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Advanced solutions for hydrogen zero emission fuel

Hydrogen Researcher Festival
Loughborough University, 04 July 2024

Institute for Innovation in Sustainable Engineering (IISE)

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Hydrogen Storage

How hydrogen is stored

Physical based →

Compressed gas

Cold-cryo compressed

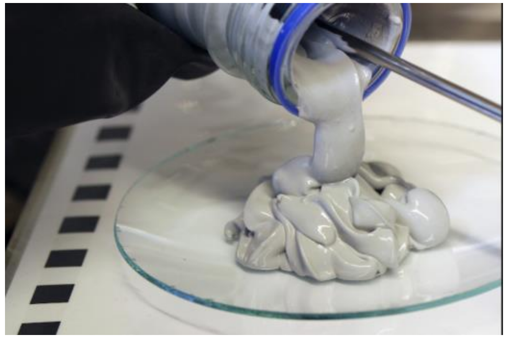
Liquid H_2

Material based

↓

Solid absorption/adsorption

Hydrogen Gel



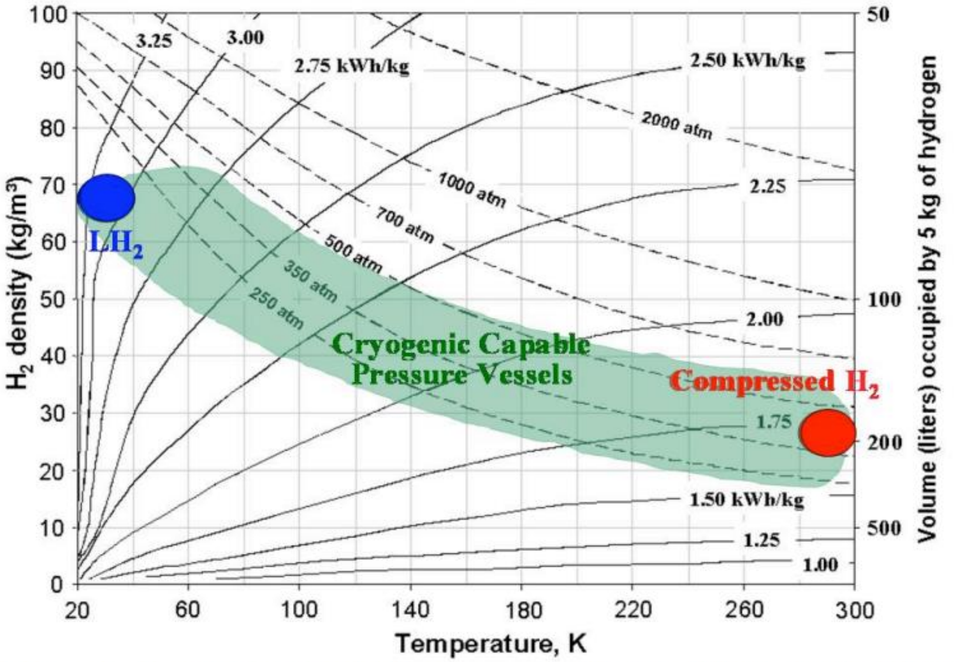


Figure 1. Commercial automotive hydrogen storage technologies occupy the extremes of this phase diagram. Hydrogen is often stored as a compressed gas (red dot) at ambient temperature (horizontal axis), very high pressure (dotted lines), and relatively low density (vertical axis). Hydrogen is much more compact as a cryogenic liquid (blue dot) but with higher energetic cost (solid lines indicate the theoretical minimum work, also known as thermomechanical exergy) to compress and/or liquefy hydrogen. Cryogenic capable pressure vessels have flexibility to operate across a broad region (shaded in green) of the phase diagram, and therefore can be fueled with gaseous H_2 at a low energetic cost when energy or fuel cost savings is important or with LH_2 when long driving range, or low-pressure operation is desired.

Hydrogen Tank Concept

Hydrogen Tank Type

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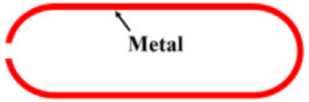
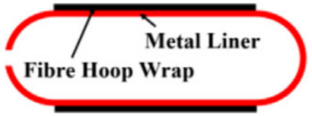
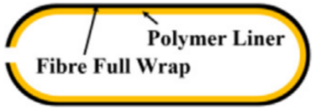
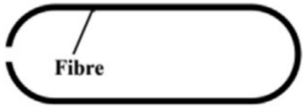
Classification and applications of different hydrogen tanks.

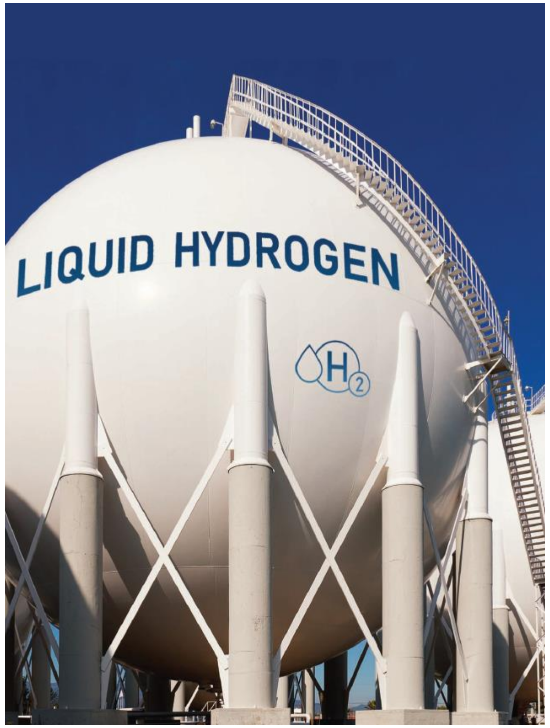
Type	Schematic	Materials		
		Metal	Composite	Polymer
I		Steel/Al	/	/
II		Steel/Al liner	Filament windings around the cylinder part	/
III		Al/Steel liner	Composite over-wrap (fibre glass/aramid or carbon fibre)	/
IV		/	Composite over-wrap (carbon fibre)	Polymer liner
V		/	Composite	/

Hydrogen Tank Applications

Hydrogen Tanks

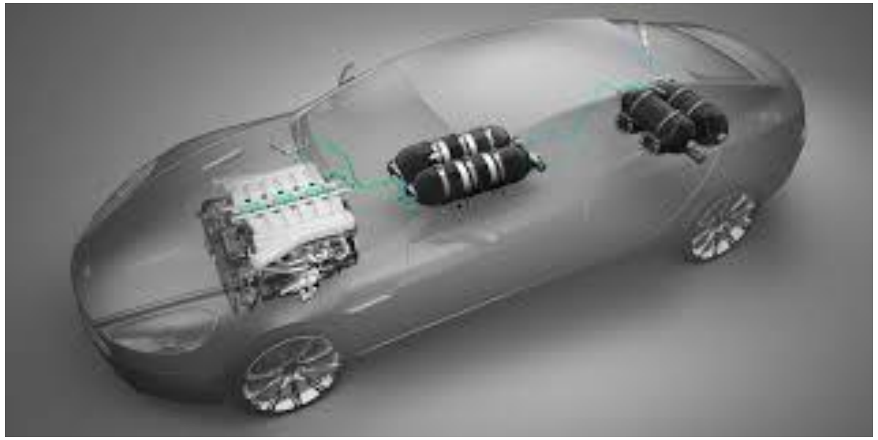
(High pressure solutions)

