SIMULATION STUDIES ON EVTOL CRASHWORTHINESS

IN THE CONCEPTUAL AND PRELIMINARY DESIGN PHASE

Matthias Waimer, Paul Schatrow, Marius Lützenburger

DLR Institute of Structures and Design

DLR

Tenth Triennial International Aircraft Fire and Cabin Safety Research Conference, October 17-20, 2022 - Atlantic City, New Jersey, USA

eVTOL crashworthiness
Focus of presented studies

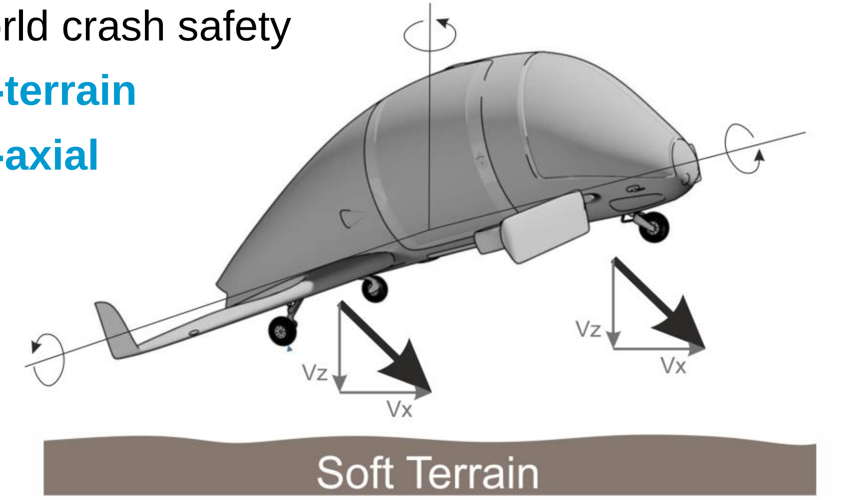
Conventional structural crash design (baseline approach)

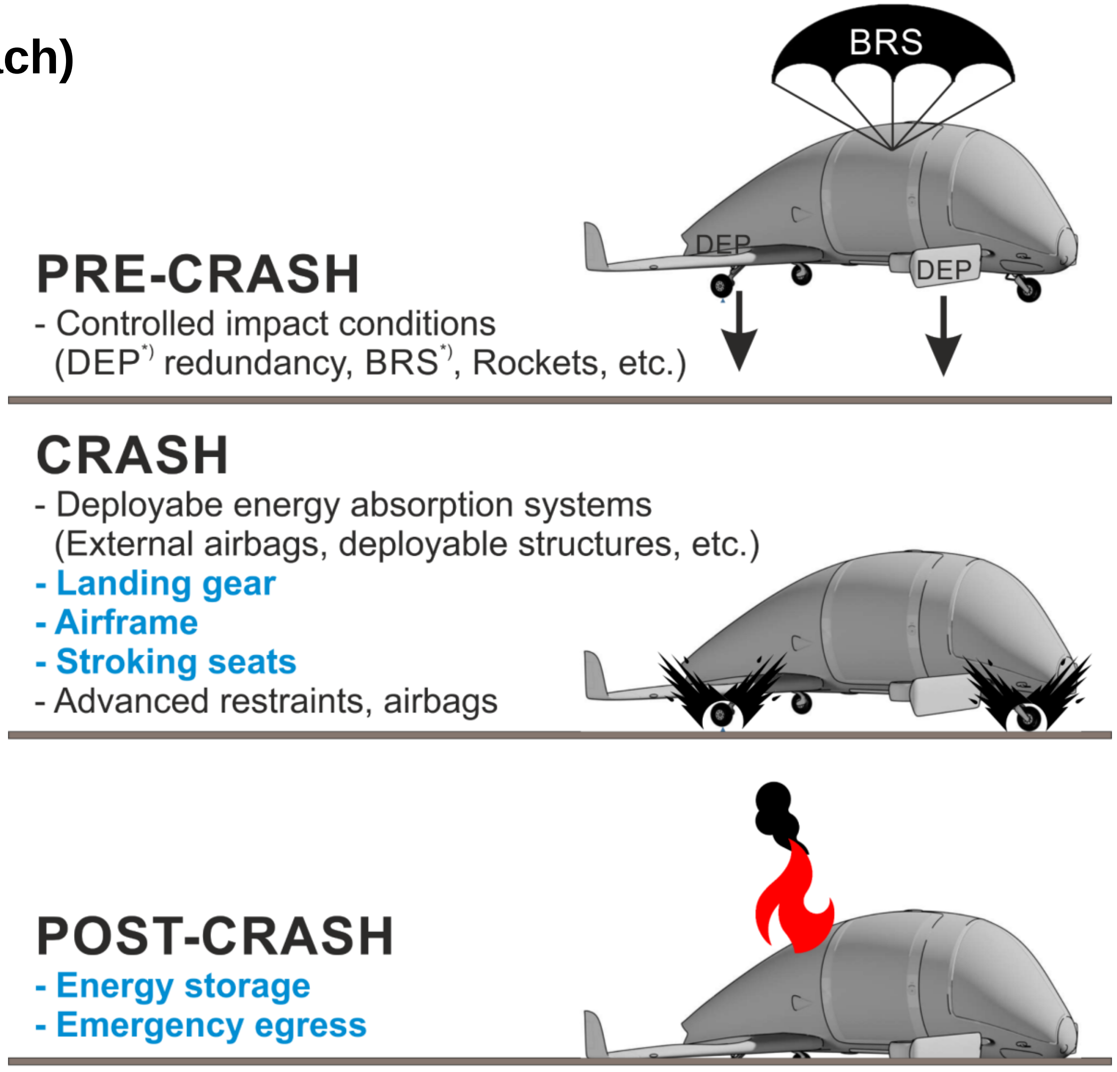
- Utilizing the given eVTOL structure, considering main energy absorption in
  - Landing gear
  - Airframe (subfloor)
  - Seats

Performance-based

Focus of presented studies

- Integrated safety approach
- Real-world crash safety
  - **Multi-terrain**
  - **Multi-axial**





*) *DEP: Distributed electric propulsion; BRS: Ballistic recovery system*

Vehicle sketch taken and modified from EASA MOC-2-SC-VTOL document

Approach
Conceptual and preliminary design studies on eVTOL crashworthiness

UAM crashworthiness requirements

- Understand new missions and novel vehicles
- Derive crashworthiness requirements

Conceptual design study*)

- Identify trends dependent on different eVTOL configurations
- Crashworthy design as baseline (static sizing not available)

Preliminary design study

- Identify design trends for one selected eVTOL configuration
- Static sizing as baseline

*) Further results of the conceptual design study were presented at the NASA/FAA eVTOL Crashworthiness Workshop, 13 April 2021. (https://nari.arc.nasa.gov/crashworthiness)

UAM crashworthiness requirements
New missions

Flight operations over metropolitan areas

- UAM operations primarily expected at large metropolises
- Large metropolis typical characteristics
  - Located at waters
  - Recreational areas
  - Streets and parking sites
  - High buildings, urban canyons
  - Obstacles such as masts and power lines
  - Congested areas

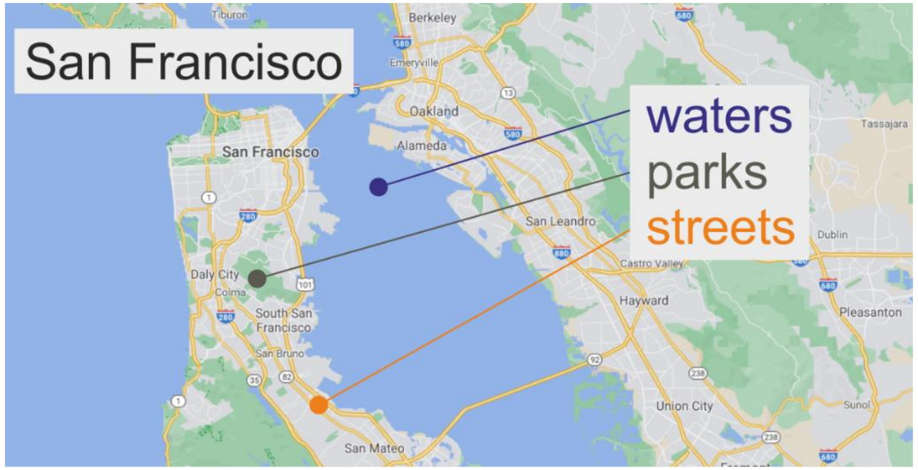
Multi-terrain (Located at waters; Recreational areas; Streets and parking sites)

Off-axis (High buildings, urban canyons; Obstacles such as masts and power lines)

