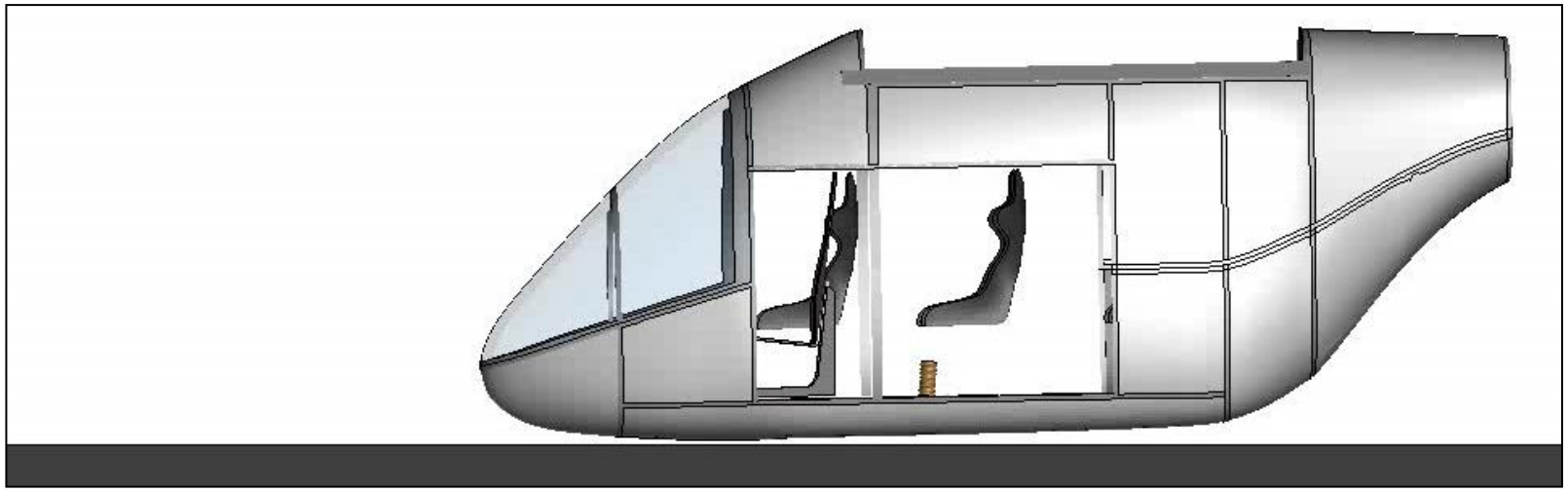


Middle Row – EA seat

Rear Row – ATD Size

Pre-Test Prediction Simulation





Test Video

- Horizontal Velocity = 38.1 ft/s, Vertical Velocity = 31.4 ft/s
- Pitch 0.6 degrees nose down, 2 degrees yaw