Industrial applications



Buildings and smart cities

Automotive



Hydrogen Tank for aviation

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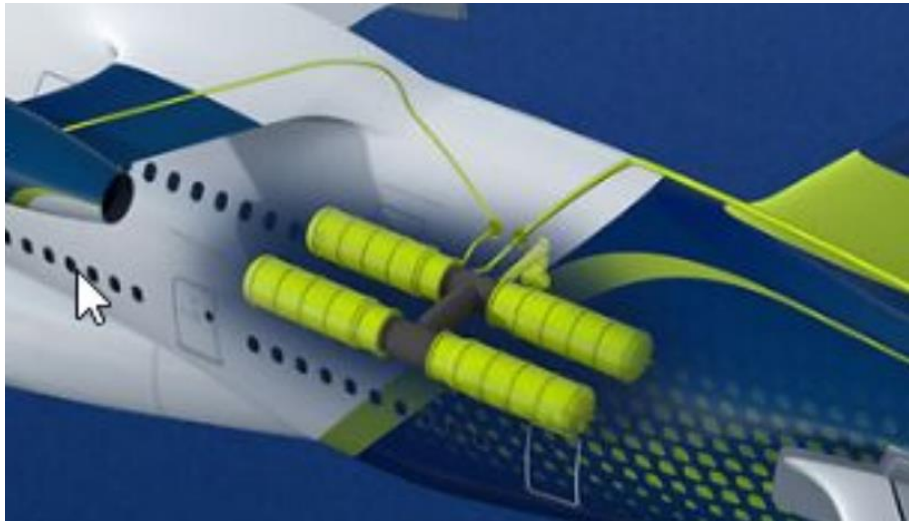
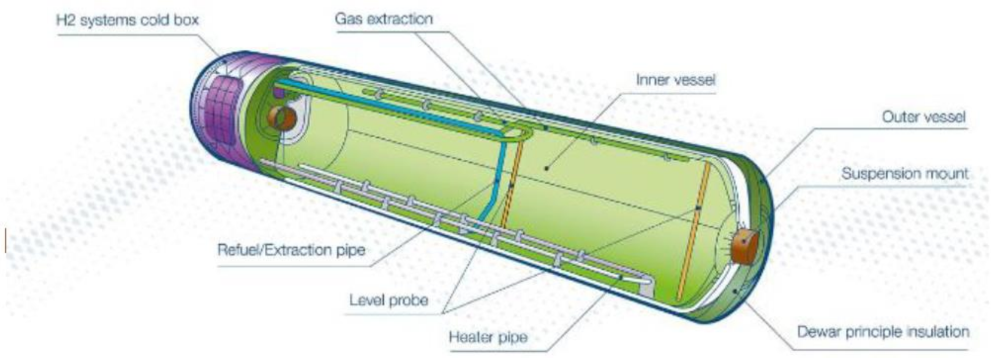
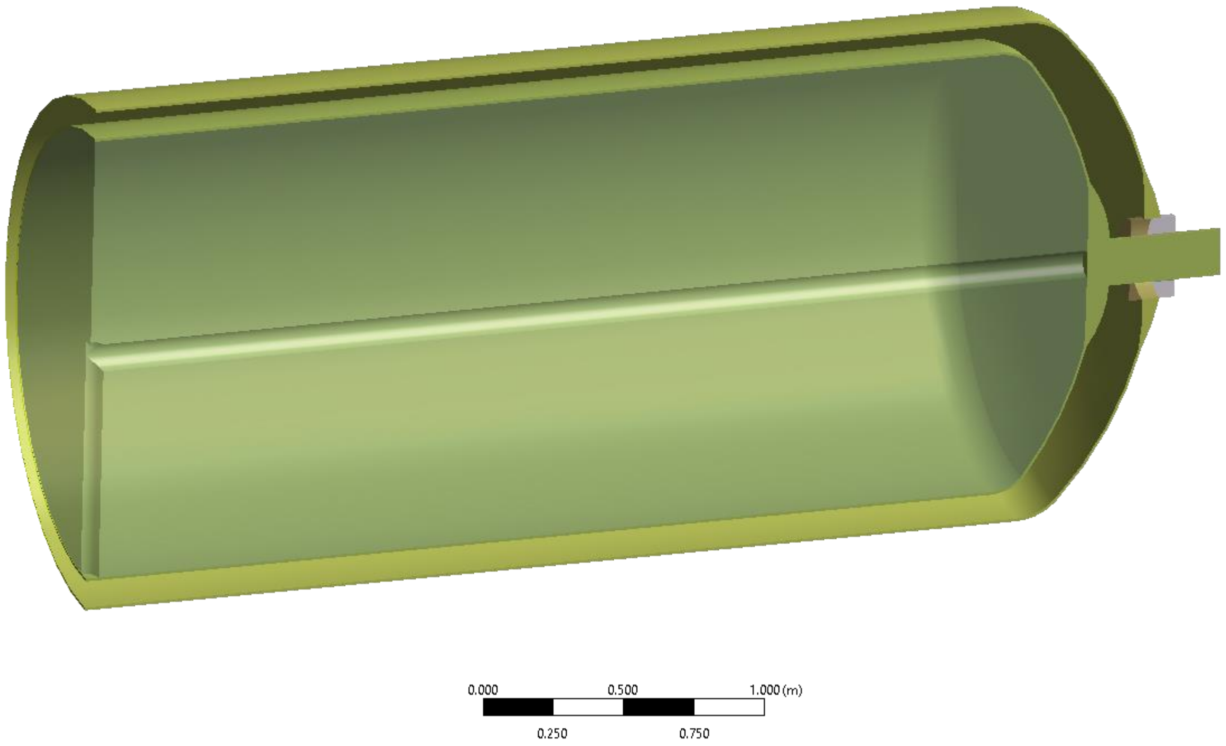


