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Design, simulation and prototyping of the multifunctional composite structure of an "Hyperloop" vehicle

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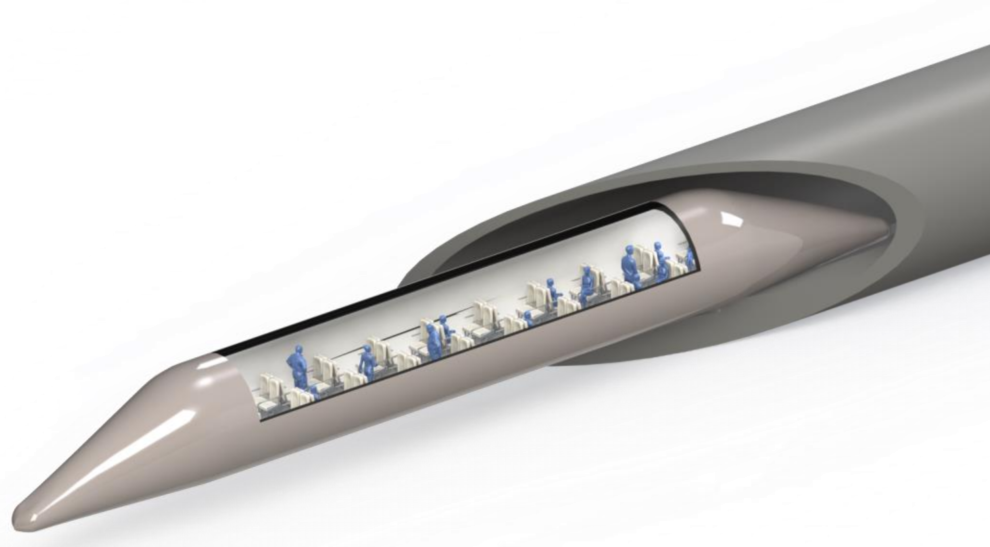
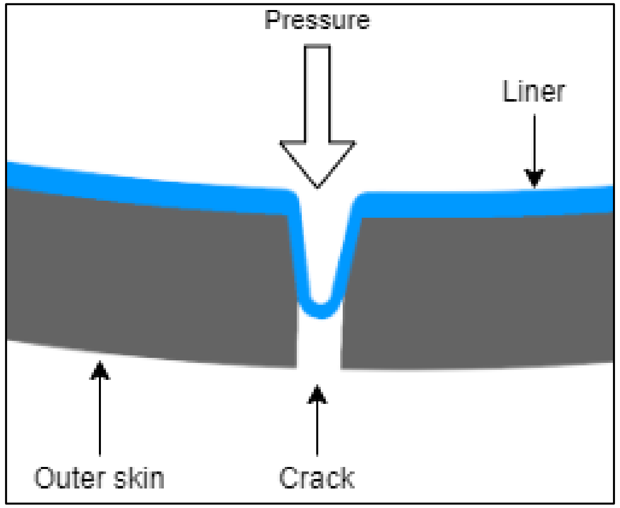
Research Project objectives

- Evaluate solutions to meet future transport needs in Switzerland
  - Short distances: 40-100km
  - Small footprint
  - Sustainable development : energy consumption < current transport
  - Support spatial planning / geographical distribution of facilities
  - Added value > train/car
- Solution considered: Vacuum levitation vehicle
  - Magnetic levitation
  - Electromagnetic propulsion
  - Aerodynamics
  - Thermal management
  - Highly reliable multifunctional structure

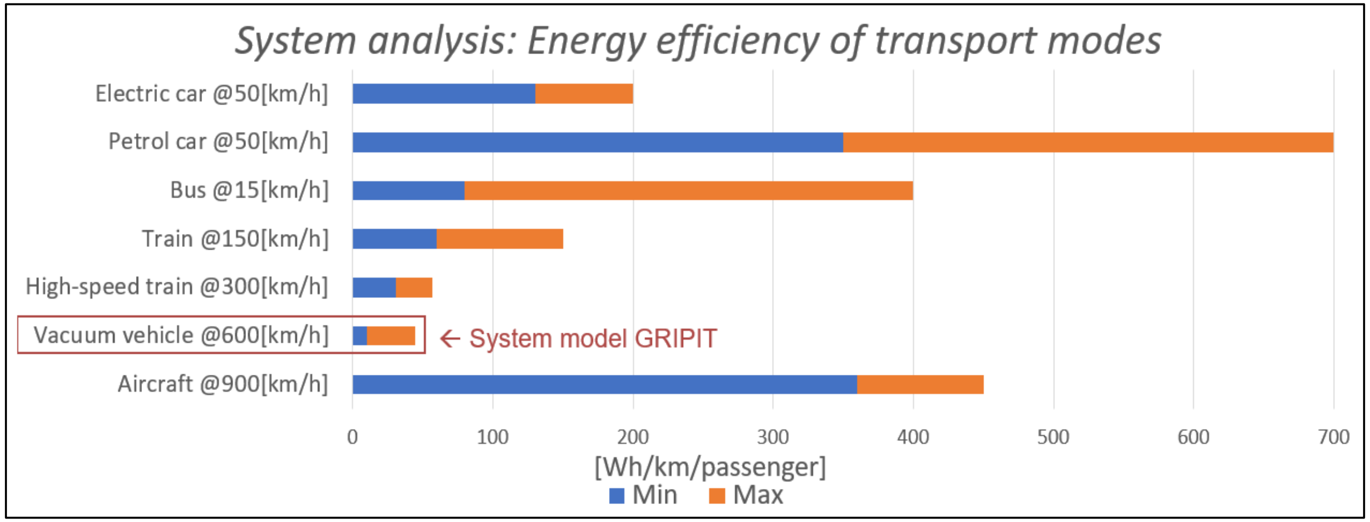


Development process

- Multi-physics 'system' model
  - Main quantities: energy, mass, dimensions, traffic
- Vehicle dynamic simulation
  - Including magnetic levitation and track defects => dynamic forces
- Concept of a reliable multifunctional composite structure
  - High fatigue resistance
  - Vacuum resistant (100 Pa)
  - Fault and crack tolerant
  - Self-sealing of cracks
  - Crack detection
  - Heat dissipation studies via the shell
- Prototyping
  - Additive manufacturing process for shell and sensors
  - Manufacture of a shell (3m) with detection system