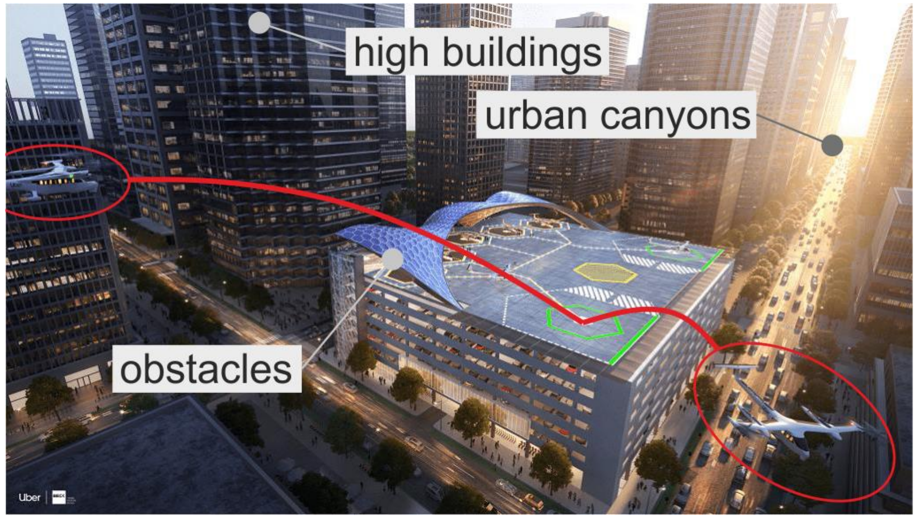
People on the ground (Congested areas)

Crashworthiness requirements

- Different flyover terrain: multi-terrain crashworthiness (hard surface, soft soil, water)
- Wind turbulences and gusts, as well as accidently contact with obstacles: Off-axis impact conditions
- Congested areas: Safety for people on the ground



[1]



[2]

[1] Pictures taken and modified from Google Maps; [2] Pictures taken and modified from Uber

UAM crashworthiness requirements

New vehicles

Novel vehicle configurations

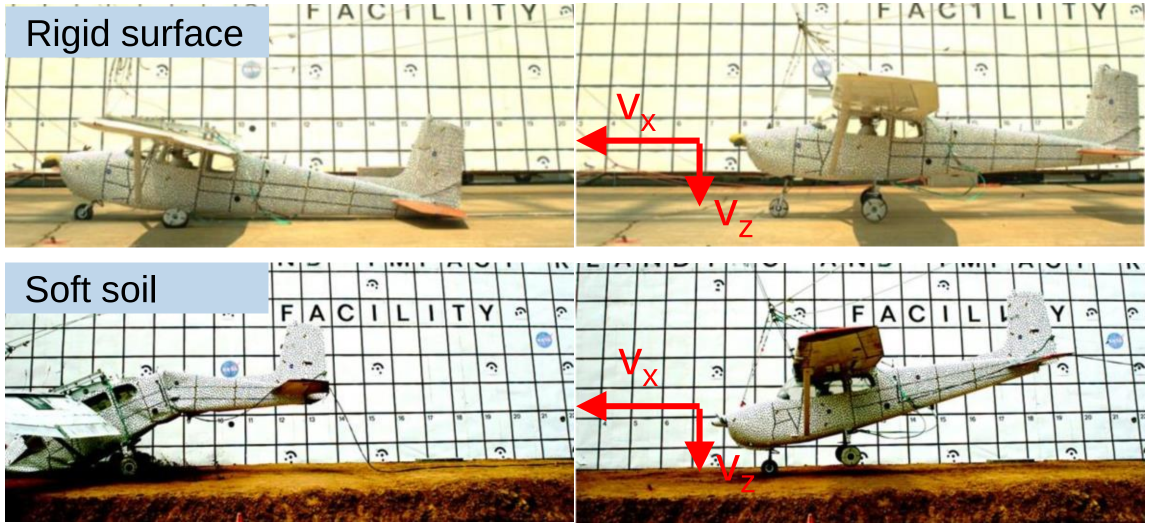
- Non-traditional mass distribution
  - Power units & batteries positioning
  - Batteries (mass items) behind the cabin
- Non-traditional vehicle design characteristics
  - Engine beams
- LIFT+CRUISE configuration
  - Capability to operate wing-lifted emergency landing

➔ **Crash kinematics under real-world crash impact conditions partly not evident.**

Crashworthiness requirements

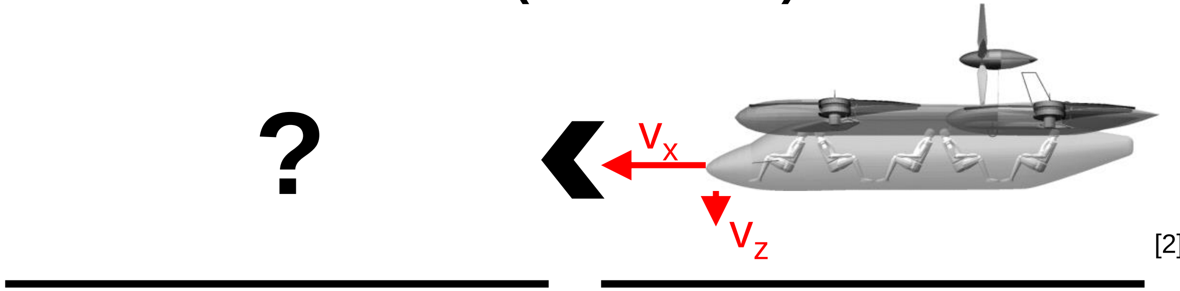
- Consider <u>combined horizontal/ vertical impact conditions</u>
  - to understand the vehicle crash performance under real-world crash impact conditions
  - to identify potential safety issues

Traditional small airplane



[1]

eVTOL (Lift+Cruise)



[2]

[1] JD Littell: „Crash Tests of Three Cessna 172 Aircraft at NASA Langley Research Center's Landing and Impact Research Facility", NASA/TM–2015-218987, 2015. [2] Model taken and modified from Uber eCRM-003_v6

UAM crashworthiness requirements

Requirements (defined for this study)

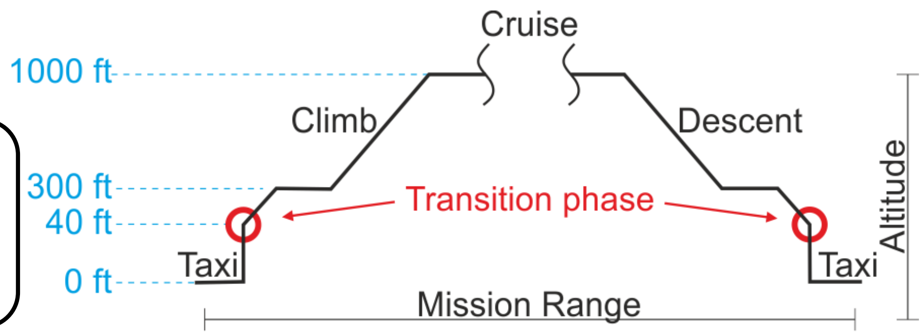
Impact conditions (derived from missions & vehicles discussion)

- **Vertical impact speed:**
  - Up to v_z = 8 m/s
  - Showing reasonable crash performance up to v_z = 10 m/s
- **Horizontal impact speed:**
  - v_x = 25 m/s (assumption: 1.2 x v_{stall})
  - Showing reasonable crash performance up to v_x = 40 m/s
- **Off-axis impact conditions:**
  - Pitch angle: +/- 10°
  - Roll angle: +/- 10°
  - Yaw angle: +/- 10°
- **Multi-terrain**
  - Hard surface (μ = 0.4)
  - Soft soil plowing approximation (μ = 0.8, hard surface)

"Dead man's curve" versus DEP redundancy:
8 m/s vertical impact speed may not cover worst case crash conditions considering complete power failure during transition at approx. 40-50 ft AGL. Sufficient DEP redundancy is assumed in this study.

Crashworthiness criteria

- **Key crashworthiness parameters**
  - Mass retention
  - Occupant loads
  - Survivable volume
  - Egress path
- **Secondary crashworthiness parameters**
  - Multi-terrain crashworthiness
  - Battery safety
  - Safety for people on the ground
  - Etc.



[1]

[1] Uber: "eVTOL Vehicle Requirements and Missions", Uber Elevate, 2018.