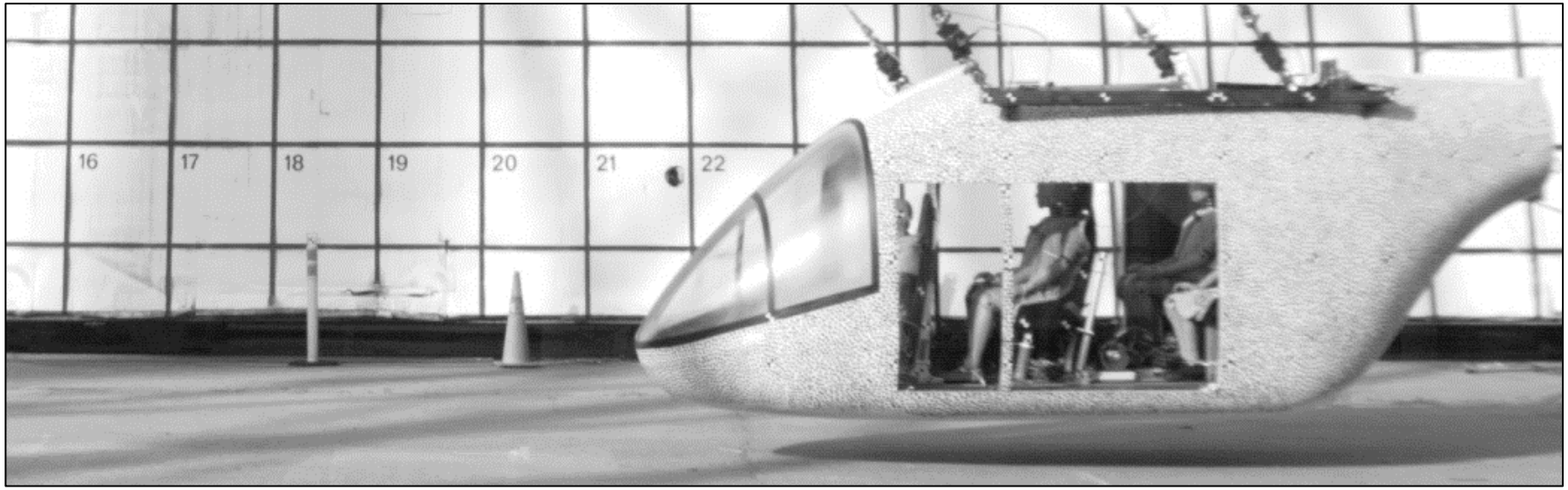
Test Video – t=0 to t + 0.050 s

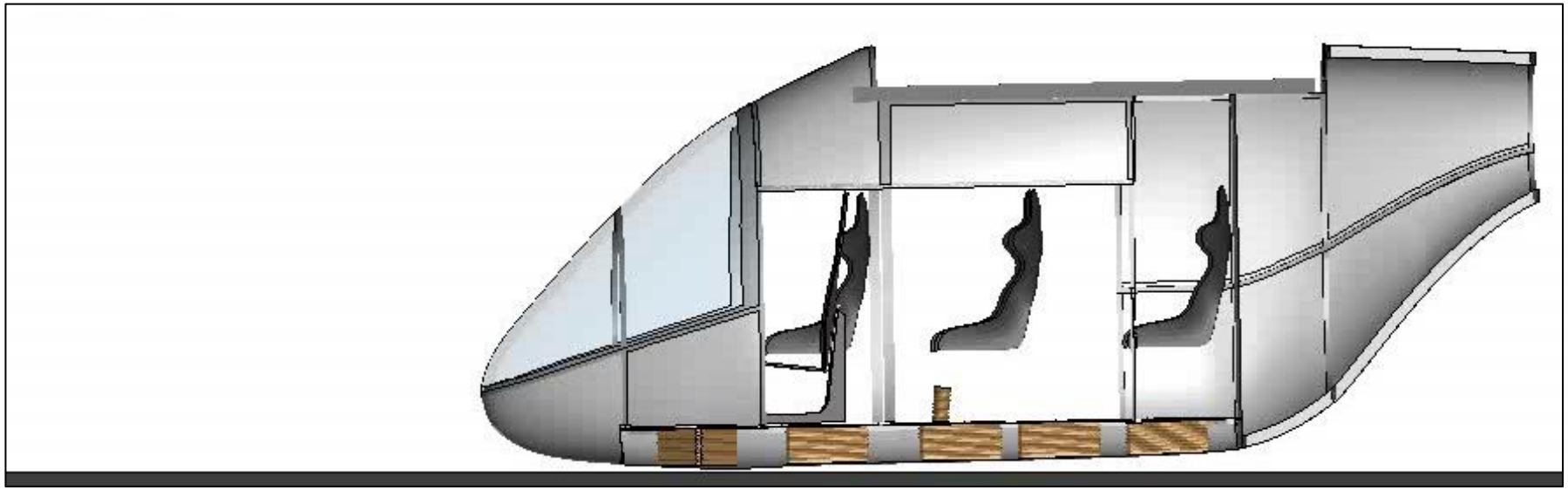
- t=0 to t+0.040-0.050 s - primary time of energy absorbers crushing and start of cabin failures

Test Video – t + 0.050 s to t + 0.200 s

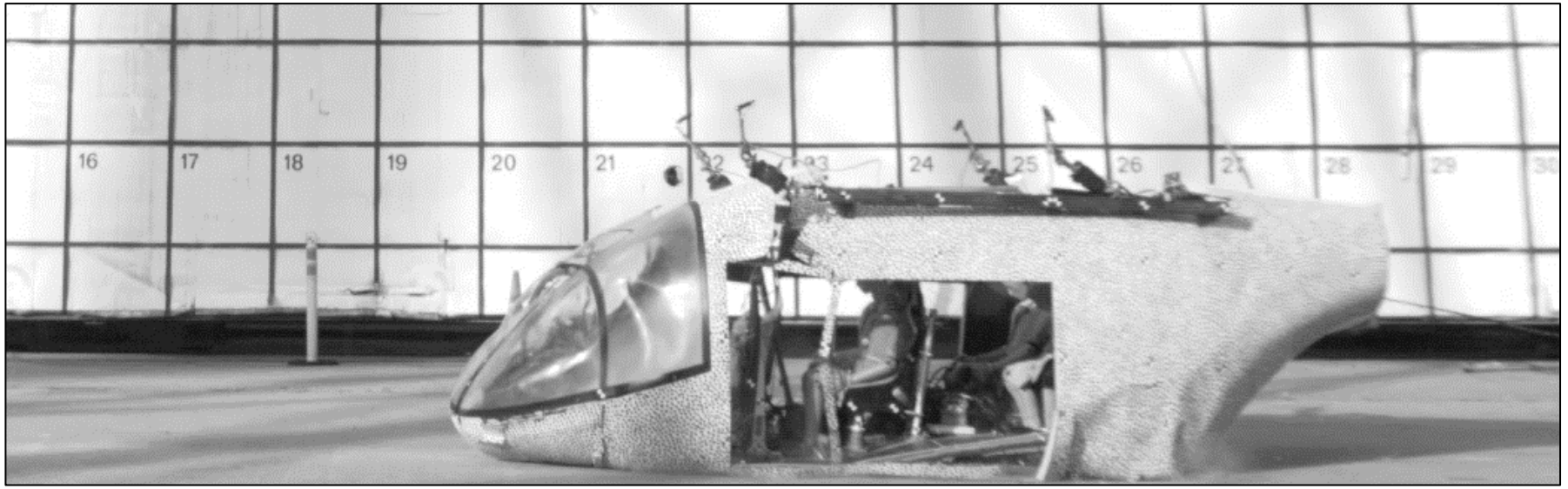
- t+0.050 s to t+0.200 ms – collapse of the overhead structure

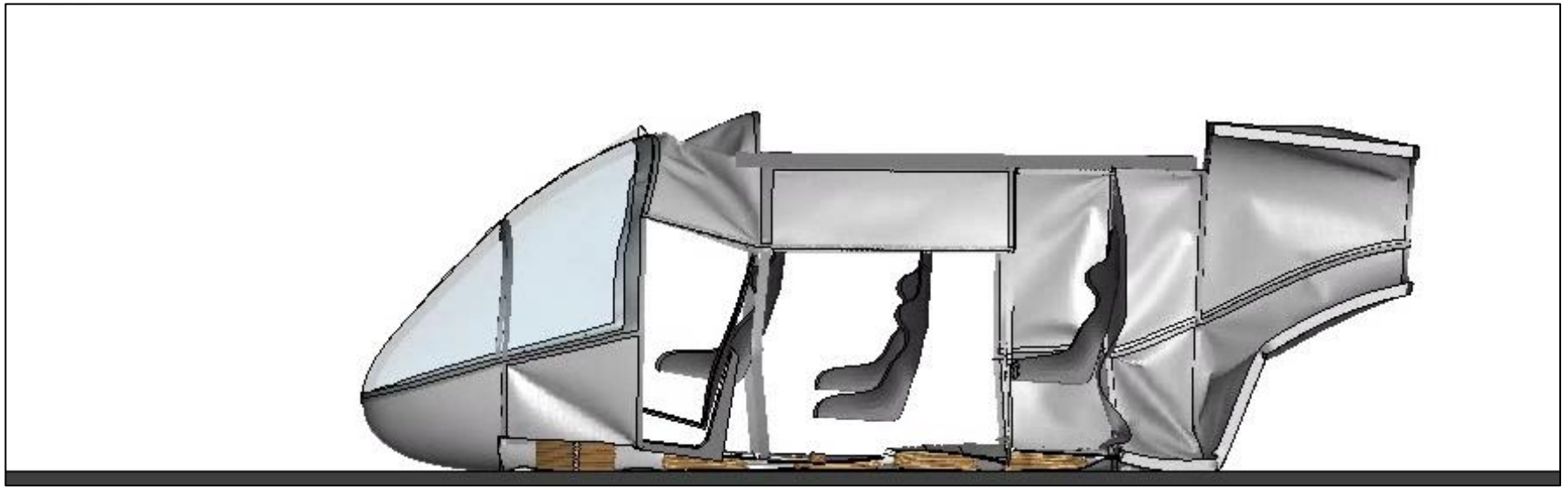
Test vs. Pre-Test Analysis – t=0 to t + 0.050 s
Occupant Compartment Loading vs Structural Failure