Courtesy of Airbus

Liquid H_2 tank

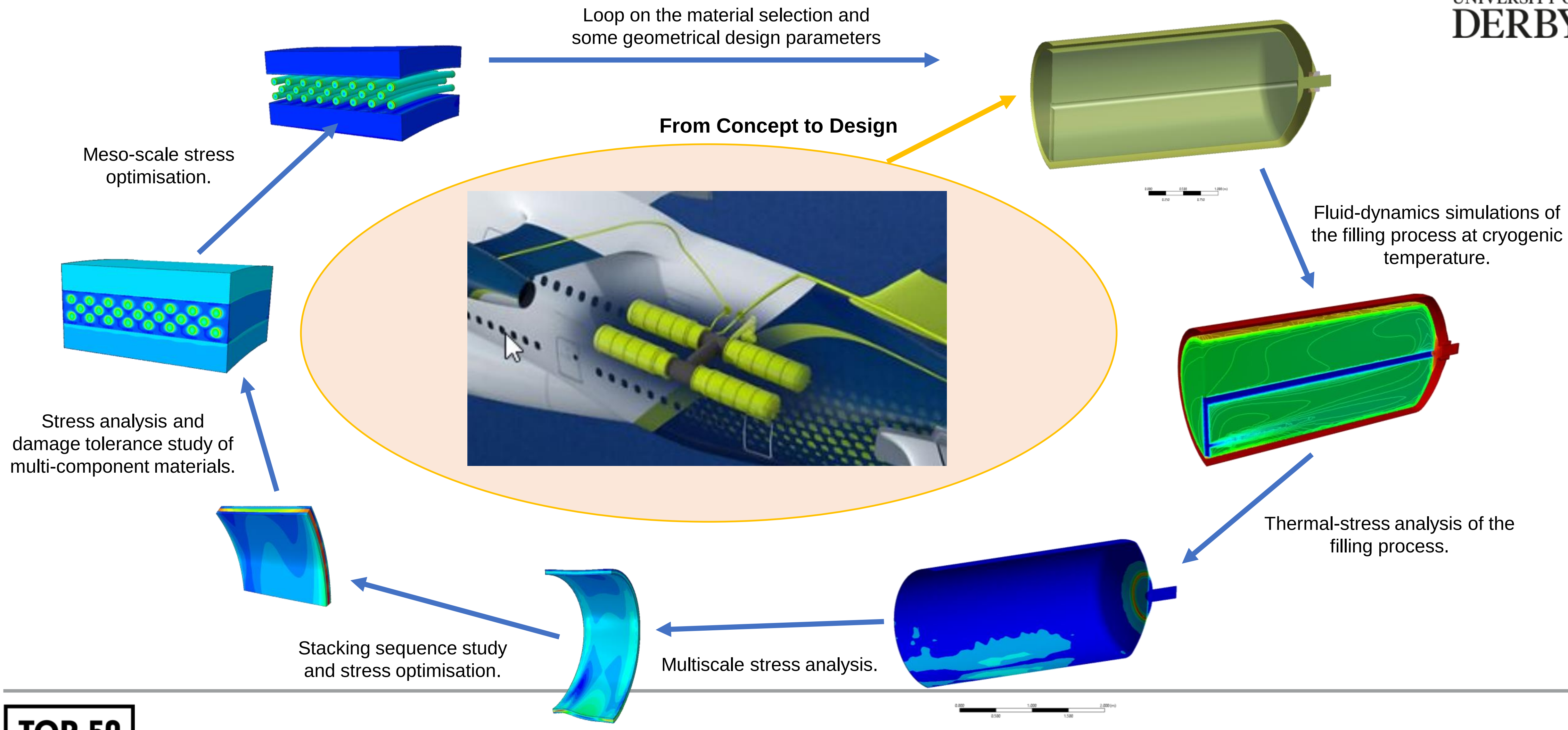


Hydrogen Tank from concept to design



AETHER project

Advanced Solutions for Hydrogen Zero Emission Fuel



Outcomes

Hydrogen Awards 2024

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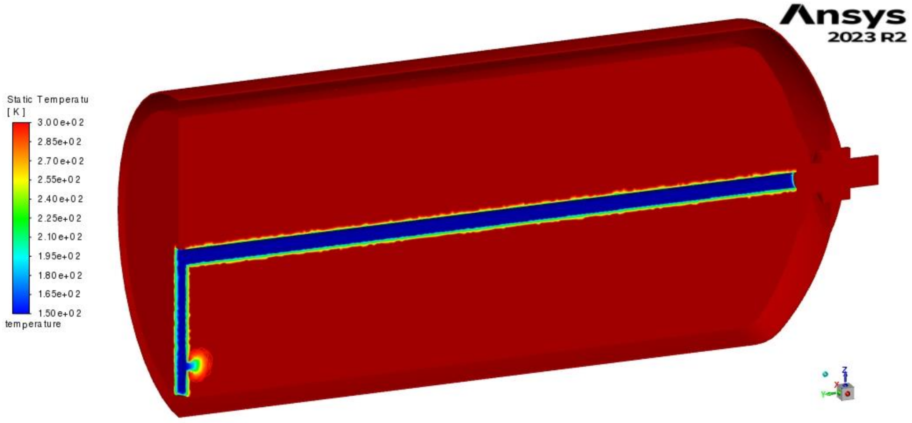
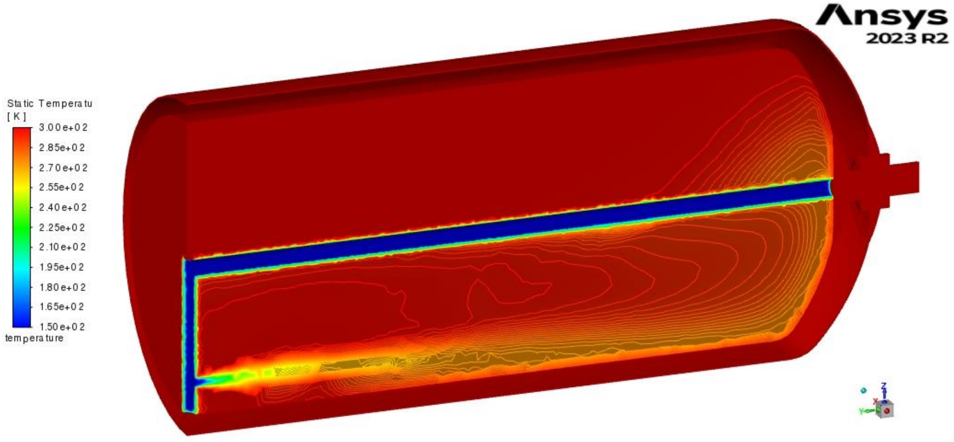
High Commendation trophy for the "UK Universities' Award for excellence in hydrogen research and innovation"

Hydrogen Tank Working Conditions:

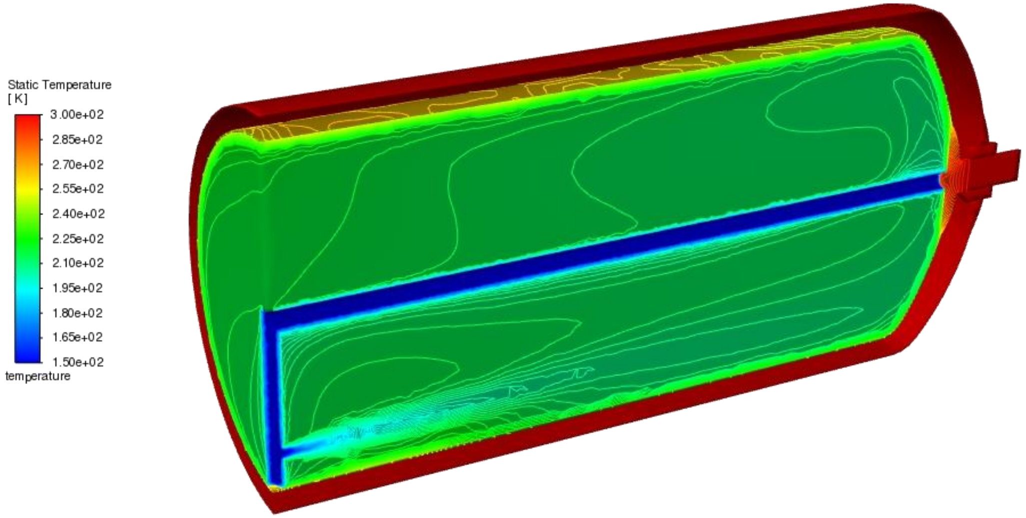
Tank Filling Simulation (Transient Analysis)

Tank Filling CFD Simulation





Gas Inlet
Temp = 150 K



Temperature fluid-structure evolution

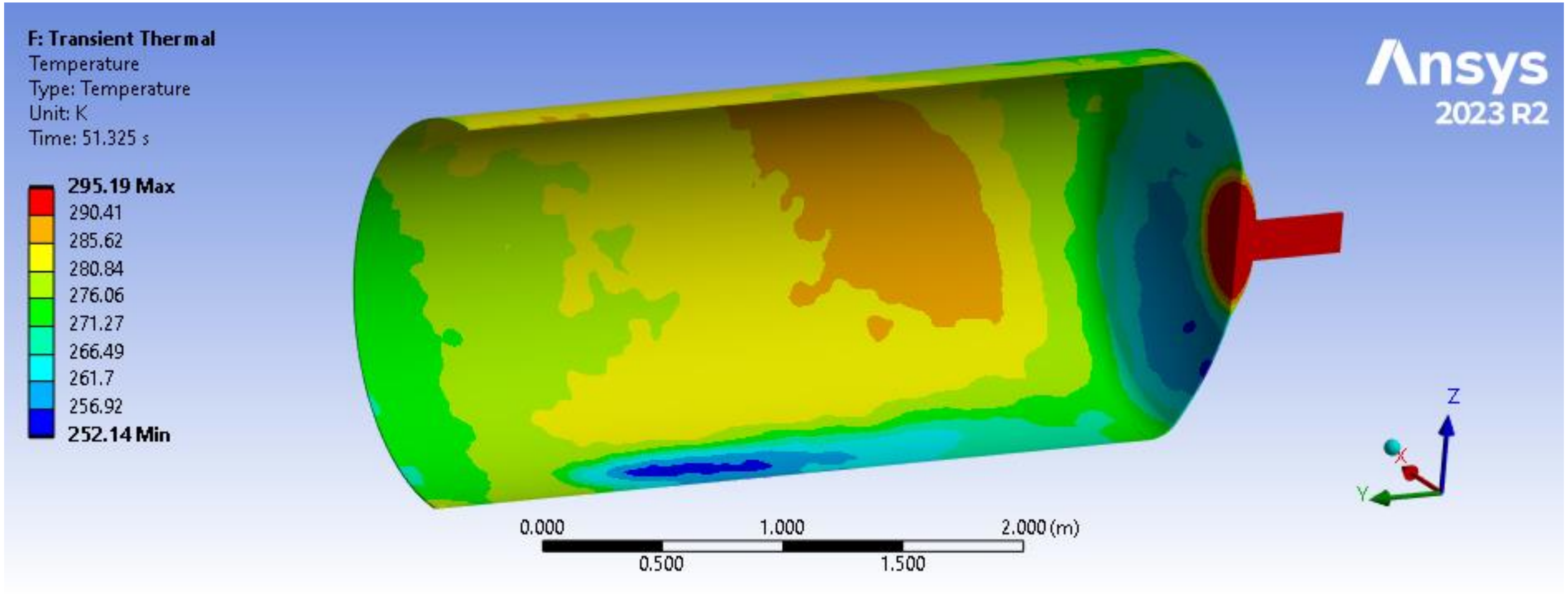
Hydrogen Tank Working Conditions:

Thermal Stress analysis of the filling simulation (Transient Analysis)

