CRASHWORTHINESS DEMONSTRATION STRATEGY FOR LH2 TANK INTEGRATION

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CLEAN AVIATION

Co-funded by the European Union

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Overview

Motivation

Requirements & crashworthiness strategy

- Crashworthiness requirements (proposal)
- Guidelines for crash-resistant energy storage systems
- Building block approach
- Crash load cases (proposal)

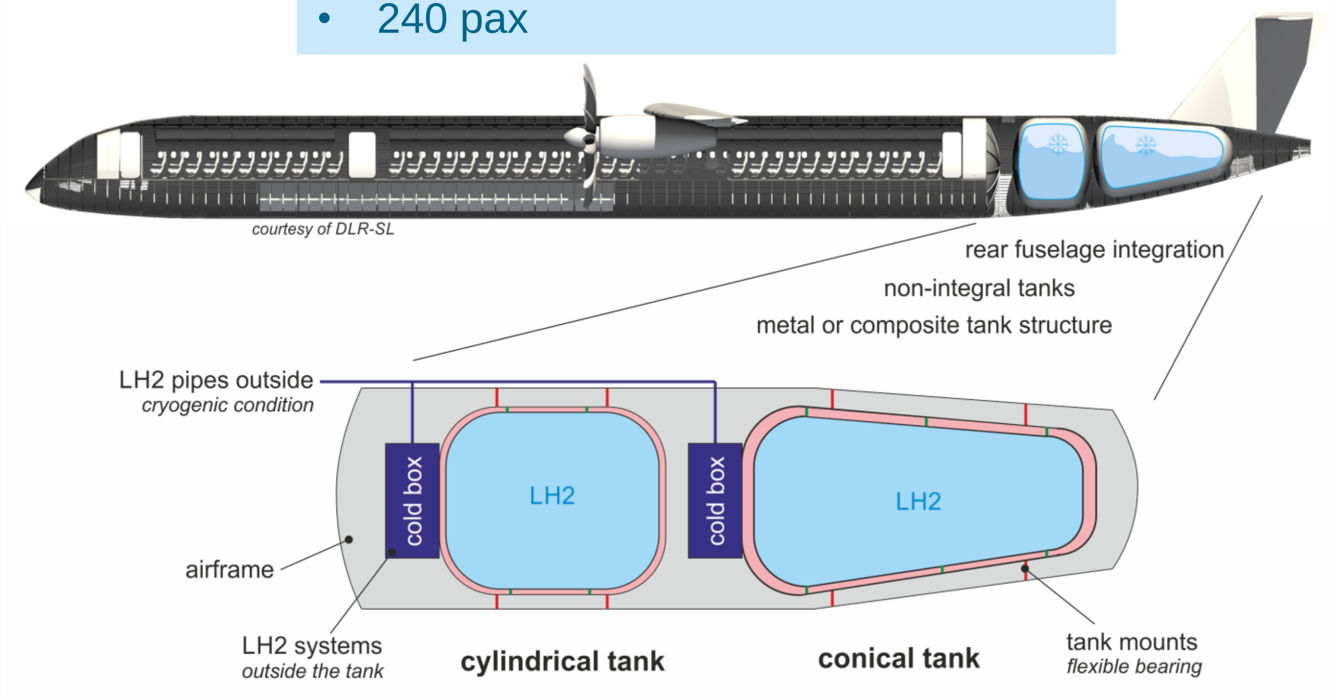
Simulation study

- Approach
- Model description
- Results

Summary

Outlook

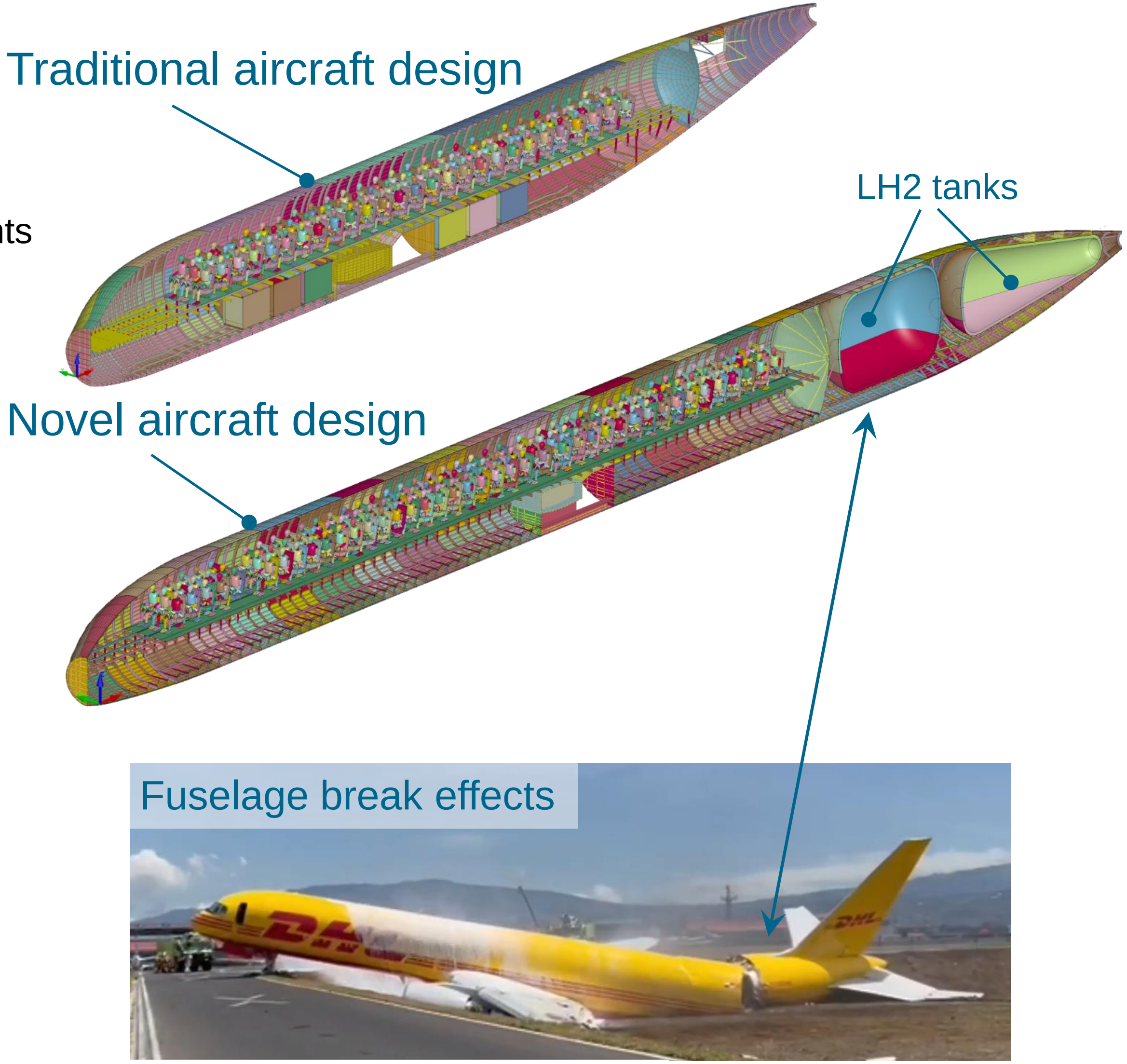
Context:
- LH2 tank rear fuselage installation
- Short/medium-range transport aircraft
- 240 pax



Motivation

Crashworthiness for novel aircraft with large LH2 tanks

- Large LH2 tanks, installed in the rear fuselage of transport aircraft, represent a novel overall aircraft design
- In case of emergency or crash landings an equivalent level of safety, compared to traditional aircraft designs, must be provided
- Due to the novelty of such aircraft designs, crashworthiness requirements (e.g. certification aspects) are not yet clarified
- Hence, initially a crashworthiness demonstration strategy had to be developed, which is comprised of
  - crashworthiness requirements for large LH2 tank integration
  - crashworthiness strategy based on the building block approach
  - crash load cases for compliance demonstration
- Full aircraft simulations are a key in this strategy as some crash safety aspects require full-scale considerations, e.g.
  - fuselage break effects
  - longitudinal crash loads
  - determination of local crash loads acting at the rear fuselage



[1] https://aviation-safety.net/database/record.php?id=20220407-0

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HYTAZER project

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Crashworthiness requirements (proposal)

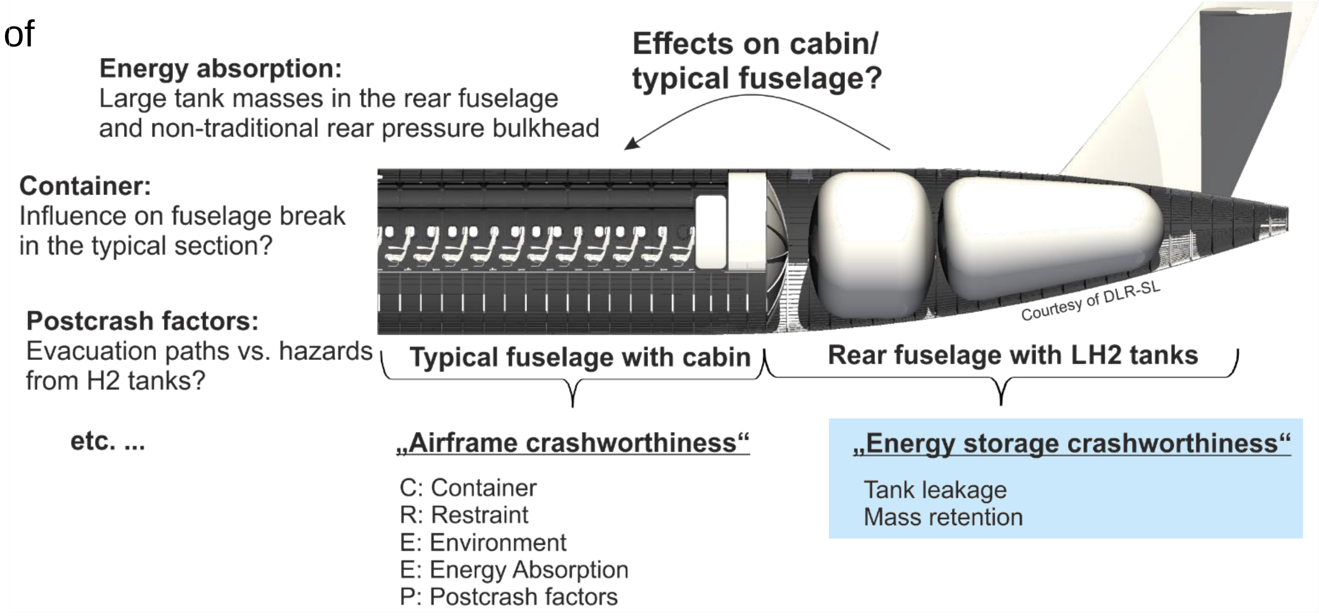
LH2 tank integration into transport airplanes

Energy storage crashworthiness

- Final aim: Occupant survivability

Main categories

- Mass retention
  - Prevent hazardous conditions caused by breaking loose of large items of mass (LH2 tank behind the cabin)
    - ➢ Robust tank mount solutions, capable to sustain longitudinal crash loads after first crash impact
- Tank leakage
  - Limit accelerations
    - ➢ Sufficient crash stroke required!
  - Prevent local intrusions
    - ➢ Proper tank surrounding structure required!
  - Prevent mechanical deformations
    - ➢ Proper crash kinematics required!