Test vs. Pre-Test Analysis – t + 0.050 s to t + 0.200 s
Occupant Compartment Loading vs Structural Failure

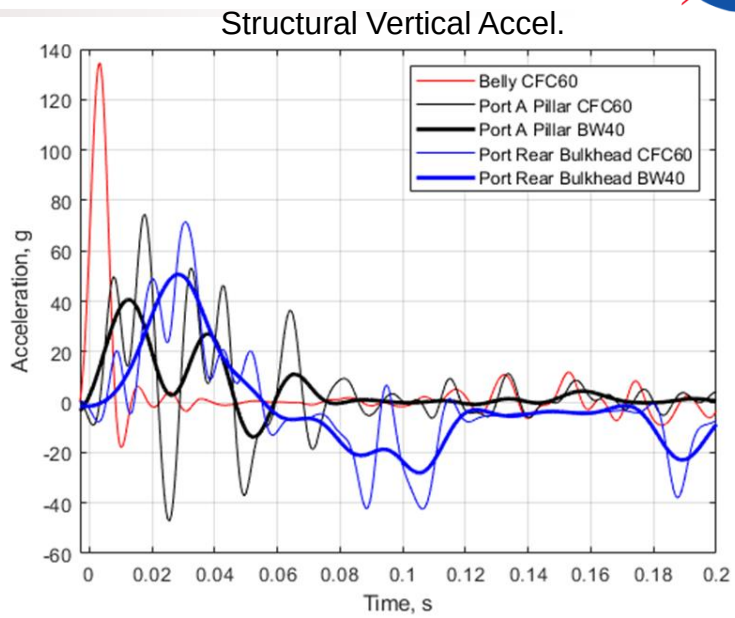


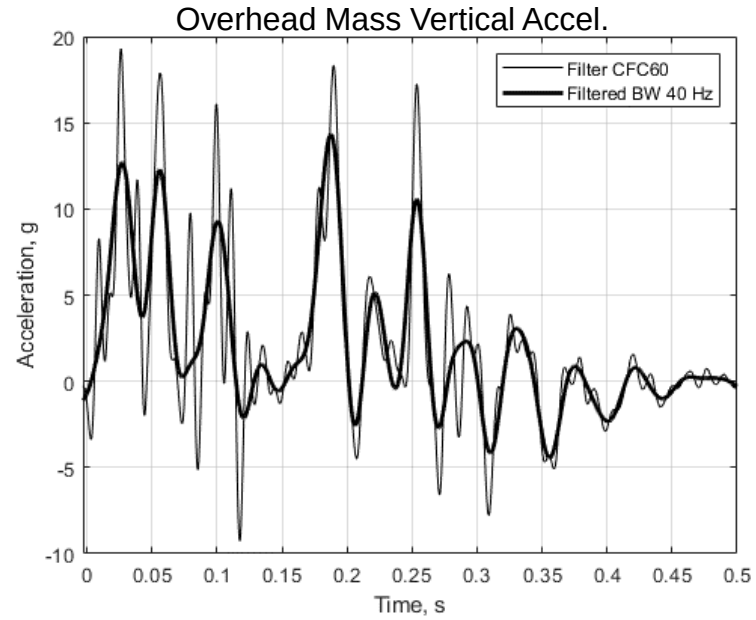


Test Pictures – Top View

Test Data – Structural Accelerations

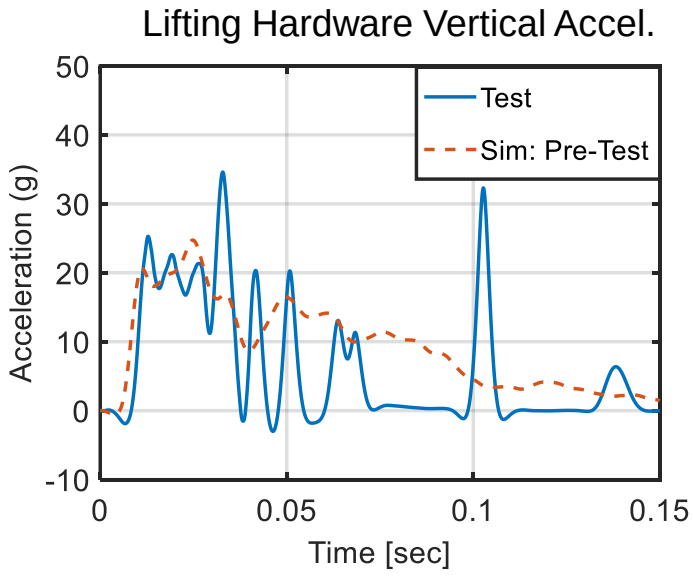
- Belly impact resembles shock loading
- Significant amount of noise in the signal after standard filtering
- Attenuated to 41 g and 51 g for the A Pillar and Rear Bulkhead, respectively using lower 40 Hz lowpass filtering
- Pulse duration between 0.06 s and 0.08 s
- Overhead structure exhibits noisy response which peaks under 20 g if using standard filtering and 12 g if using a lower-pass filter
- Noise is the structure collapsing and the overhead mass sinking into the cabin