UAM crashworthiness requirements
Load cases

Load cases
- Energy absorption (EA) management → ①
- Off-axis robustness (vertical impact) → ②
- Off-axis robustness (combined x/z-impact) → ③
- Multi-terrain (soft soil plowing: μ = 0.8) → ③ **)

Goals
- Identification of trends
  - Energy absorption management
  - Risk assessment of unfavorable vehicle crash performance

Reference Load Case → D

Group	Load case*) [-]	v_z [m/s]	v_x [m/s]	Roll [°]	Pitch [°]	Yaw [°]	Payload [%]
①	A	4	0	0	0	0	50
①	B	4	0	0	0	0	100
①	C	8	0	0	0	0	50
①	D	8	0	0	0	0	100
①	E	10	0	0	0	0	100
②	F	8	0	-10	0	0	100
②	G	8	0	0	10	0	100
②	H	8	0	0	-10	0	100
③	I **)	8	25 / 40	0	0	0	100
③	J	8	25 / 40	-10	0	0	100
③	K	8	25 / 40	0	10	0	100
③	L	8	25 / 40	0	0	-10	100
③	M**)	8	25 / 40	-10	10	-10	100

*) All load cases with friction coefficient μ = 0.4.

**) Load cases additionally simulated with friction coefficient μ = 0.8.

Conceptual design study

- Identify trends dependent on different eVTOL configurations
- Crashworthy design as baseline (static sizing not available)

Conceptual design study

Vehicle configurations (Lift+Cruise)

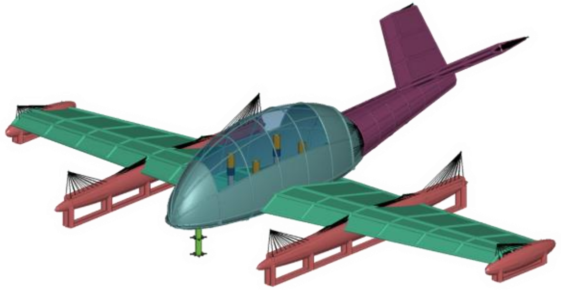
Constants

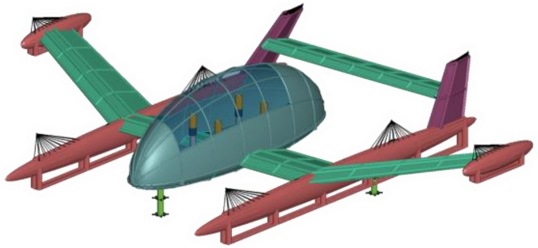
- 4 PAX (4 x 77.7 kg + 4 x 22.3 kg luggage)
- MTOM ≈ 1870 kg
- 8 power units (8 x 50 kg) & batteries (400 kg)
- Similar structural design
  - With individual adaptations, e.g. main frames
- Engine beams

Parameters

- Wing configuration → **different EA management**
- Empennage configuration



Selected configurations for results presentation

Mid-wing

High-wing

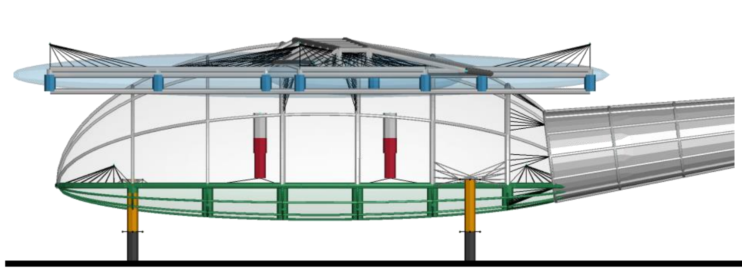
Low-wing

Conceptual design study

Energy absorption management

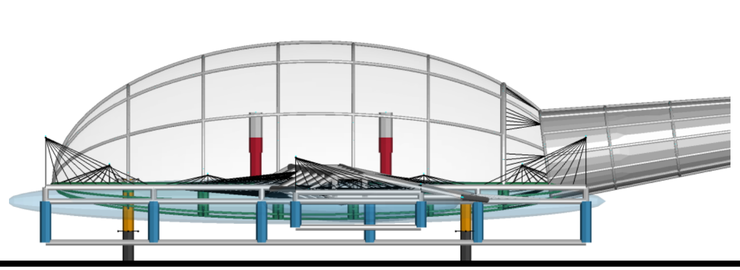
Crashworthy design as baseline

High-wing

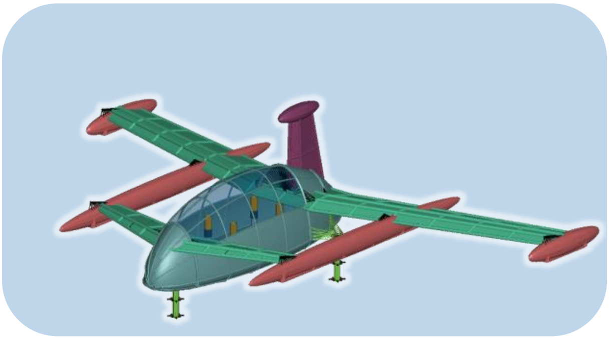


① Landing gear oleo damper
② Landing gear crash absorber
③ Sub-floor structure
④ Stroking seat

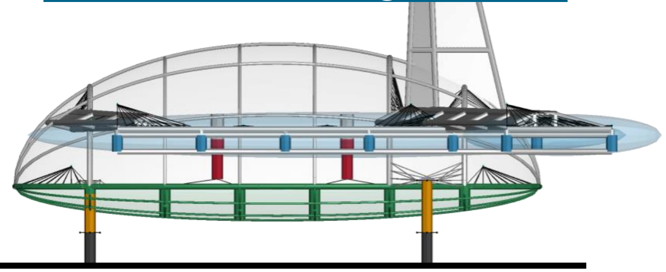
Low-wing



① Landing gear oleo damper
② Engine beam absorber
③ Landing gear crash absorber
④ Sub-floor structure (limited: wing box)
⑤ Stroking seat



Mid-wing

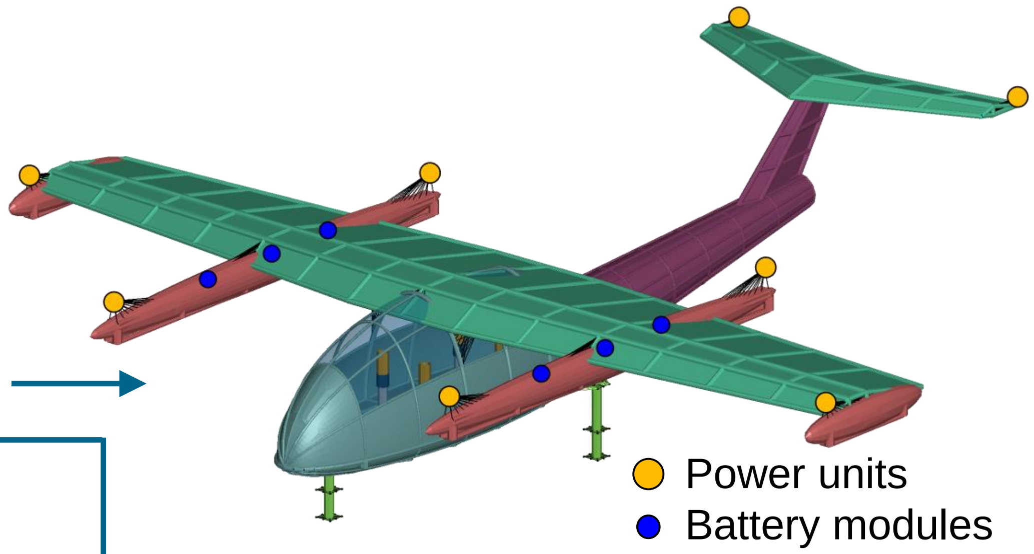


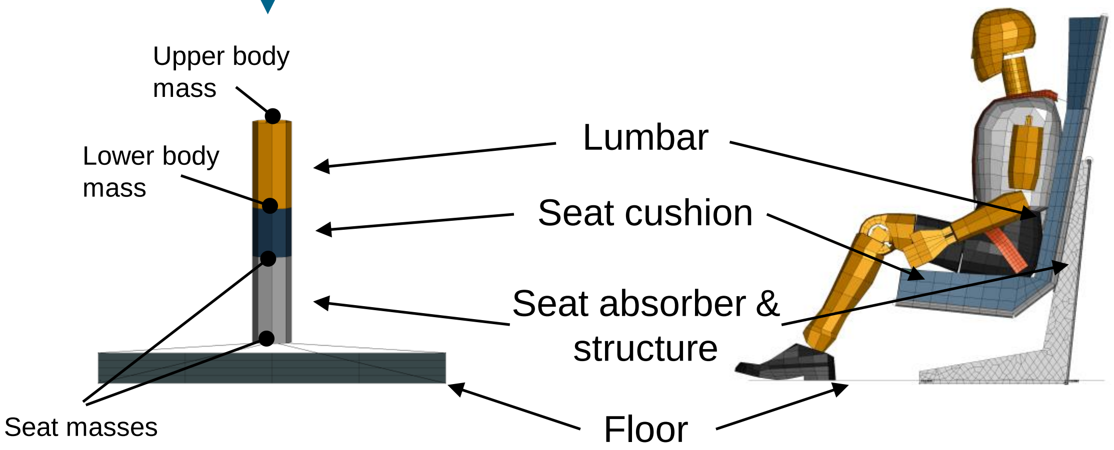
① Landing gear oleo damper
② Landing gear crash absorber
③ Sub-floor structure
④ Stroking seat

