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

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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://www.aurora.aero/pav-evtol-passenger-air-vehicle/
https://www.volocopter.com/en/
https://vahana.aero
https://nari.arc.nasa.gov/crashworthiness
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
“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
Double Accordion (DA)

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

<table>
<thead>
<tr>
<th>Baseline</th>
<th>No significant change with additional horizontal loading component</th>
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<tbody>
<tr>
<td></td>
<td>Stiff initial loading response</td>
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<tr>
<td></td>
<td>Minimal EA effectiveness</td>
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<tr>
<td></td>
<td>Smooth initial energy absorption response</td>
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<tr>
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<td>Horizontal loading increased wall tearing</td>
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<td>Reduced vertical loading prevented resulted in not bottoming out</td>
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<tr>
<td></td>
<td>Horizontal loading had no effect on crush response</td>
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<tr>
<td></td>
<td>Very little crush with reduced vertical energy</td>
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</tbody>
</table>

SA

| 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 x 10 in x 4 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
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**
  - $V_n = 26$ ft/s
  - $V_t = 0$ ft/s
- **Combined Impact**
  - $V_n = 26$ ft/s
  - $V_t = 42$ ft/s
Vertical Impact Simulation - Results

Baseline

Single Accordion (SA)

Double Accordion (DA)

![Graph showing acceleration over time for Baseline, Single Accordion (SA), and Double Accordion (DA) scenarios.](image-url)
Combined Impact Simulation - Results

Baseline

Single Accordion (SA)

Double Accordion (DA)

![Graph showing acceleration vs time for Baseline, SA, and DA](image-url)
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
Questions?

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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
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*)

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