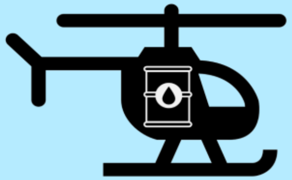


Certification aspects

- Special conditions (SC), that align with existing CS and SCs, are expected
  (e.g. CS25, SC-E25.963-01, SC 25-537-SC, ARAC TACDWG)

Crashworthiness

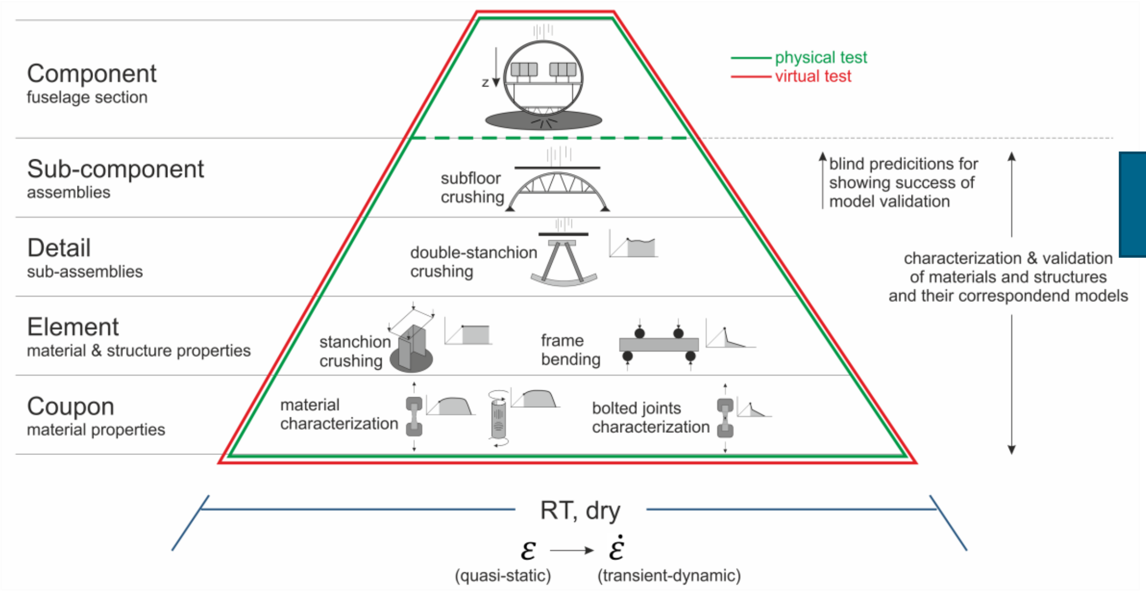
Crash-Resistant LH2 System

Crash-Resistant **Energy Storage** System Guidelines	 Crash-Resistant **FUEL** System (CRFS)	 Crash-Resistant **LH2** System ($CRLH_2S$)
Main Objective:	**Prevent Leakage**	**Prevent Leakage,** Mass Retention
Spatial Arrangement:	- Installation area relative to crash zone (tank overloading) and cabin area (mass retention) - Spatial separation of energy storage and occupants (e.g. bulkheads, vents, fire walls)	
Systems Approach		
Surrounding structure: Ultimate strength & failure behavior	- Resist ultimate inertia forces and provide proper failure behavior to prevent puncture and rupture	- Resist ultimate inertia forces and provide proper failure behavior to prevent puncture and rupture
Energy storage: Frangible / deformable attachment	- Design attachment to prevent rupture or local tear-out of fuel tank attachments and fuel system components	- Tank mount and surrounding airframe structure designed for mass retention and load attenuation
Distribution system: Frangible / deformable cables & hoses	- Reinforced installation areas - (Self-sealing) breakaway couplings and mounts - Flexible / reinforced / extra long cables and hoses	- Reinforced installation areas - (Self-sealing) breakaway couplings and mounts - Flexible / reinforced / extra long cables and pipes
Energy storage: Impact and tear resistance	- Fuel tank bladder material impact, cut and tear resistant	- Crashworthy tank design with impact, cut and tear resistance regarding true crash loads beyond CS-25.561
Ignition source control	- Spatial separation of fuel tank and ignition sources - De-energizing / Shielding electrical sources - Inerting hot surfaces	- Crashworthy vent pipe to discharge boil off - Spatial separation of LH2 and ignition sources - De-energizing / shielding electrical sources

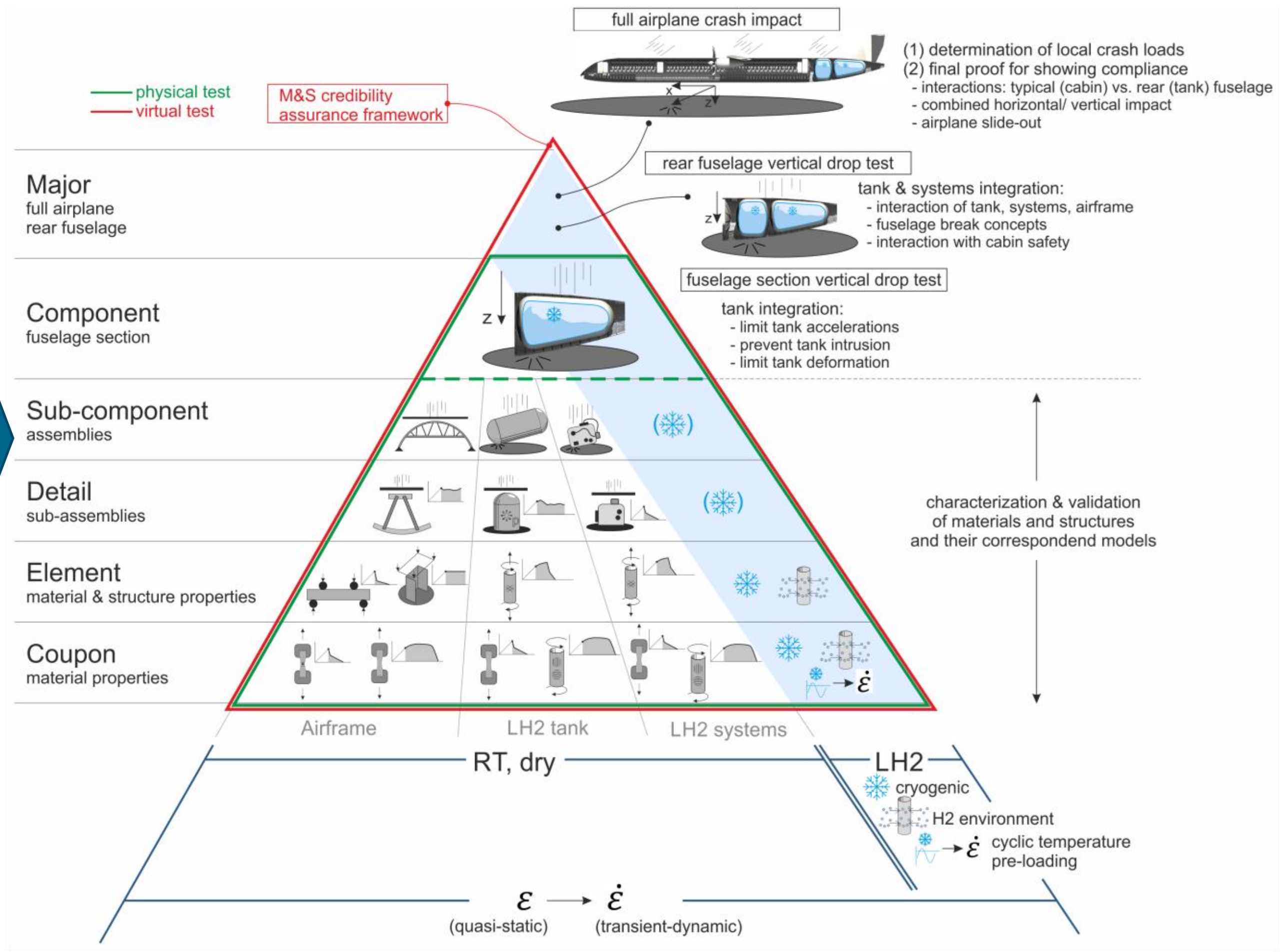
Building block approach

Proposal of a crashworthiness strategy for LH2 tank integration into transport airplane

Classical crashworthiness building block approach



Proposed approach for LH2 tank integration



Crash load cases (proposal)

LH2 tank integration into transport airplanes

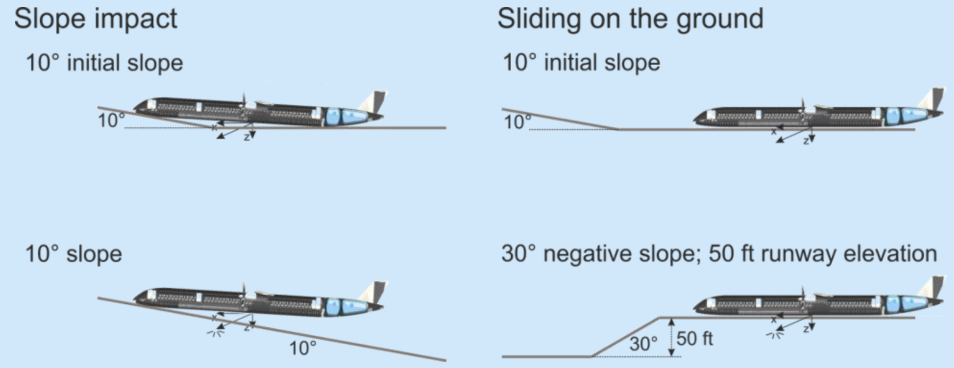
Categories

- Fuselage section: Fuel tank integrity drop test
  - Crash kinematics and general performance
  - Crash energy absorption management
- Airplane level crash impact
  - Combined horizontal / vertical crash loading
  - Impact into sloped terrain
  - Fuselage break effects
  - Robustness under realistic crash conditions
- Airplane level sliding on the ground
  - Sliding on the ground (different LG configurations)
  - Sliding into sloped terrain
  - Obstacles

Categories			Load cases
fuel tank integrity drop test (fuselage section drop test)	beyond minor crash landing	various impact speeds	
		various impact energies	
		robustness	
airplane level crash impact	minor crash landing	minor crash landing	
	beyond minor crash landing	Vzmax crash landing (variations as for minor crash landing)	
		various impact speeds (LG extended)	
		robustness	
		slope impact	
		fuselage break	
airplane level sliding on the ground	minor crash landing	sliding on the ground	
		LG failure	
		engine failure	
	beyond minor crash landing	sliding on the ground	
		LG failure	
		engine failure	
		slope	
		terrain	

Load cases based on proposed crashworthiness requirements

Load case parameters:
Vz; Vx; Landing gear configuration; Aircraft mass; Payload (pax / cargo); Fuel states; Pitch angle; Roll angle; Yaw angle; Terrain (hard / soft); Terrain (flat / sloped); Obstacles: Loss of LG; Obstacles: Loss of engine



Crash load cases (proposal)

LH2 tank integration into transport airplanes

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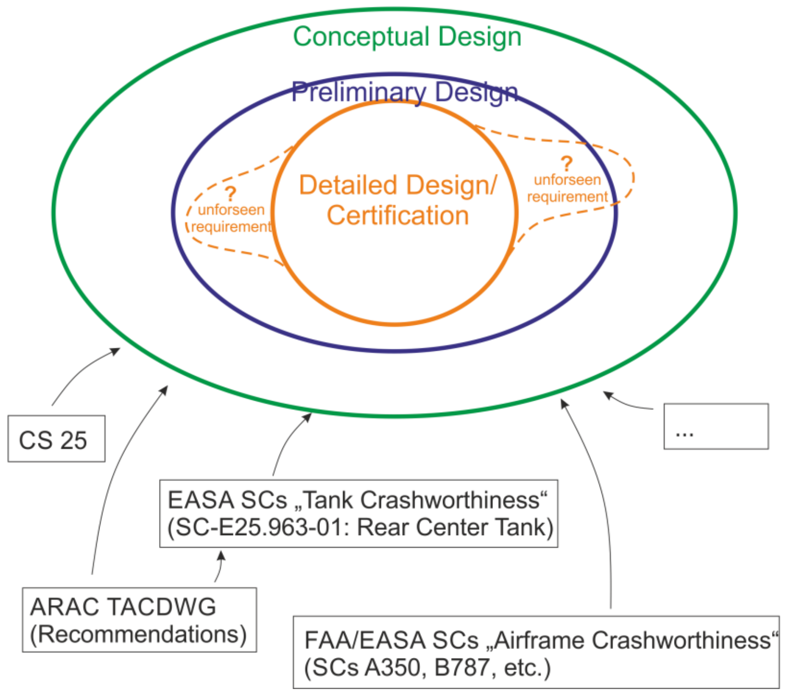
Selected load cases presented in this conceptual design study:

- **Fuselage section – Vertical crash impact**
  - v_z = 30 ft/s (9.1 m/s) , φ = 5.25° (pitch angle)
  - Based on EASA/FAA SCs and drop tests performed in the past
- **Fuselage section - Horizontal crash pulse**
  - Triangular pulse with 18g peak
  - Based on EASA CS25.562 + safety margin (conceptual design)
- **Airplane level – Combined crash impact**
  - v_z = 30 ft/s (9.1 m/s), v_x = 262 ft/s (80 m/s), φ = 5.25° (pitch angle)
  - Based on historical research data [7]

Load cases selected from a scientific point of view, and with regard to conceptual design studies:

Envelope of crashworthiness requirements & load cases:



[7] G. Wittlin and B. LaBarge, "KRASH dynamics analysis modeling - transport airplane controlled impact demonstration test," DOT/FAA/CT-85/9, 1985, Available: https://apps.dtic.mil/sti/tr/pdf/ADA168975.pdf.

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FASTER H2

Clean Aviation project

HYTAZER DLR

DLR project

Summary

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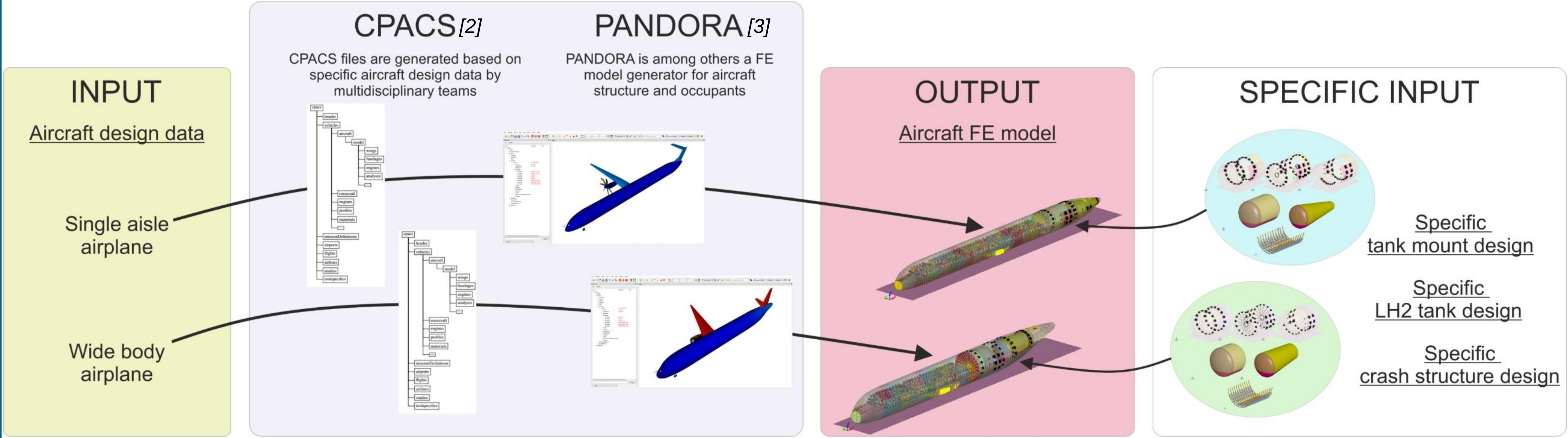
Approach

Process chain tool for full aircraft crash simulation



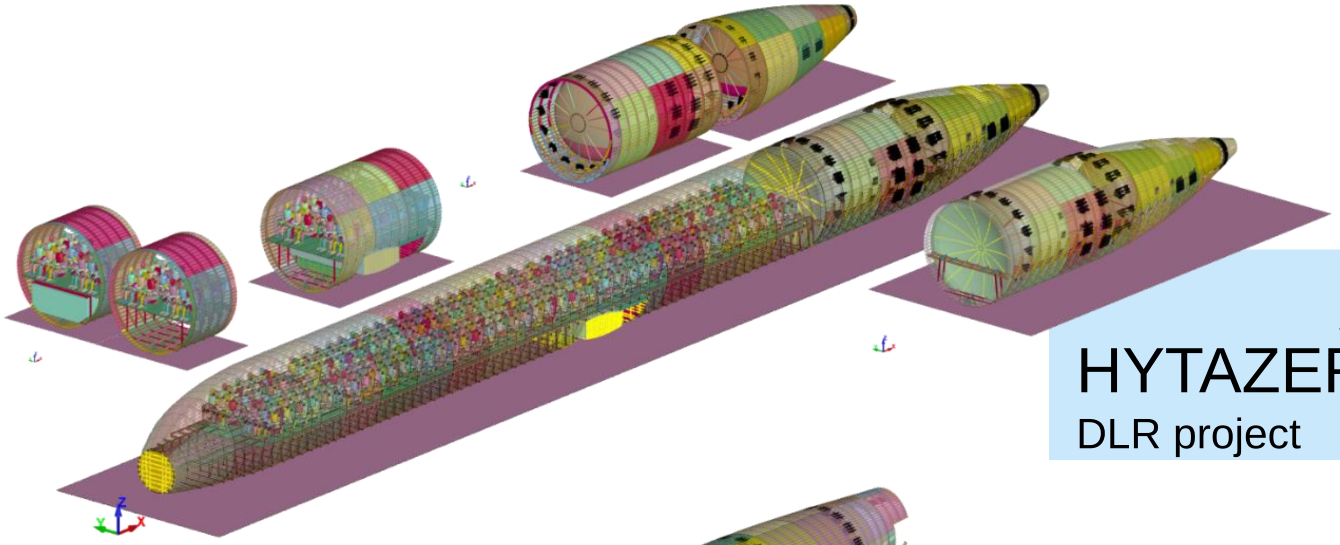
[2] M. Alder, E. Moerland, J. Jepsen, and B. Nagel, "Recent Advances in Establishing a Common Language for Aircraft Design with CPACS," presented at the Aerospace Europe Conference 2020, Bordeaux, Frankreich, 2020. Available: https://elib.dlr.de/134341/
[3] M. Petsch, D. Kohlgrüber, and J. Heubischl, "PANDORA - A python based framework for modelling and structural sizing of transport aircraft," presented at the 8th EASN-CEAS International Workshop, Glasgow, Schottland, 2018. Available: https://elib.dlr.de/124181/
[4] J.-N. Walther, C. Hesse, J. Biedermann, and B. Nagel, "Extensible aircraft fuselage model generation for a multidisciplinary, multi-fidelity context," presented at the ICAS 2022, Stockholm, Schweden, 2022. Available: https://elib.dlr.de/189459/

Model description

Overview

Single aisle aircraft

- Short/medium range aircraft
- Design range: 1500 nm (2778 km)
- Passengers: ≈ 240 (6 seats abreast)
- Configuration from EXACT project [8]

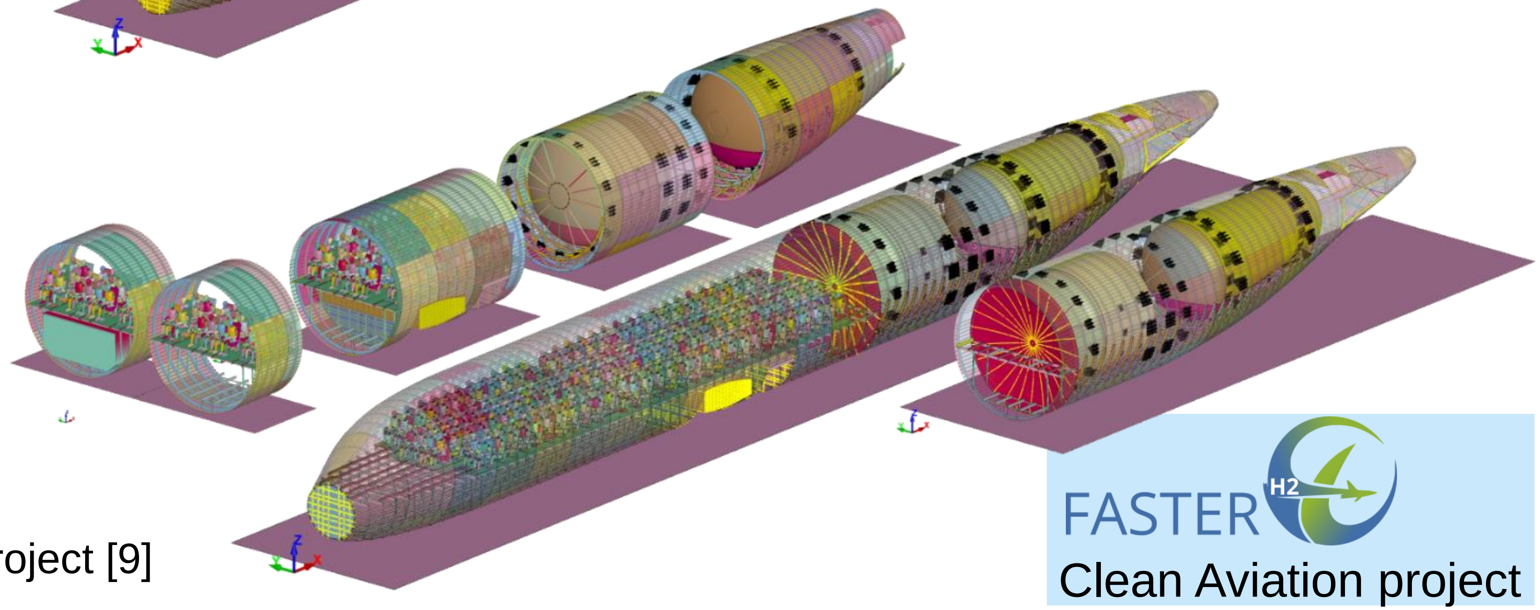


HYTAZER DLR

DLR project

Wide body aircraft

- Medium range aircraft
- Design range: 2500 nm (4630 km)
- Passengers: ≈ 240 (8 seats abreast)
- Configuration from Clean Aviation ACAP project [9]



FASTER H2

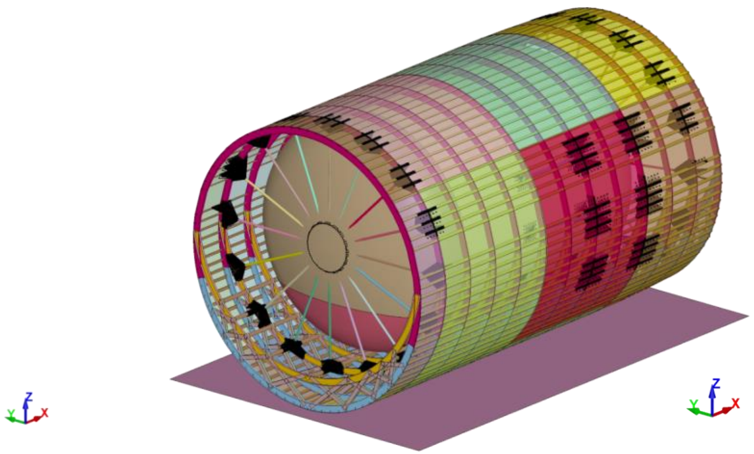
Clean Aviation project

[5] T. Burschyk, D. Silberhorn, J. Wehrspohn, M. Kühlen, and T. Zill, "Scenario-based implications of liquid hydrogen storage tank insulation quality for a short-range aircraft concept," presented at the AIAA Aviation 2023 Forum, San Diego, USA, 2023. Available: https://elib.dlr.de/199226/
[6] European Union, "Clean Aviation Joint Undertaking - Work programme and budget 2024-2025," https://clean-aviation.eu/sites/default/files/2024-01/Work-Programme-and-Budget-2024-2025-December-2023.pdf (accessed Sep 2024),

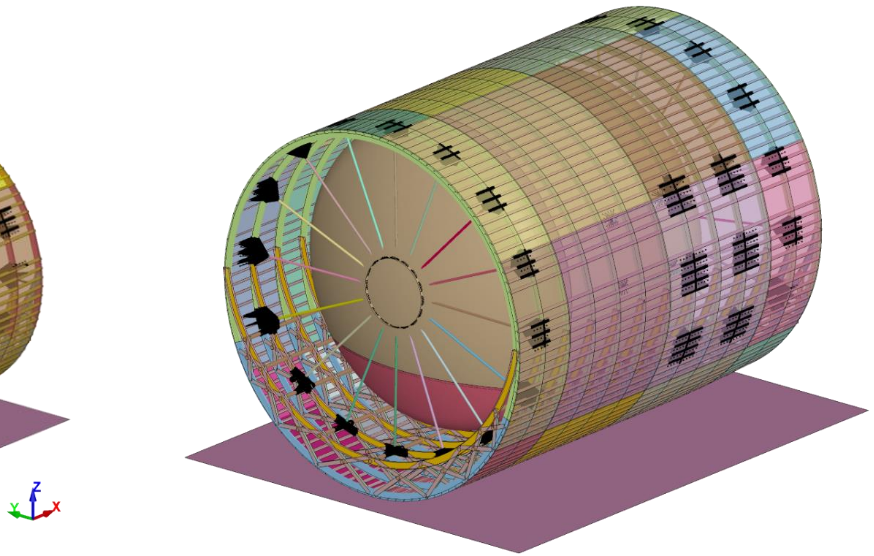
Model description
Masses

Forward LH2 tank is focused in this presentation!

Single aisle aircraft



Wide body aircraft

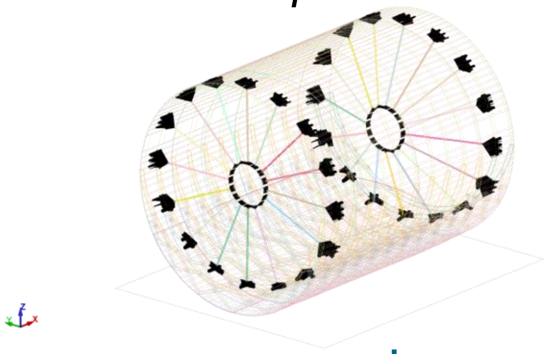


	Single aisle aircraft	Wide body aircraft
LH2 tank volume [m³]	≈ 31	≈ 45
Outer tank diameter [m]	≈ 3.4	≈ 4.5
Structural tank mass [kg]	≈ 2500	≈ 4500
Total tank mass [kg]	≈ 4700	≈ 7700
Fuselage section length [m]	≈ 6.5	≈ 6.5
Total fuselage section mass [kg]	≈ 6000	≈ 9600

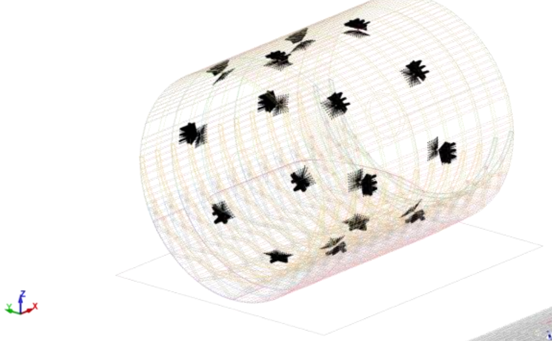
Model description
LH2 tank integration concept

Different tank mount configurations were analysed:

Spoke

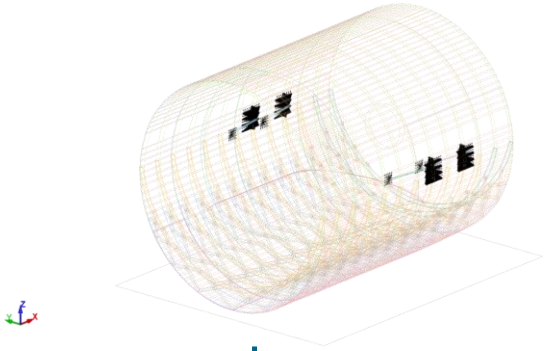


Standard

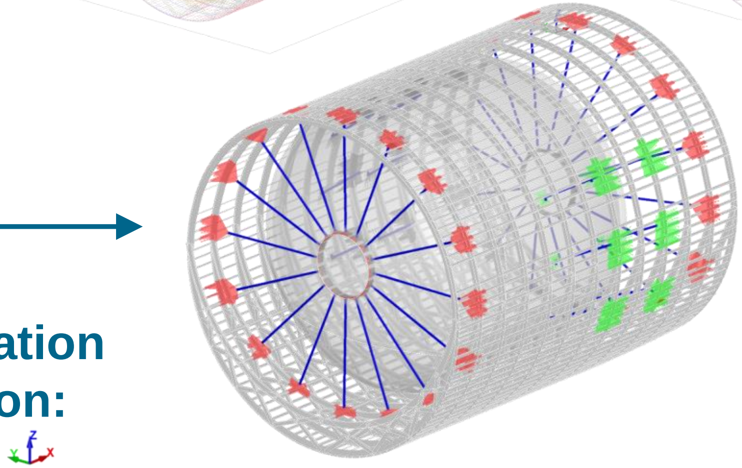


Palette

X-rod



Selected configuration for this presentation:



Spoke / *X-rod*

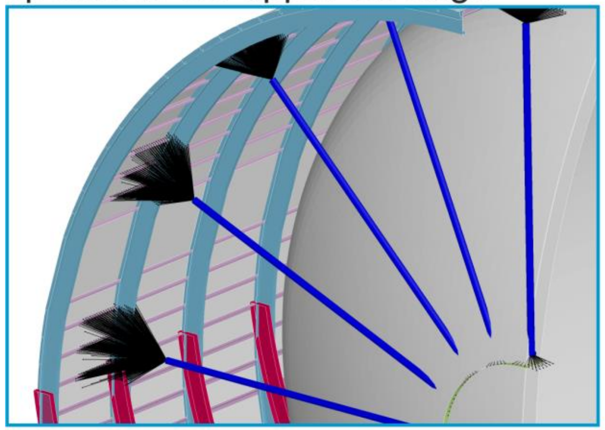
Spokes:
- Main tank mount structure
- Vertical crash loads

X-rods:
- Horizontal crash loads

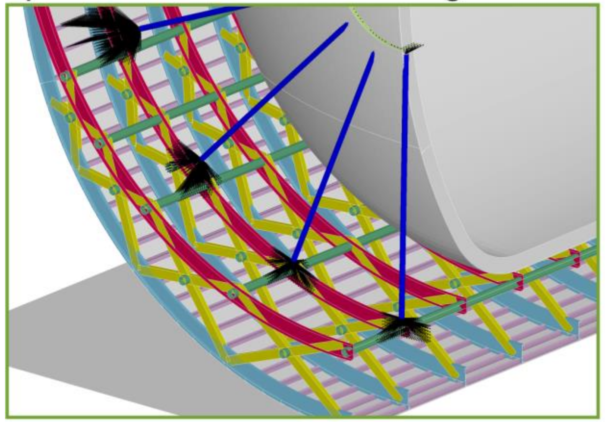
Model description

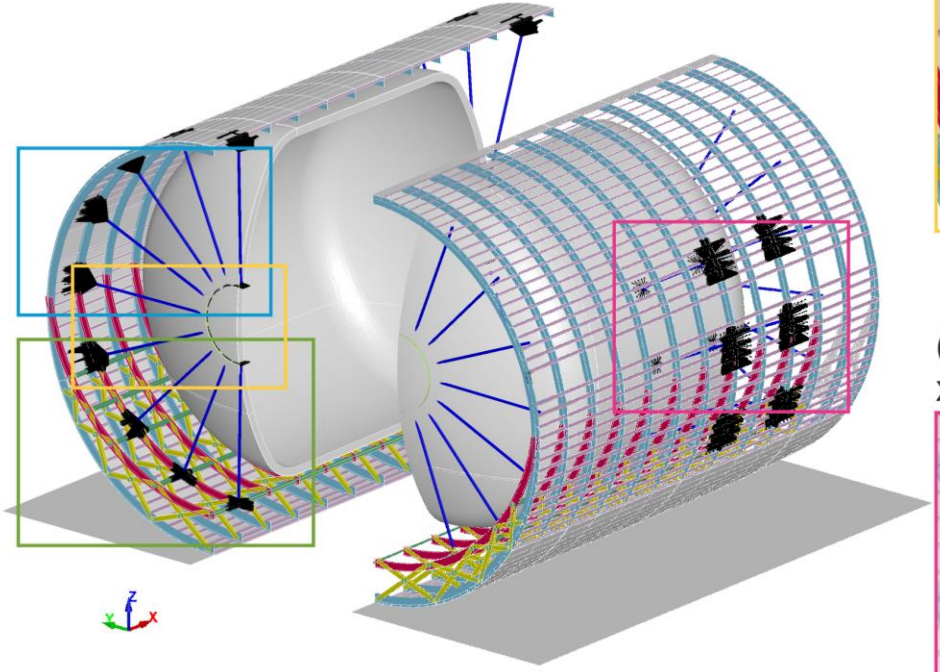
LH2 tank integration concept

(A) Attachment of the
spokes to the upper fuselage

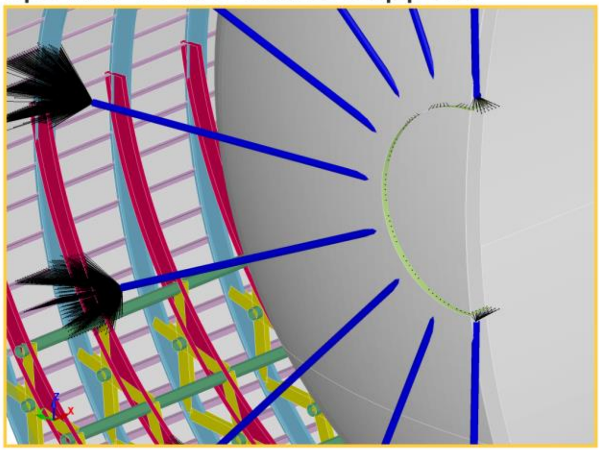


(B) Attachment of the
spokes to the lower fuselage

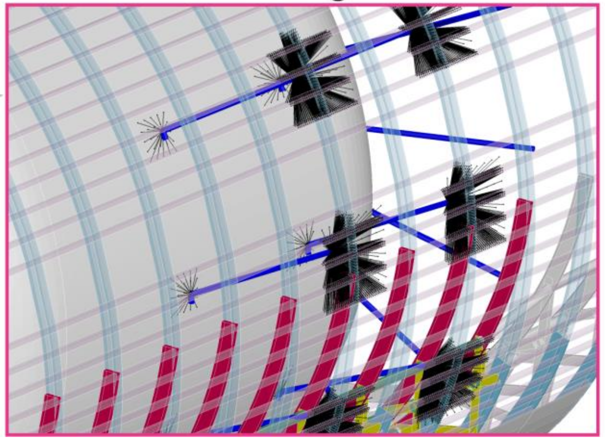




(C) Attachment of the
spokes to the dome support



(D) Attachment of the
x-rods to the fuselage and LH2 tank

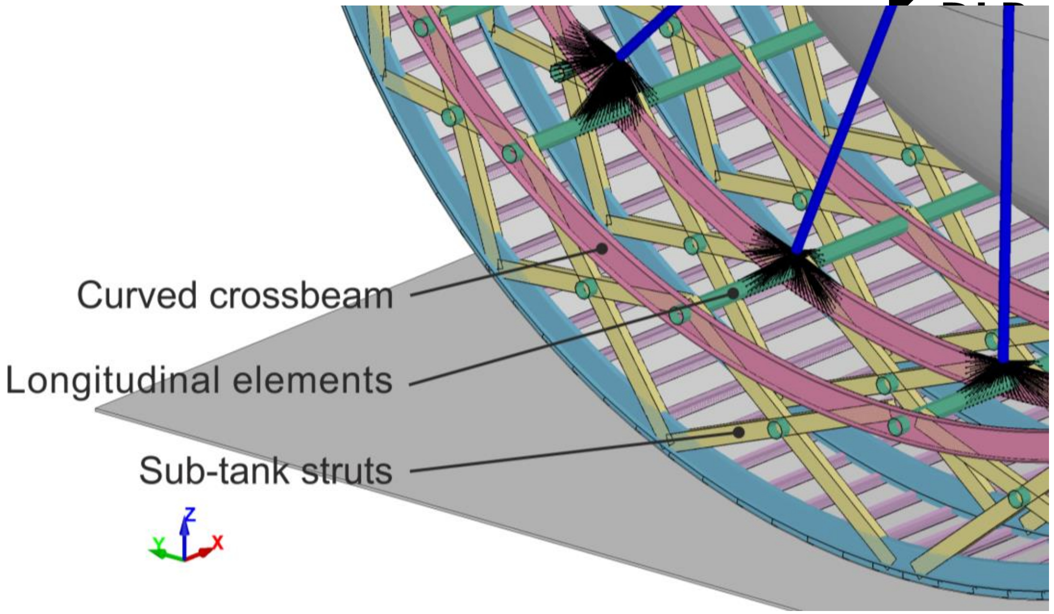


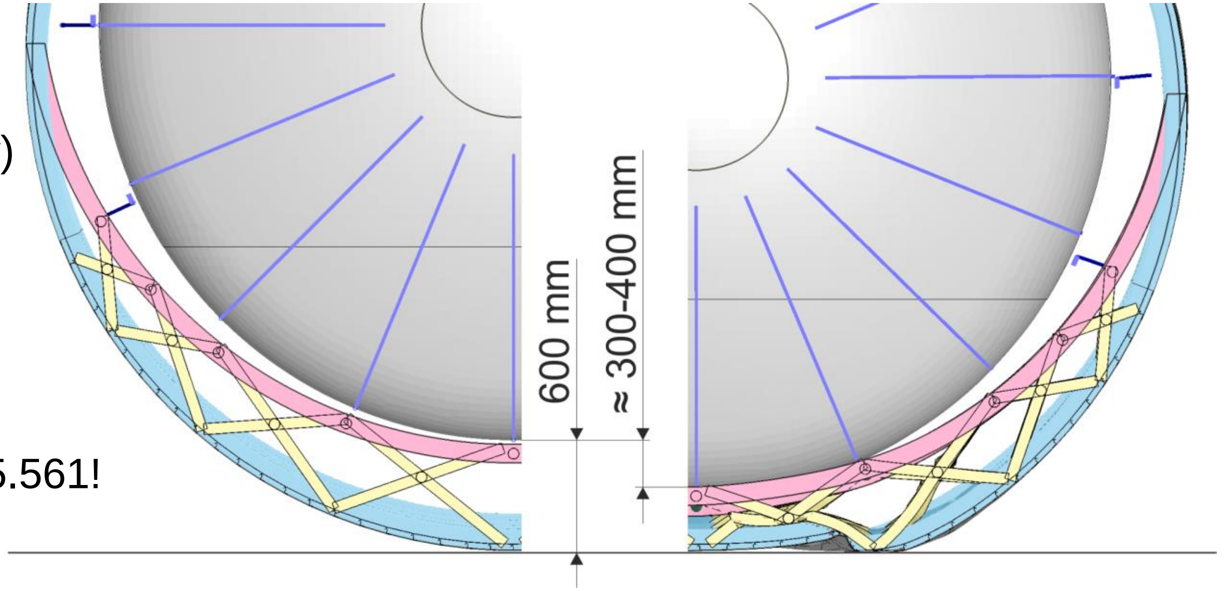
Attachment modelling:
*CONSTRAINED_INTERPOLATION (LS-Dyna)

Model description
Sub-tank crushing structure

Crash kinematics

- The sub-tank framework consists of
  - Curved crossbeam: withstands crushing loads from the sub-tank struts and protects the LH2 tank
  - Sub-tank struts: absorb kinetic energy during the impact
  - Longitudinal elements: stabilize the curved crossbeam and sub-tank struts under vertical loads and transfer the tank inertia under horizontal loads
- The sub-tank struts are arranged tangentially to the tank surface to minimize the risk of tank penetration
- The max. distance between LH2 tank surface and fuselage skin is 530 mm (single aisle) - 600 mm (wide body)
- However, available crush distance is ≈ 300-400 mm
- Assuming ideal constant deceleration and an impact velocity of v_z = 30 ft/s (9.1 m/s), the theoretical minimum tank acceleration is 14.2g – 10.6g
  - The tank crash sizing requirement exceeds 6g from 25.561!



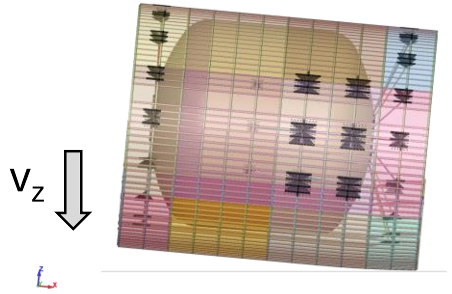


Model description

Load cases

Selected load cases presented in this conceptual design study:

- **Fuselage section – Vertical crash impact**
  - v_z = 30 ft/s (9.1 m/s) , φ = 5.25° (pitch angle)
  - Based on EASA/FAA SCs and drop tests performed in the past



- **Fuselage section - Horizontal crash pulse**
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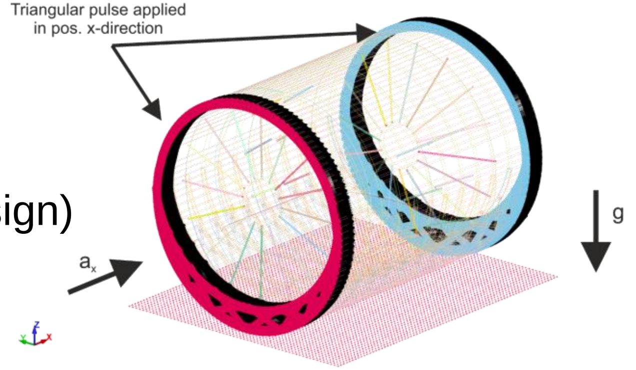

- **Airplane level – Combined crash impact**
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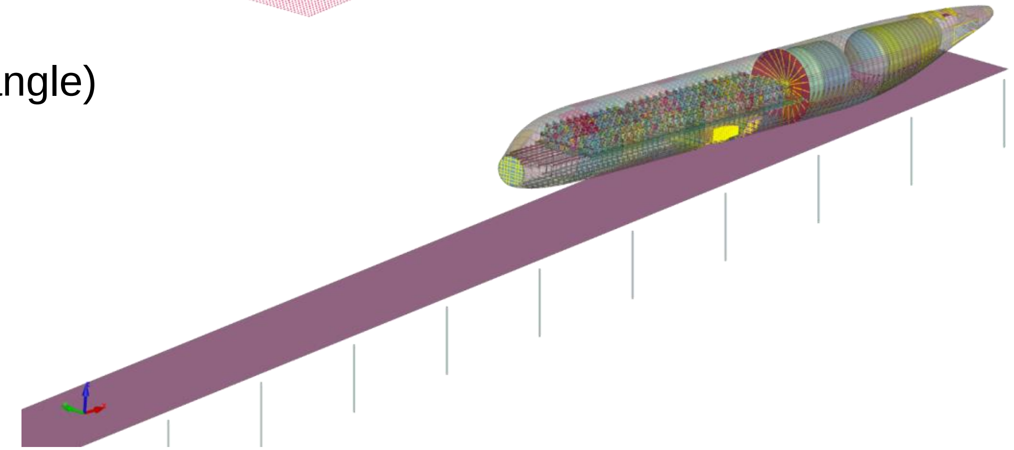


[7] G. Wittlin and B. LaBarge, "KRASH dynamics analysis modeling - transport airplane controlled impact demonstration test," DOT/FAA/CT-85/9, 1985, Available: https://apps.dtic.mil/sti/tr/pdf/ADA168975.pdf.

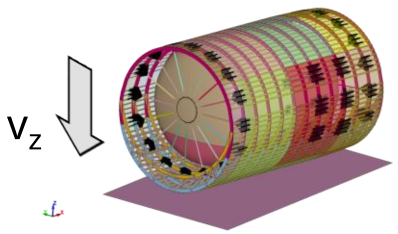
Results

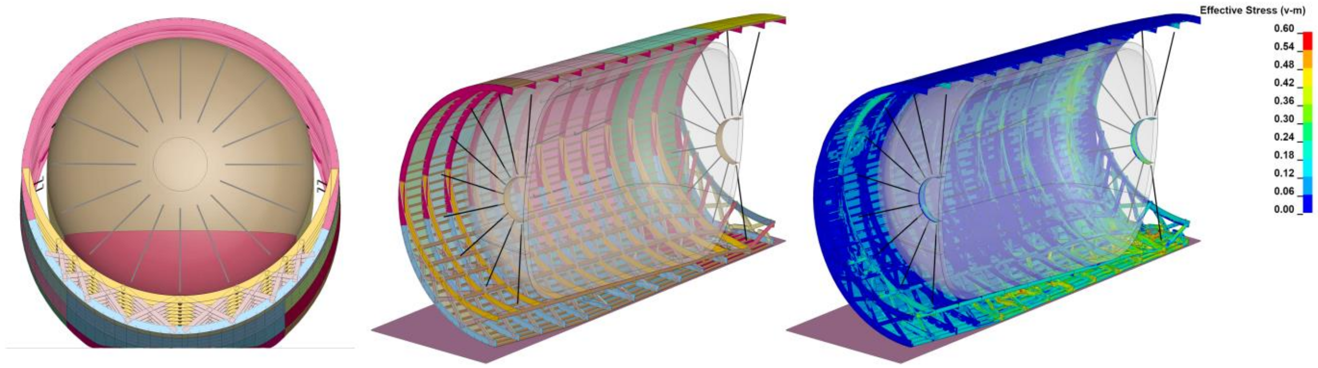
Forward tank section with cylindrical LH2 tank

Vertical load case

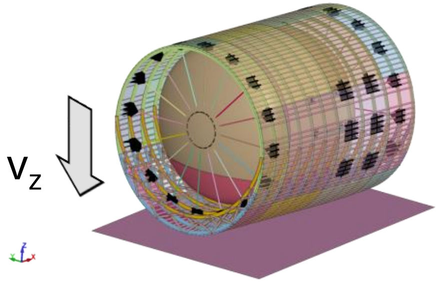
- v_z = 30 ft/s (9.1 m/s), φ = 5.25° (pitch angle)

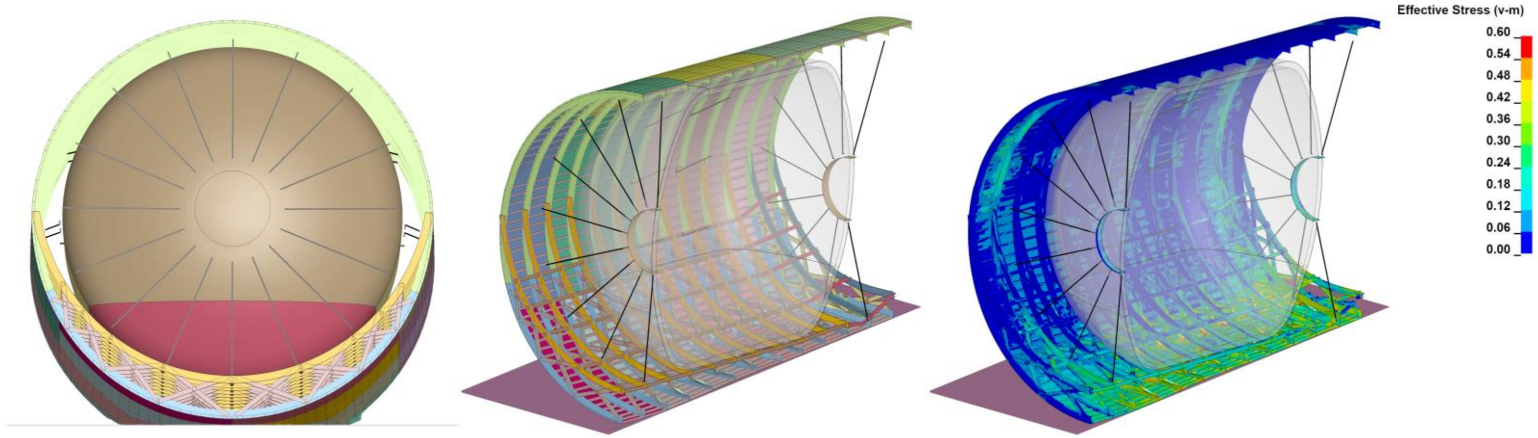
Single aisle aircraft





Wide body aircraft

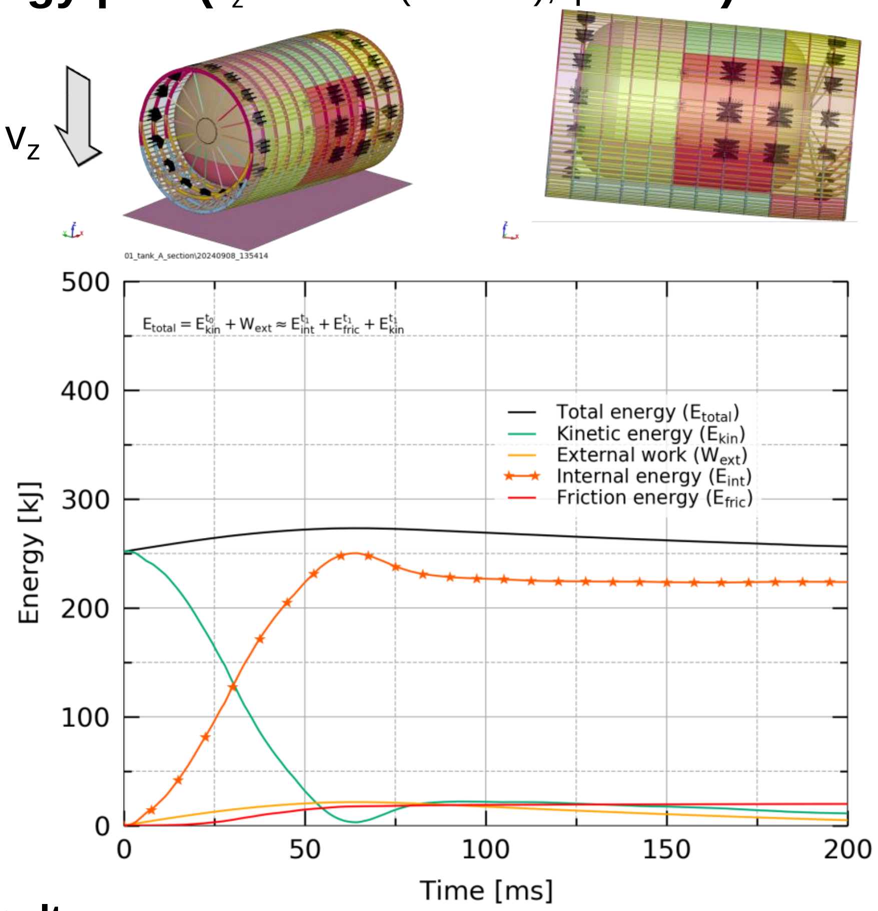


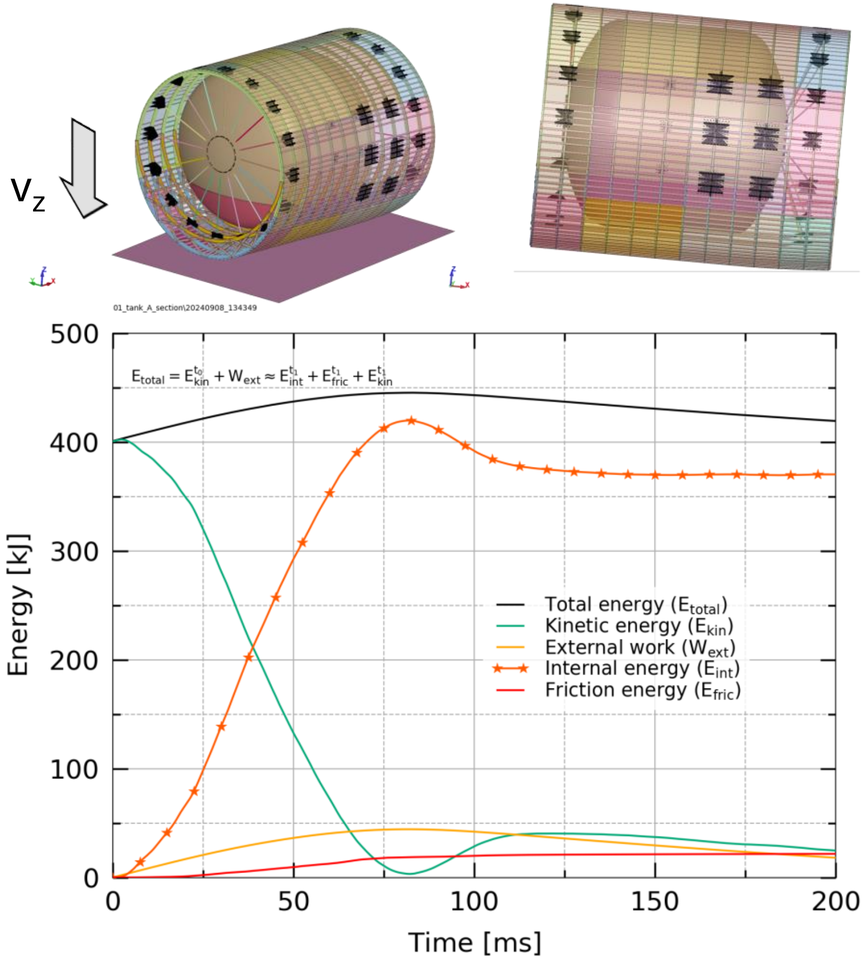


Results

Forward tank section with cylindrical LH2 tank

Energy plot (v_z = 30 ft/s (9.1 m/s), φ = 5.25°)





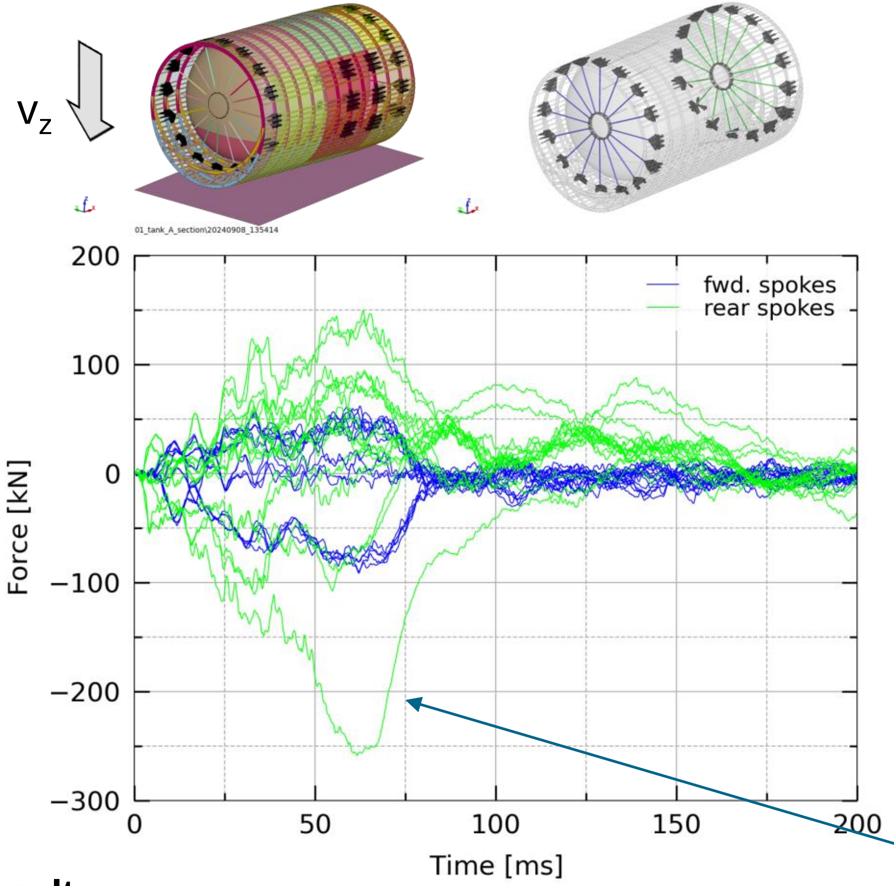
Result:

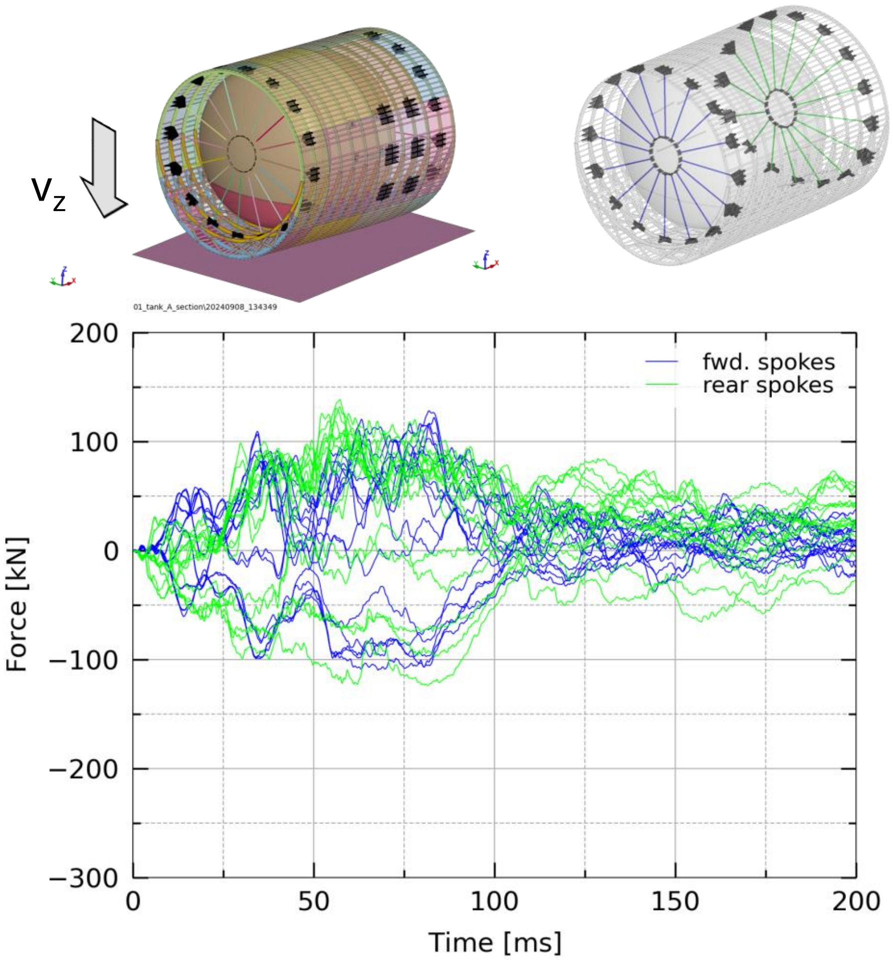
- Same crash kinematics for both A/C sizes
- Significantly higher crash energy for wide body A/C due to higher masses

Results

Forward tank section with cylindrical LH2 tank

Spoke forces (v_z = 30 ft/s (9.1 m/s) , φ = 5.25°**)**





Result:
- Similar range of spoke forces for both A/C sizes
- Non-zero pitch angle resulted in full stroke of rear sub-tank structure and high force in central spoke due to direct impact

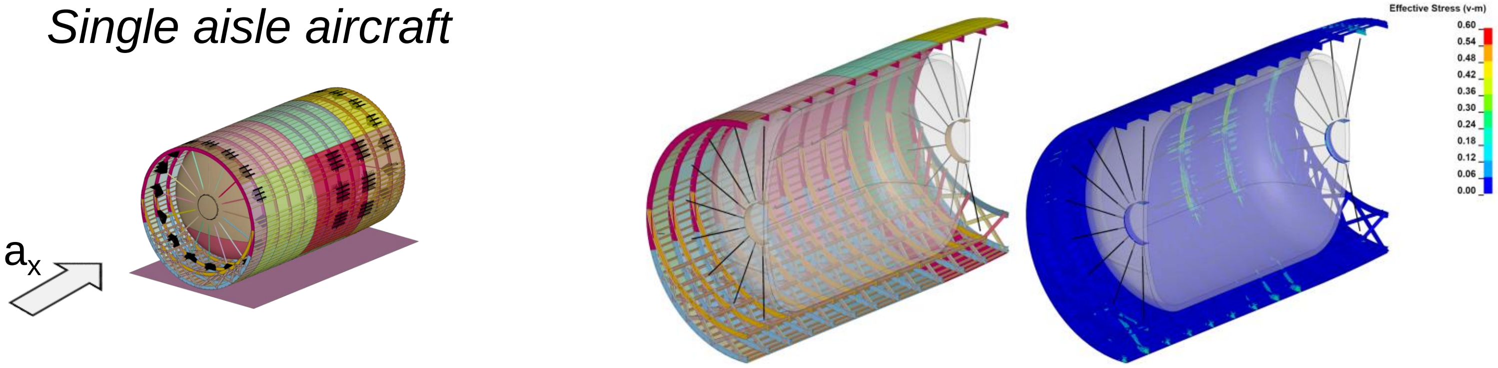
Results

Forward tank section with cylindrical LH2 tank

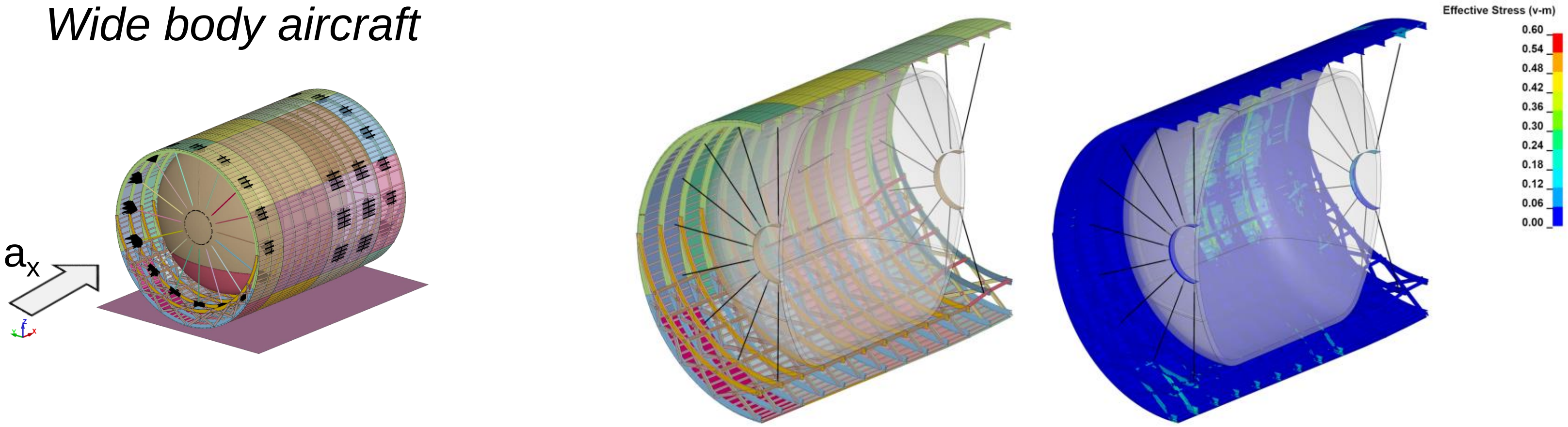
Horizontal load case

- 18g triangular pulse

Single aisle aircraft



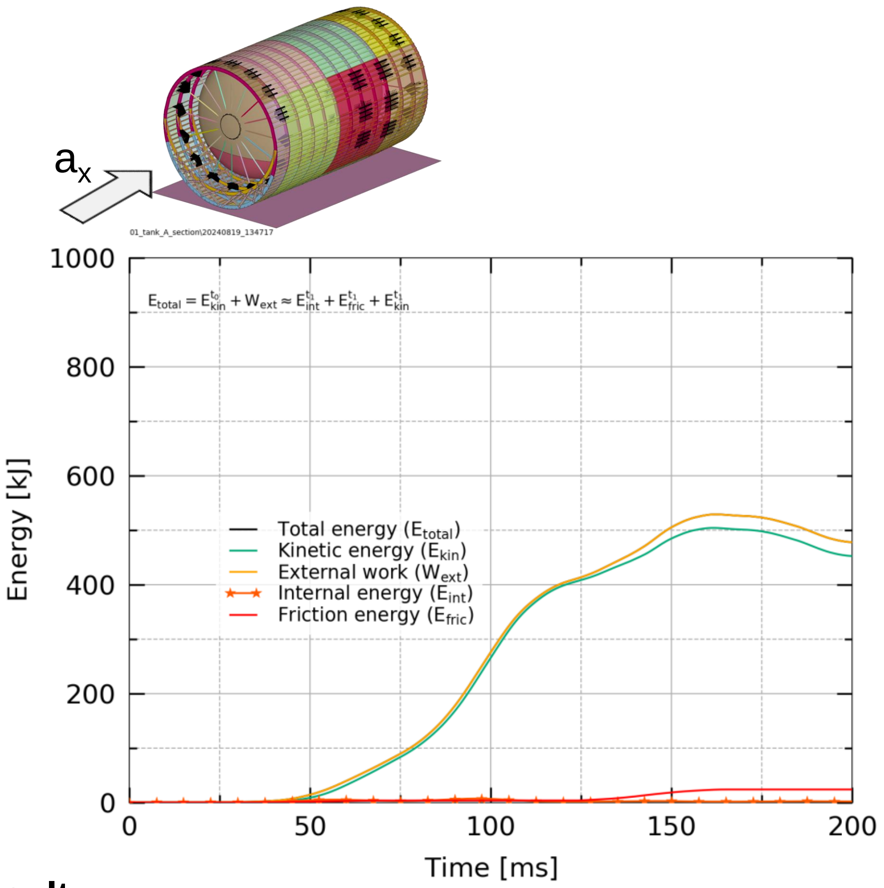
Wide body aircraft

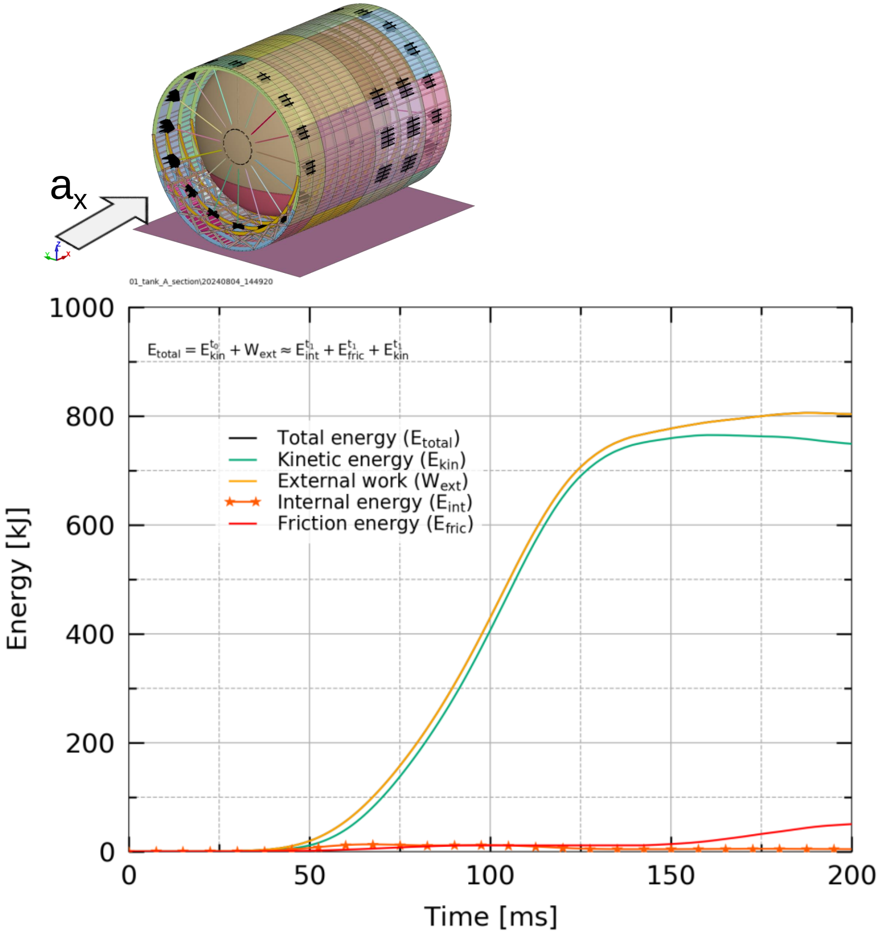


Results

Forward tank section with cylindrical LH2 tank

Energy plot (18g triangular pulse)



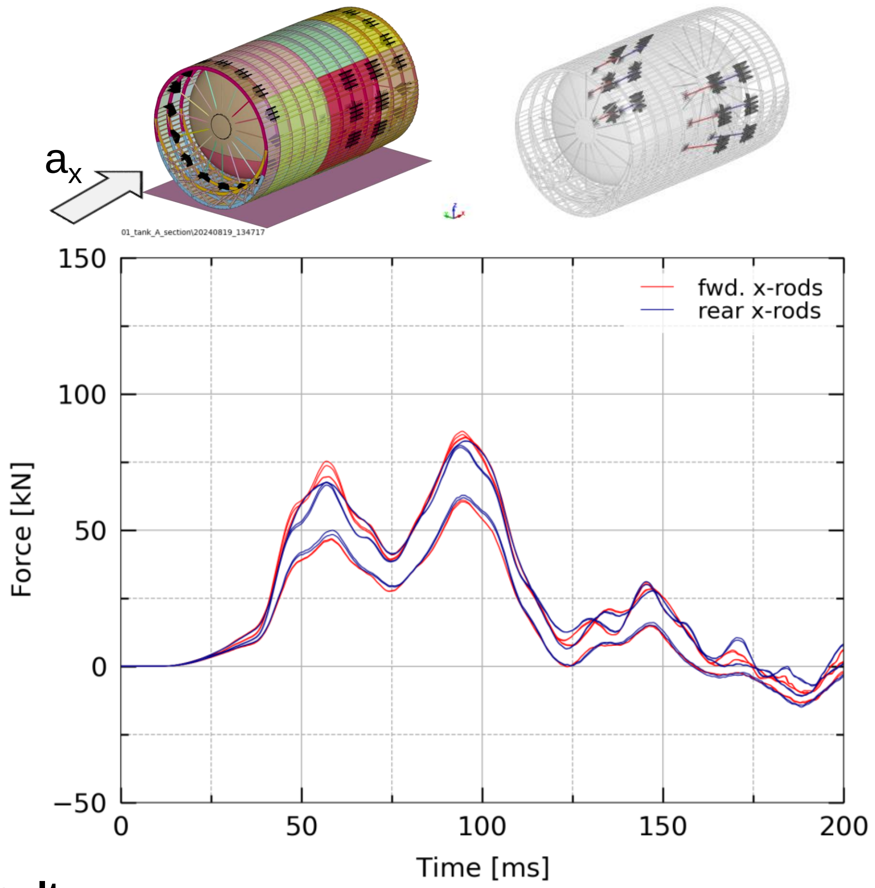


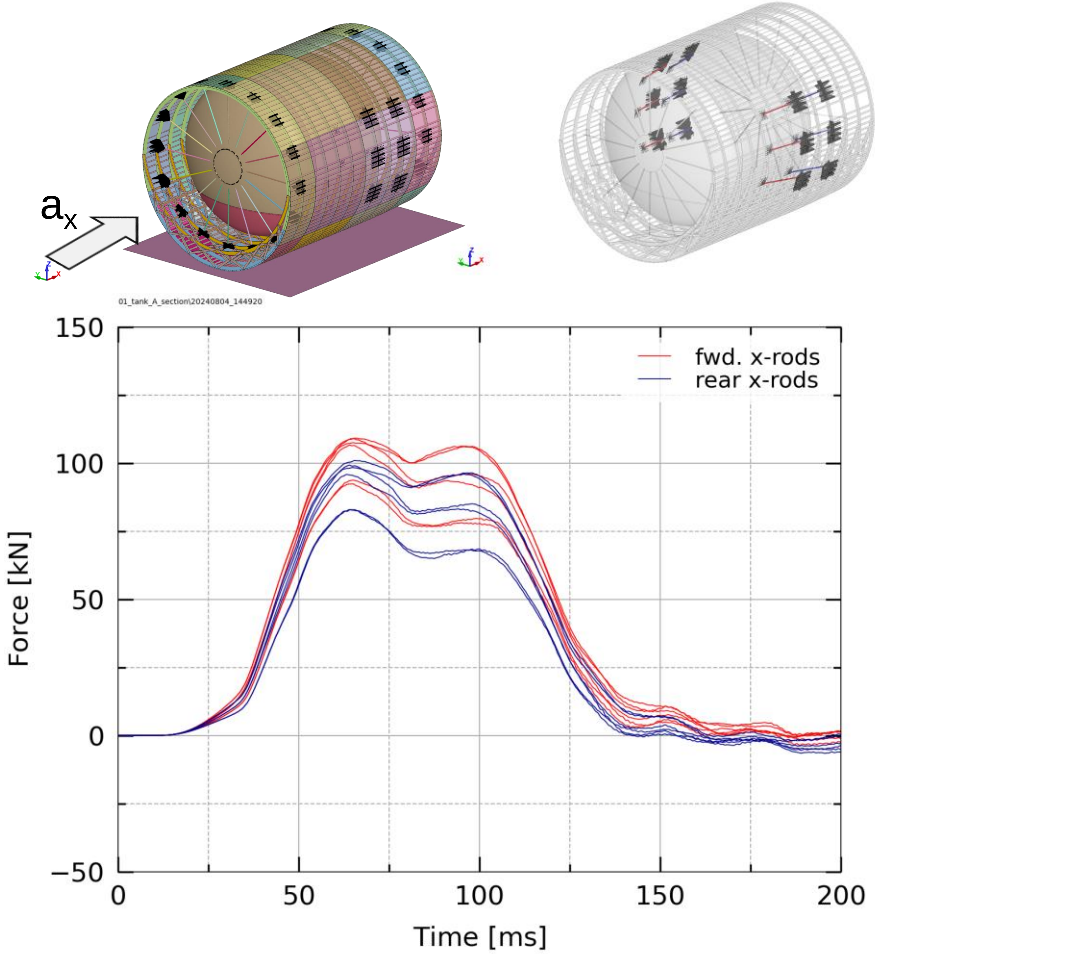
Result:

- As desired, no structural failure (zero internal energy)
- Significantly higher kinetic energy for wide body A/C due to higher masses

Results
Forward tank section with cylindrical LH2 tank

X-rod forces (18g triangular pulse**)**





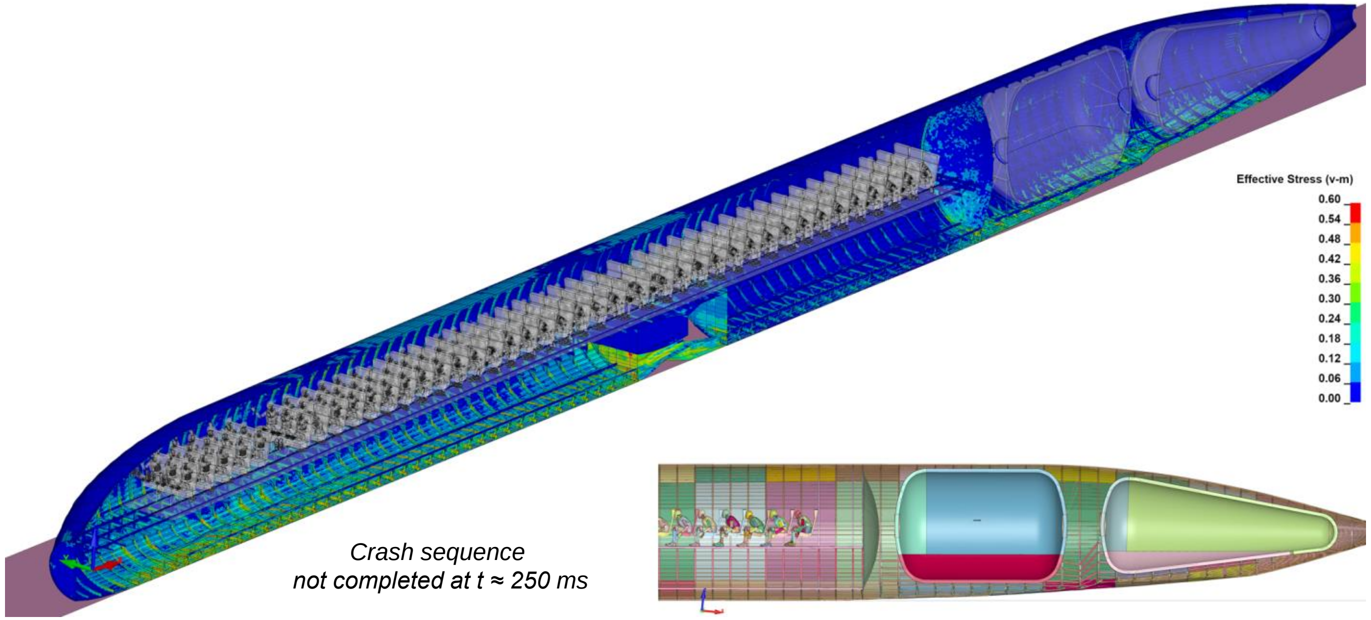
Result:

- Higher x-rod forces for wide body A/C
  Reasonable result, as number of x-rods is the same but tank mass is higher compared to single aisle A/C

Results
Full aircraft

Combined load case

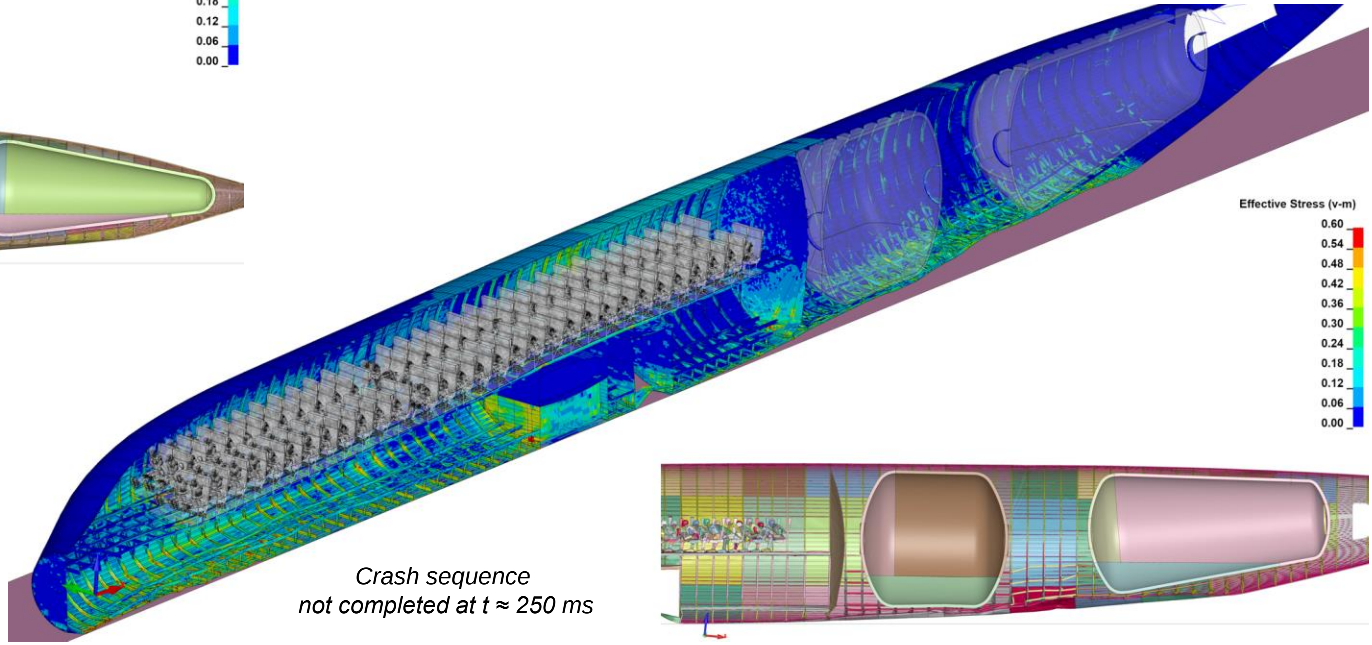
- v_z = 30 ft/s (9.1 m/s), v_x = 262 ft/s (80 m/s), φ = 5.25° (pitch angle)



Crash sequence
not completed at t ≈ 250 ms

Result:

- More distinct failure compared to fuselage section simulation
  → LH2 tank deformation (for wide body A/C)!
  Explanation:
  The kinetic energy of the entire A/C is effective during first crash impact at the rear fuselage leading to higher stroke compared to fuselage section simulations.



Crash sequence
not completed at t ≈ 250 ms

Summary

Requirements & crashworthiness strategy

- Novel aircraft designs with large LH2 tanks require thorough investigations to ensure crashworthiness
  - Guidelines for crash-resistant energy storage (LH2) system
  - Extended building block for crashworthiness demonstration of LH2 aircraft
  - Crash load cases specifically for LH2 tank integration aspects
- The need for full aircraft analysis was identified
  - Understanding the aircraft response and crash performance during a crash landing
  - Analysis and evaluation of effects that cannot be captured at the fuselage section level

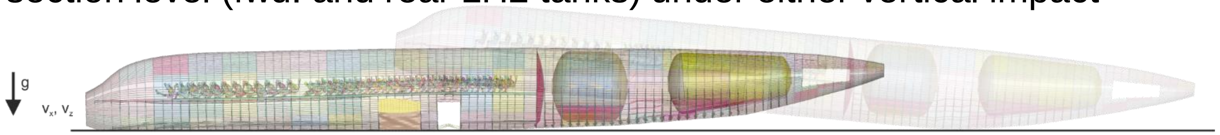
Simulation study: LH2 tank integration depending on aircraft size (‘single aisle’ versus ‘wide body’ configuration)

- Based on one specific tank mount configuration: spokes & x-rods
- Fuselage section level: Vertical and horizontal load cases (only fwd. LH2 tank presented)
- Full aircraft level: Combined horizontal/vertical crash load case on flat surface
- Although fuselage section versus full A/C simulations show similar results, effects were identified that require additional full A/C analysis
  - e.g. the involved kinetic energy in local crash zone: Differences of fuselage section versus full A/C consideration!
- **DLR continues development and application of full aircraft simulations to further support the introduction of novel aircraft configurations.**

Outlook

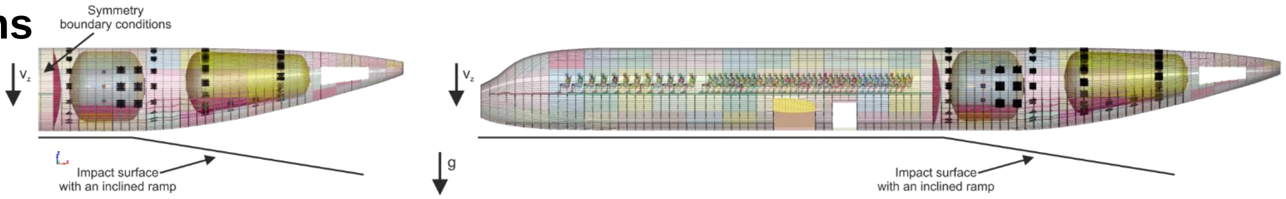
Scope of the current study

- Analysis of various tank mount configurations mostly at the fuselage section level (fwd. and rear LH2 tanks) under either vertical impact velocity or horizontal pulse to assess the loads in the tank mounts
- Analysis of first full aircraft simulations under combined impact velocities (horizontal & vertical components) as well as non-zero pitch angle



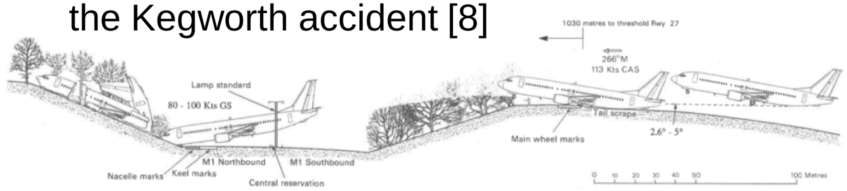
Planned investigation of fuselage break-up mechanisms

- Introducing high bending moments into the rear fuselage area
- Ensuring that the fuselage breaks between the LH2 tanks or before the bulkhead



Planned investigation of complex full aircraft load cases

(1) E.g. crash impact on sloped terrain, as obtained in the Kegworth accident [8]



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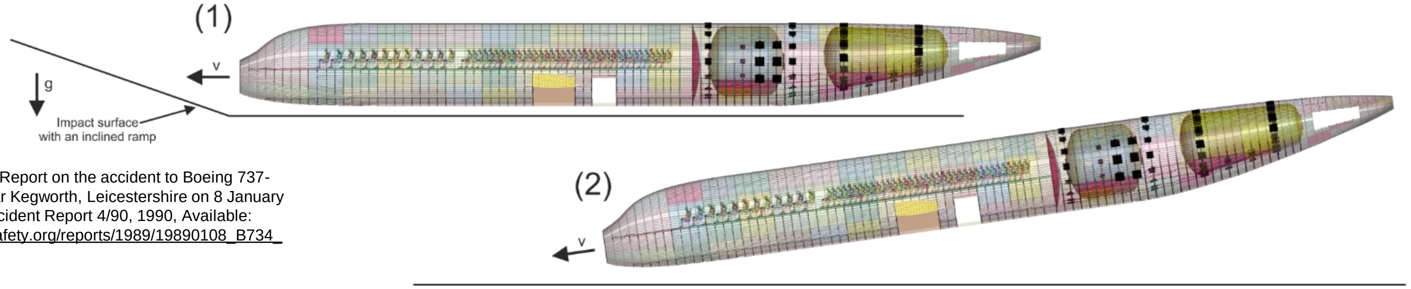

(2) E.g. crash impact with nose down on flat terrain

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Disclaimer

Co-Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

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