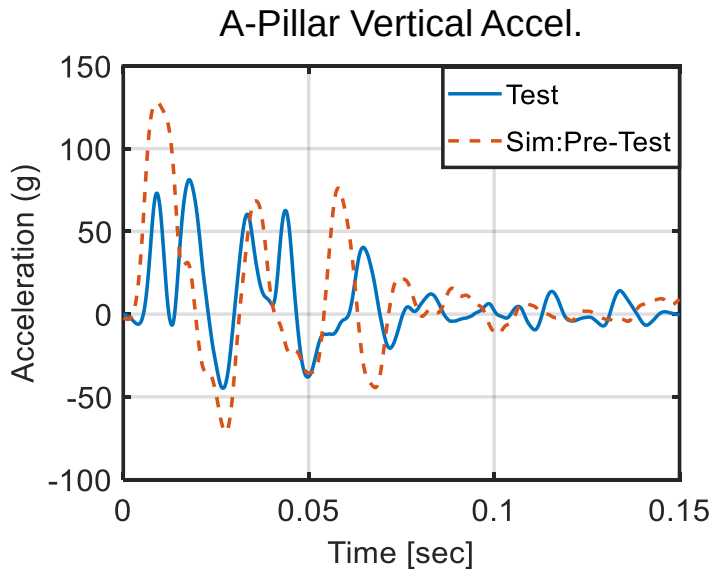


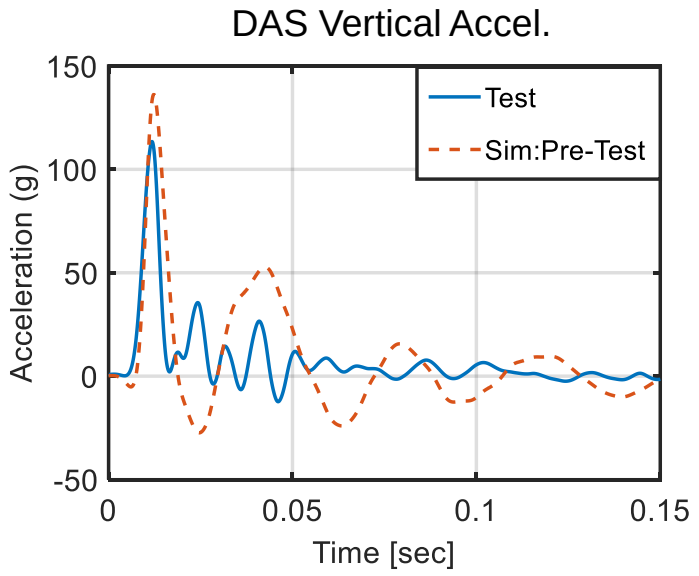


Pre-Test Simulations – Structural Acceleration Predictions

- Although composite structure failure was not captured, the accelerative load measured in structure was generally predicted by the test article FEM
  - Primary acceleration load occurred before composite failure progression







Test Data – Photogrammetry Analysis: Examination of Failures

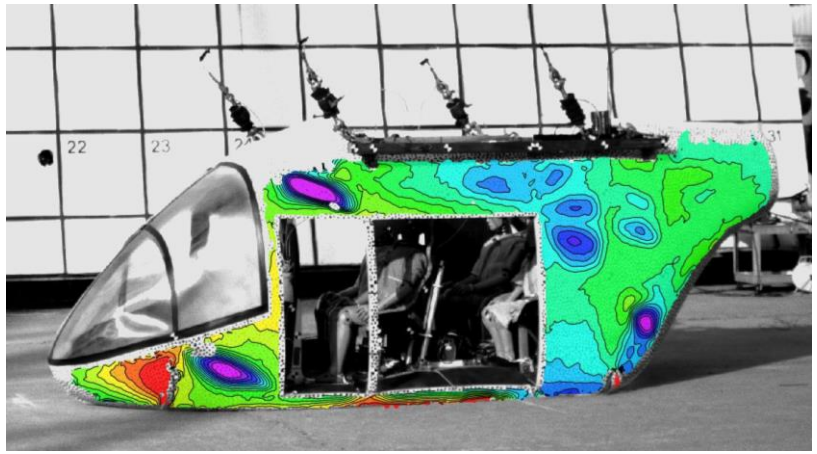
- Plotting Sigma which is pixel deviation from reference.
  - High Sigma values indicate failure locations
- Video goes through the first 0.150 seconds

Test Data – Photogrammetry Analysis: Failures (cont.)

- Plotting vertical deformation to determine items such as cabin intrusion
  - Data shows deformation from reference, which needs to be proceeded to determine the delta between ceiling and floor

t + 0.150 seconds

- Plotting lateral (out of plane) deformation to determine skin buckling and additional failure locations
  - Data will be used for computational modelling