Conceptual design study
Modeling & simulation approach

Motivation
- Conceptual design phase: Identification of trends!
- Computational efficiency vs. reasonable accuracy

Modeling
- Structure: Hybrid macro/FE (FE: beam & shell elements)
- Seats & Occupants: Dynamic Response Index (DRI) model
  - Seat absorber: Macro element F-d input characteristics
  - Seat cushion: Macro element F-d input characteristics
  - Occupant: DRI model
  - Output
    - Seat absorber stroke
    - Seat cushion deformation
    - Injury criterion: DRI





Simulation
- Model size (approx.): 40,000 nodes, 37,000 elements
- CPU time: 26 min (elapsed time) on 4 core processors (LS-Dyna)
- Optimization runs for sensitivity analysis and direct optimization (LS-Opt)

Conceptual design study

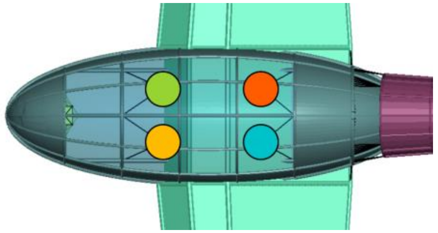
Results

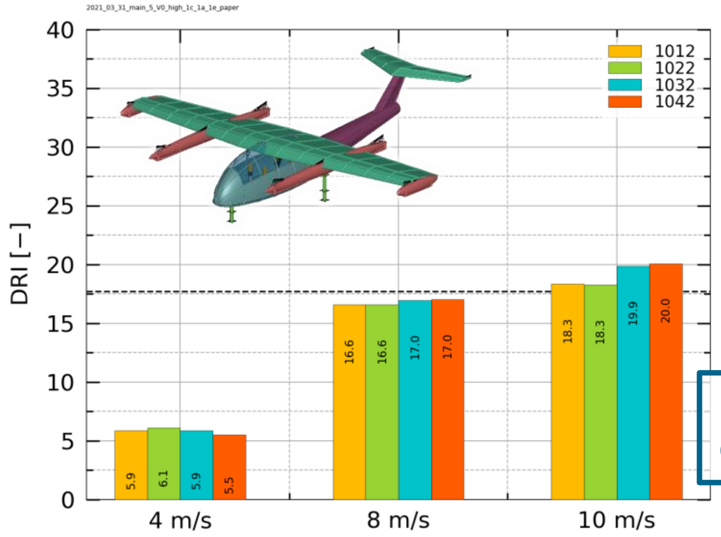
Accelerations loads experienced by the occupants (Dynamic Response Index (a_z))

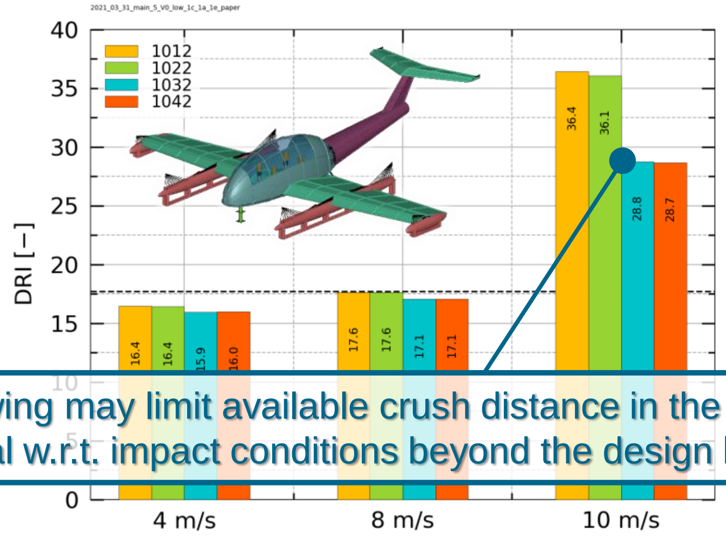
- **High wing / Mid wing**
  - v_z = 4 m/s: EA by landing gear (oleo strut & absorber)
  - v_z = 8 m/s: Further EA by sub-floor structure and seat absorber
  - v_z = 10 m/s: Full utilization of EA capacity

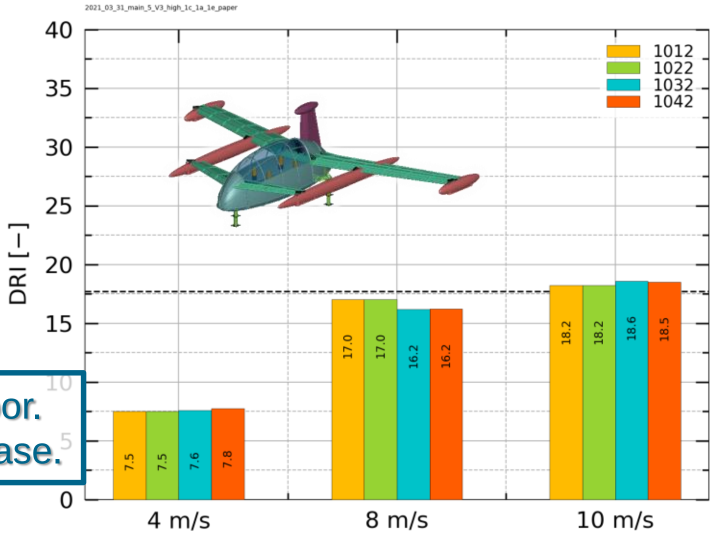
Load case	v_z [m/s]	v_x [m/s]	Roll [°]	Pitch [°]	Yaw [°]	Payload [%]
B	4	0	0	0	0	100
D	8	0	0	0	0	100
E	10	0	0	0	0	100

- **Low wing**
  - v_z = 4 m/s: EA by landing gear oleo strut AND by engine beams (stiff response → high DRI)
  - v_z = 8 m/s: Further EA by engine beams and seat absorber
  - v_z = 10 m/s: Full utilization of EA capacity. Seat absorber capacity exceeded → high DRI values









Low wing may limit available crush distance in the subfloor.
Critical w.r.t. impact conditions beyond the design load case.