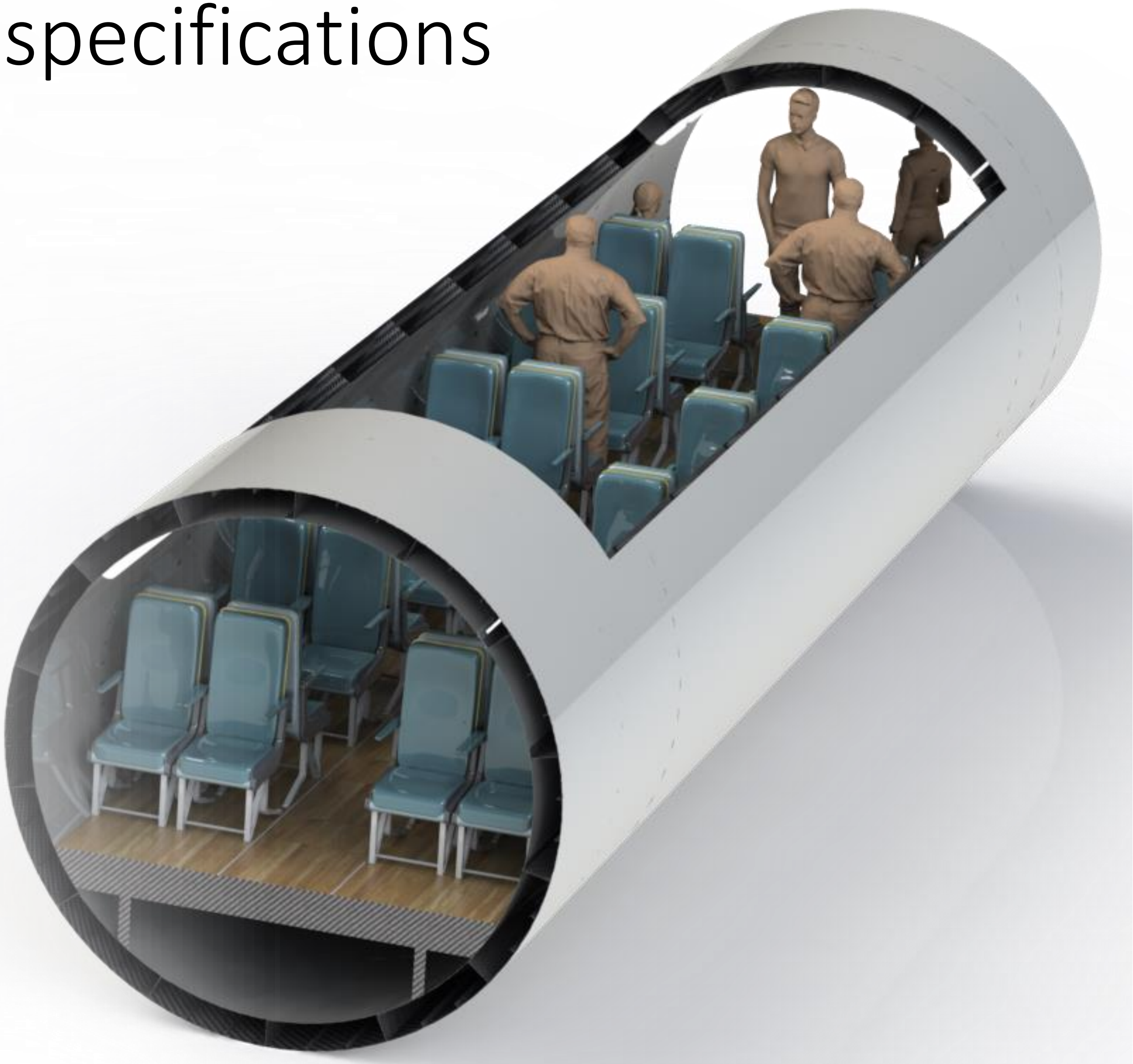


Schematic of self-sealing

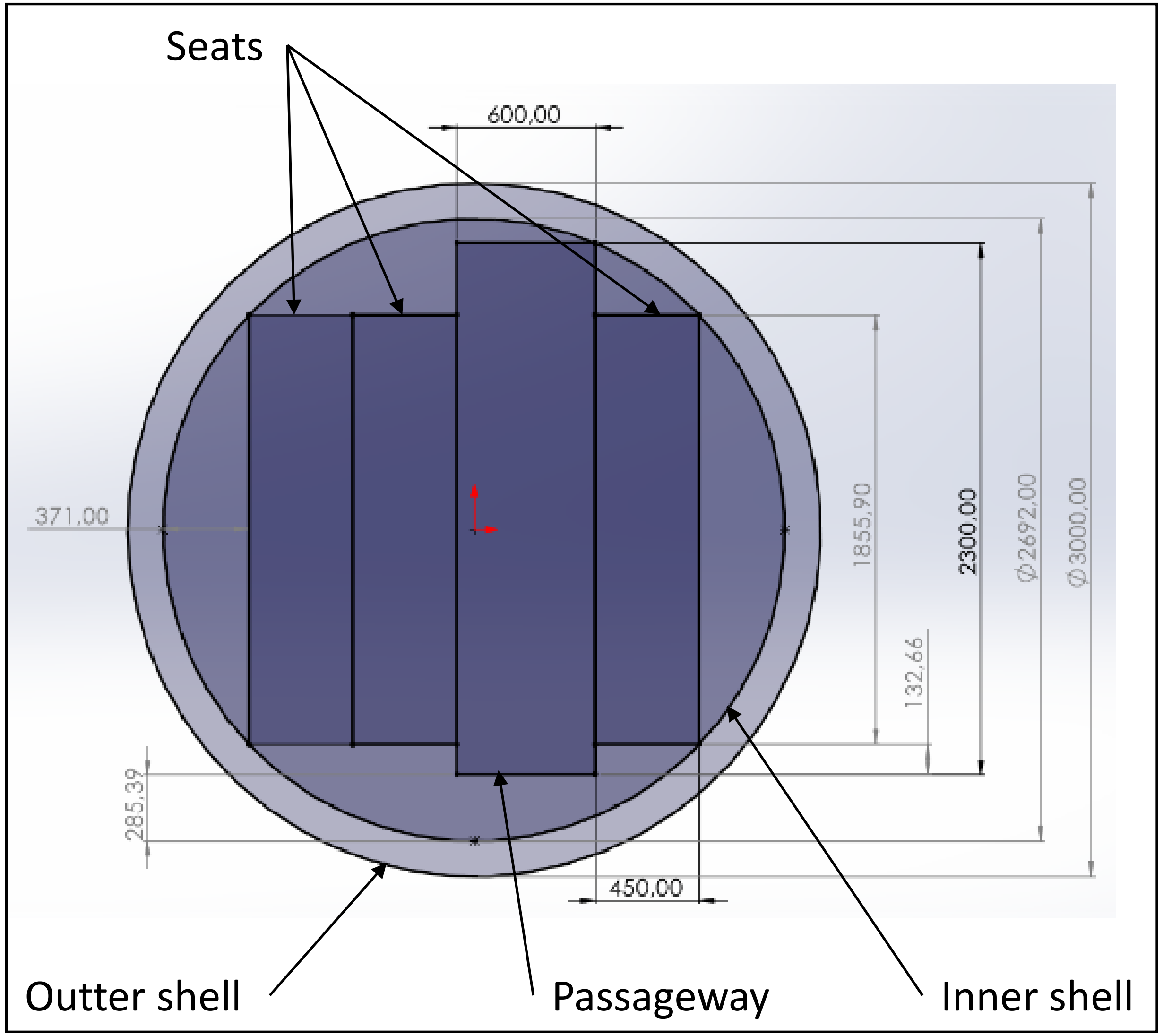


Vehicle dimensions and specifications

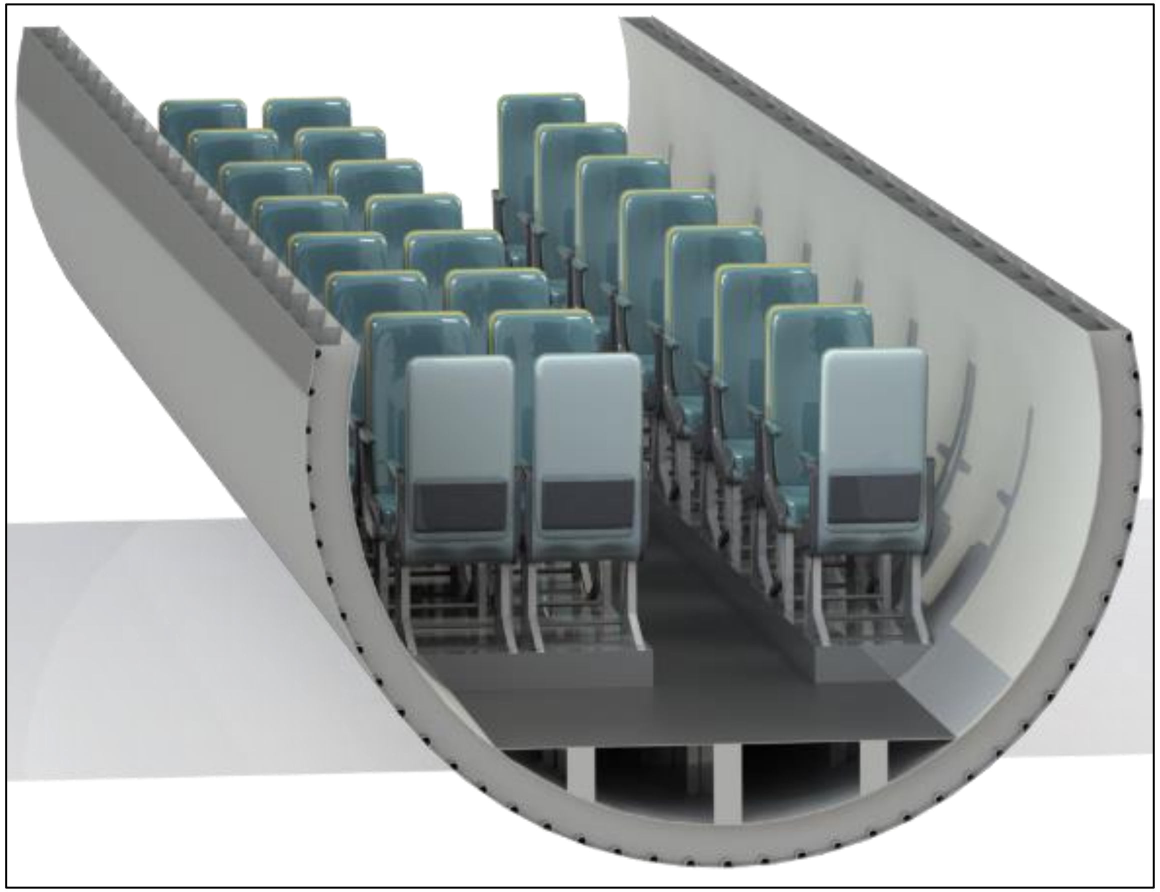
- Typical range: 60km
- Vehicle diameter: 3m
- Tunnel diameter: 4.5m
- Vehicle length: 15m
- Capacity: 42 passengers
- Rated speed: up to 600km/h
- Cabin pressure: 1013 hPa
- Tunnel pressure: 100 Pa
- Lifetime of 160'000 pressurisation cycles



