Full Scale Crash Testing at NASA Langley Research Center's Landing and Impact Research Facility with Application Toward Electric Vertical Take off and Landing (eVTOL) Crashworthiness

ASTM Powerplant meeting
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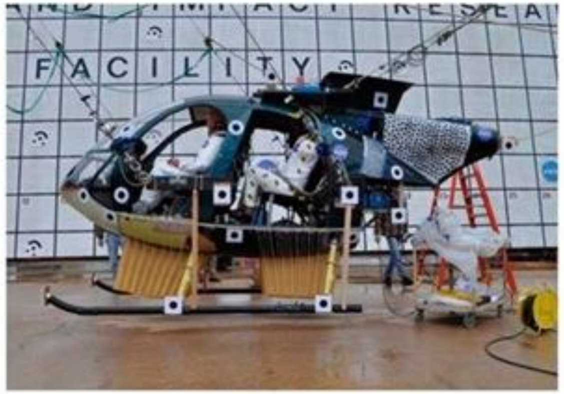
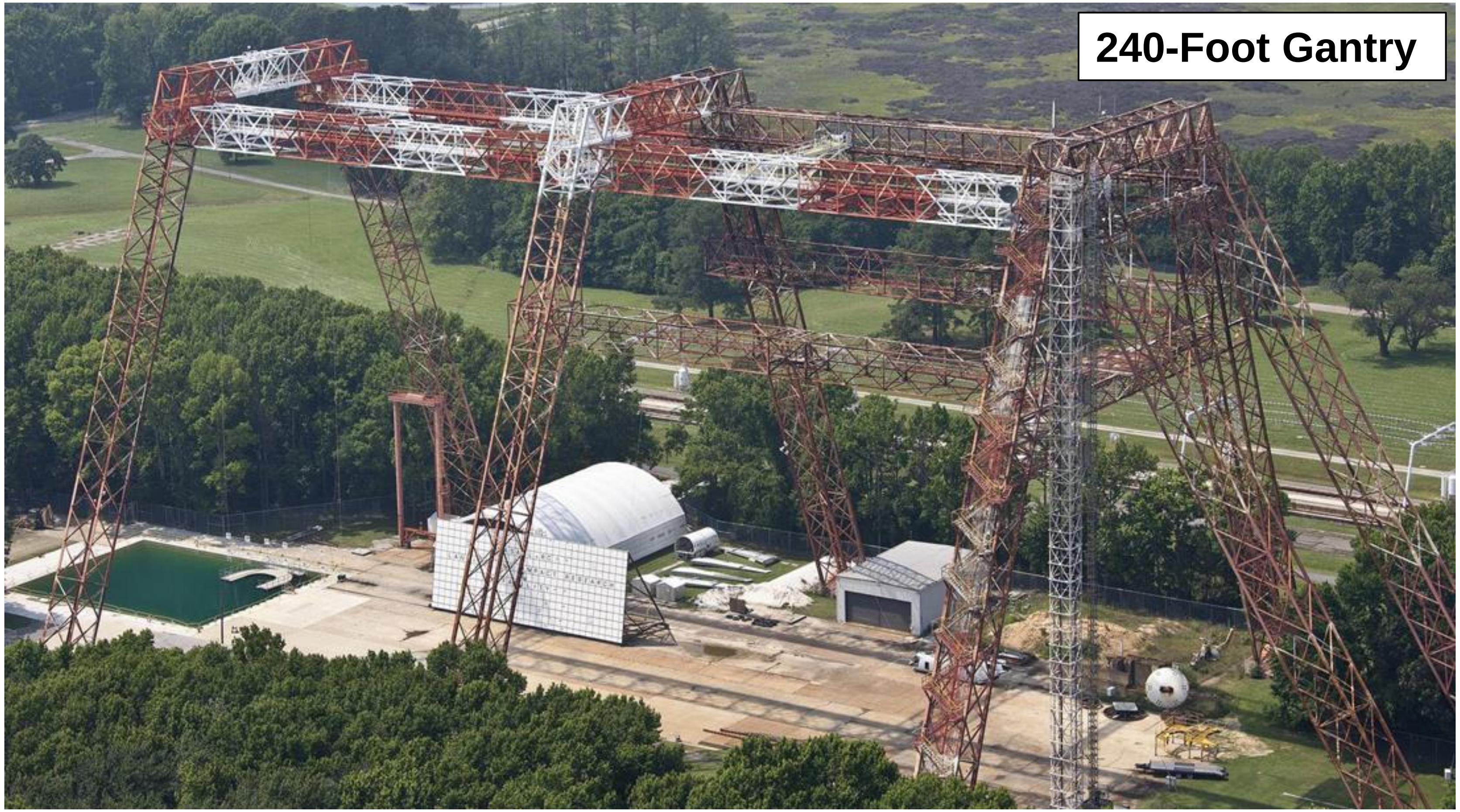


NASA Full Scale Crash Testing / Research Programs
(not a complete list)

- Metallic General Aviation (GA) Aircraft Tests and Analysis
  - 1970-1980s - Historical
  - 2015 - Emergency Locator Transmitter Survivability and Reliability (ELTSAR) Project
- Transport Category Crashworthiness
  - Boeing 737 fuselage section drop tests
  - 2019 - Fokker F28 full scale crash test
- Composite General Aviation Aircraft Tests
  - 1994 - Lear Fan
  - Beech Starship
  - Lancair
- Composite Energy Absorbing (EA) evaluations
  - 2009-2010 - MD-500 Tests with Deployable Energy Absorber (DEA) Development
  - Transport Rotorcraft Airframe Crash Testbed
- Electric Vertical Take off and Landing (eVTOL)
  - 2022 - NASA Lift+Cruise
- *Discussion on test data acquisition and usage, analysis methodology, and knowledge obtained from conducting full scale crash testing*

Landing and Impact Research Facility (LandIR)




Outdoor 70’ and 50’ Drop Tower


Indoor 30' and 15' drop tower

- Subscale & full-scale landing/impact dynamics test facility
- Landing/impacts onto water, concrete, or soil
- Free flight conditions can be simulated by releasing swing cables just before impact. *i.e. pendulum swing*

Historical GA Crashworthiness

- In 1974, a cooperative research program was initiated between NASA, the FAA, and the GA industry to assess and improve the crash safety of small aircraft.