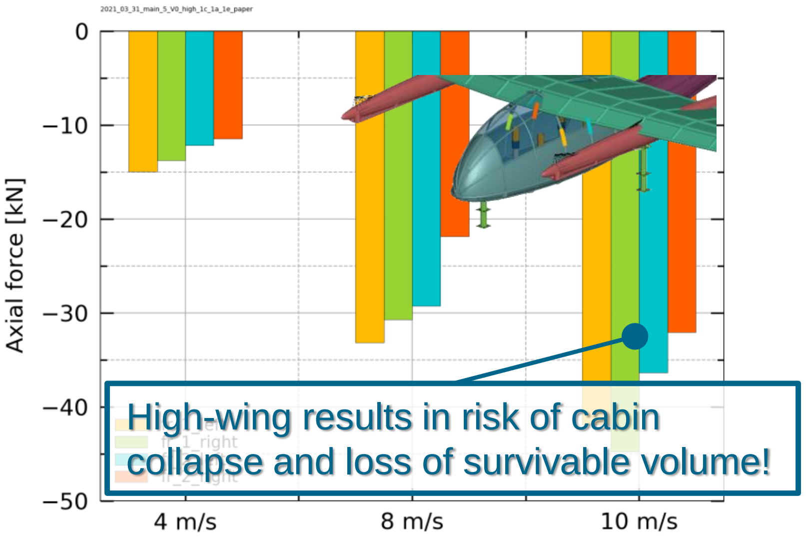
Conceptual design study

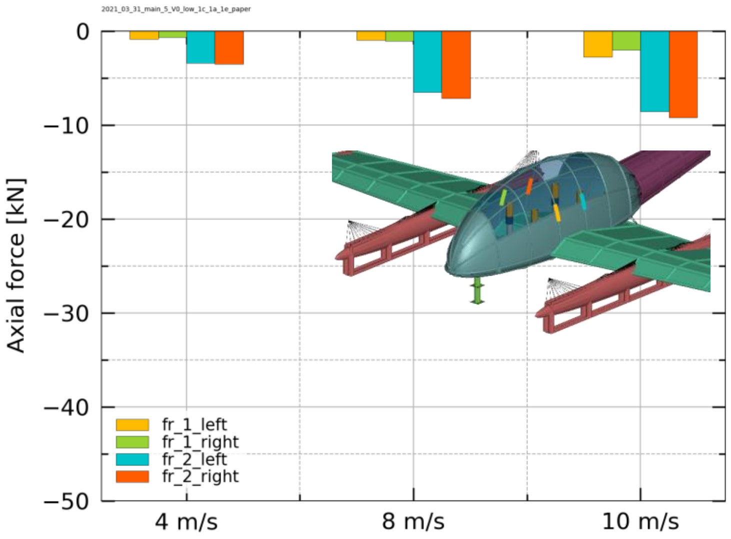
Results

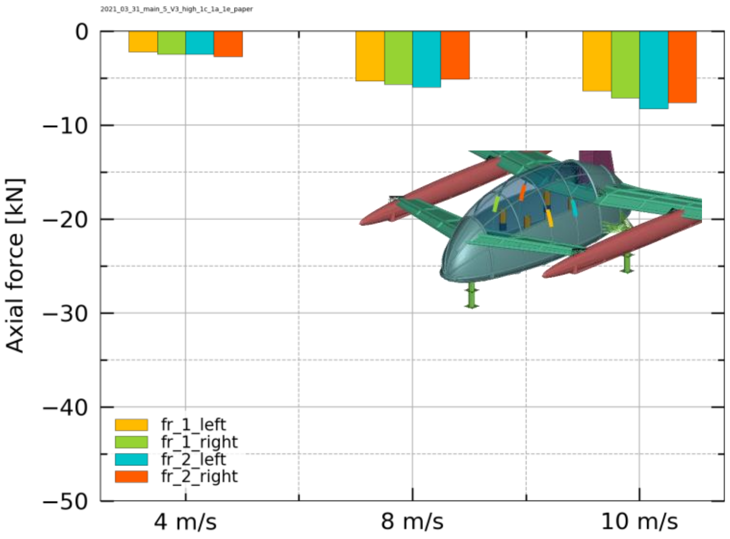
Maintenance of survivable volume (Main frame axial force)

- **High wing**
  - v_z = 4/8/10 m/s: High frame loads due to overhead mass (wing equipped with engine beams: batteries & power units)
- **Low wing/ Mid wing**
  - v_z = 4/8/10 m/s: Low frame loads due to the absence of overhead masses
- **Low wing:**
  - Pitch moment due to crash kinematics affects frame loads (front vs. rear main frame)

Load case	v_z [m/s]	v_x [m/s]	Roll [°]	Pitch [°]	Yaw [°]	Payload [%]
B	4	0	0	0	0	100
D	8	0	0	0	0	100
E	10	0	0	0	0	100







Conceptual design study

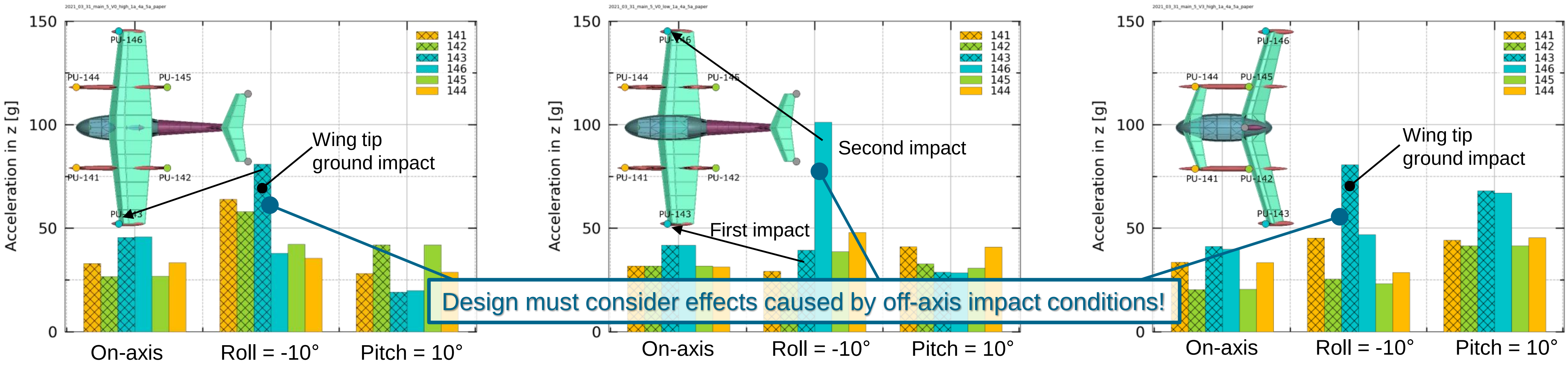
Results

Retention of items of mass (Power unit acceleration (a_z))

- **High wing / Mid wing**
  - Roll = -10°: Wing tip ground impact → Load limiters not designed for ground impact → high acceleration loads
- **Low wing**
  - Roll = -10°: Severe second impact with local impact speed > nominal impact speed → load limiter capacity exceeded → high acceleration loads

Load case	v_z [m/s]	v_x [m/s]	Roll [°]	Pitch [°]	Yaw [°]	Payload [%]
D	8	0	0	0	0	100
F	8	0	-10	0	0	100
G	8	0	0	10	0	100

Sampling frequency: 10,000 Hz; Butterworth filter frequency: 60 Hz; Plot of positive z-accelerations



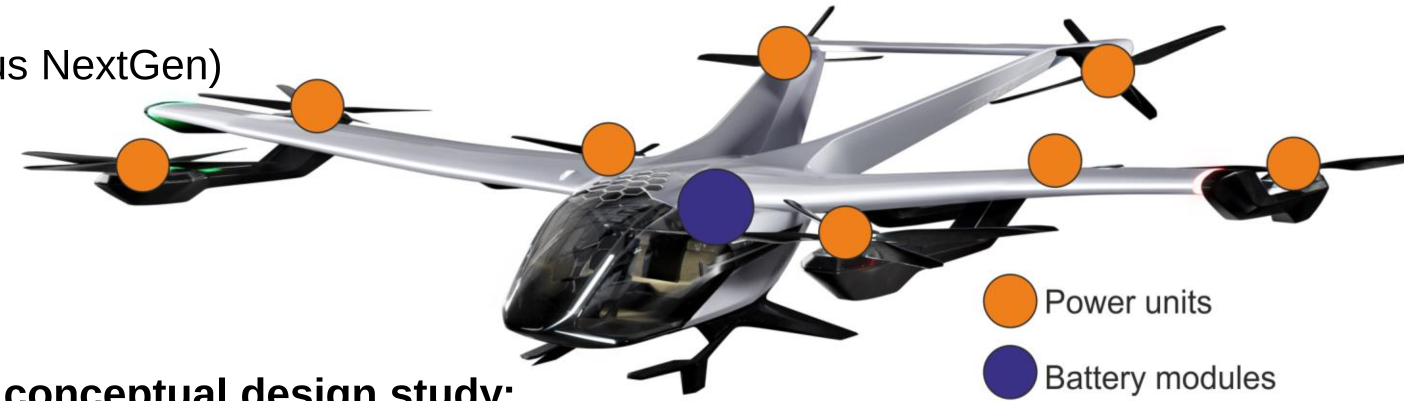
Preliminary design study

- Identify design trends for one selected eVTOL configuration
- Static sizing as baseline

Preliminary design study
Selected vehicle configuration (Lift+Cruise)

Generic design

- Several design assumptions (inspired by CityAirbus NextGen)



Characteristics

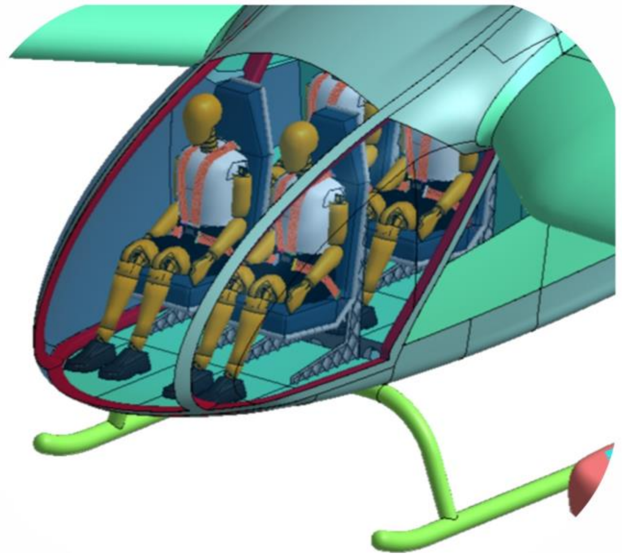
- 4 PAX (4 x 77.7 kg + 4 x 22.3 kg luggage)
- 8 power units & one battery module
- MTOM ≈ 2 tons