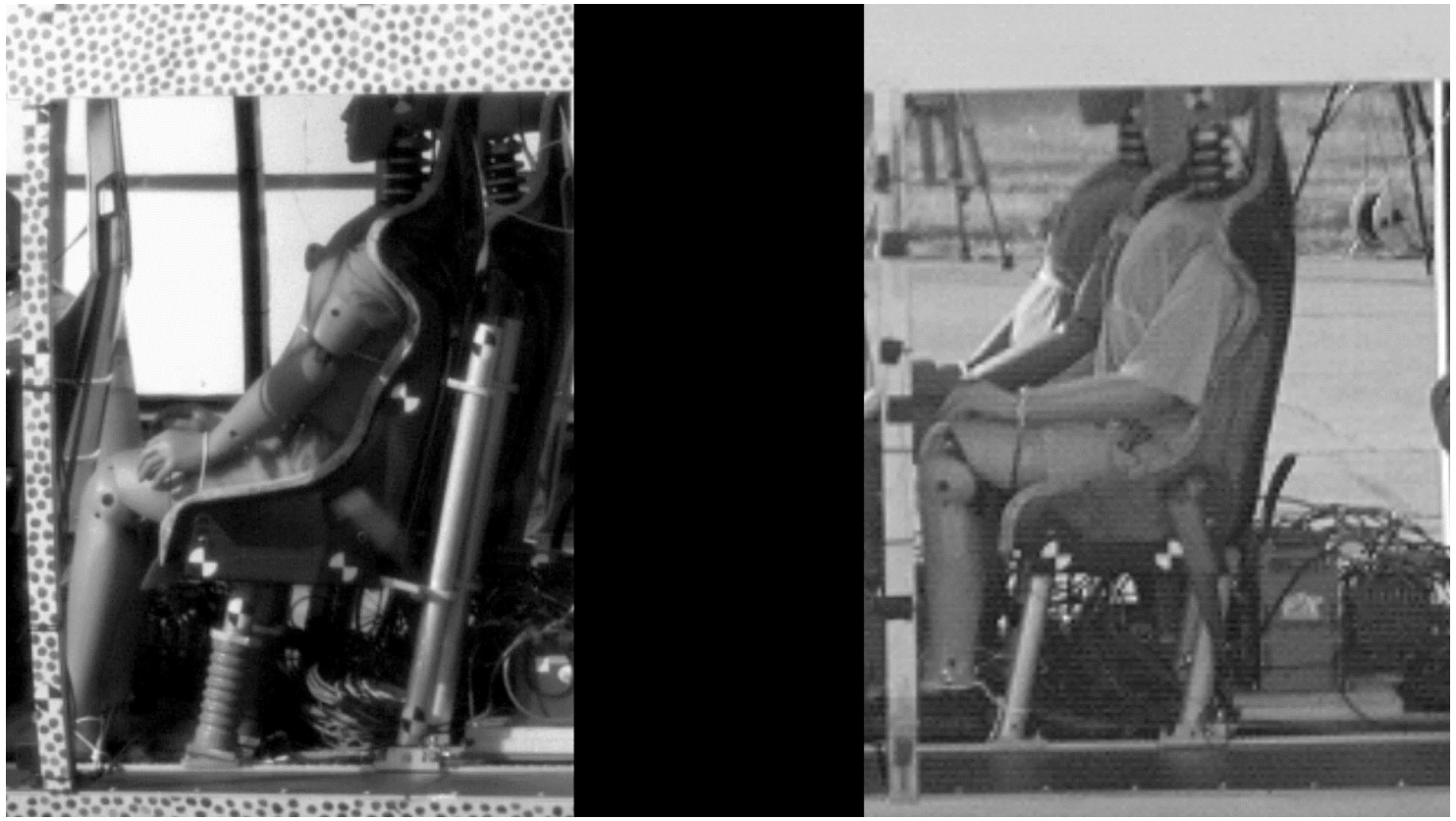


t + 0.020 seconds

Test Data – ATD Lumbar Load Injury Metrics

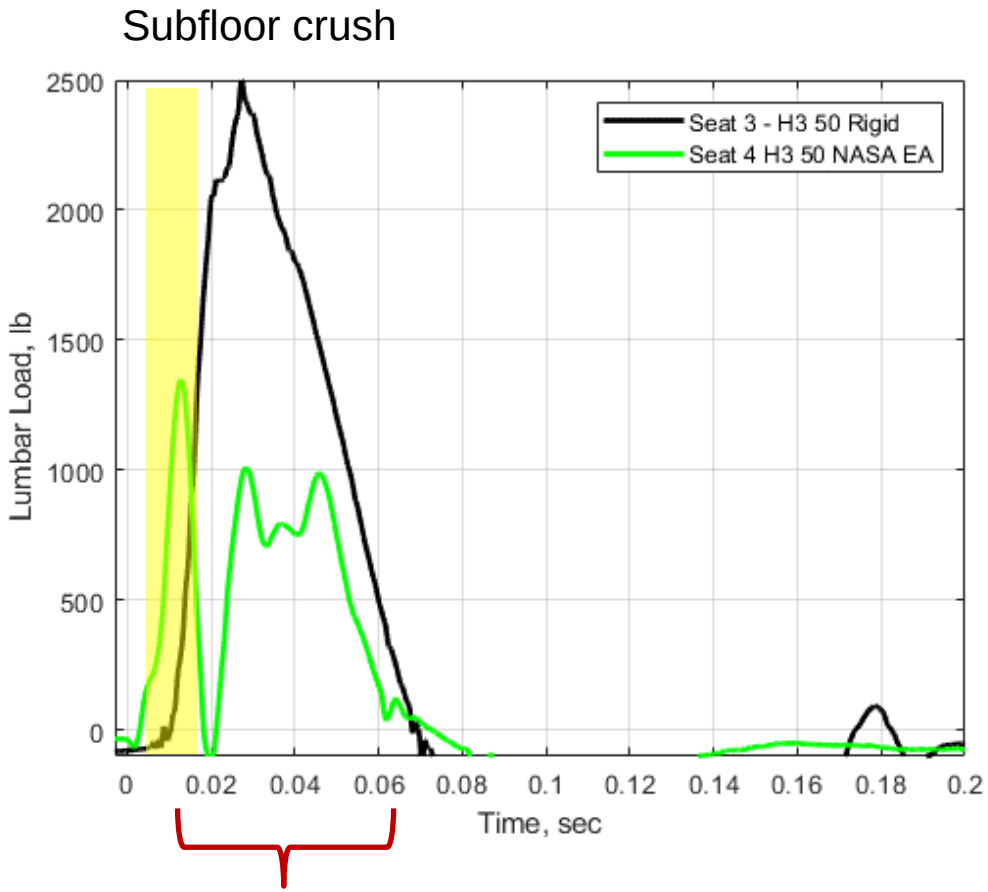
- Lumbar loads both over and under regulatory limits
- EA seats produced lumbar loads below limits
- Rigid seat above limits
- Non-standard ATDs evaluated against Full Spectrum Crashworthiness Criteria
  - 95th limit 1757 lb – 1.1 normalized value
  - 5th limit 933 lb – 2.3 normalized value