Heat transfer analysis based on CFD results

Metal liner

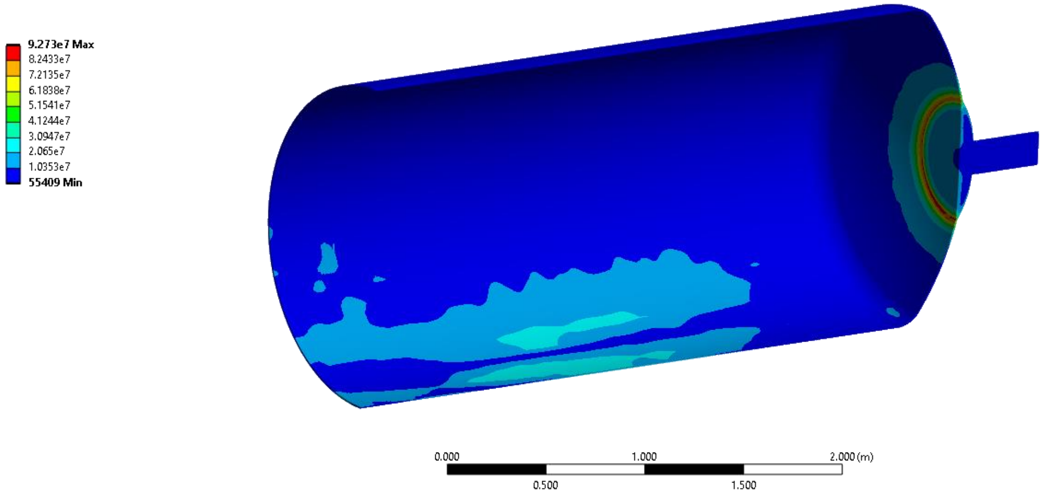
Temperature distribution at 51 s

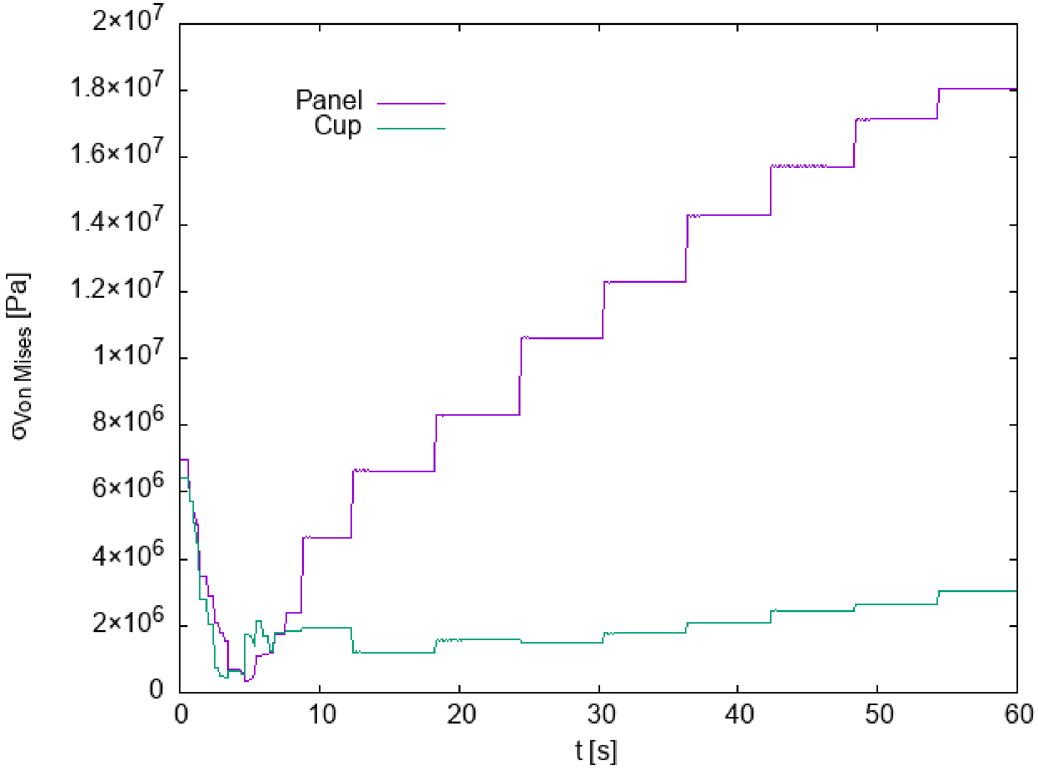


Thermo-mechanical transient Stress analysis

Metal liner

Von Mises stress



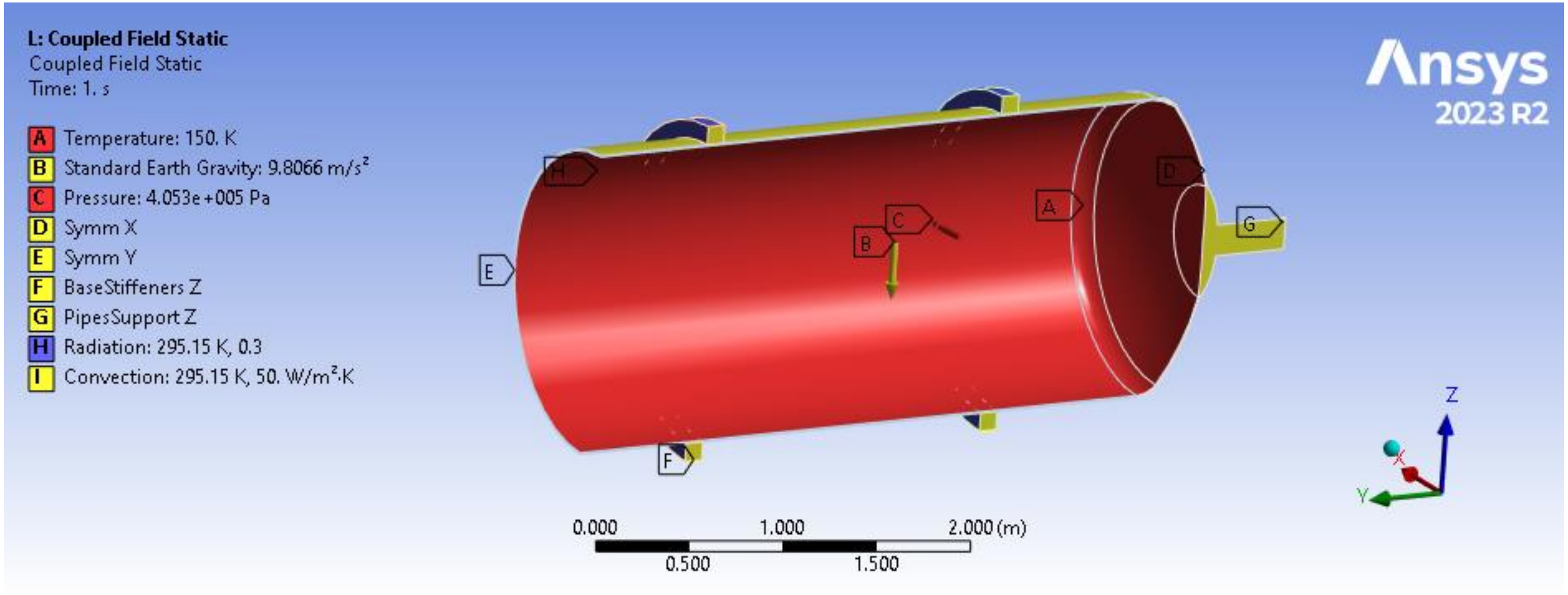


Hydrogen Tank with single wall:

Multilayered design study

Thermo-mechanical static analysis

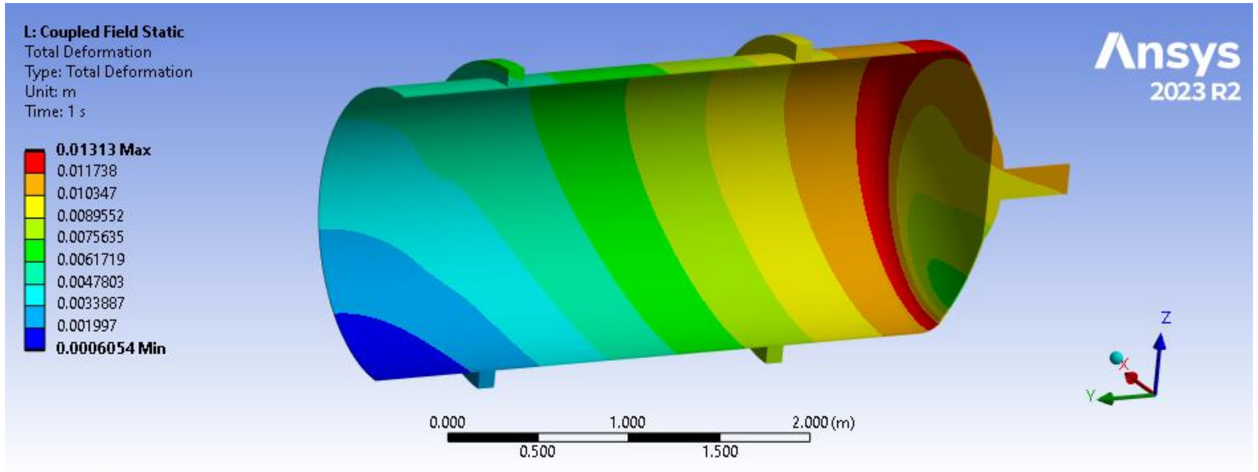
Loads and boundary conditions

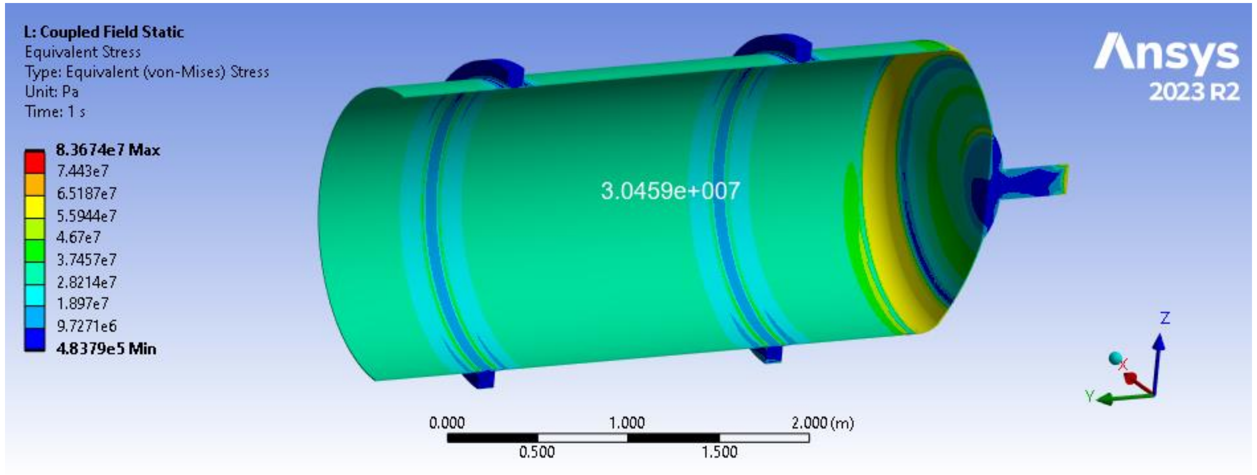


Thermo-mechanical static stress analysis

1 Aluminum layer wall

Total displacement



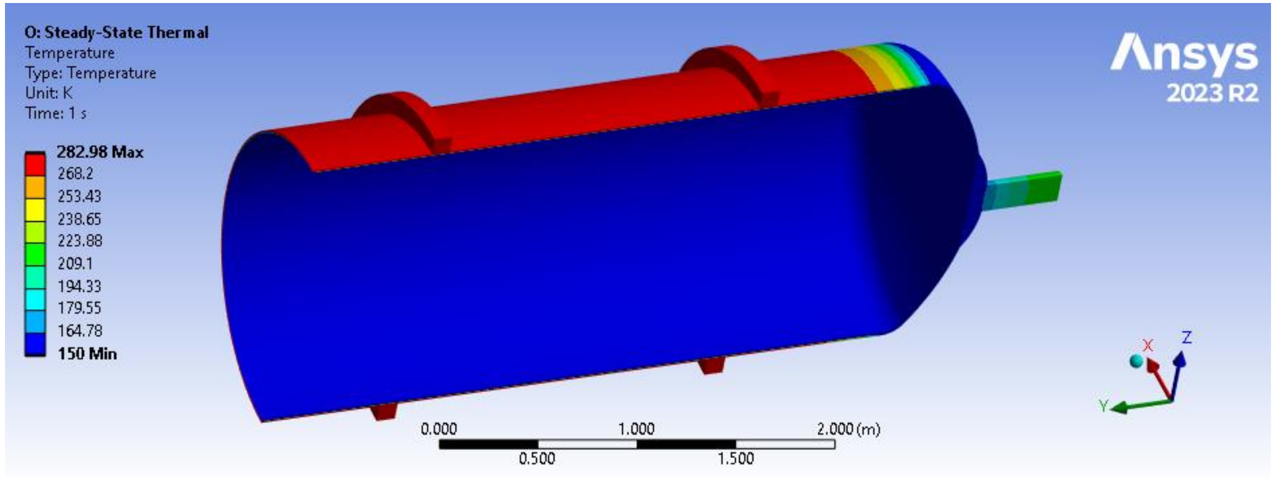


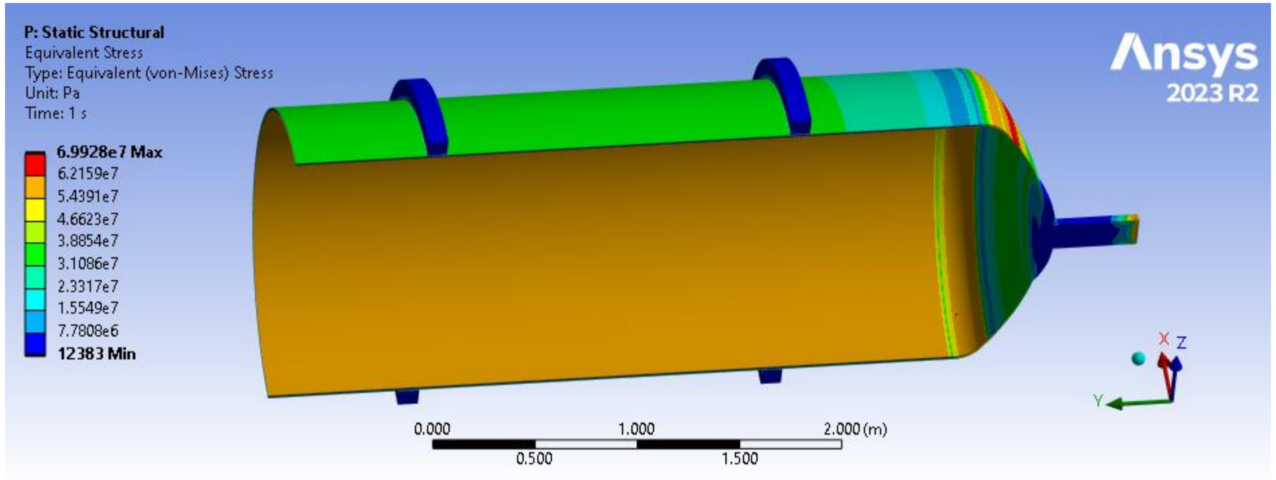
Von Mises stress

Thermo-mechanical static stress analysis

3 layers wall [Aluminum / Foam /Aluminum]