From conceptual design study:

- Prevent overhead masses
- Prevent stiff wing box below cabin
- Integrate battery in a safe position

Crashworthiness features

- High-wing with cabin in front of the wing
  - No overhead mass items
  - Safe emergency egress path
- Crashworthy energy storage installation in a stiff surrounding framework of main frames, wing box and subfloor structure
- Forward subfloor and diagonal cabin frame designed to prevent cabin crushing under horizontal crash loads
- Large masses (energy storage) in the rear fuselage may prevent earth plowing / rollover



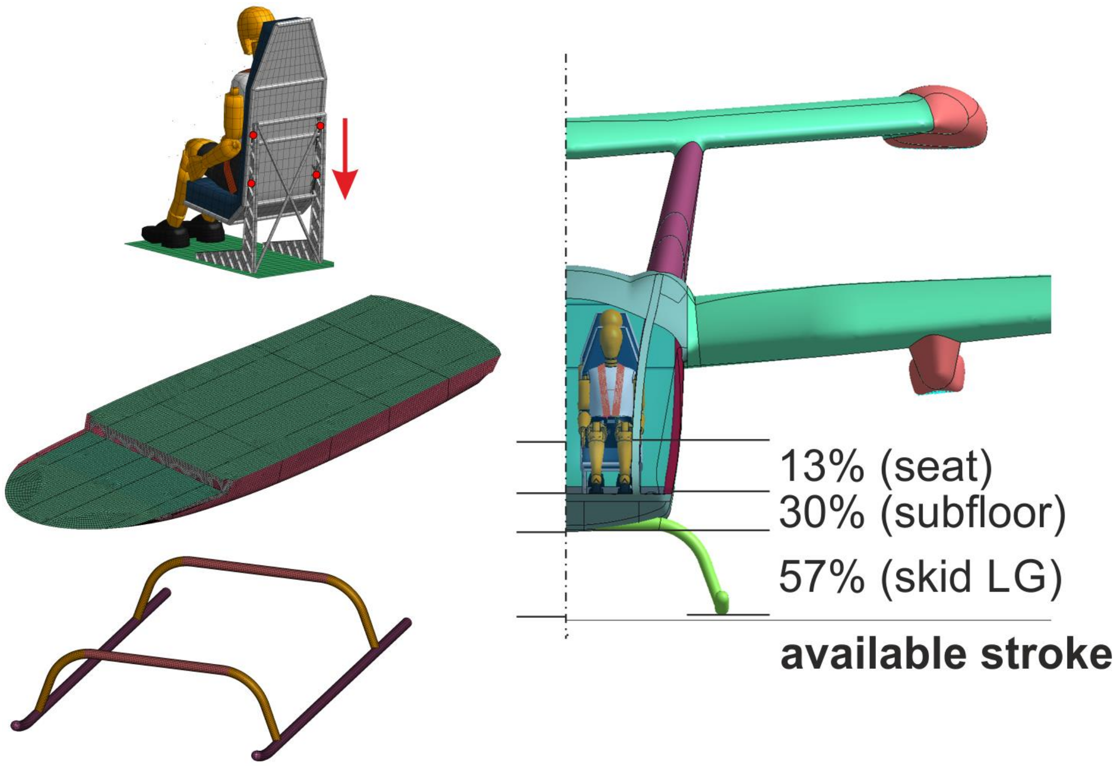
Preliminary design study
Energy absorption management

Approach for preliminary crash sizing

- Use static sizing as baseline (now available)
- With crashworthy design input from conceptual design phase
- Subfloor structure as main design parameter
  - Individual adjustments for rear (energy storage) and forward (cabin) subfloor

Energy absorption management

- Skid landing gear
  - Conventional design, sized for hard landing (limited energy absorption capacity)
- Crushable subfloor
  - Surrogate design for preliminary sizing, later to be replaced by final design*)
- Stroking seats
  - 130 mm @ 10-12 kN

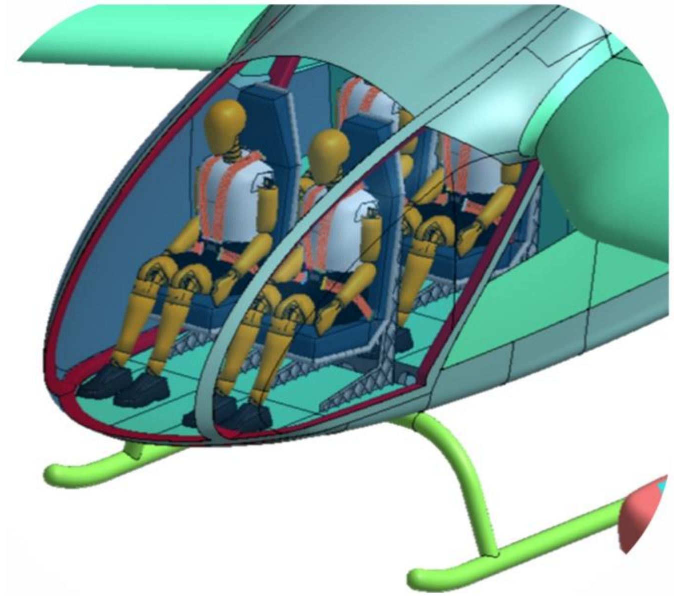


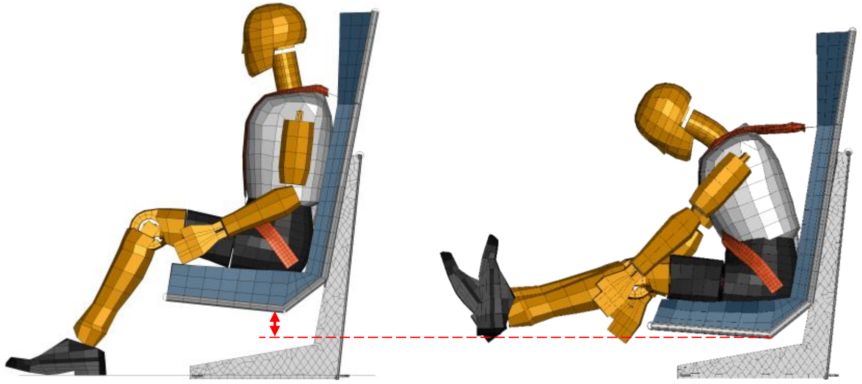
*) eVTOL subfloor structure designed for multi-terrain and off-axis crashworthiness as well as crashworthy battery integration will be part of future publications

Preliminary design study
Modeling & simulation approach

Motivation
- Preliminary design phase: First design & sizing available!
- Reasonable accuracy for preliminary crash sizing

Modeling
- Structure: FE (primarily shell elements)
- Seats & Occupants: Seat structure & ATD model
  - Seat absorber: Macro element F-d input characteristics
  - Seat cushion: *MAT_LOW_DENSITY_FOAM (*MAT_057)
  - Occupant: LSTC Hybrid III 50th percentile FAST ATD
  - Restraints: 4 point harness
  - Output
    - Seat absorber stroke
    - Seat cushion deformation
    - Injury criterion: Lumbar load (automotive ATD!)