Test Data – Middle Row Experiment: EA Seat to Non-EA Seat



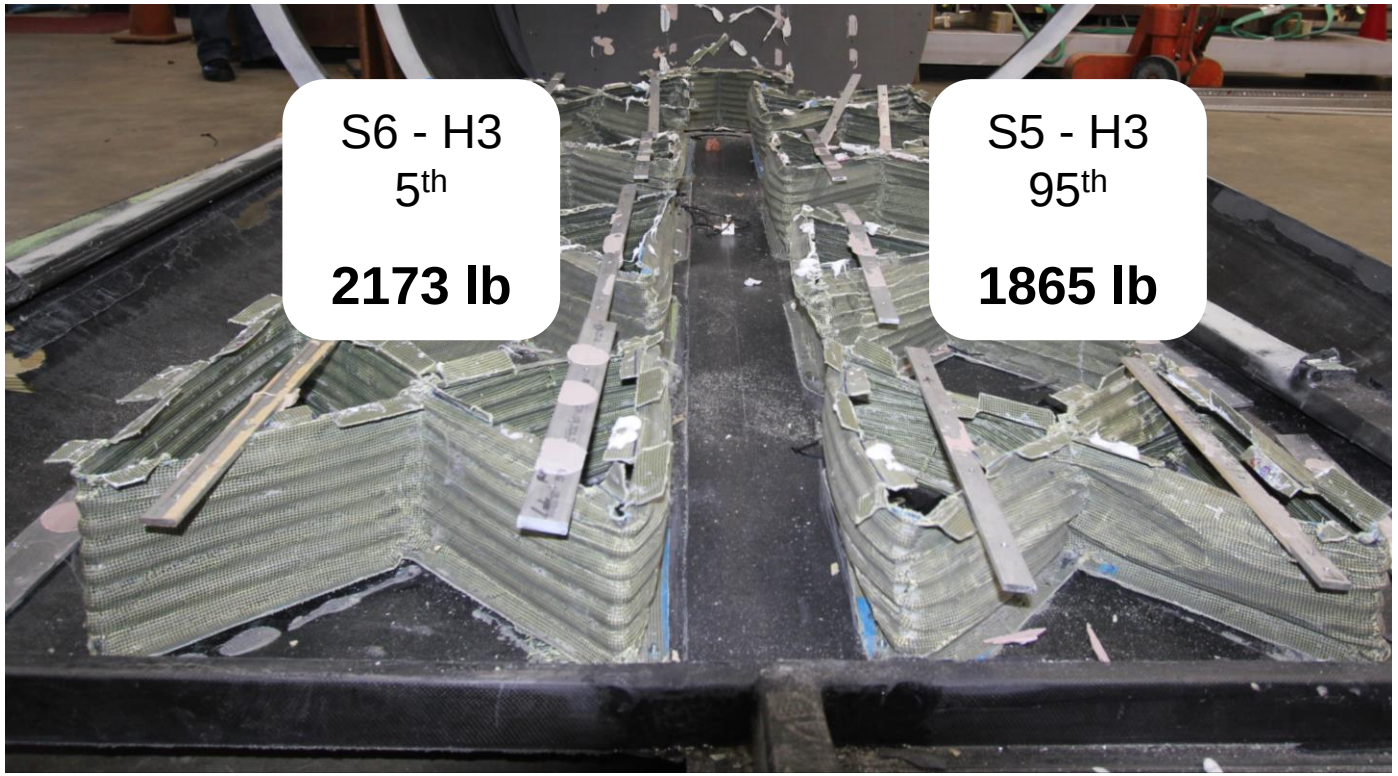
EA Seat

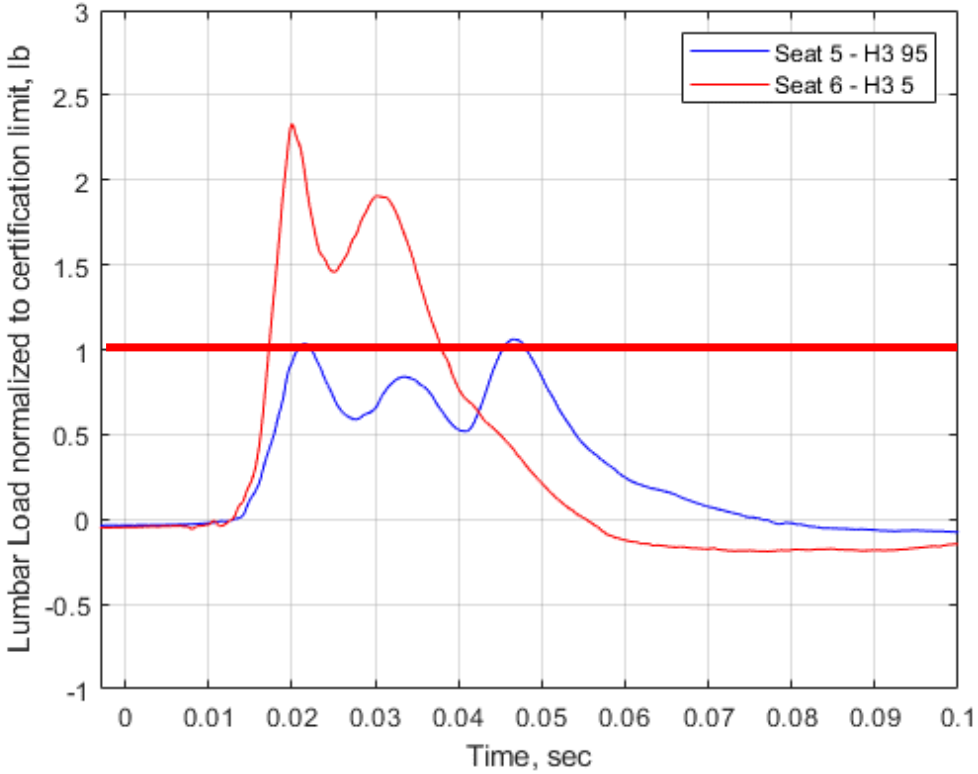
Non-EA Seat



Test Data – Energy Absorbing Subfloor for Non-Standard ATD Sizes

- Examining the subfloors in row 3 of seats, which contained the 5th and 95th percentile ATDs

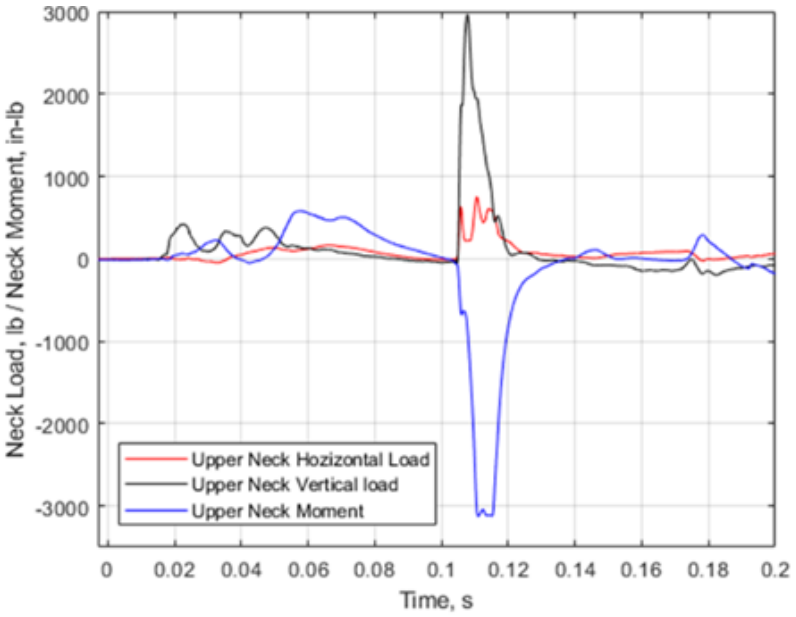




Test Data – Head and Neck Injury Metrics

- All measured locations showed below injury limit values for the Head Injury Criteria (HIC) using a 36 millisecond window
  - Using a limit of 1000
- 95th ATD neck injury criteria (Nij) fell out of family with the others and it is suspected that the overhead mass impacted this ATD head
  - Using a limit of 1