Temperature



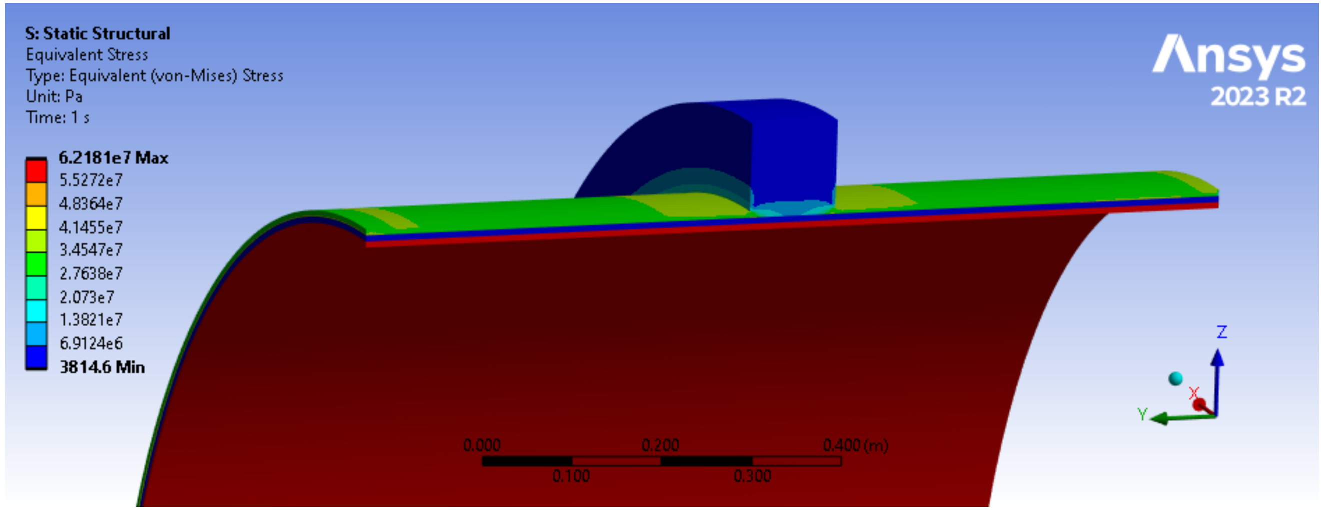


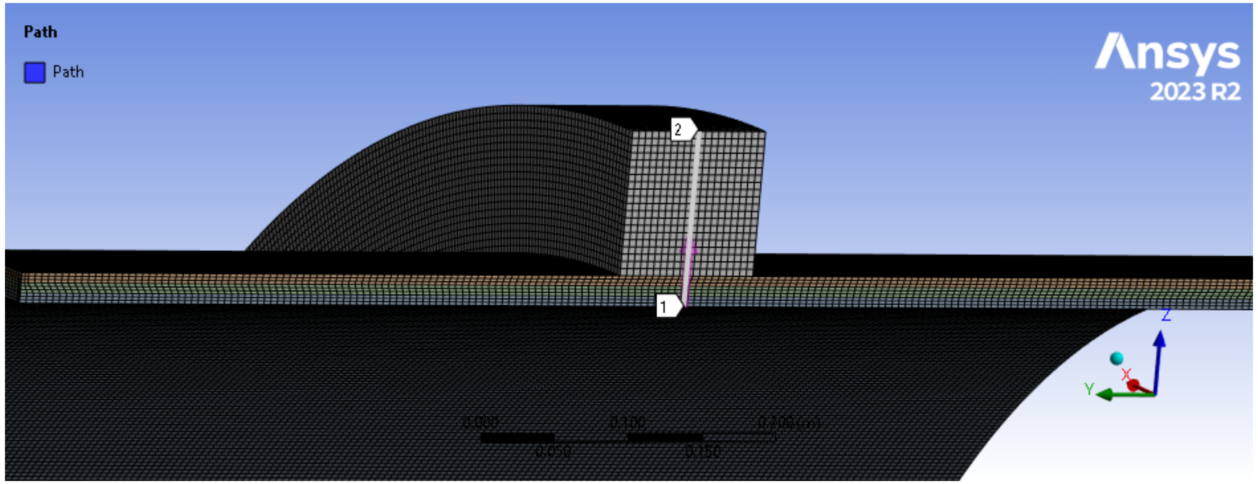
Von Mises stress

Thermo-mechanical static stress analysis

3 layers wall [Aluminum / Foam /Aluminum]

Von Mises stress

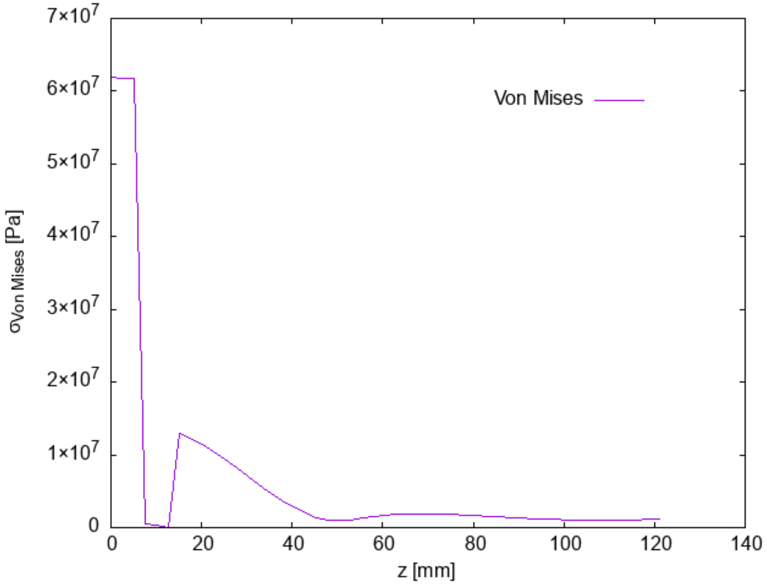


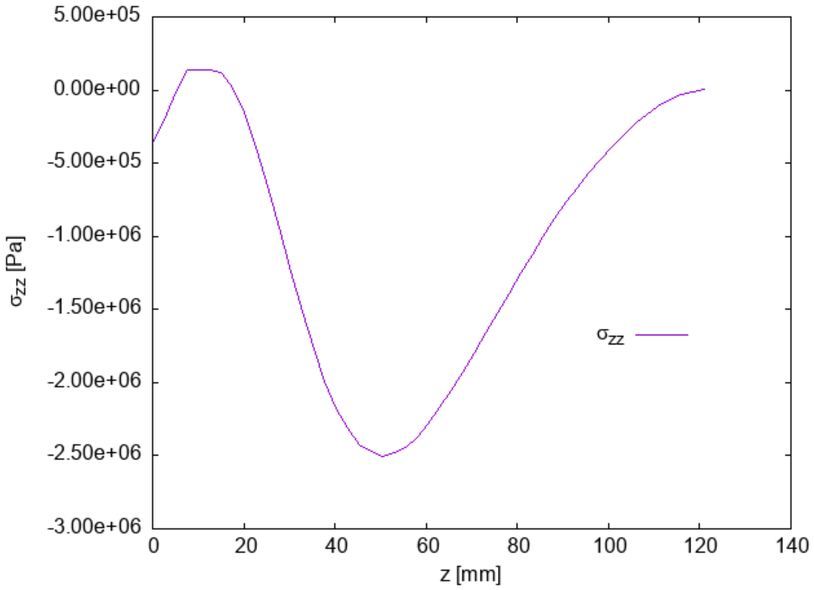


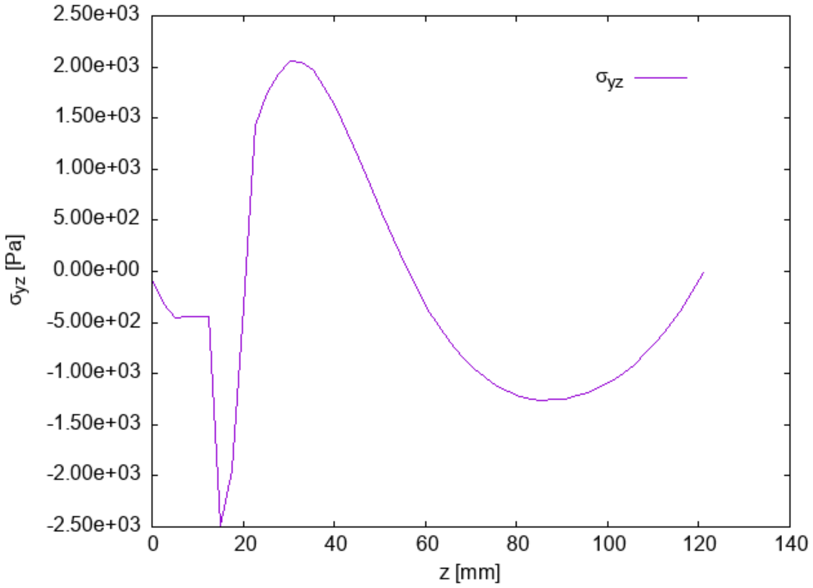
Through-the-thickness path

Thermo-mechanical static stress analysis

3 layers wall [Aluminum / Foam /Aluminum]





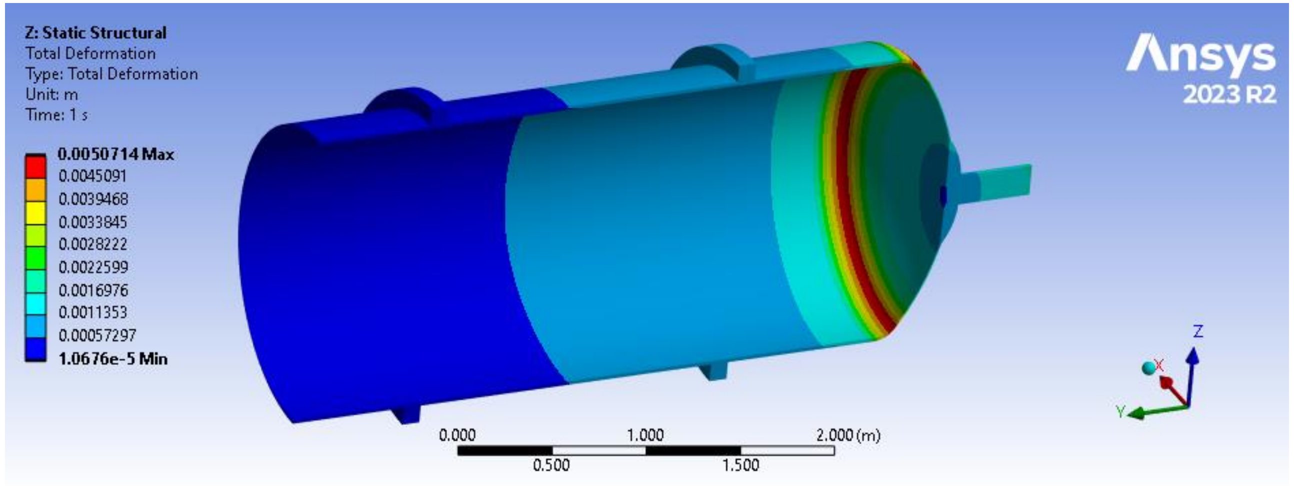


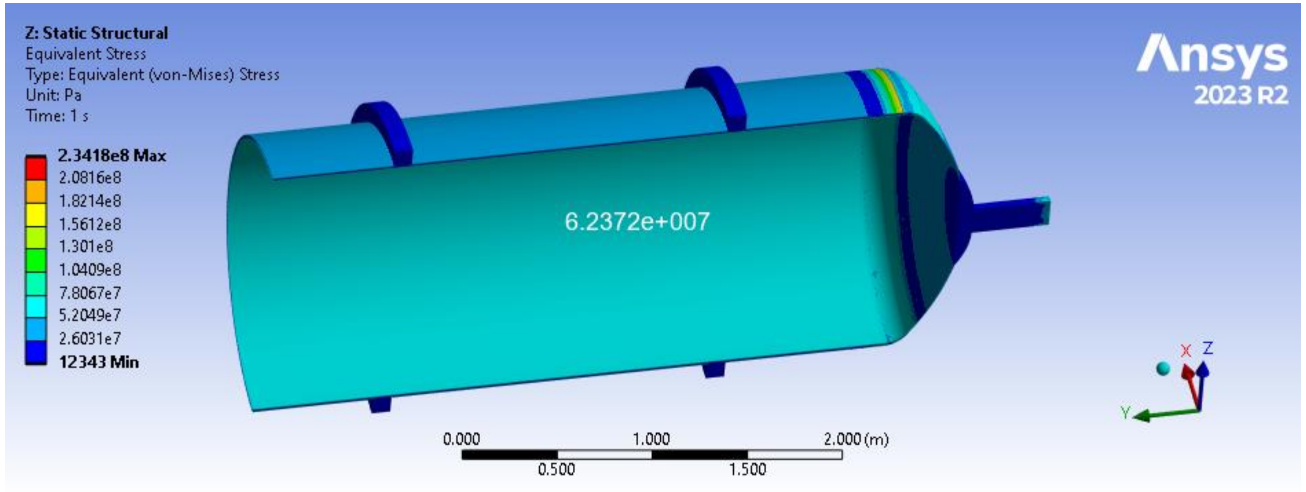
Von Mises stress **Normal stress** **Shear stress**

Thermo-mechanical static stress analysis

3 layers wall [Composite / Foam /Aluminum]

Total displacement





Von Mises stress

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Thermo-mechanical static stress analysis

3 layers wall [Composite / Foam /Aluminum]

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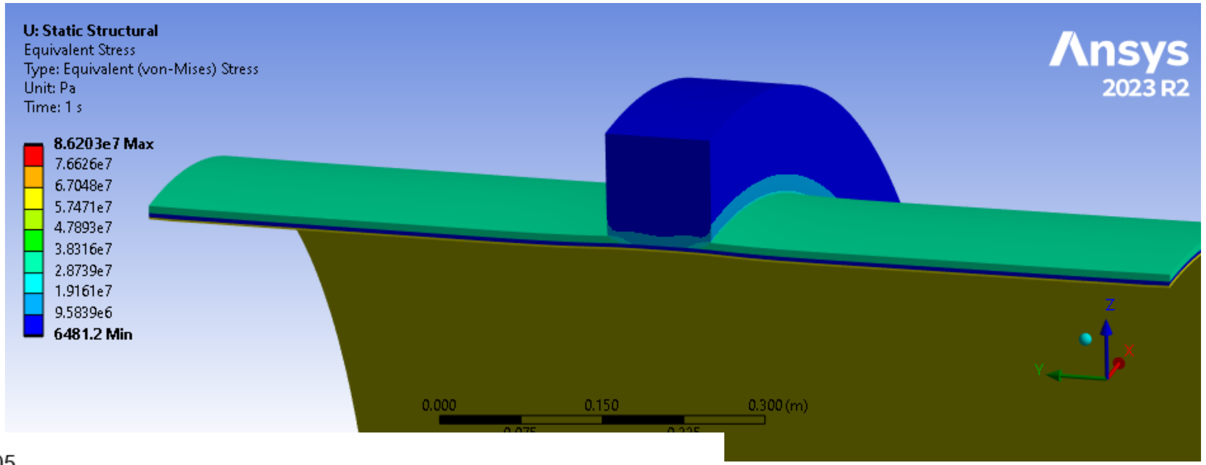
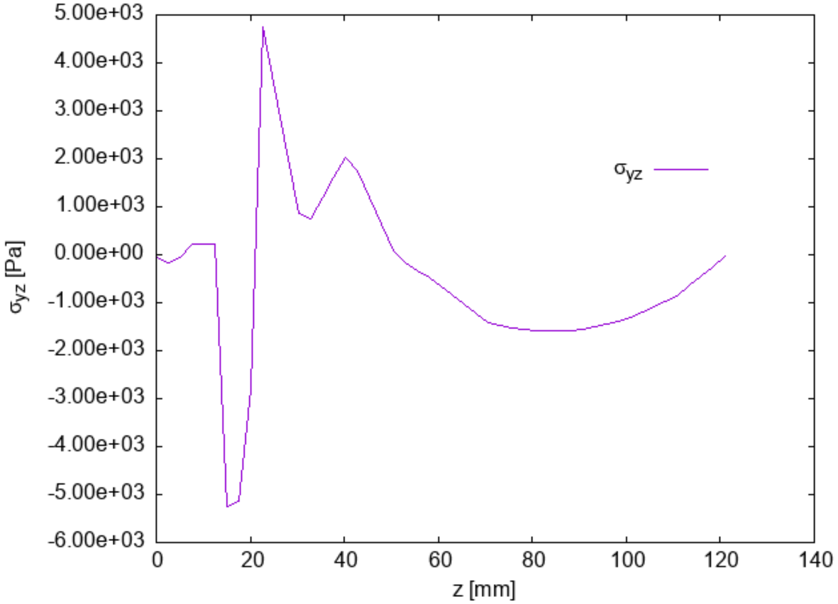
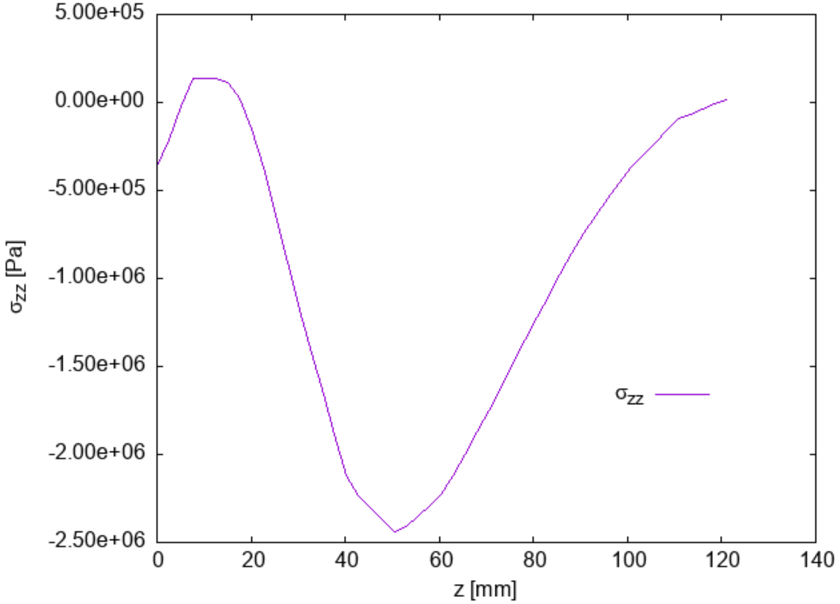
Von Mises stress