CS27.562 30g acceleration pulse

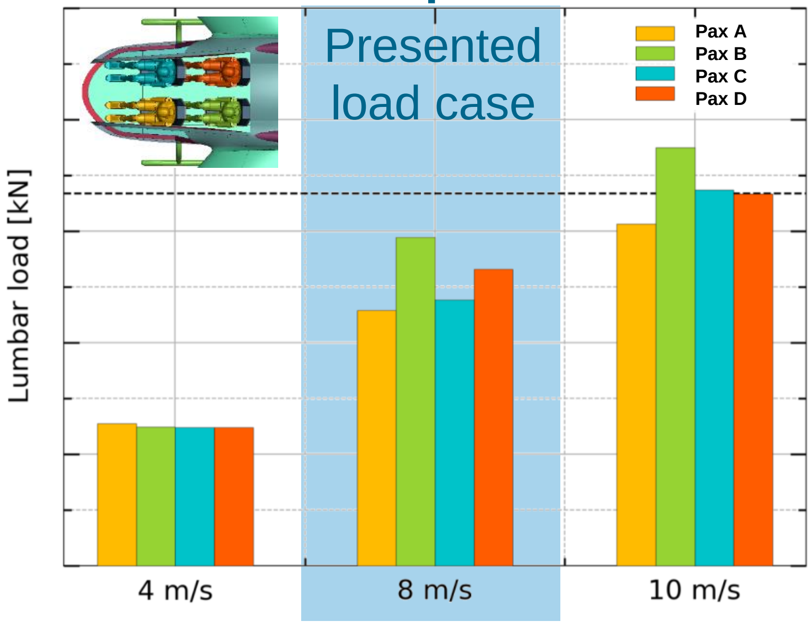
Simulation
- Model size (approx.): 375,000 nodes, 346,000 elements
- CPU time: 21-35 h (elapsed time) on 16 core processors (LS-Dyna)

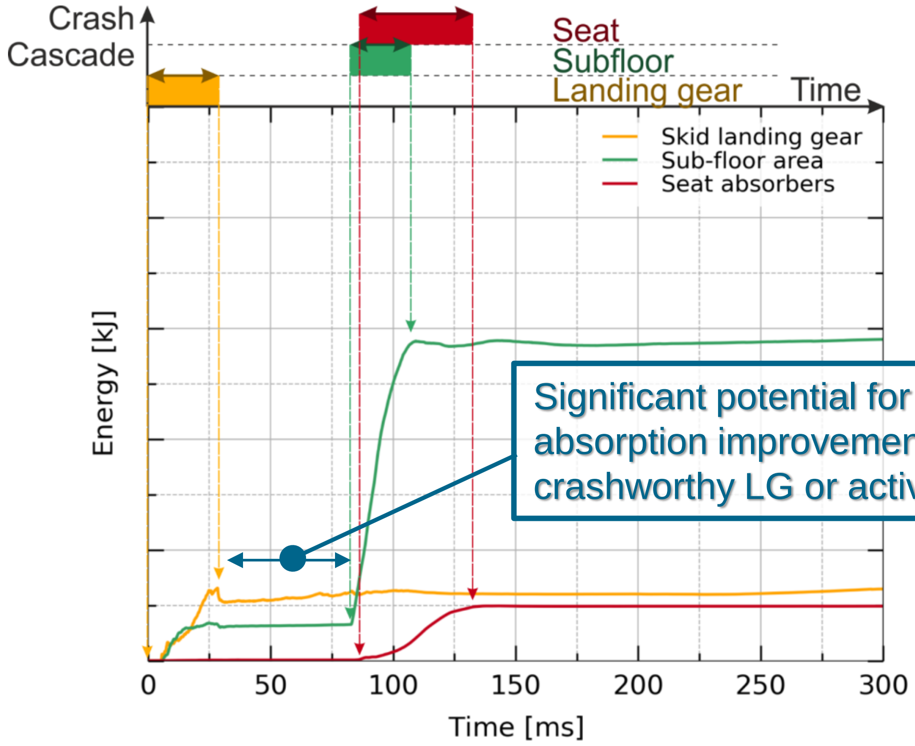
Preliminary design study

Results

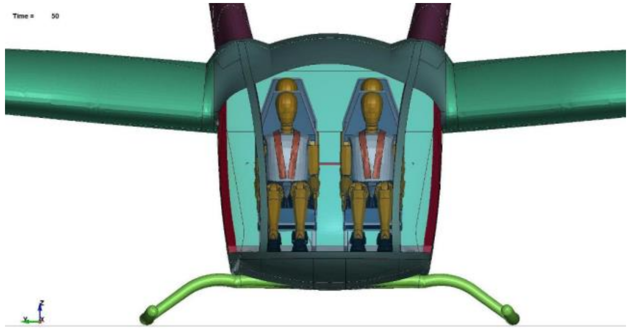
<u>Reference load case ‘D’</u> (v_z = 8 m/s, v_x = 0 m/s, on-axis, rigid surface)

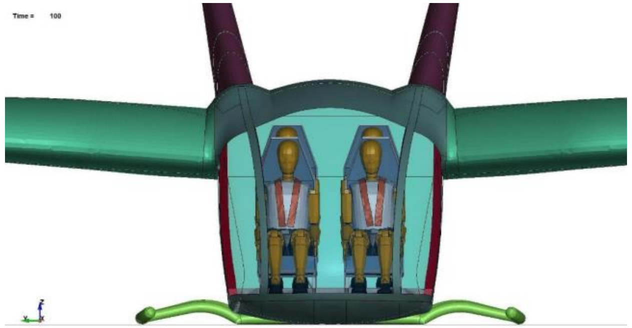
- **Crash cascade as expected**
  - Landing gear: Limited EA capacity due to conventional hard landing design
  - Subfloor: Symmetric crushing
  - Seat stroke: Approx. 110 mm
- **Acceptable injury risk beyond reference load case**

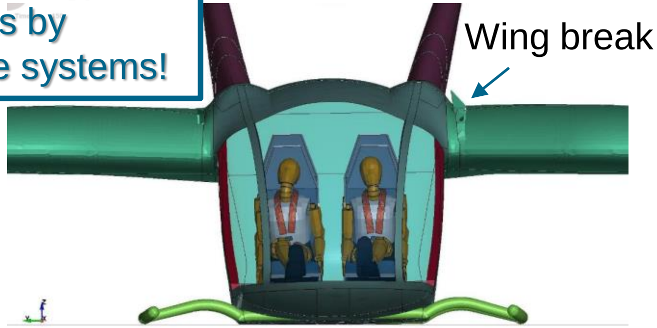




Significant potential for energy absorption improvements by crashworthy LG or active systems!