- Objectives of the research program were to determine:
  - Dynamic responses of the airframe, seats, and occupants
  - Effect of flight parameters at impact on the magnitude and pattern of structural damage
  - The failure modes of seats and occupant restraint systems
  - The impact loads imposed on the occupants

- 33 crash tests were performed between 1974 - 1983 on Piper Navajos, Aztecs, and Cherokees, along with Cessna 172s

Historical GA Crash Test Video

Historical GA Crash Results

TABLE I.- SUMMARY OF DATA FROM CONTROLLED CRASH TESTS OF AIRPLANES

(a) Experimental and calculated normal pulse parameters

Test	Flight-path angle, γ, deg	Pitch angle, θ, deg	Flight-path velocity, V_{fp}, m/sec	Experimental normal pulse parameters				Calculated normal pulse parameters	
				Maximum deceleration, $\ddot{z}_{a,max}$, g units	Pulse duration, Δt, sec	Velocity change, ΔV_z, m/sec	Impulse, $\ddot{z}_{a,max}\ \Delta t$, sec	Impulse, $\ddot{z}_{a,max}\ \Delta t$, sec	Velocity change, ΔV_z, m/sec
2	-16	-12	27	20	0.089	8.5	1.78	1.49	7.44
3	-18.75	-18	26.2	28	.05	8.74	1.40	1.63	8.42
4	-15	4	27	16	.102	8.5	1.63	1.42	6.99
5	-20.5	-19.5	26.1					1.76	9.14
6	-16	14	27	18	.110	10.4	1.98	1.47	7.44
7	-47.5	-47.25	28.6	20	0.174	20.73	3.48	2.92	21.1
8	-30	-31	27	18	.135	13	2.43	2.36	13.5
9	-16	-13	26.3					1.44	7.25
10	-18	-14	27.8					1.70	8.59
11	-31	-27	25	12	.132	10	1.58	2.34	12.87
12	-15	9	25	12	0.149	9.5	1.79	1.30	6.47
13	-29	-26	25	27	.049	13	1.32	2.22	12.12
14	-16.75	-11.75	32.7					1.88	9.42
15	-18	-12	41	46	.064	17	2.94	2.53	12.67
16	-15	-4	40	46	.054	15	2.48	2.11	10.35
17	-30	-38	40	42	0.097	19	4.07	3.22	20.0
18	-30	-31	27.9	27.2	.083	11.3	2.26	2.34	13.5
19	-15	-17.7	27	16	.12	10.6	1.92	1.38	6.99
20	-15.4	2	26.6	31	.057	9.1	1.77	1.43	6.99
21	-30	-29.5	27.1	29.9	.096	12.3	2.87	2.39	13.5
FAA-1	-32	-30	25	21	0.120	11	2.52	2.34	13.24
FAA-2	-17	-13.5	23	7	.160	6	1.12	1.33	6.72
FAA-3	-34.5	-39	25.9	18	.12	13.8	2.2	2.33	14.7
FAA-4	-32	-34.5	25.3	18	.13	14.8	2.34	2.25	13.41

Carden, H. “Correlation and Assessment of Structural Airplane Crash data with Flight Parameters at Impact.” NASA TP 2083. 1982

2015 – ELTSAR Project – Crash Tests of GA Aircraft

- N8834B
- 1958 C172
- TTAF* 4,400 hrs
- Airworthy and current on annual inspection

- N9400B
- 1958 C175
- Purchased out of probate
- On ramp ~ 10 years

- N9804V
- 1974 C172
- TTAF >28,000 hrs
- Airworthy and current on annual inspection

- Main ELTSAR Objective - System level Emergency Locator Transmitter (ELT) tests (beacon, cabling, antennas, remote switches, and associated hardware) to examine ELT system functionality and survivability
- Added objective #1 – Evaluate differing types of restraint systems
- Added objective #2 – Evaluate stand-alone onboard crash data recorders

*total time on airframe

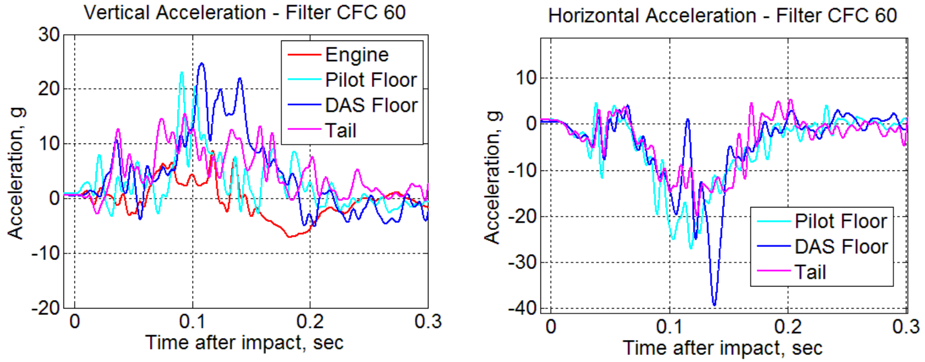
Littell, J.D. “Crash Test of Three Cessna 172 Aircraft at NASA Langley Research Center’s Landing and Impact Research Facility.” NASA TM-2015-218987. 2015

ELTSAR Test 2 – 2015 - Controlled Flight into Terrain (CFIT) Nose Down

- Flight Path Velocity = 74 ft/sec (44 kt)
- Horizontal Velocity = 68.6 ft/sec
- Vertical Velocity = 28.7 ft/sec
- Pitch Angle = 12.2 deg nose down
- https://www.youtube.com/watch?v=FsRwlr7RDkk