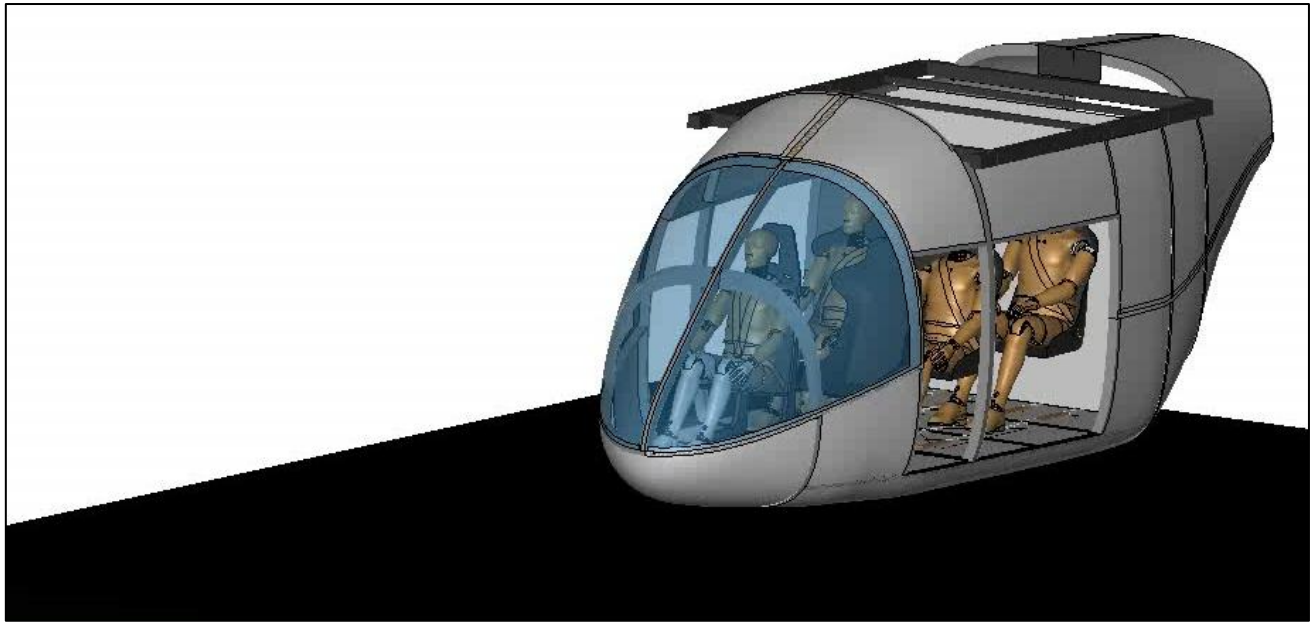
ATD	HIC36 Value	Nij Value
1 – HIII 10 YO - Front Stbd	Not Calculated	Not Calculated
2 – HII 50th - Font Port	Not Available	Not Calculated
3 – FAA HIII 50th - Middle Stbd	140	0.66
4 – FAA HIII 50th - Middle Port	98	0.33
5 – HIII 95th - Rear Stbd	Not Available	3.36
6 – HIII 5th - Rear Port	202	0.73

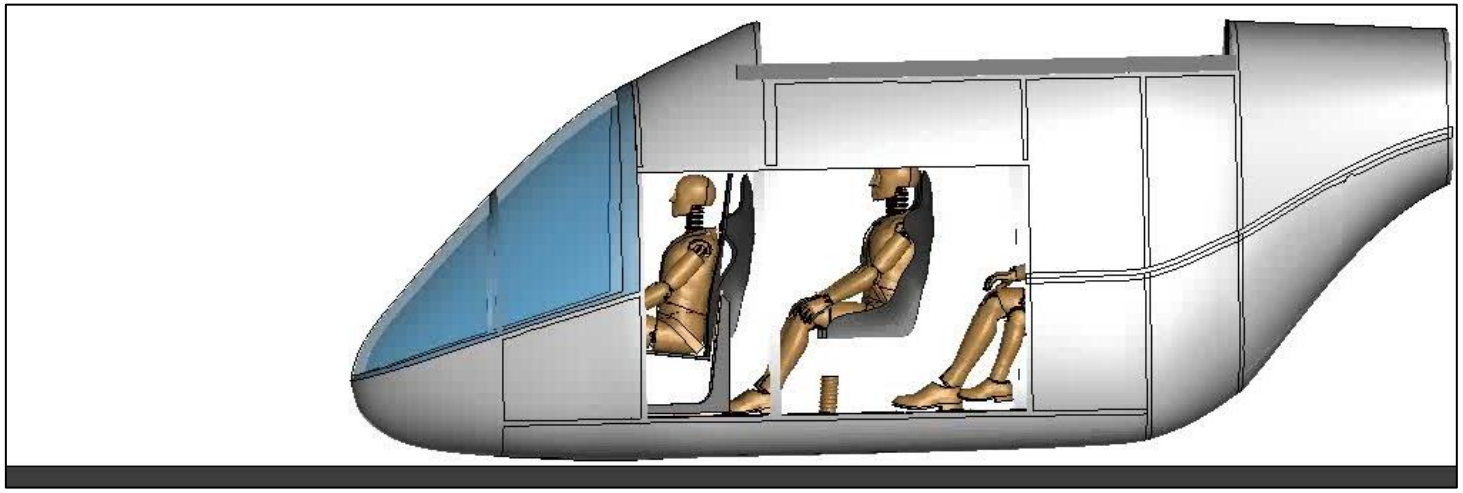


Post-Test Model Calibration

- L+C model was calibrated to improve test correlation
- Tuned parameters which defined damage and failure within the C/C structure material model
  - Element erosion strain limit (ERODS): 0.5 to 0.15
  - Material strength degradation after stress limit (SLIMS): 0.8 to 0.5
- ATD models were included in the vehicle simulation
  - De-coupling of occupant mass from seat found to have effect on accelerations predicted within occupant compartment
  - EA components in seat and subfloor sensitive to timing of seat/occupant mass interaction

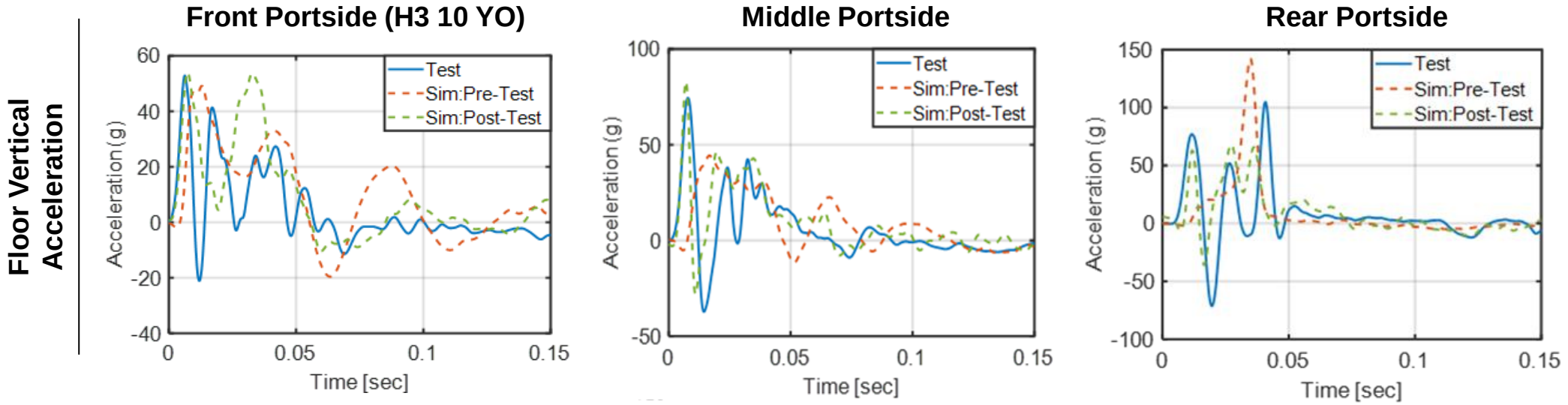
Post-Test Model Simulation





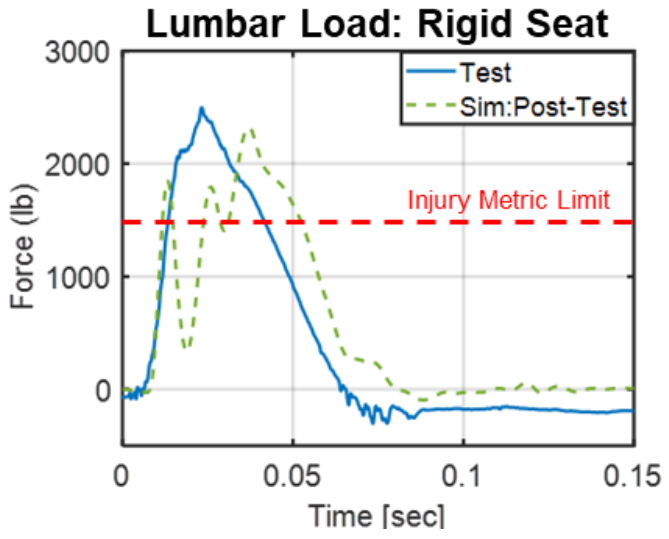
Post-Test Model Simulation – Acceleration Predictions

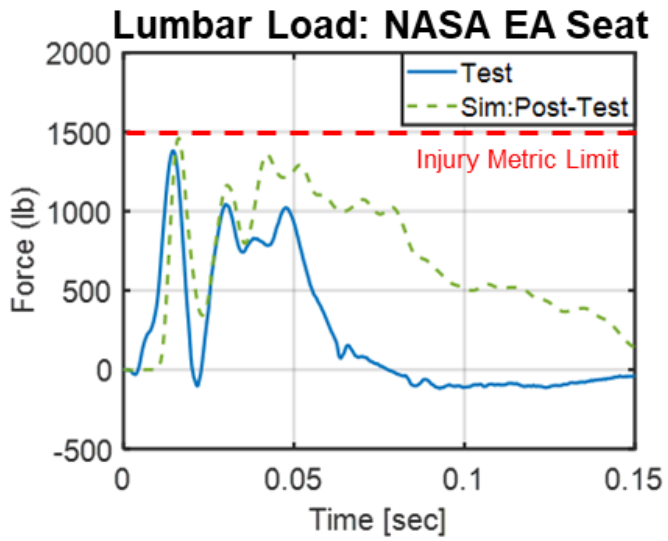
- Prediction of occupant compartment acceleration time history improved with inclusion of ATD models
  - Initial peak acceleration and oscillations in acceleration shape better captured
- Prediction improvement marginal at seat location which retained rigid mass representation of H3 10 YO ATD



Post-Test Simulation – ATD Injury Metric Prediction

- Post-test model simulation accurately identified capability of EA components to reduce occupant injury risk
  - Lumbar load ATD response closely predicted in rigid and NASA EA seat configurations
- Results provide confidence in using model to predict EA mechanism capability for future design optimization



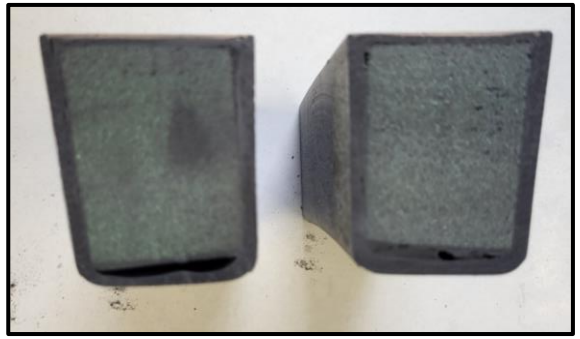


Summary

- Test was conducted to satisfy four objectives
- Test article was primarily designed through the use of computational simulations
  - Sizing
  - Layout
  - Impact conditions
- Test article pre-test predictions matched loading conditions and deformations up until the point of failure
- Test data and further testing was utilized to update pre-test models
- Post-test models matched both deformation and failure
- ATDs in energy absorbing seats below threshold limits

Conclusion and Next Steps

- All four objectives satisfied
- Energy absorbers limited loads in the occupants, however interactions between occupants/seats likely affected response
- ATD injury varied depending on ATD size and seated location
- Second Lift+Cruise test article currently at NASA Langley Research Center. Analyses ongoing to determine test conditions
  - In the process of defining upcoming test conditions
- Verification of tuned L+C model
  - Extensibility of model outside tuned conditions
- Verification of final EA Mechanism design
  - Optimized using tuned L+C model



- Additional testing of components of structural specimens gathered from the L+C test article
- Additional assessment of composite structural response variability between builds

Questions?