General dimensions

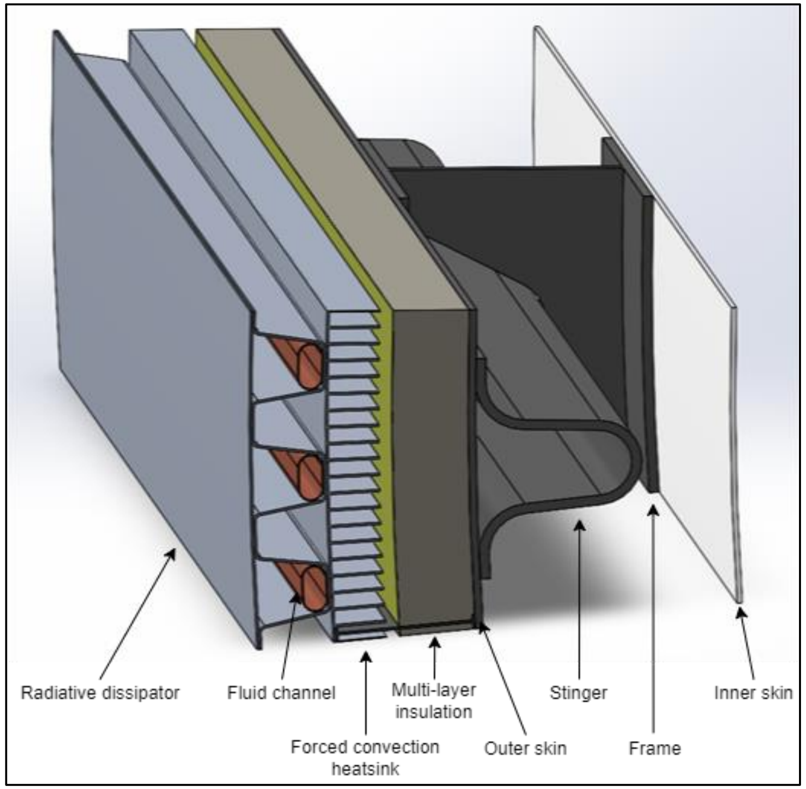


The interior dimensions are bus-like and maximized for a fixed hull diameter.
The current pre-design is only a first step towards the structural analysis & feasibility study.



Heat dissipation via the shell

- Tunnel : 15°C @100 Pa
- Vehicle interior temperature : 25°C
- Power to be dissipated: 343 kW
- Concepts considered:
  - Accumulator (water tank)
  - Evaporative cooling
  - Radiation and external convection
  - Radiation, internal and external convection
  - Frontal radiator



Heat sink concept by radiation and forced convection

Comparison of concepts

- 120-day period between two pressurizations of the tunnel (maintenance)
- Includes compensation for tunnel leakage and vacuuming
- Each solution includes an accumulator to store the undissipated energy

	Total vehicle mass [kg]	Battery mass [kg]	Water tank mass [kg]	Average consumption of the tunnel-vehicle system [kWh/km/passenger]	Efficiency * compared to the accumulator
Accumulator (water tank)	18900	362	830	0,036	
Evaporative cooling	18000	350	66	1,246	3461%
Radiation and external convection	21700	402	832	0,039	108%
Radiation, internal and external convection	22400	413	823	0,040	111%
Frontal radiator	19000	364	834	0,036	100%

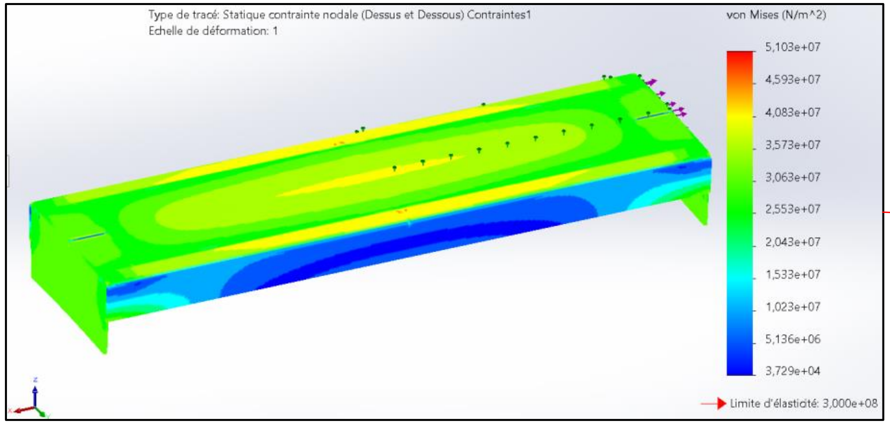
Evaporative cooling: Low weight but high vaccuum energy

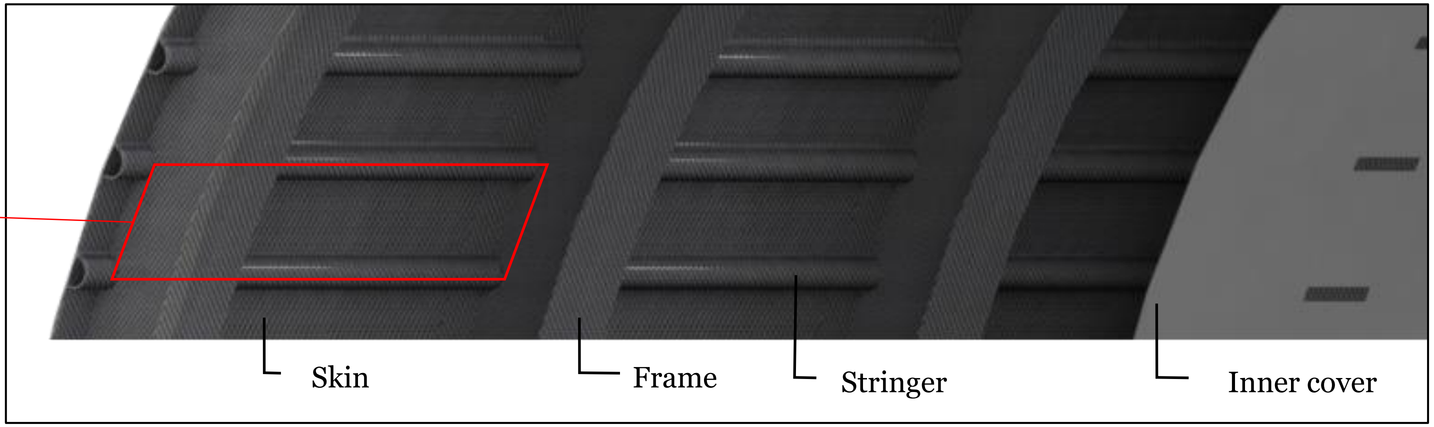
Shell with heat exchange: No gain in these conditions

* Lower = better

Composite shell design

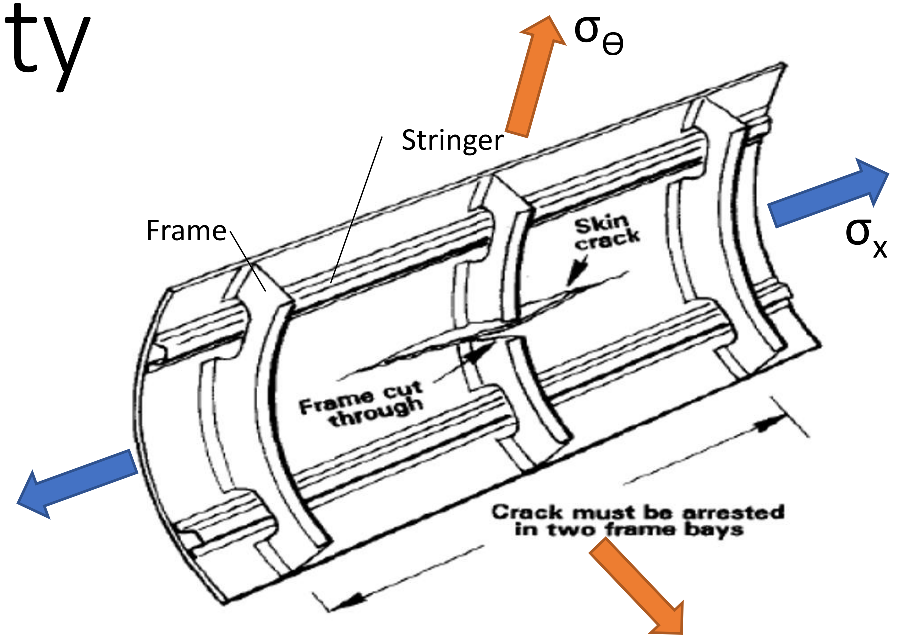
- The chosen fuselage is of the semi-monocoque type
  - Hull thickness = 3mm, Mostly quasi-isotropic carbon/epoxy, Fiber : Toray T700 or equivalent
- Spacing of stringers and frames is determined to stop a critical crack in two bays
  - Stinger spacing = 135mm, Frame spacing = 545mm
- Load sharing between skins and frame structure:
  - The skin is designed to withstand 100% of the pressure loading.
  - The reinforcements are designed to withstand 80% of the pressure loading as a safety measure. Frame spacing at half the critical crack length for crack arrest.
- The total mass of the composite fuselage is 2960kg



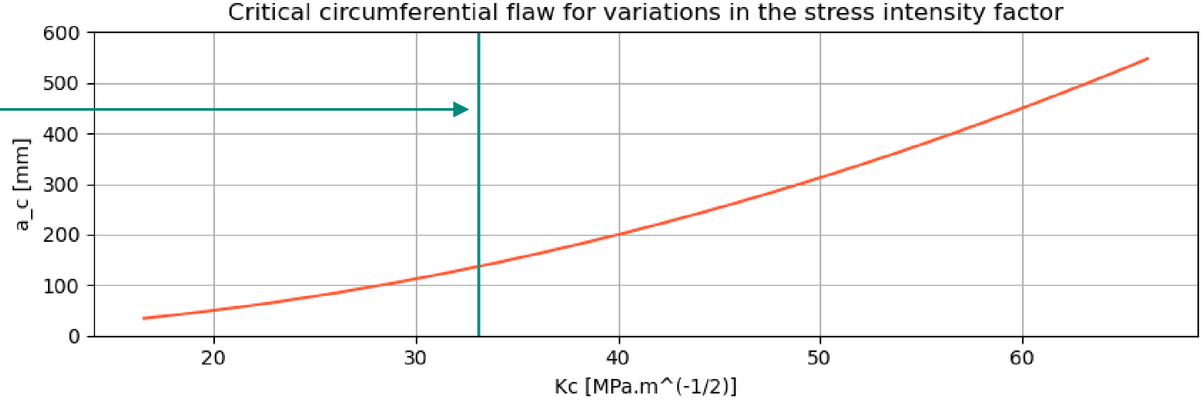


Fuselage crack arrest capability

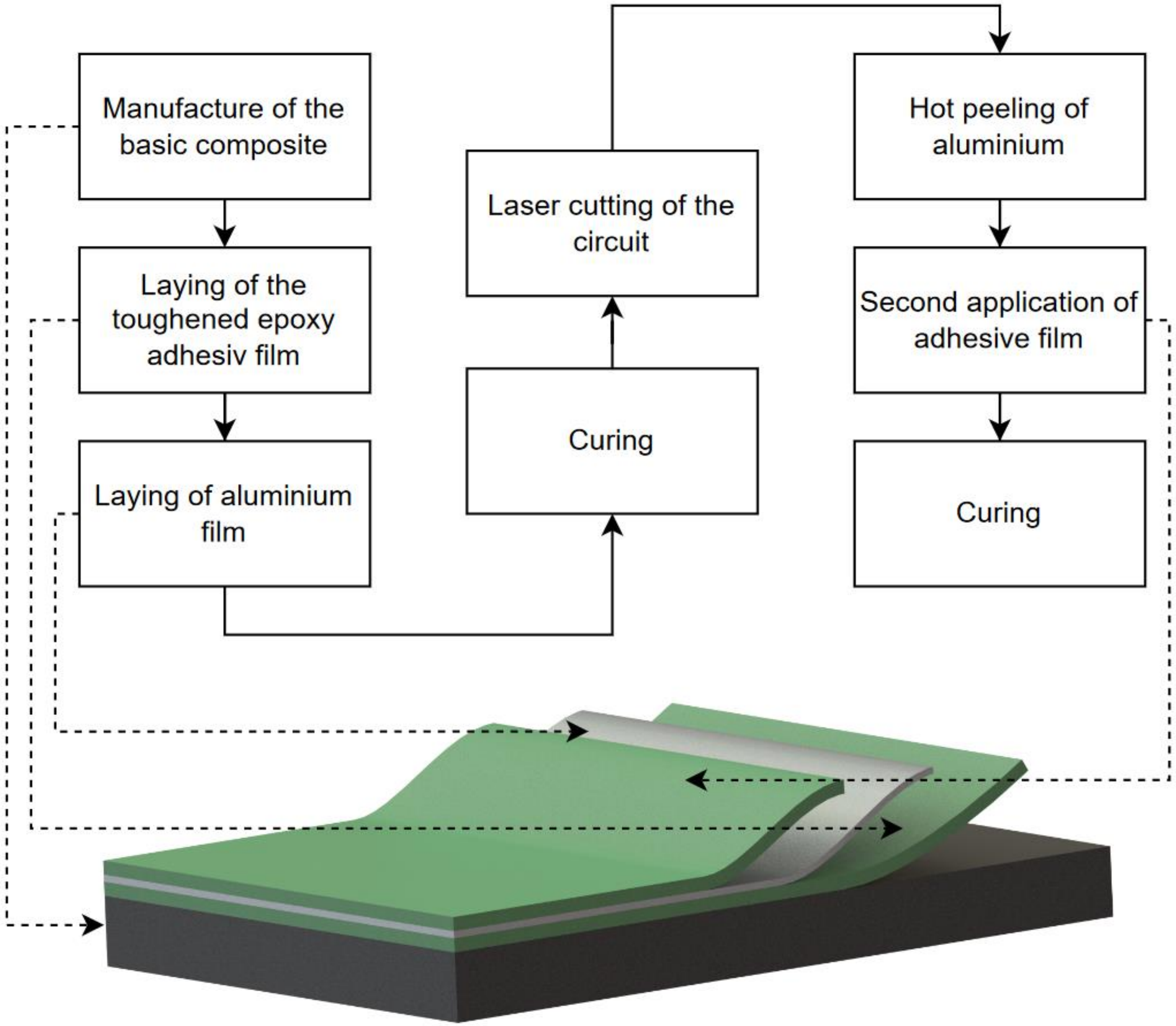
- Critical crack length $= 2a_c$
- Critical flaw size which will cause brittle failure to occur in one cycle: $a_c = \frac{1}{\pi}\left(\frac{K_c}{\sigma}\right)^2$
  - K_c: Mode I critical stress intensity factor
  - σ_x: Circumferential stress: $\sigma_x = 2\sigma_\theta$
  - σ_θ: Axial stress: $\sigma_\theta = \frac{pr}{2t}$
  - t: Shell thickness is calculated to withstand pressure without reinforcements: $t = 3mm$
  - p: Inside - outside pressure difference : $p = 101200Pa$
  - r: Mean hull radius : $r = 1498{,}5mm$
- With $K_c = 3{,}31 \cdot 10^7 \frac{Pa}{\sqrt{m}}$
  - $a_{cx} = 0{,}545mm$
  - $a_{c\theta} = 0{,}135mm$

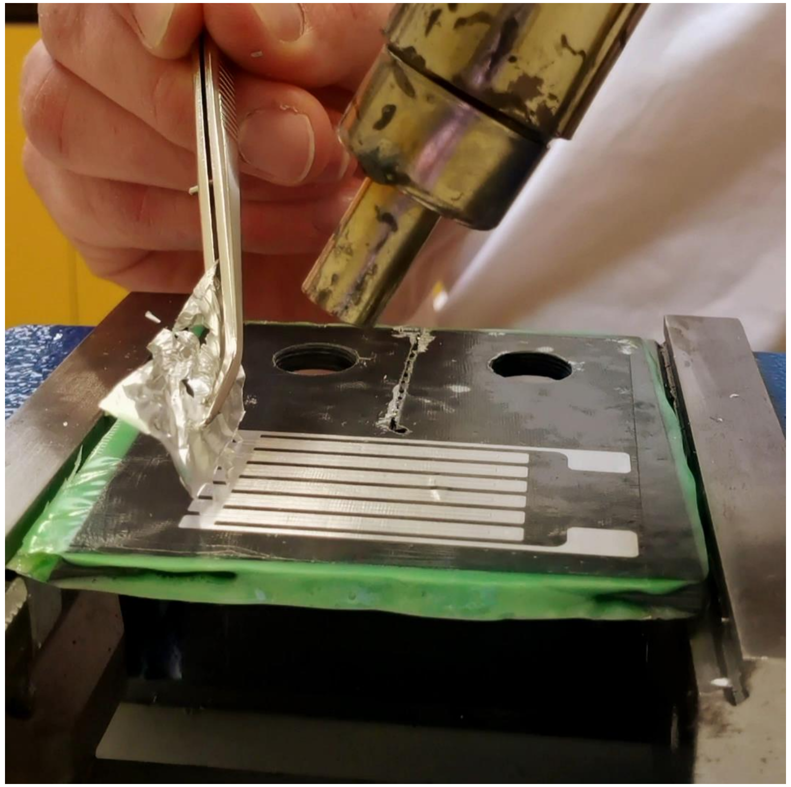


Source : B K, Venkatesh & S, , & E, Girish. (2012). Analytical Evaluation of Fatigue Crack Arrest Capability in Fuselage of Large Transport Aircraft. 1. 13-22.



Integrated crack detection sensor

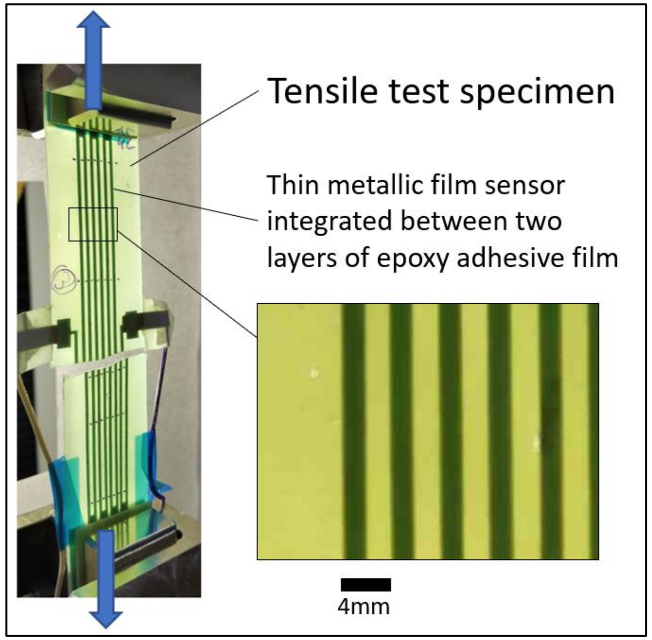


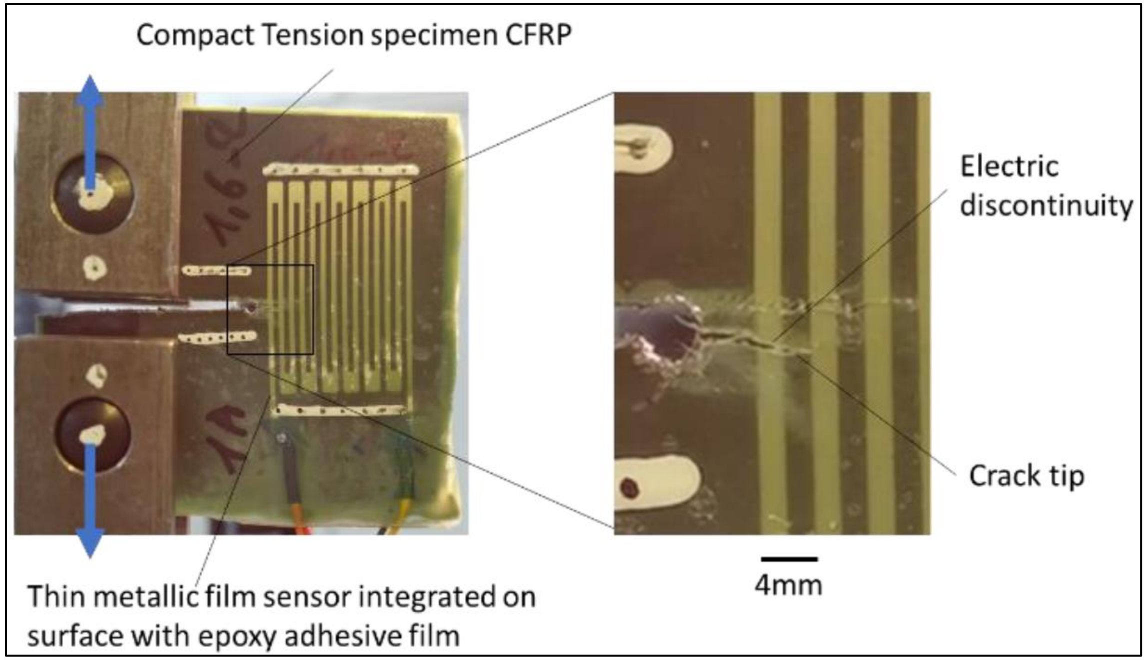


Video of hot peeling

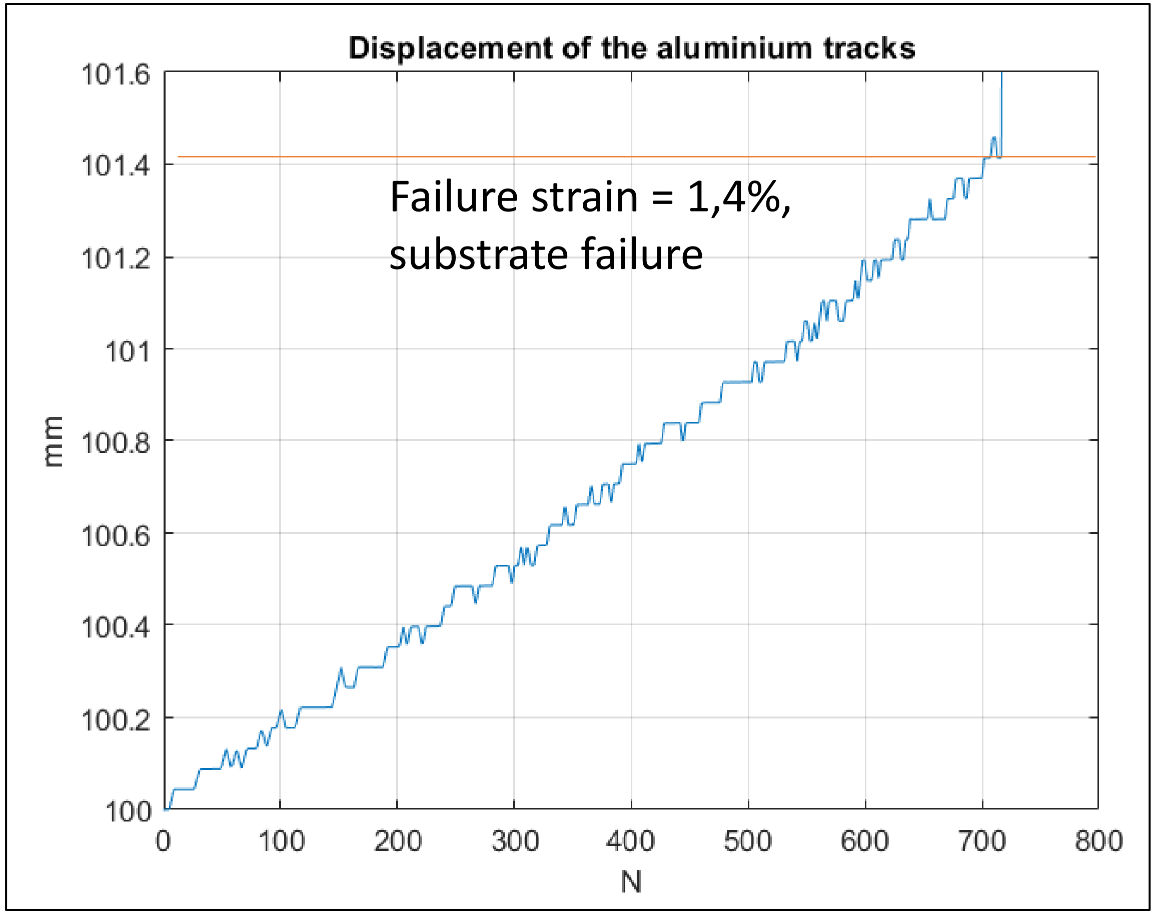
Description of mechanical tests

- Tensile test specimen:
  - 30 x 100 x 0,5mm
  - Two layers of epoxy adhesive with glass carrier Gurit SA80
  - Up to 800N
- Compact tension specimen:
  - 75 x 75 x 4mm
  - Initial crack length = 40mm
  - Carbon fibber and epoxy
  - Up to 9000N
- Aluminium strips:
  - 30 x 2 x 0,08mm

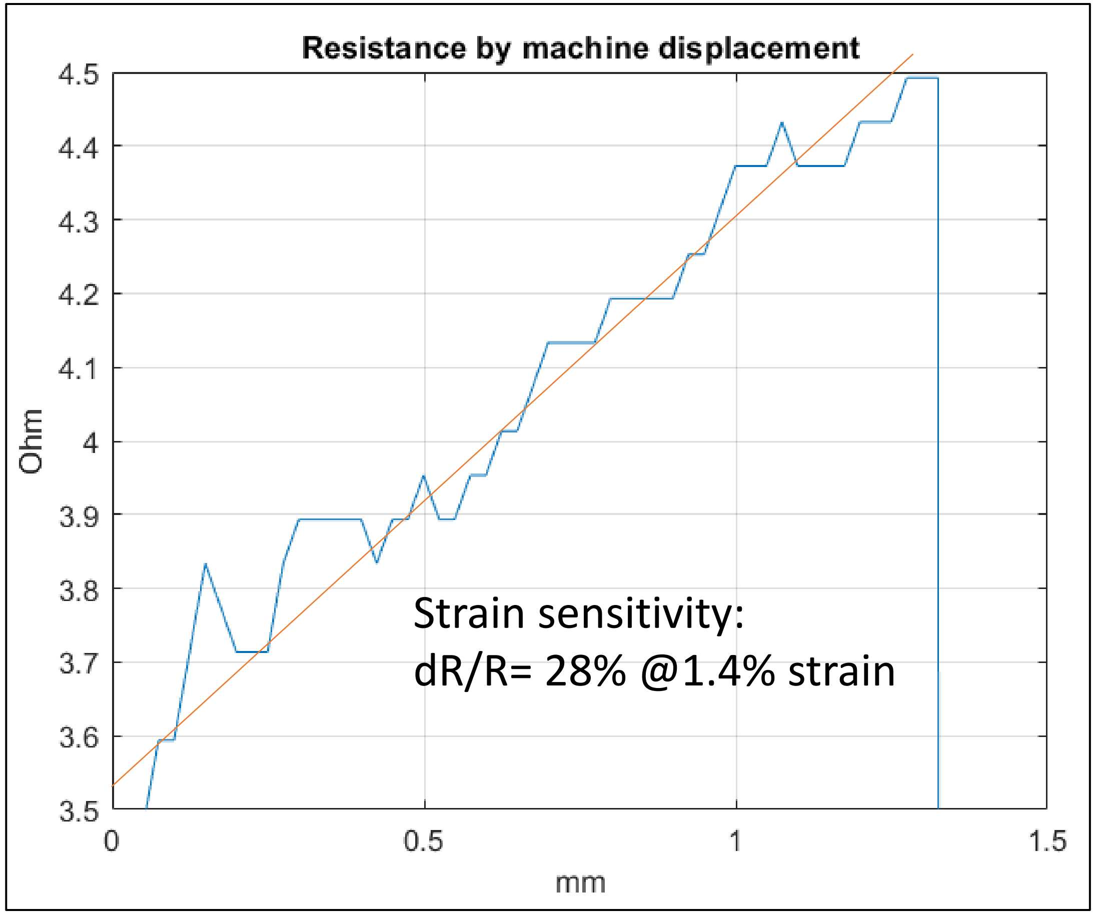




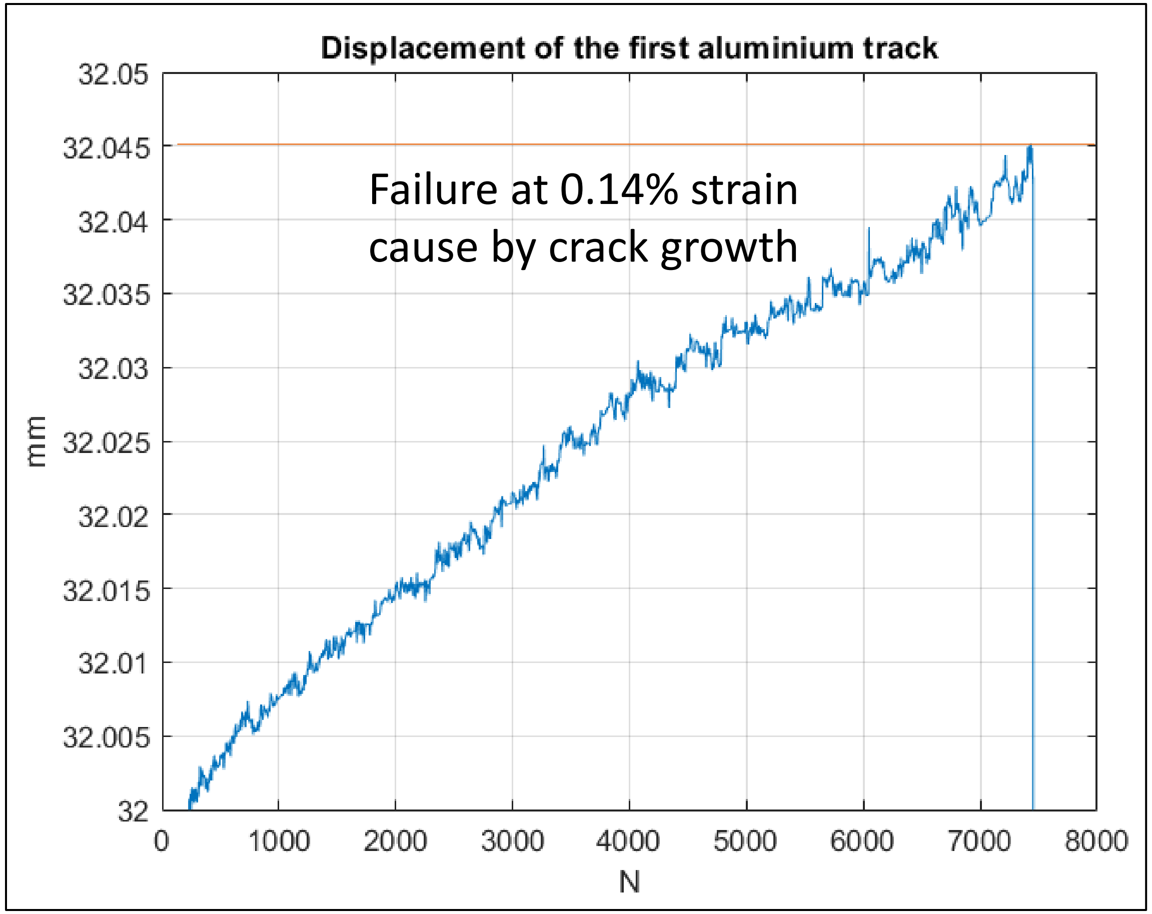
Tensile test results

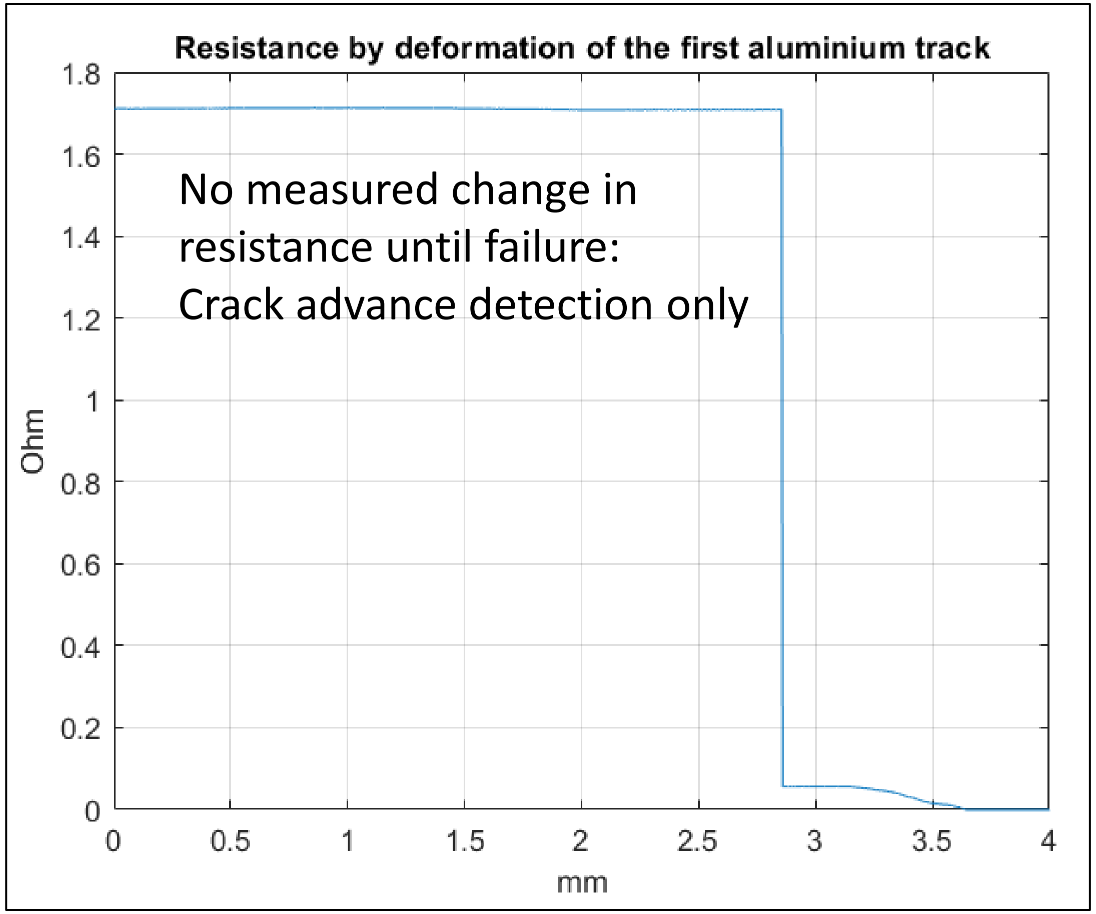


Initial length = 100mm



Compact-tension tests results

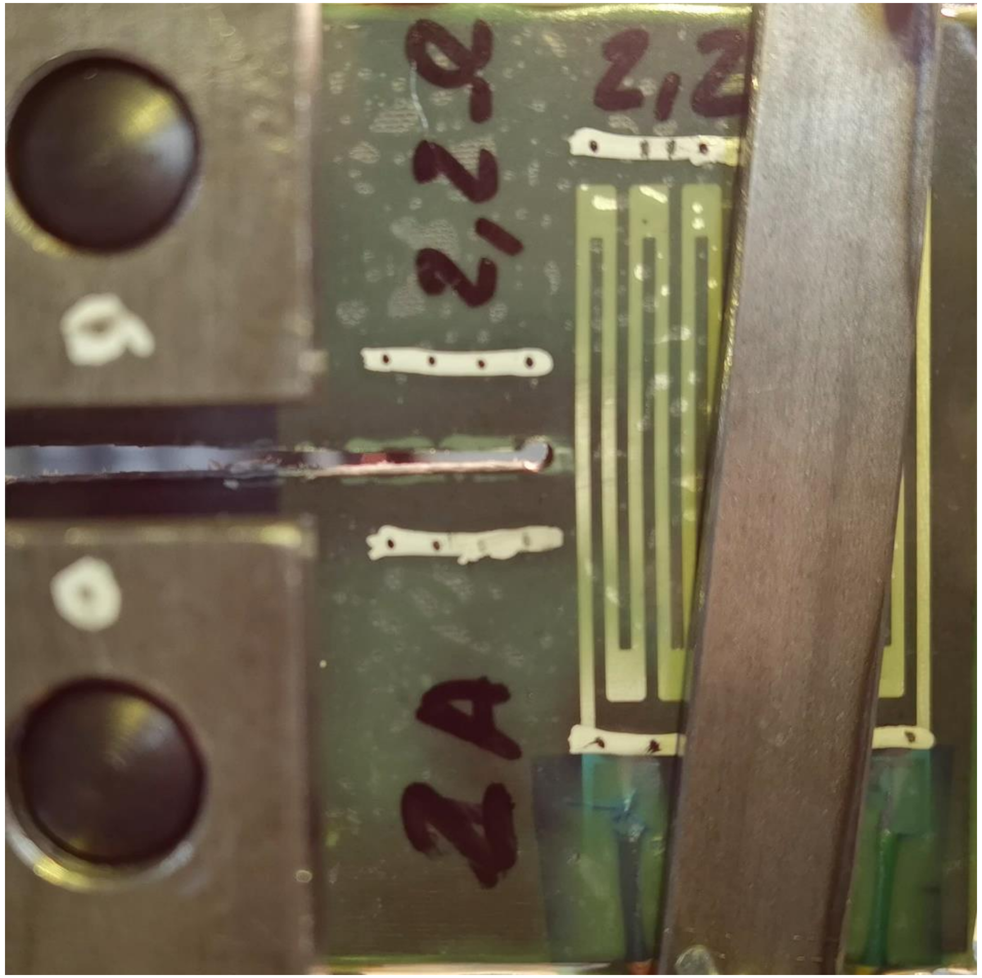




Gauge length = 32 mm

Videos of mechanical tests

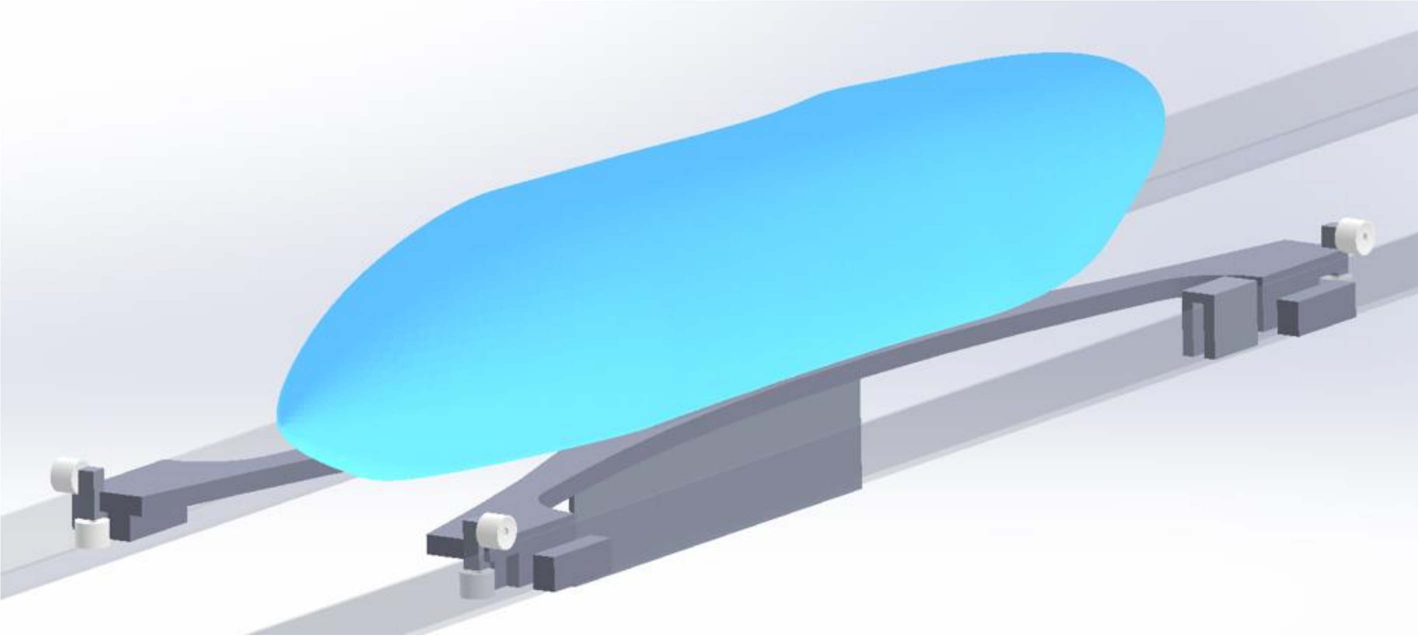
Tensile test



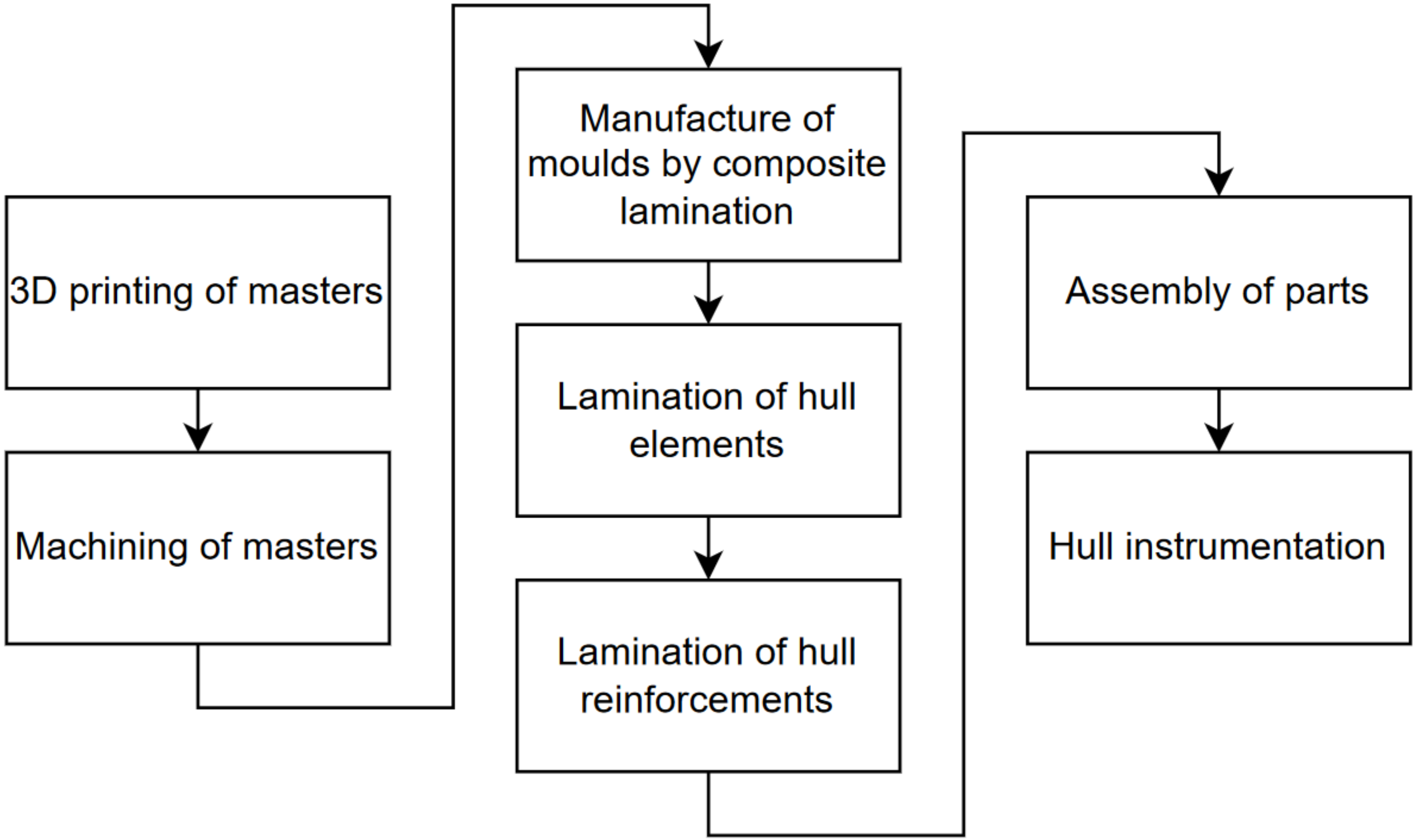
Compact tension test

Prototype for test tunnel

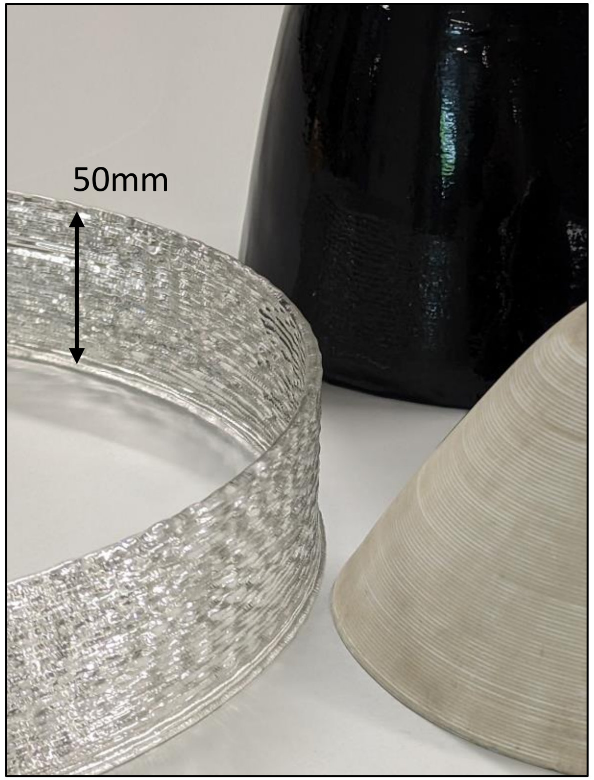
- Tunnel length: 120m
- Tunnel diameter: 2m
- Tunnel pressure: 100Pa
- Hull length: 3m
- Hull diameter: 0.6m
- Hull pressure: unpressurised
- Hull thickness: 1.5mm
- Acceleration: 8g
- Deceleration: 10g
- Maximum speed: 34m/s



Multi-functional composite shell prototyping



Robotic 3d printing of masters



3D printing of the master parts → Surfacacing and drilling → Assembly of parts → Sanding and smoothing → Vynil wrapping

Conclusions

- Evaluated many different designs to optimize energy per passenger
- Pre-design of a 40 seats vehicle
- Developed a multi functional composite hull to address the main challenges
- Heat management:
  - integrated heat exchange in the hull does not bring significant benefits vs its complexity. But could be useful for much longer travel distances.
- Structural safety:
  - risk of high cycle fatigue cracking, managed by a classical aeronautic skin/frame design for crack arrest and structural redundancy
- Crack detection monitoring :
  - simple integrated metallic film sensor design that can be mass produced and integrated in the skins during manufacturing
- Prototype development:
  - Use large scale robotic additive manufacturing for mold production and sensor integration (in progress)

Thank you for your attention !

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For more details, see: https://shorturl.at/yRUY2