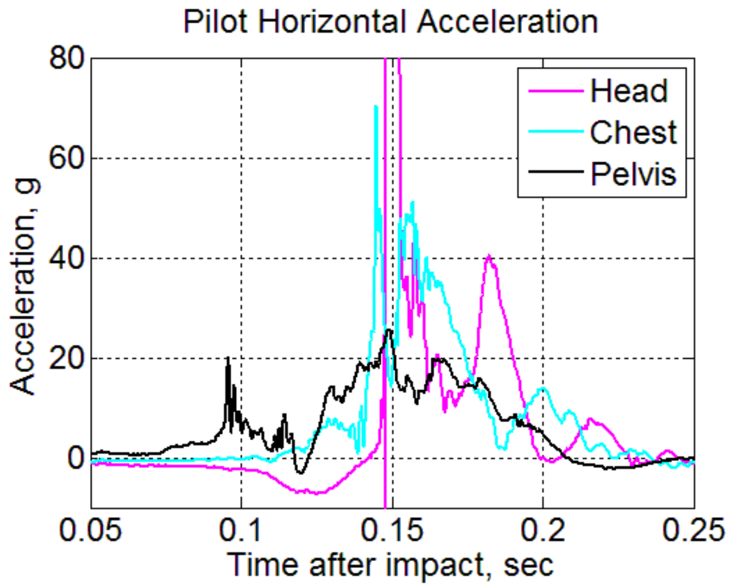
Airframe Response – Data Collection

Loading environment

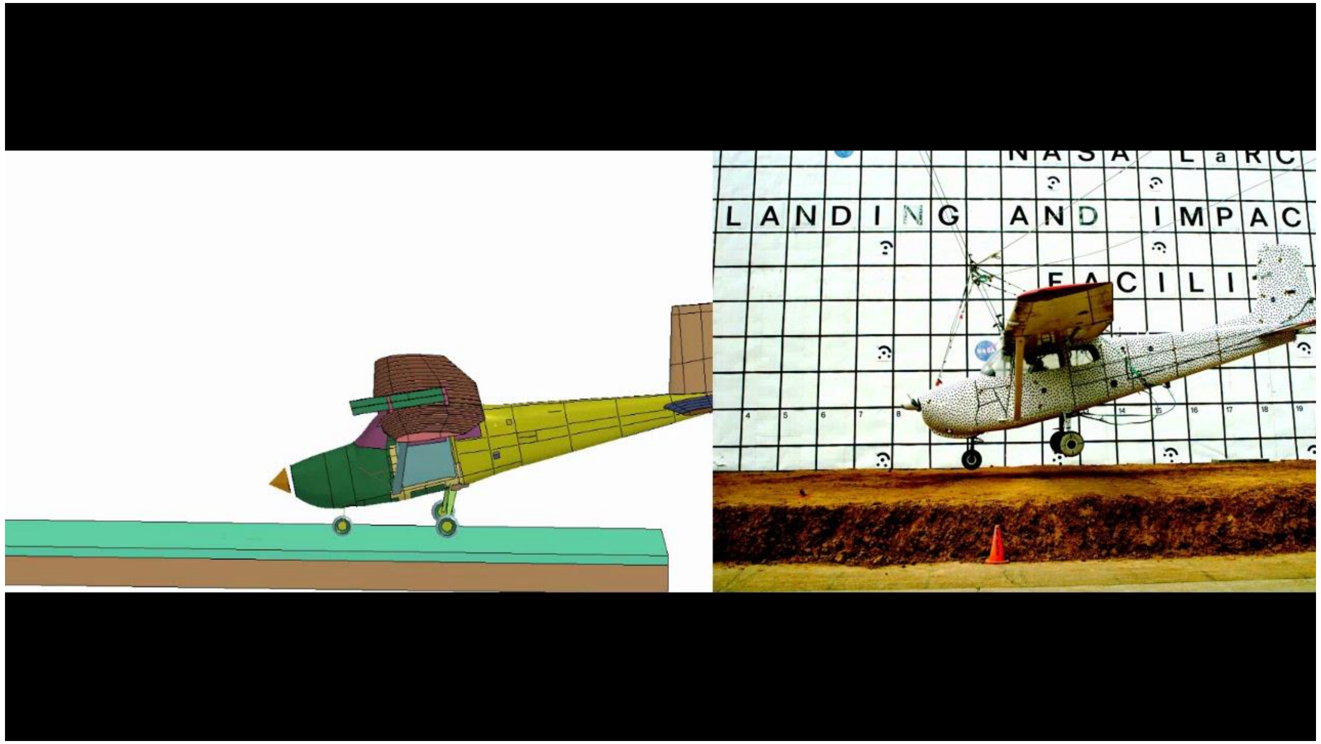


- Pilot head hitting yoke caused high accelerations, leading to high Head Injury Criteria (HIC) value (4241)
- Even with Co-Pilot restraint failing, y-harness was able to restrain Co-Pilot enough to avoid yoke, leading to low HIC value (274)
- Lumbar loads below established limit of 1,500 lb
- Pilot injurious crash

- Vertical Acceleration
  - Triangular to trapezoidal in nature
  - Peaks of 23.2 g and 24.7 g for Pilot floor and DAS floor, respectively
- Horizontal Acceleration
  - Triangular in nature with peaks of 27.1, 39.5 and 19.9 g in Pilot Floor, DAS Floor and Tail
  - Uniform in shape
  - Large spike in DAS floor could be from any number of dynamic events onboard



ELTSAR Calibrated Model



- Airframe, soil, lifting hardware all modelled
  - Peak acceleration is over predicted, but timing is close
- Occupants and seats are not modelled

Fasanella, E.L., and Jackson, K.E. "Crash Testing and Simulation of Cessna 172 Aircraft: Pitch Down Impact into Soft Soil. LS-DYNA 14th Users Conference. June 12-14, 2016. Dearborn, MI.

Conclusion

- Full-scale crash test data feeds into standards developments and minimum operational performance standards (MOPS)
  - RTCA DO204 RevB (2018)
    - Table 4.4 – drop testing
    - Chapter 6
  - Full Spectrum Crashworthiness Criteria for Rotorcraft

- Full-scale crash test data feeds into design guides and other reference materials
  - Small Airplane Crashworthiness Design Guide
  - Aircraft Crash Survival Design Guide Vol iii

Fokker F28 Full Scale Crash Test - Purpose

- Evaluate transport category aircraft under dynamic conditions which includes a forward velocity
  - Evaluate missing factors from a pure vertical component test
- Evaluate advanced Anthropomorphic Test Devices (ATD’s aka crash test dummies) for injury
- Evaluate experimental ATDs
- Generate data for computer modelling purposes

F-28 taxi into LaRC - 2001

F-28 before paint – Oct 2018

Fokker F28 – 2019 - Full Scale Crash Test - Video

Composite GA with Crashworthiness

- Testing conducted under
  - NASA AGATE Advanced Crashworthiness Group
  - Aviation Safety Program

Lear Fan – 1994 - Composite Baseline

- Baseline configuration, ~7053 lb.
- Impact conditions: V_v = 31 ft/sec, V_h = 81 ft/sec, AoA = 0 degree
- 7 seats installed, both 9 g static and dynamic prototype
  - Dynamic limited loads, but still over 1,500 lb. criteria
- Determine composite aircraft structural behavior for crash loading conditions and provide baseline for similar aircraft

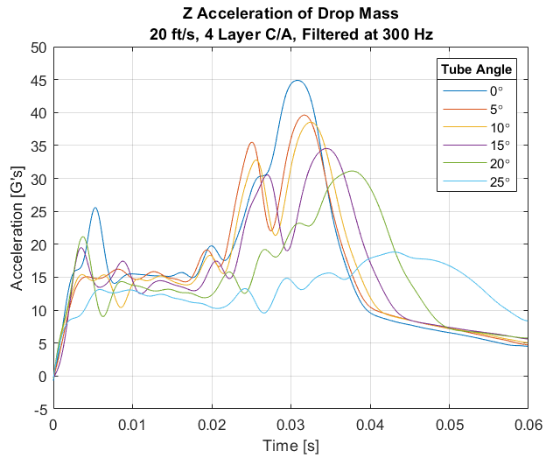
Jones, L.E. and Carden, H.D. "Overview of Structural Behavior and Occupant Responses from a Crash Test of a Composite Airplane." NASA-TM-111954. May 1995.

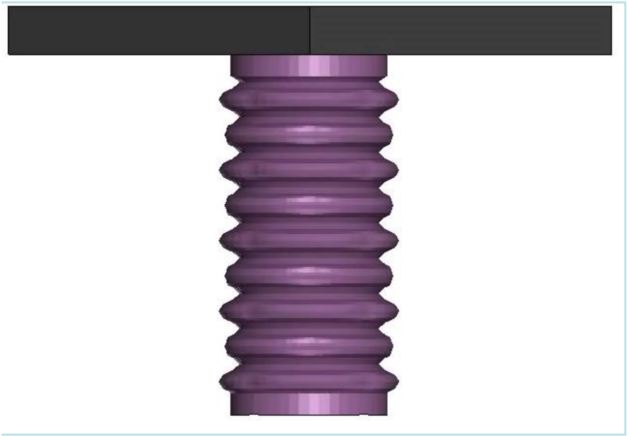
Composite Aircraft Crashworthiness

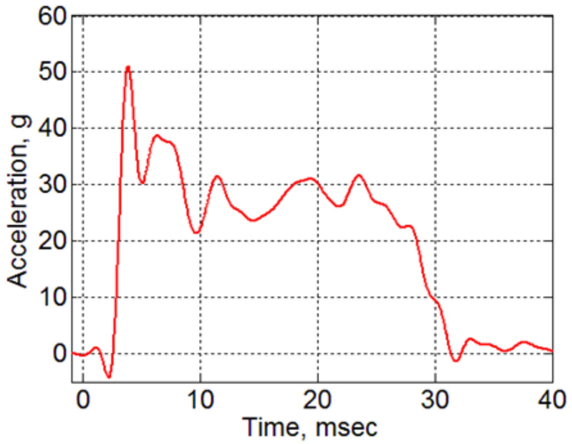
- Limited amount of full-scale test data is available for the study of composite crashworthiness
- NASA Langley has tested composite airframes and components to generate test data
- eVTOL vehicles will incorporate new technologies such as all-composite fuselage design, electric powertrain systems and other novel features

Energy Absorber Development

- Limit dynamic loading transmitted to onboard occupants to tolerable levels
- Composites are used to save weight, however crashworthiness is mostly overlooked
  - How do the composites fail?
  - Many aircraft/parts are built from “black aluminum”
    - 1 for 1 replacement composite retrofit
  - Is a skin stringer (semi-monocoque) system the way to go?
- NASA Langley has evaluated many energy absorbing designs, ranging from seat crush tubes to subfloors to external devices
- Designs are be developed at subscale level, then tested in full-scale aircraft







Deployable Energy Absorber (DEA) for GA/Rotorcraft Concept

- Retrofit on existing small aircraft
- One example of crash energy management developed by NASA
- Kevlar honeycomb which can be folded and stowed

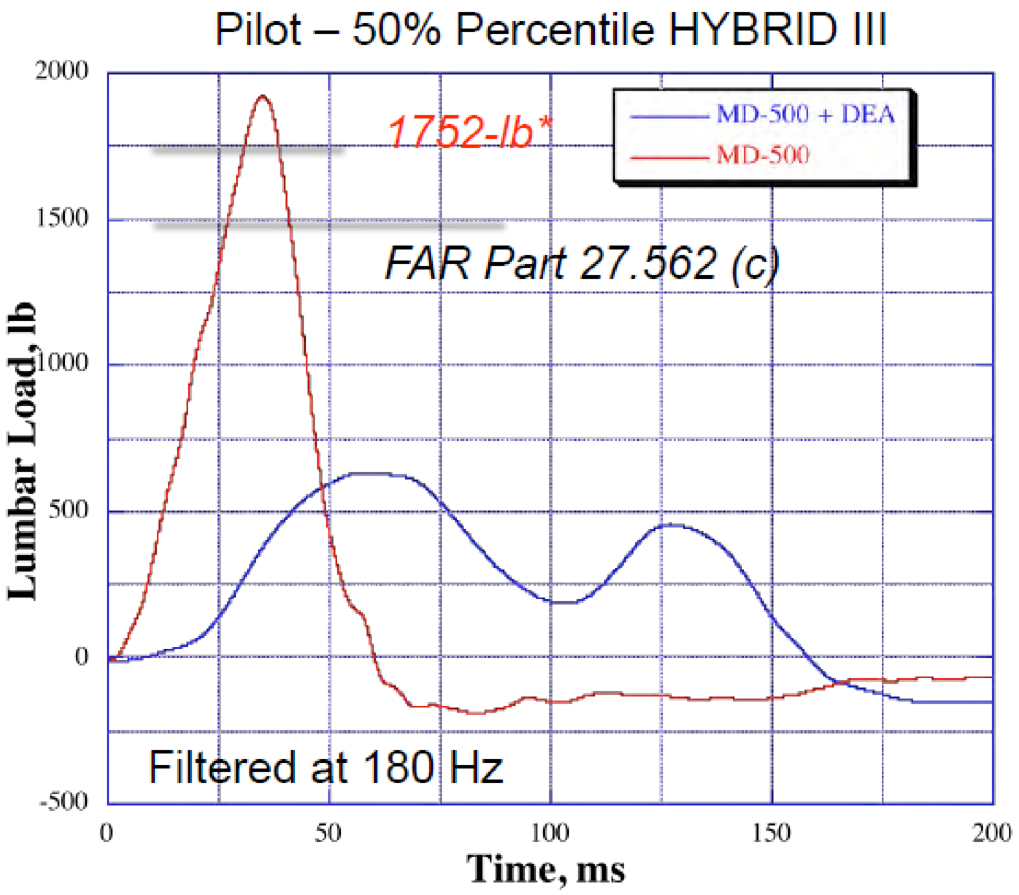
Kellas S., "Deployable Rigid System for Crash Energy Management," US Patents 6,755,453, June 29, 2004, 6,976,729 December 20, 2005, and 7,040,658 May 9 2006

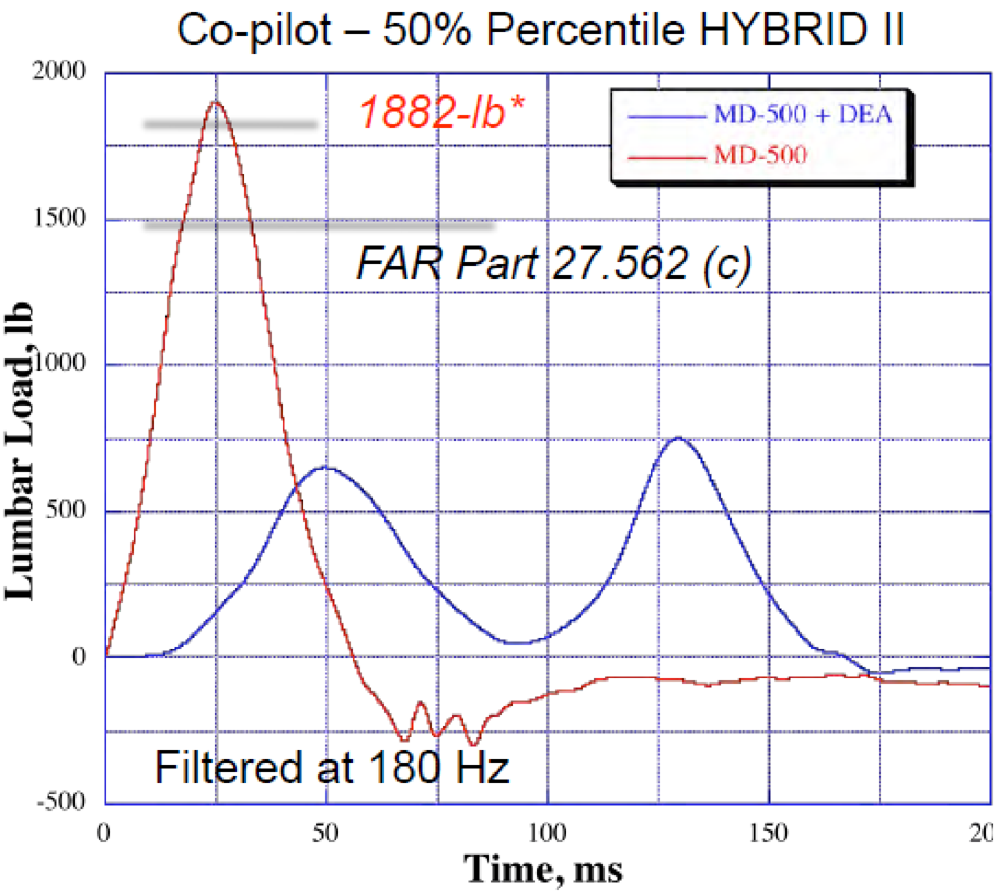
DEA Application – 2009/2010 - Full Scale MD-500 Tests

- Two identical tests conducted, one with and one without DEA
- DEA test conducted first, presented in reverse order here

Kellas, S., and Littell, J.D. "Full-Scale Crash Test of an MD-500 Helicopter with Deployable Energy Absorbers." AHS 64 Annual Forum, Montreal, CA. April 29-May 1, 2008.