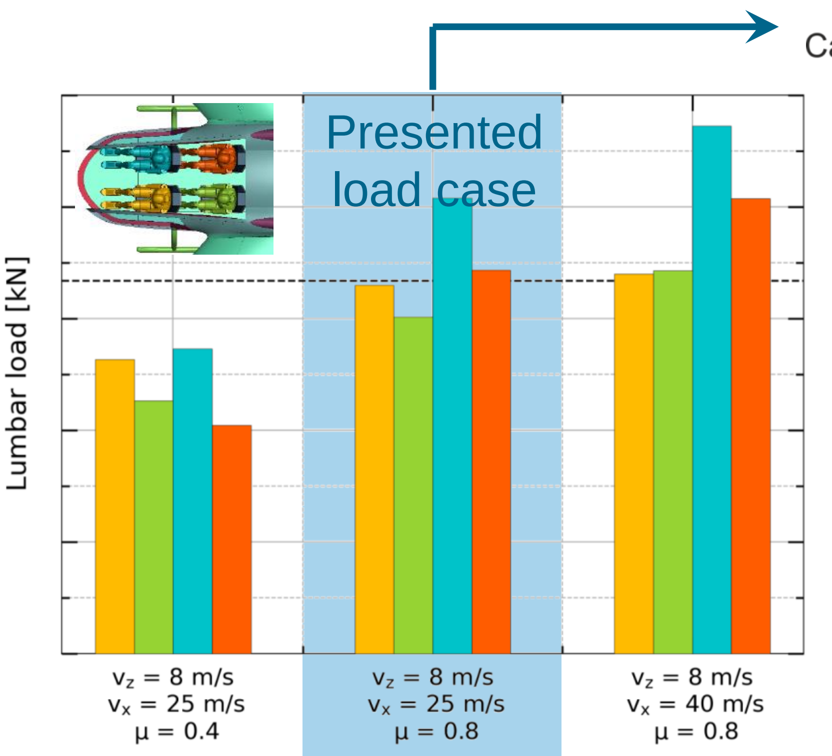


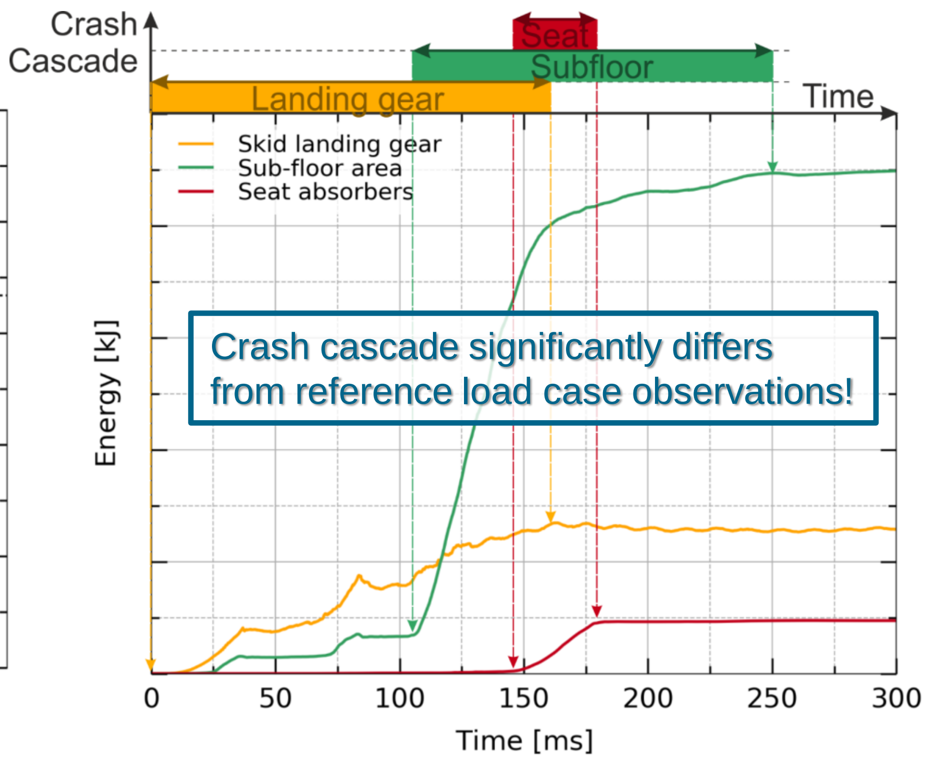
Preliminary design study
Results

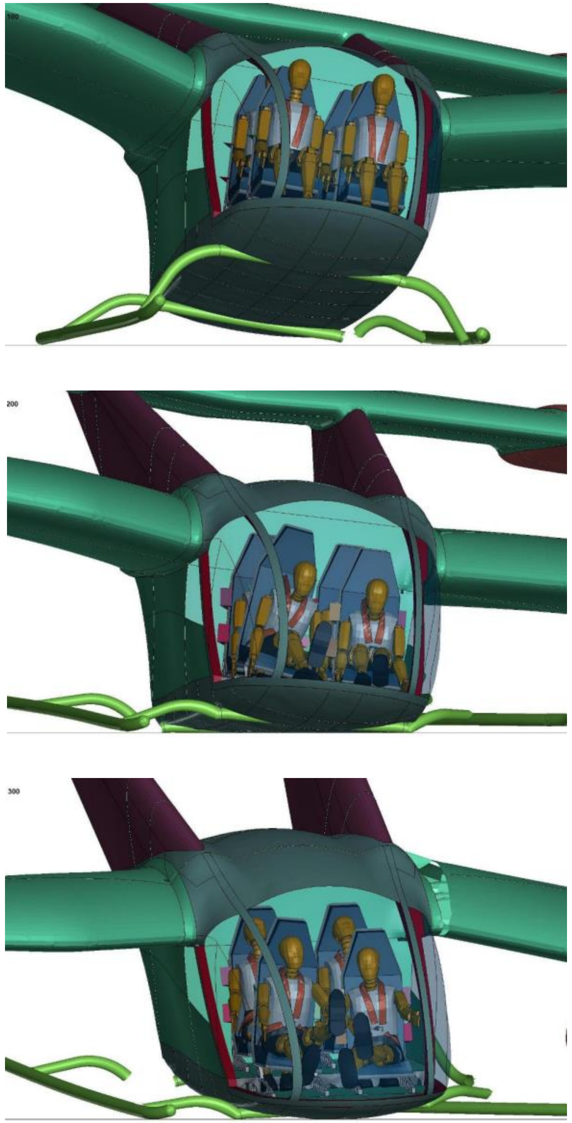
Robustness load case 'M' (v_z = 8 m/s, v_x = 25 m/s, off-axis, soft soil surrogate: μ = 0.8)

Severe (real-world) crash conditions for crashworthiness assessment beyond design load cases

- **Crash cascade significantly differs from reference load case observations**
  - Parallel activation and crushing of skid LG, subfloor structure and seat absorbers
  - Subfloor: Asymmetric crushing & 150% energy absorption compared to reference LC
- **Reasonable injury risk partly beyond limits**



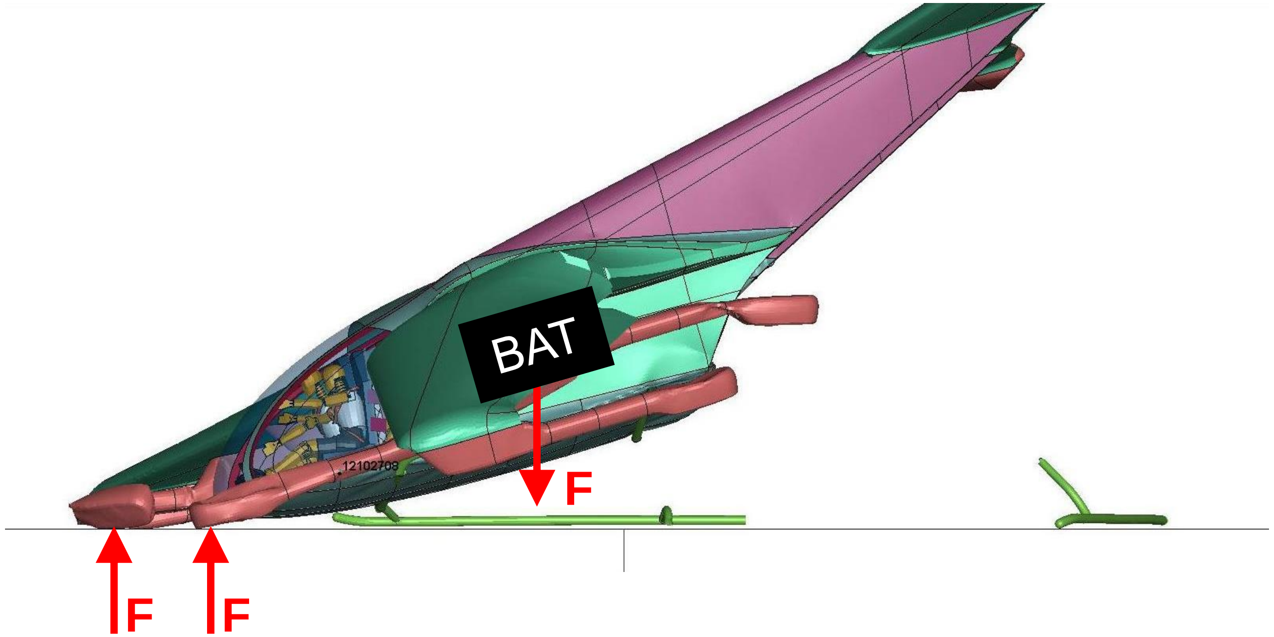




Preliminary design study
Results

Robustness load case 'M' (v_z = 8 m/s, v_x = 25 m/s, off-axis, soft soil surrogate: μ = 0.8)
Severe (real-world) crash conditions for crashworthiness assessment beyond design load cases

- **Extreme load case for high-wing configuration w.r.t. risk of rollover**
  - High horizontal impact speed: v_x = 40 m/s
  - High friction coefficient to introduce extreme horizontal loads (soft soil surrogate)
- **Assessment: eVTOL design characteristics are effective against risk of rollover**
  - Negative wing-sweep + engine beams
  - Heavy battery masses in the rear fuselage



Outcomes

Conceptual design

- **Non-traditional eVTOL vehicles & missions might require the consideration of a larger range of impact conditions**
  - to identify potential unfavorable vehicle crash performance
  - to develop proper design solutions already in the conceptual design
- **Simulation studies in the early design process can be useful to identify trends for reasonable crashworthiness**
  - beyond the design load cases
  - under complex crash impact conditions

Preliminary design

- **Consideration of robustness load cases (real-world impact conditions) showed significant influence on energy absorption management and crash cascade**
  - multi-axial: combined horizontal-vertical impact speeds and off-axis (roll, pitch, yaw)
  - multi-terrain: effect of high horizontal loads due to earth plowing

Outlook

Next steps: Detailed design solutions

eVTOL subfloor demonstrator (design & testing)

- Multi-terrain crashworthiness (rigid surface, soft soil, water)
- Off-axis robustness
- Combined horizontal/vertical impact conditions

Crashworthy battery integration

- Assessment of battery integration concepts
  - With respect to mechanical overloading (acceleration, deformation, intrusion)
- Development of design solutions
  - Prevent versus allow mechanical overloading (contained leakage and/or fire)
- Methods for efficient simulation of battery behavior (thermal runaway)

Thank you for your attention!

Acknowledgements

The authors wish to thank Martin Blacha, Christian Reichensperger and Stefan Boehnel from Airbus Helicopters for great collaboration in this research project.

Parts of the research leading to these results were accomplished in the framework of the 5th Aeronautical Research Program of the German Federal Ministry of Economic Affairs and Energy (BMWI) under grant 20W1715B, as part of the LuFo-V project HYBSH-SAVE.

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag