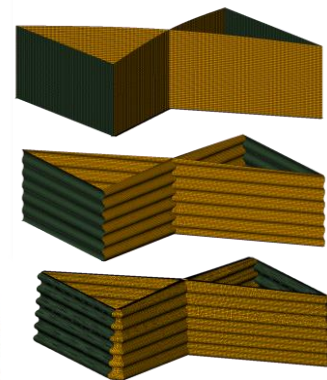
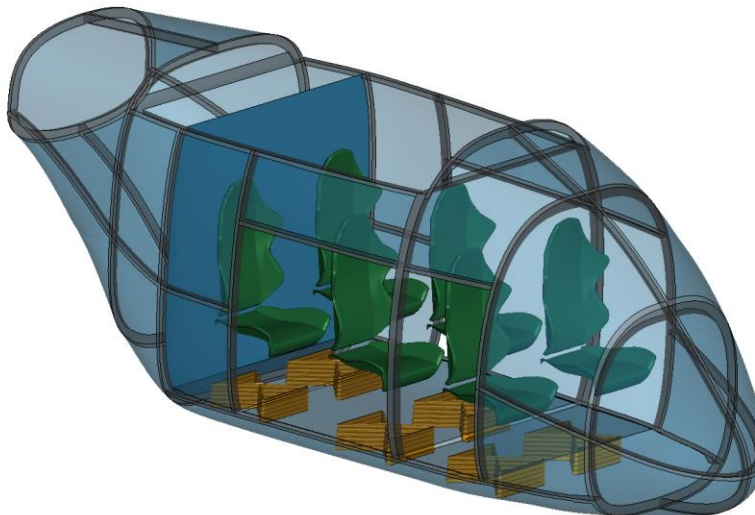




Development of Energy Absorbing Subfloor Concepts to Improve Crashworthiness of eVTOL Aircraft

VFS 78th Annual Forum
Fort Worth, TX,
May 10, 2022

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NASA Langley Research Center



Urban Air Mobility and Demand for eVTOL Technology



- Urban Air Mobility (UAM) emerging market for transport through urban airspace
- Made possible through advancements in electric Vertical Takeoff and Landing Technology (eVTOL)
 - Quieter than traditional helicopter engine/turbine
 - Distributed lift (turbines) allows for improved public safety
 - Reduced footprint/weight requires less infrastructure



<https://nari.arc.nasa.gov/crashworthiness>

<https://www.aurora.aero/pav-evtol-passenger-air-vehicle/>



<https://www.velocopter.com/en/>



<https://yahana.aero>



Occupant Safety Risk Reduction



Emergence of new UAM market allows unique opportunity to influence design paradigms and improve occupant safety

- **Crash Mitigation**

- Crash Avoidance (Autonomy will reduce but difficult to eliminate)
- Ballistic Parachutes (Limited effectiveness under 300 ft)

- **Occupant Protective Design**

- Designs to absorb impact energy within the vehicle structure rather than passing it directly through to the occupant
- Common Design Mechanisms including:
 - Energy Absorbing Materials
 - **Energy Absorbing Subfloor**
 - Energy Absorbing Seats
 - Energy Absorbing Landing Gear
 - Internal Airbags
 - Energy Absorbing Deployables

NASA Historic Subfloor Development Research



- Research into energy absorbing development focused on two areas
 - Material – ductile and lightweight
 - Geometry – high crush efficiency and directionally robust
- Previous research efforts led to development of “Conusoid” subfloor beam (US patent # 9,616,988)
 - Carbon/Kevlar shaped into interlocking conical shape
 - Retrofit into CH-46 helicopter
 - 50% weight savings over aluminum

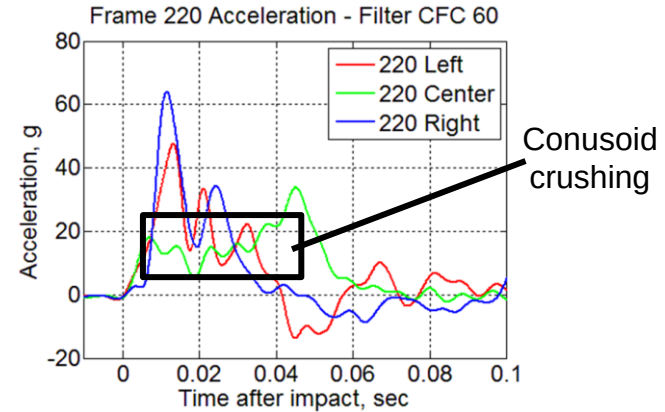


NASA Historic Subfloor Development Research



- “Conusoid” subfloor beam exhibited excellent capability in vertical fuselage drop
 - Reduction of peak acceleration in floor section above subfloor component
 - Smooth crush response
 - Significant weight reduction
- Capability limited in combined horizontal-vertical impact condition
 - Geometric failure under off-axis loading

Iterate upon the lessons learned from “Conusoid” subfloor testing to develop energy absorbing (EA) subfloor concepts specific to eVTOL needs



Study Goal



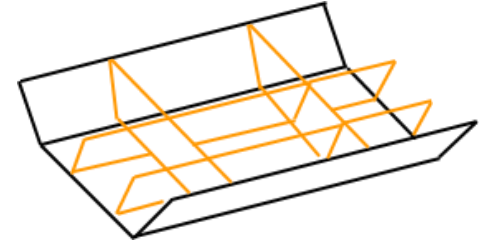
- 1) Develop energy absorbing subfloor concepts which are applicable to eVTOL vehicle requirements
 - a) Lightweight and modular
 - b) Robust to complex loading environment
- 2) Evaluate design concepts within representative eVTOL crash environments

Subfloor Design – Self Supported Energy Absorbing Structure

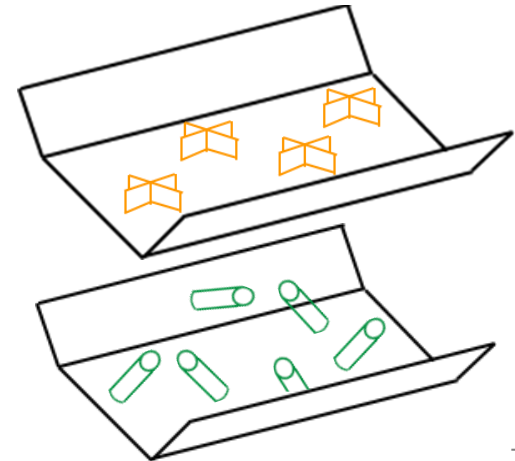


- Traditional subfloor design
 - Repeating beam-bulkhead lattice
 - Fixed within standard airframe geometry
 - Fills subfloor space
- Modular subfloor design (study goal)
 - Capability independent from vehicle structure
 - Applicable to unique subfloor geometry
 - Layout optimized specific to design requirements
 - Space + weight optimization
 - Energy absorbing optimization

Traditional “lattice” subfloor



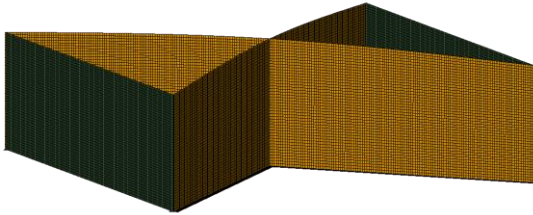
Modular subfloor components



Modular Subfloor Component Designs Generated



Baseline



Configuration: Cruciform

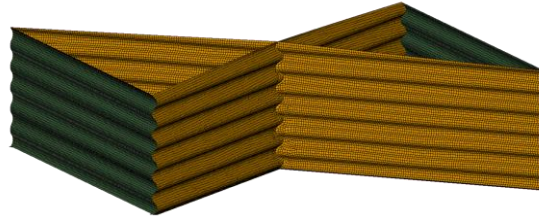
Panel Section: Flat w/ top curvature

Material: 4 layers Carbon/Kevlar (C/K) (0.0125 in) @ 45°

Dimensions: 24 in x 24 in x5 in

Weight: 1.3 lb

Single Accordion (SA)



Configuration: Cruciform

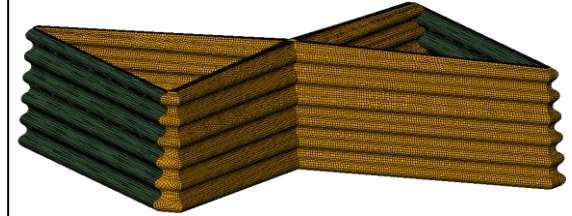
Panel Section: Single corrugated sheet

Material: 4 layers C/K (0.0125 in) @ 45°

Dimensions: 24 in x 24 in x5 in

Weight: 1.4 lb

Double Accordion (DA)



Configuration: Cruciform

Panel Section: Double corrugated sheets w/ hollow interior

Material: 4 layers C/K (0.0125 in) @ 45°

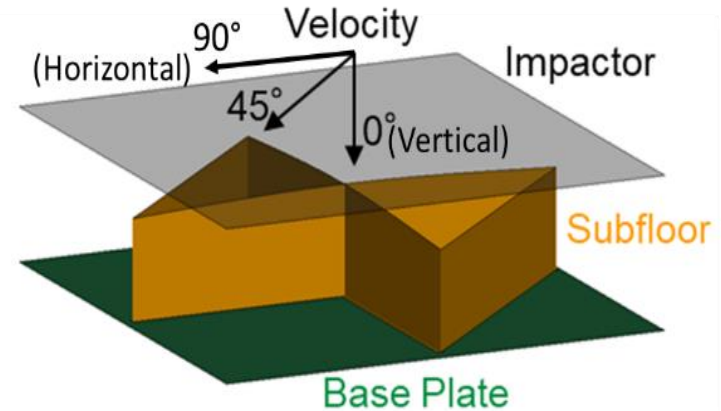
Dimensions: 24 in x24 in x5 in

Weight: 2.9 lb

Design Sensitivity Analysis



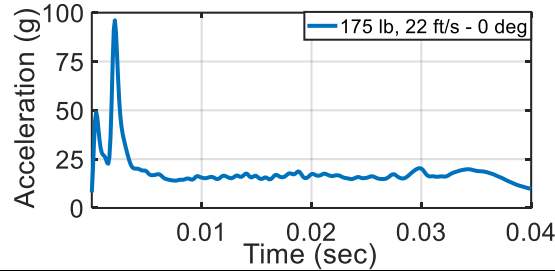
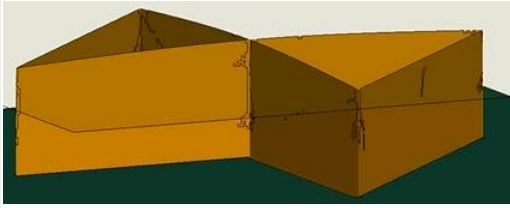
- Component designs simulated under simple impactor test condition
- Sensitivity of subfloor components to impact direction, energy, and composite layup evaluated
 - Impact directions: Vertical (0°), combined (45°)
 - Impactor mass: 125 lb, 175 lb, 225 lb
 - Impact velocity: 15 ft/s, 22 ft/s, 25 ft/s
 - Composite layup: 3-6 layers



Design Sensitivity Analysis – Vertical Impact Results

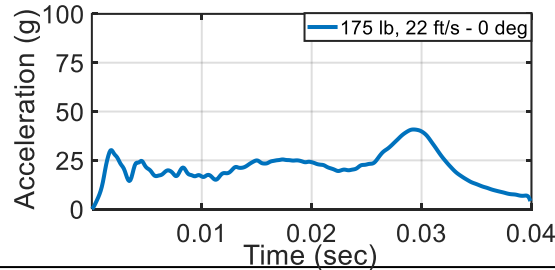
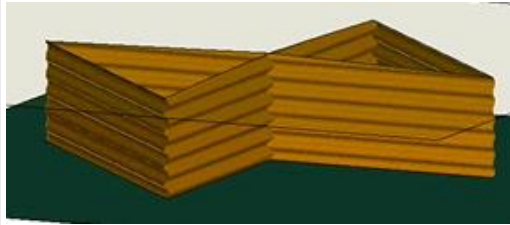


Baseline



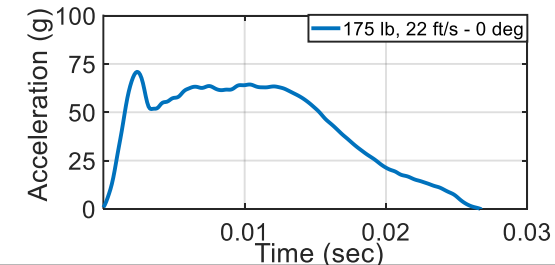
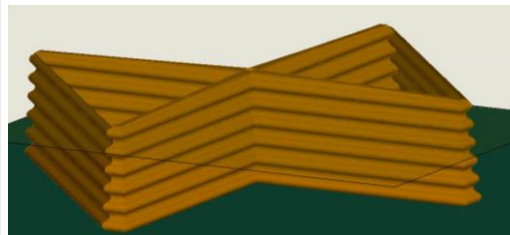
- Stiff initial loading response
- Minimal EA post crush initiation
- Energy absorption through wall tearing and folding

SA



- Smooth initial energy absorption response
- Component bottoms out at end of impact
- Energy absorption through wall crushing and folding

DA

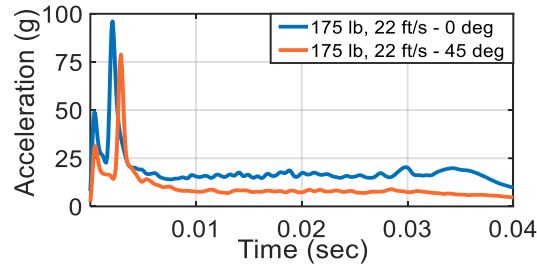
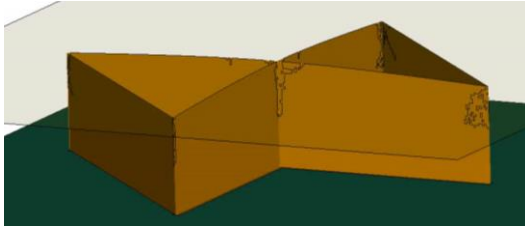


- Smooth energy absorption response throughout impact
- ~25% of crush area utilized
- Energy absorption through wall crushing

Design Sensitivity Analysis – Combined Impact Results

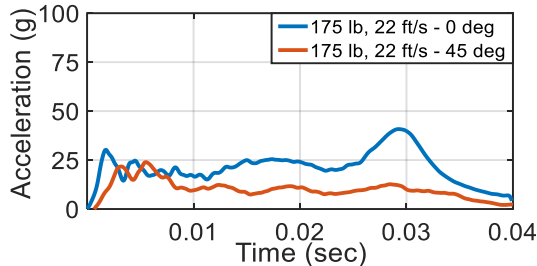
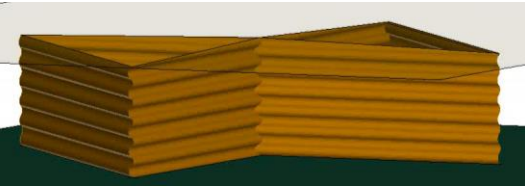


Baseline



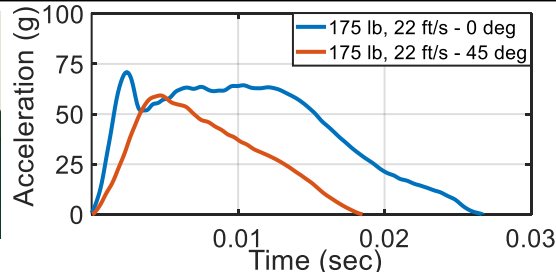
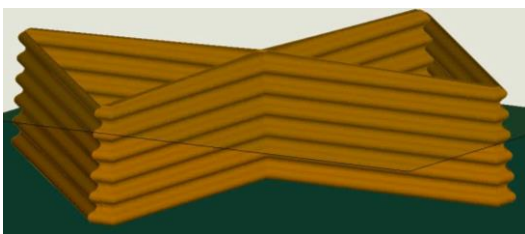
- No significant change with additional horizontal loading component
- Stiff initial loading response
- Minimal EA effectiveness

SA



- Smooth initial energy absorption response
- Horizontal loading increased wall tearing
- Reduced vertical loading prevented resulted in not bottoming out

DA

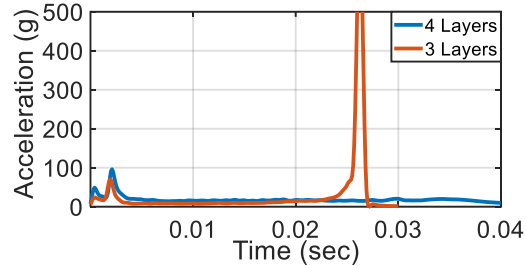
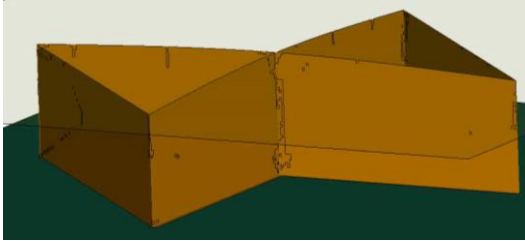


- Horizontal loading had no effect on crush response
- Very little crush with reduced vertical energy

Design Sensitivity Analysis – Layup Results

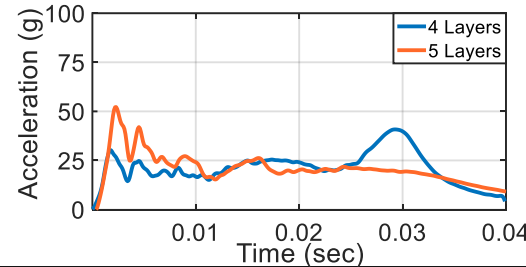
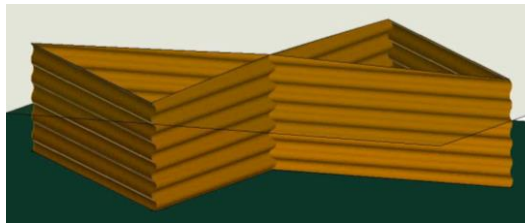


Baseline



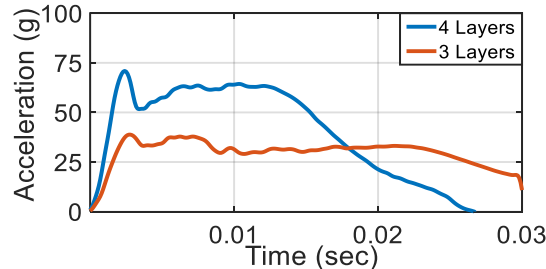
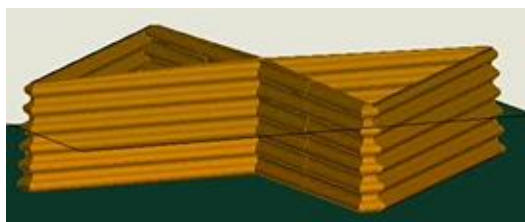
- High crush initiation force traded for high compaction force
- EA capability limited by geometry

SA



- Increase in crush initiation balanced with total compaction force
- Potential to optimize EA capability through material and geometry

DA



- Reduced composite layers reduced steady crush response
- Ideal EA geometry
- Response tunable to input energy through material

Subscale Testing – Baseline Subfloor



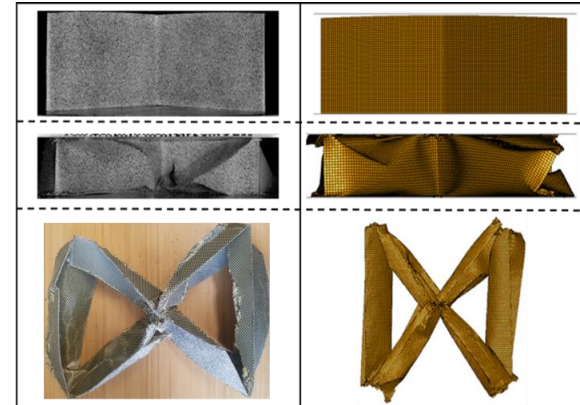
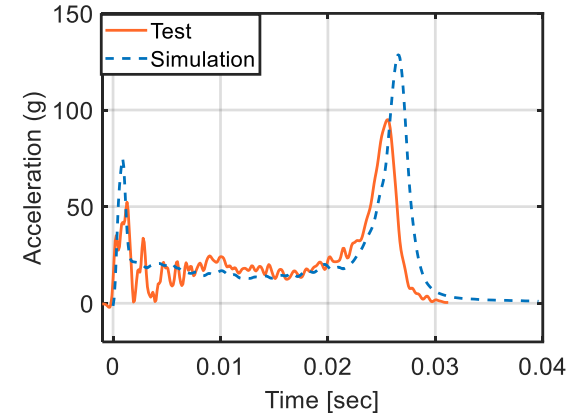
- Drop tower testing performed on baseline subfloor design
 - Subscale subfloor geometry: 10 in x10 in x4 in
 - Impactor: 110 lb
 - Velocity: 22 ft/s
- Goal: Evaluate predictive accuracy of finite element model (FEM)
- Testing planned for all subfloor geometries



Baseline Subfloor Subscale Testing – Correlation Results



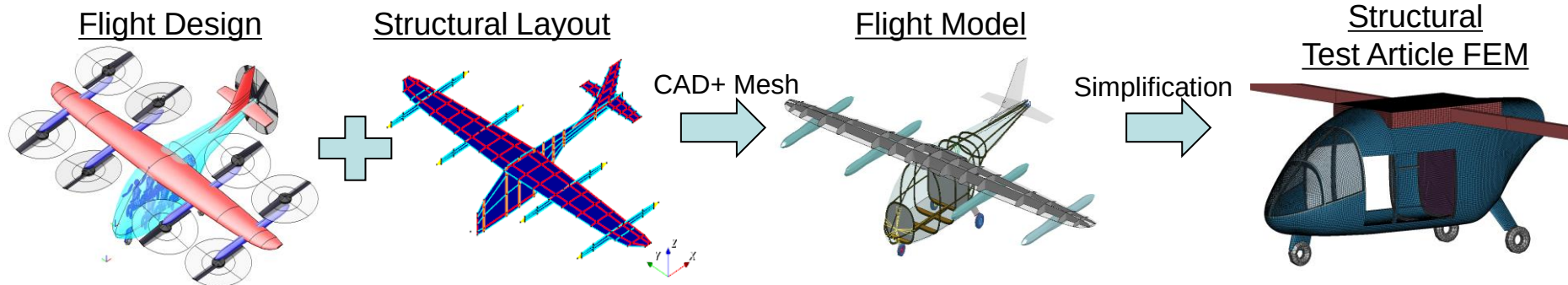
- Crush characteristics of baseline design similar to model predictions
 - High crush initiation force
 - Minimal EA during crush
 - High compaction force
- Bowtie compaction geometry
 - Sheet folding
- Simulation overpredicts peak acceleration
 - Additional contact environment calibration needed



Development of eVTOL Reference Vehicle Model – NASA L+C



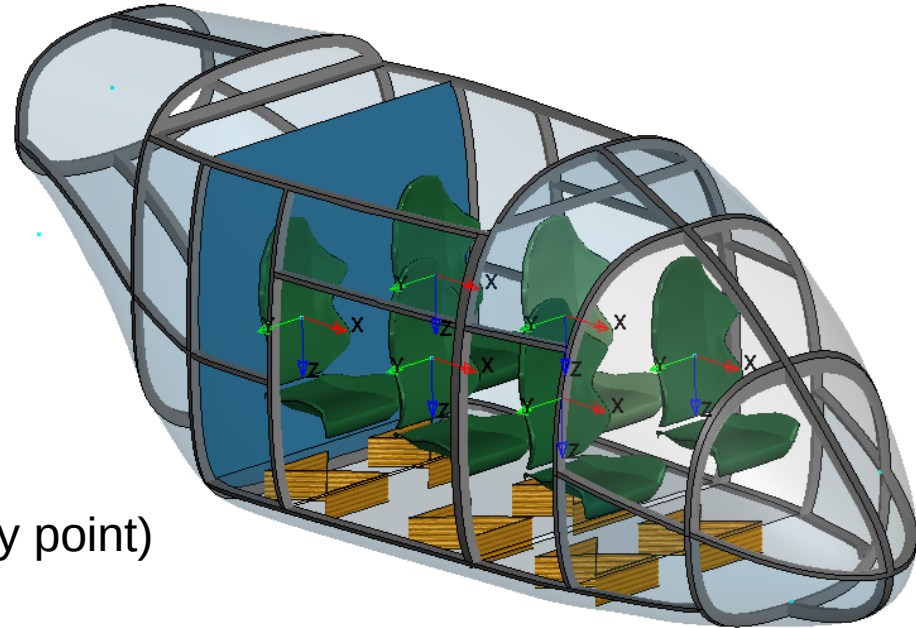
- NASA Lift + Cruise (L+C) eVTOL reference design vehicle used to study crashworthiness concepts
- Design reduced to structural airframe
 - Wingbox replaced with beam structure
 - Tail section shortened
 - Non-structural components replaced with point mass elements
- Frames, ribs, and bulkhead components modeled based on structural layout
- Outer mold line and structural components modeled as C/C material
- Meshed using ~1 in x 1 in quadrilateral shell elements



Vehicle FEM Subfloor / Interior Integration



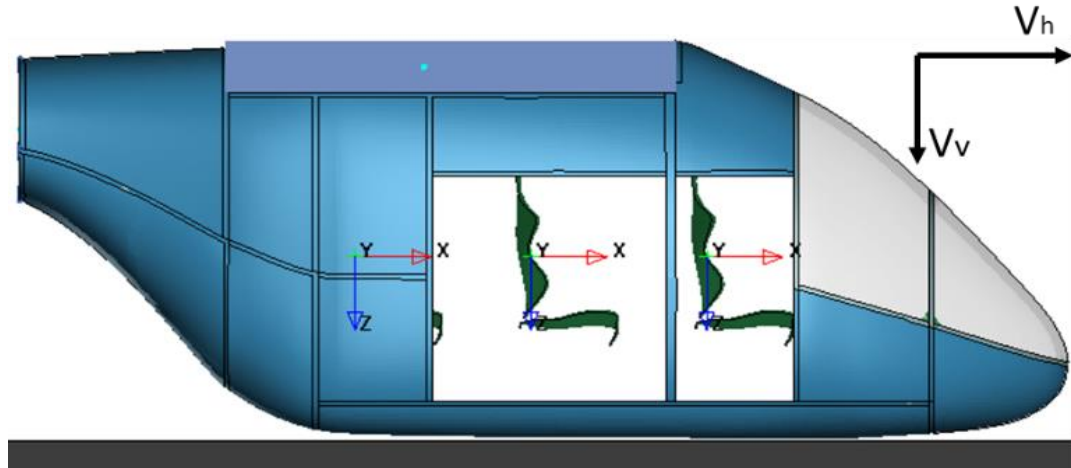
- Three vehicle configurations generated
 - Baseline: 6 layers C/K @ 45°
 - SA: 6 layers C/K @ 45°
 - DA: 3 layers C/K @ 45°
- Subfloor component integrated into vehicle structure
 - One subfloor under each seat
 - Tied contact between vehicle bottom skin and subfloor component
- Accelerations recorded at seat (Brinkley point)
 - Used to compare EA effectiveness



Vehicle Impact Conditions Simulated



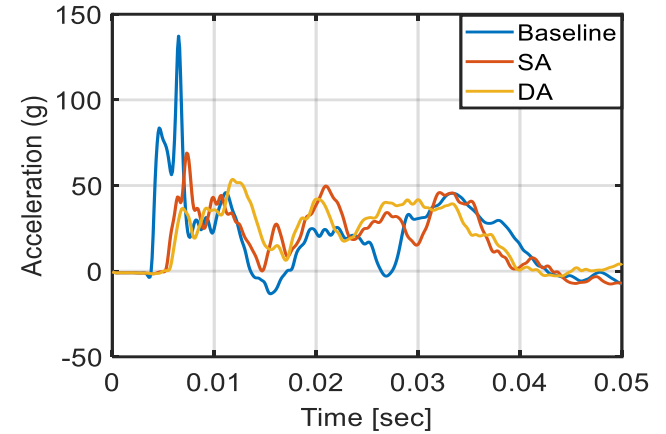
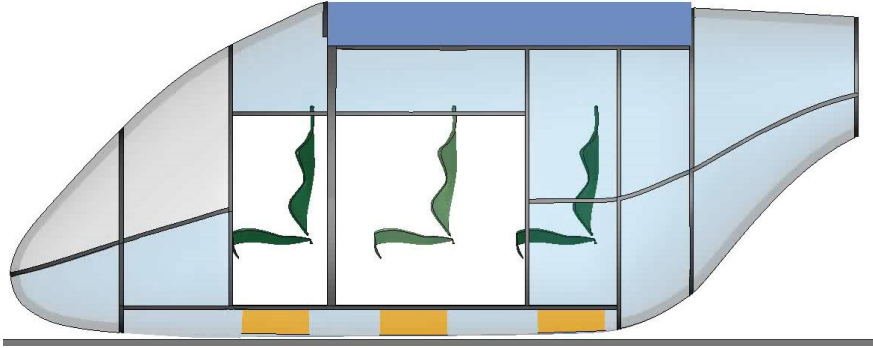
- Vehicle impact onto a concrete surface simulated
- Two crash orientations simulated to apply equal vertical load over increased impact complexity
- Vertical Impact
 - $V_n = 26 \text{ ft/s}$
 - $V_t = 0 \text{ ft/s}$
- Combined Impact
 - $V_n = 26 \text{ ft/s}$
 - $V_t = 42 \text{ ft/s}$



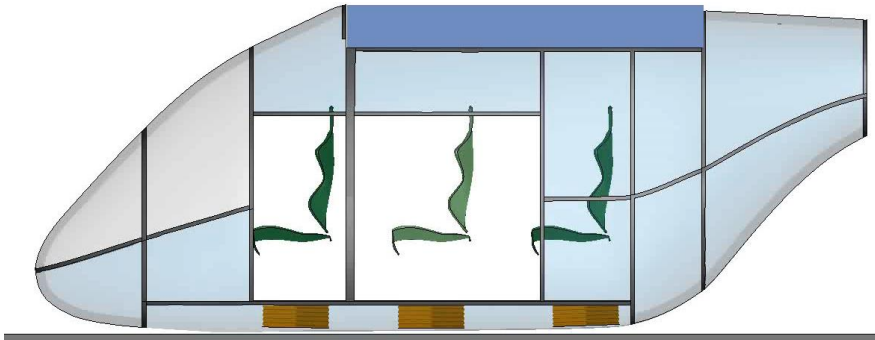
Vertical Impact Simulation - Results



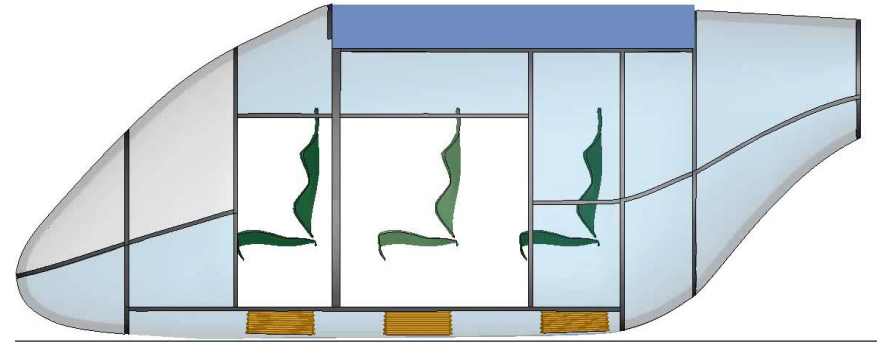
Baseline



Single Accordion (SA)



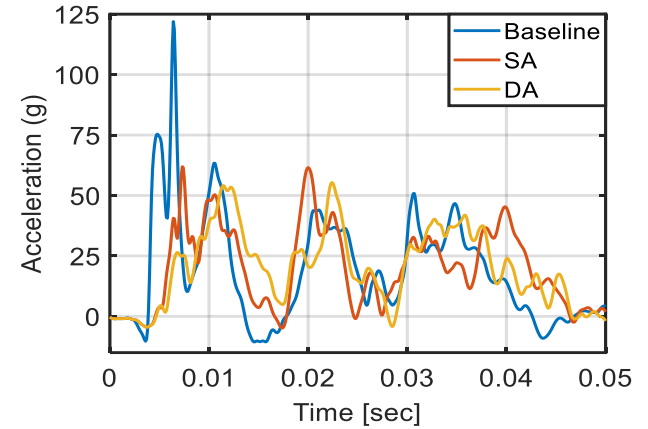
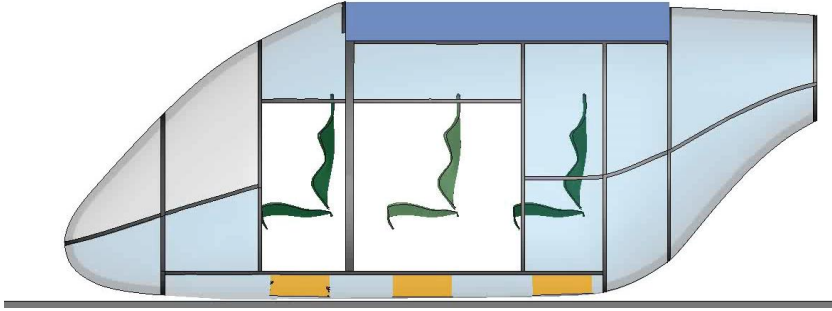
Double Accordion (DA)



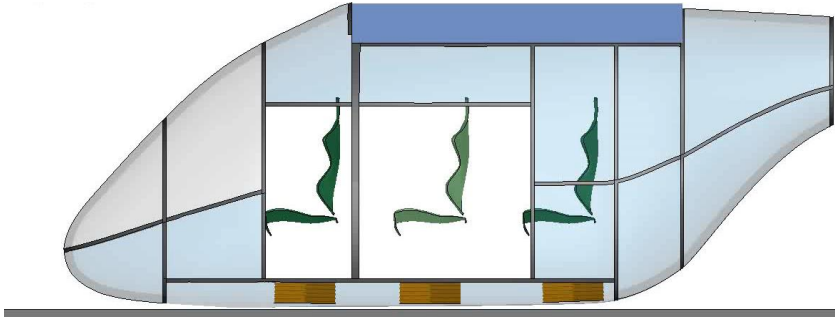
Combined Impact Simulation - Results



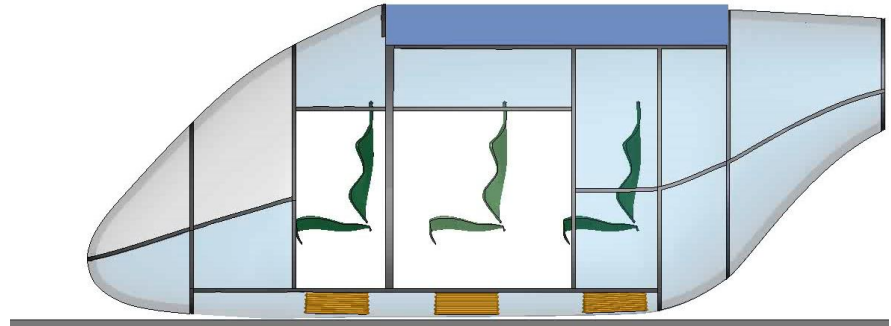
Baseline



Single Accordion (SA)



Double Accordion (DA)



Conclusions



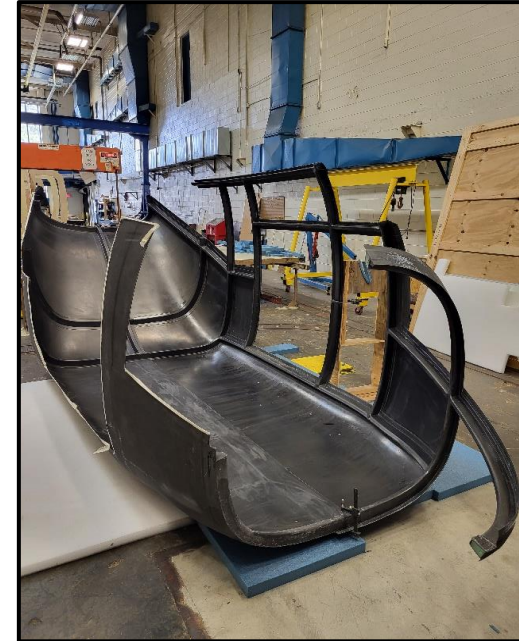
- Self supported cruciform geometry exhibited robust response to multi-axis loading
 - Similar crush response across impact energy and direction variations within subfloor designs
- Preliminary component testing indicated accurate prediction of subfloor crush characteristics
 - Additional testing ongoing to validate response of all geometries
- Baseline geometry demonstrated poor EA response (sheet folding)
 - Wall geometry important in EA capability
- SA geometry demonstrated effective EA response
 - Response tunable through composite material layup
- DA geometry demonstrated ideal EA response
 - Limitation in ease of fabrication

Upcoming work



- Full-scale test of NASA L+C test article
 - Quantify structural response of eVTOL representative composite fuselage in dynamic loading environment
 - Validate response of developed EA component designs (cruciform subfloor, crush tubes)
 - Compare seat/occupant configurations
- Notional impact condition:
 - Concrete surface
 - 26 ft/s vertical
 - 42 ft/s horizontal

L+C Test Article Fabrication





Questions?

Jacob Putnam

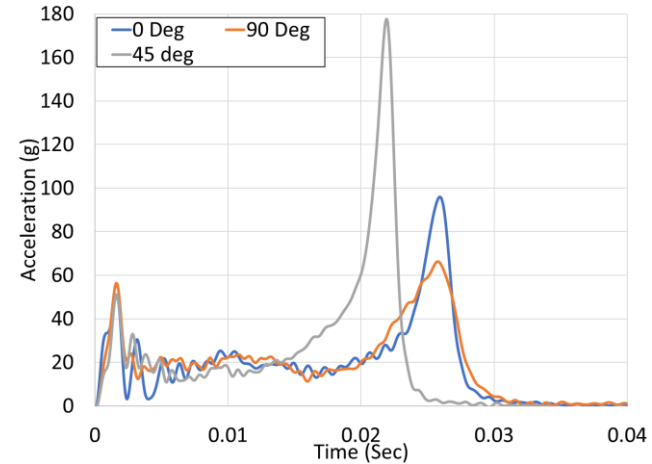
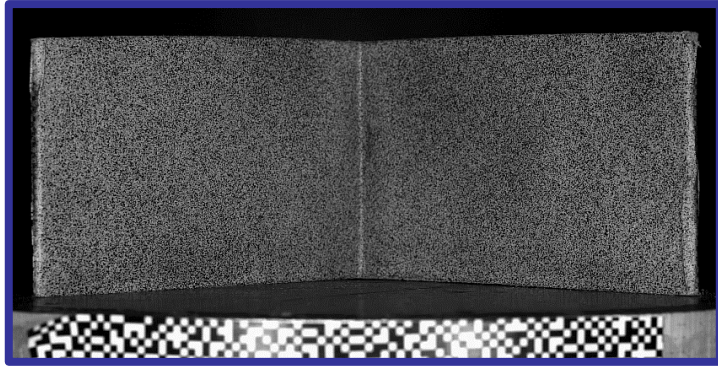
jacob.b.putnam@nasa.gov



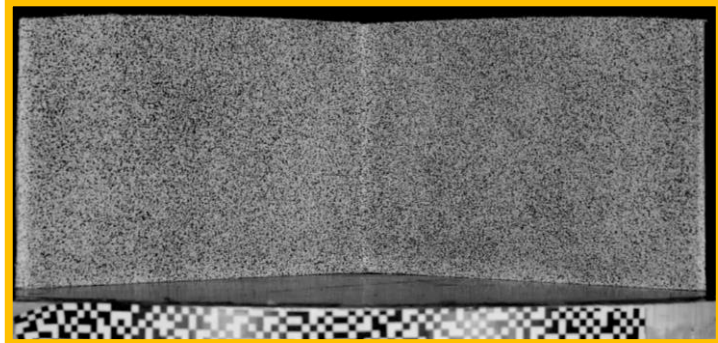
Baseline Subfloor Subscale Testing – Layup Orientation



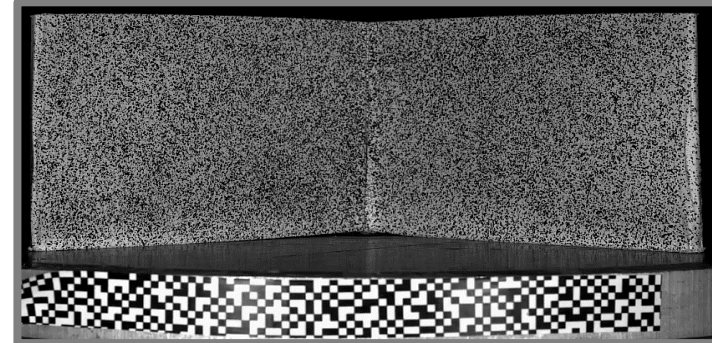
0 Degree



90 Degree



45 Degree



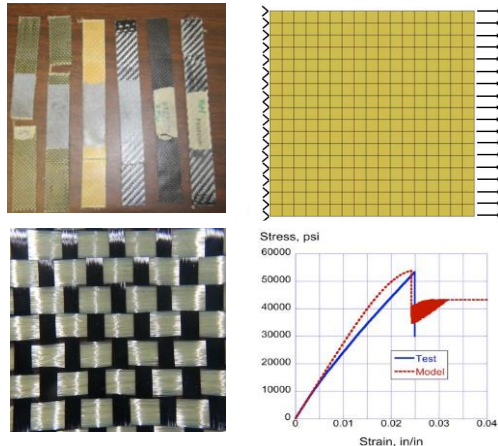
Material Model Development



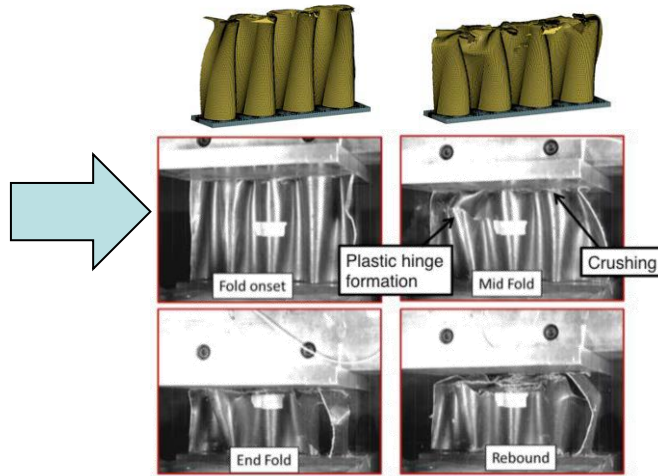
Carbon Fiber and Carbon/Kevlar Materials

- Carbon/Composite material parameters defined through coupon testing
- Calibrated against conusoidal energy absorber testing
- Failure response validated against Crush Tube testing

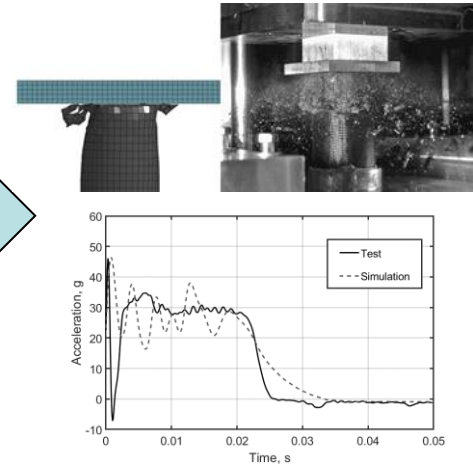
Material Model Definition



Material Model Calibration



Material Model Validation



Model Applicability



- The developed FEM has not been validated against a physical counterpart
 - Intention is to provide a testbed to evaluate gross sensitivities to design changes
 - Results not intended to predict absolute response of this vehicle
- Increased reliance on accuracy of material models implemented in the FEM
 - Each material model defined in this study had previously been validated against physical tests previously performed at NASA Langley Research Center
 - Building block approach used in definition, calibration, and validation of material models

Material Model Definitions



Composites (*Mat 58)

	Carbon Material	C/K Material
RO, lb.-s ² /in. ²	1.29E-4	1.29E-4
EA, psi	6.5E+6	6.3E+6
EB, psi	6.5E+6	2.76E+6
PRBA	0.1095	0.1095
TAU1, psi	7.94E+3	4.50E+3
GAMMA1, in/in	0.0246	0.0246
GAB, psi	3.0E+5	3.0E+5
SLIMT1	0.8	0.8
SLIMC1	1.0	1.0
SLIMT2	0.8	0.8
SLIMC2	1.0	1.0
SLIMS	1.0	1.0
AOPT	N/A*	N/A*
ERODS	0.5	0.5
FS	-1	-1
A1,A2,A3	N/A*	N/A*
D1,D2,D3	N/A*	N/A*
E11C, in/in	0.011	0.013
E11T, in/in	0.0143	0.0143
E22C, in/in	0.011	0.025
E22T, in/in	0.0143	0.025
GMS, in/in	0.142	0.142
XC, psi	7.00E+4	7.00E+4
XT, psi	8.90E+4	8.90E+4
YX, psi	7.00E+4	5.00E+4
YT, psi	8.90E+4	5.40E+4
SC, psi	7.10E+3	7.10E+3