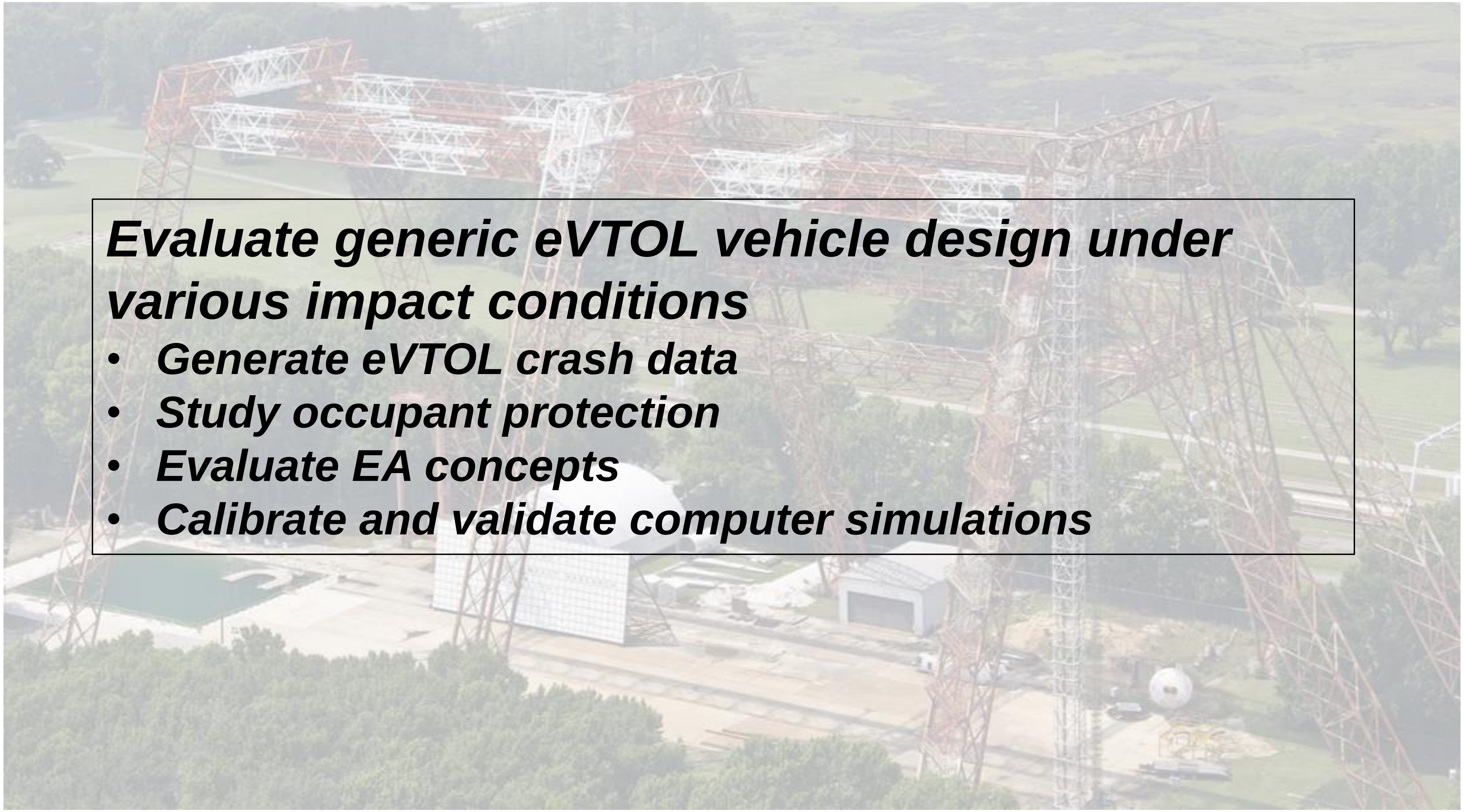
DEA Performance





- 67% and 60% Peak load attenuation for pilot and co-pilot respectively when using the DEA

Electric Vertical Take-off and Landing (eVTOL)Full Scale Crash Testing - Goal

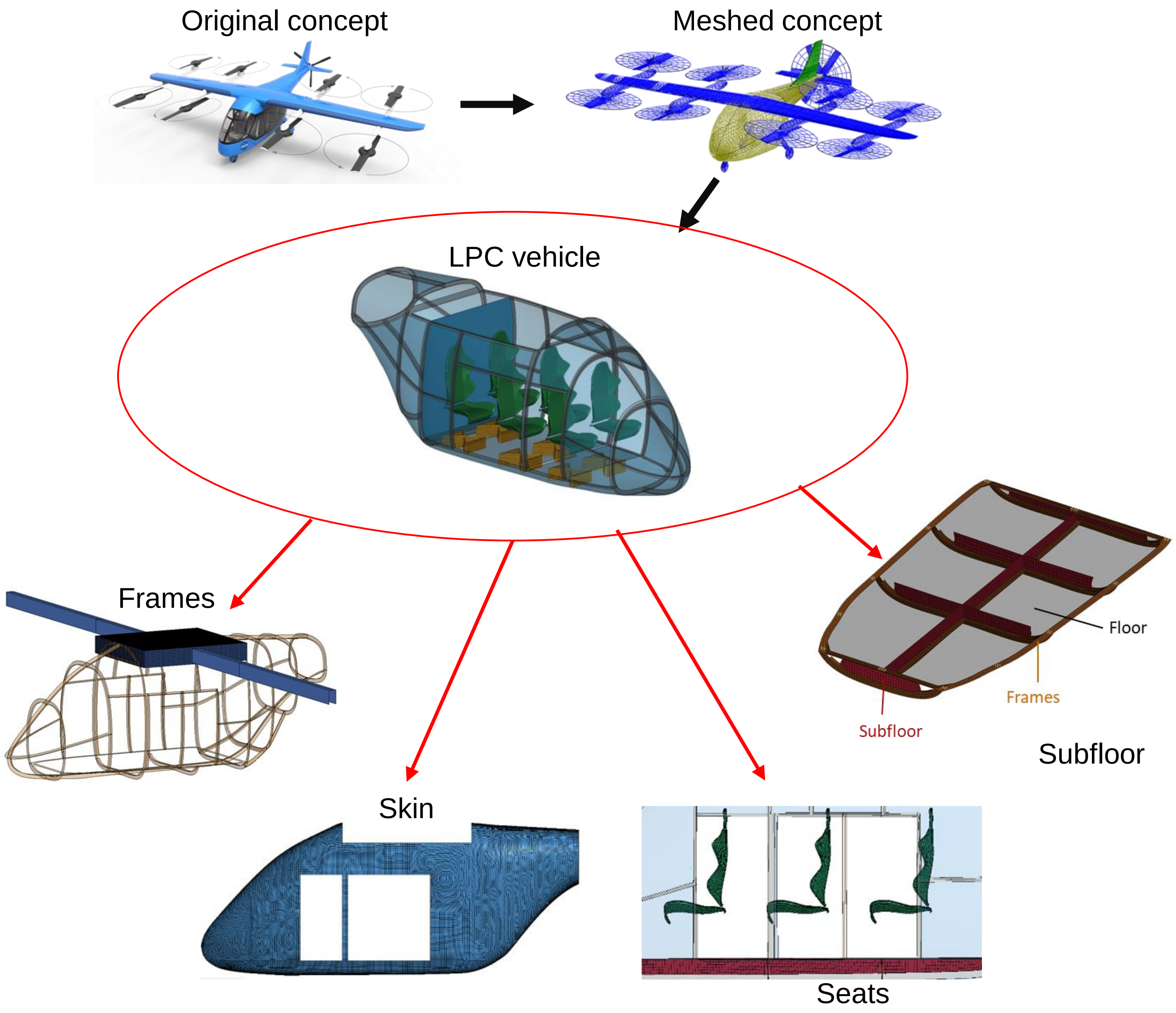


Evaluate generic eVTOL vehicle design under various impact conditions

- ***Generate eVTOL crash data***
- ***Study occupant protection***
- ***Evaluate EA concepts***
- ***Calibrate and validate computer simulations***

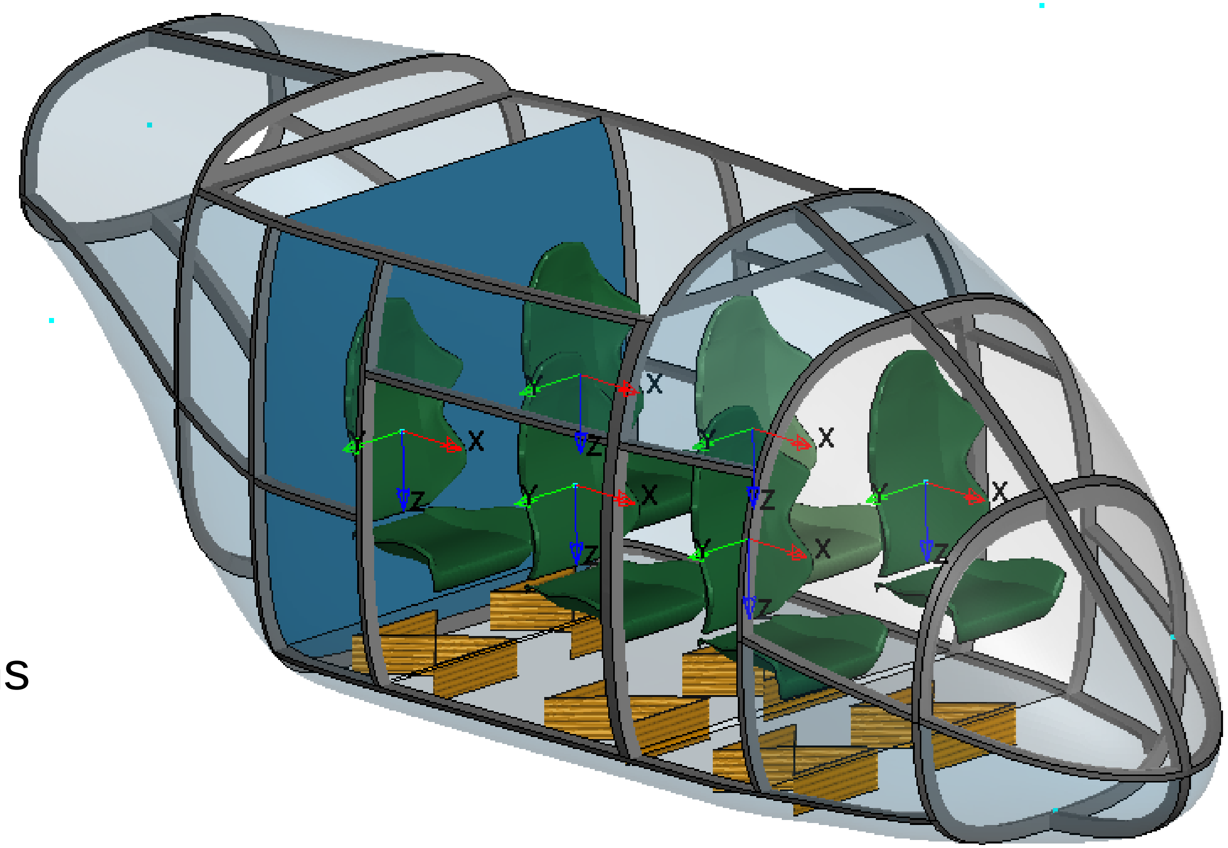
eVTOL Full Scale Crash Testing – Vehicle Development

- NASA Lift + Cruise (L+C) concept vehicle chosen for full-scale test campaign
- Test Article Specifications
  – Dimensions: 18’x6’x7’
  – Seats: 6 passenger
  – Wing Type: High wing
- Design features
  – Carbon fiber weave skin
  – Carbon fiber weave frames
  – Rigid overhead Wingbox area
  – Rigid and energy attenuating seats
  – In-house EA designs
    - Seat, Subfloor



eVTOL – L+C Energy Absorber Integration

- After development, a single accordion modular subfloor design was used in the subfloor region of the L+C
- Self supported cruciform geometry exhibited robust response to multi-axis loading
  - Similar crush response across impact energy and direction variations within subfloor designs
- Subfloor component integrated into vehicle structure



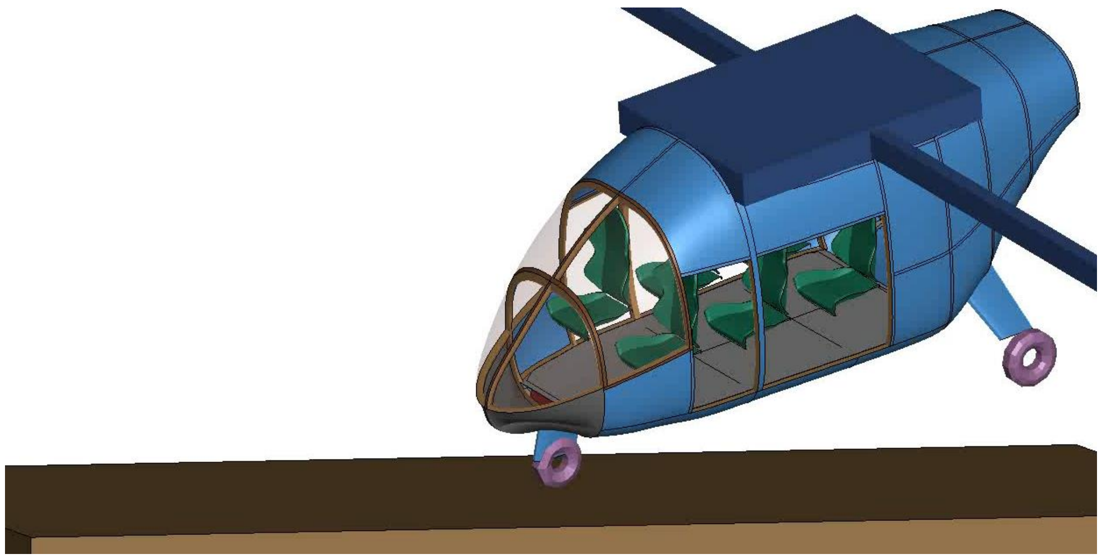
- Subfloor, in conjunction with energy absorbing seats, is intended to achieve loading levels below established limits

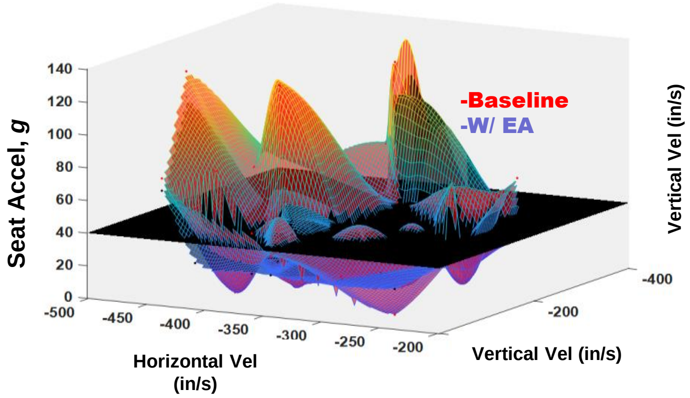
Putnam, J.B., et al. “Development and Analysis of Energy Absorbing Concepts to Improve eVTOL Crashworthiness.” VFS 78 Forum. Ft. Worth, TX, USA, May 10-12, 2022.

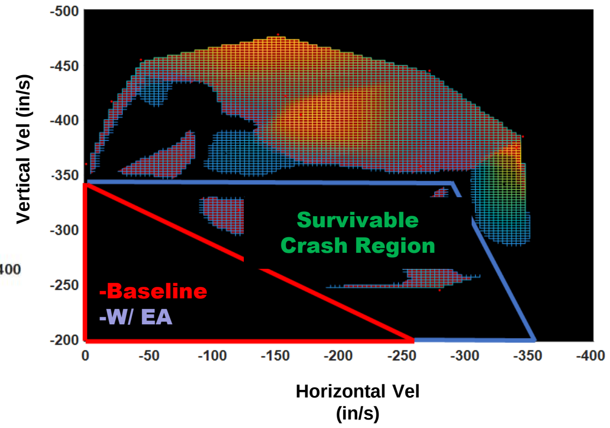
eVTOL - Lift + Cruise Full Scale Test – November 9, 2022

eVTOL - Finite Element Modeling (FEM)

- Evaluate capability of FEM to predict vehicle crash response
  - Validation of composite structural models through full scale test data
  - Validation of EA mechanisms under multi-axis integrated loading environment
- Demonstrate analytical techniques for defining "survivable" crash space
  - Expansion of crashworthiness through EA mechanisms
  - Validation through enveloping test selection
- Extend the full-scale crash matrix by simulating additional cases







Full Scale Crash Test Summary

- NASA has extensive history in GA aircraft crash testing and data from NASA testing is published
- Full scale test data guides regulations and provides industry knowledge
- NASA has tested composite historical composite aircraft and new designed eVTOL reference vehicles as a way to generate test data for evaluation
- NASA has designed and tested various internal and external energy absorbing systems as a way to limit occupant loads in a crash
- Crashworthiness involving a systems level approach must be able to address the features as a system
  - Subscale / individual tests give insight into systems behavior
  - Full scale dynamic test is necessary to verify system performance
- NASA Lift+Cruise eVTOL concept used to generate crash test data to inform development of eVTOL specific crashworthiness regulations
  - Utilize NASA's test capabilities and experience to conduct full-scale crash testing of generic eVTOL vehicle designs

- Numerical simulations supplement full scale data where applicable