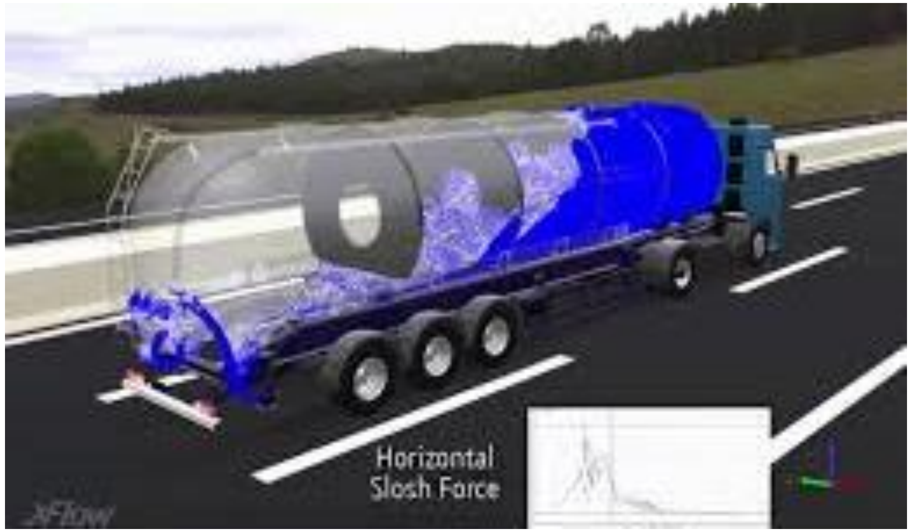
Shear stress

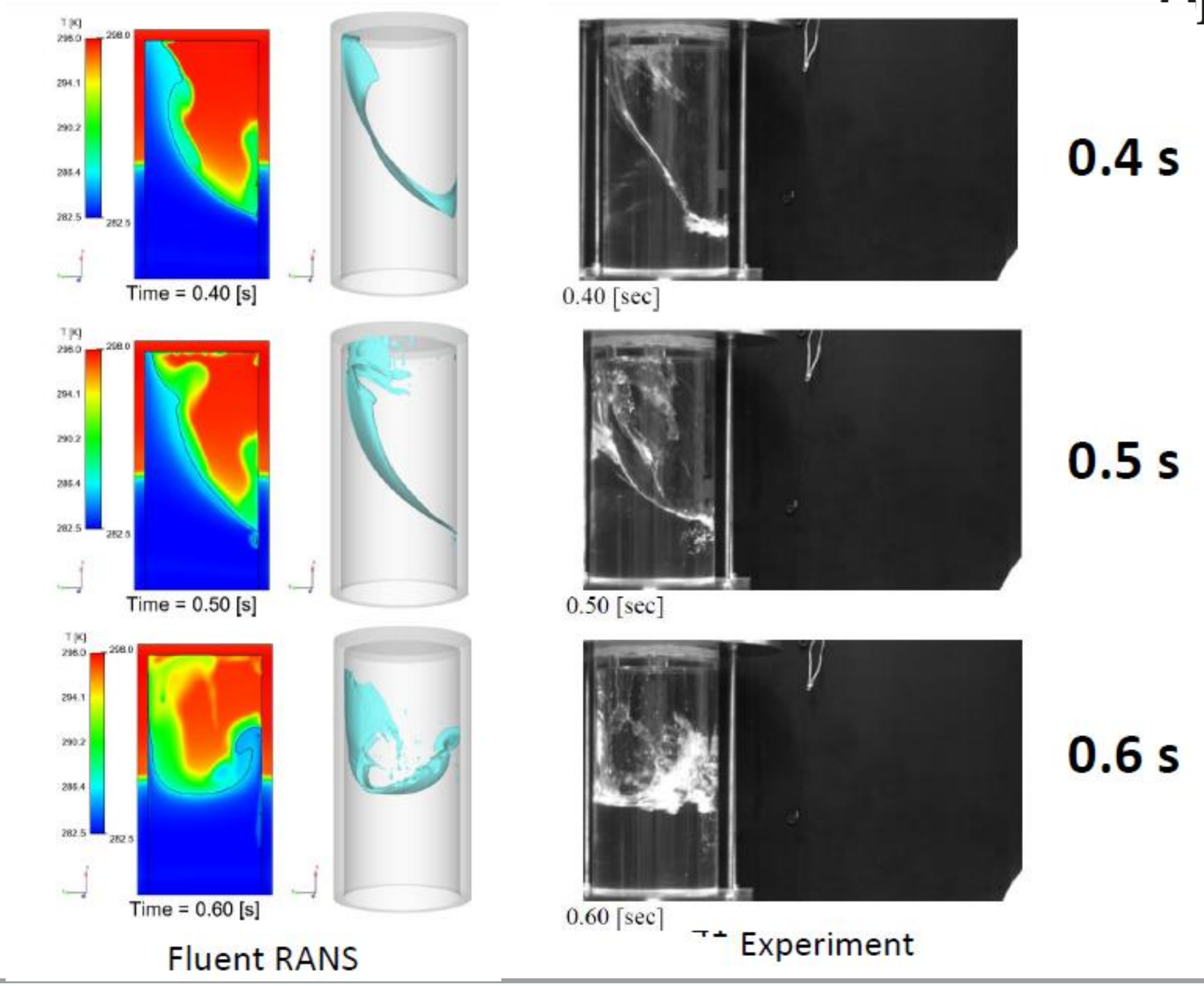




Normal stress

Slosh analysis for liquid fuel tanks

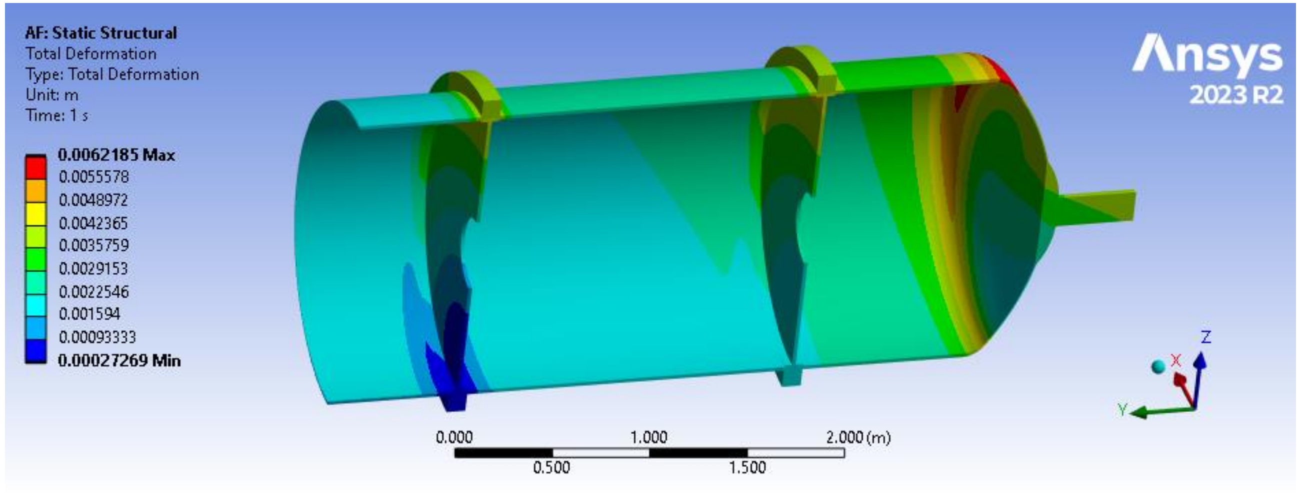


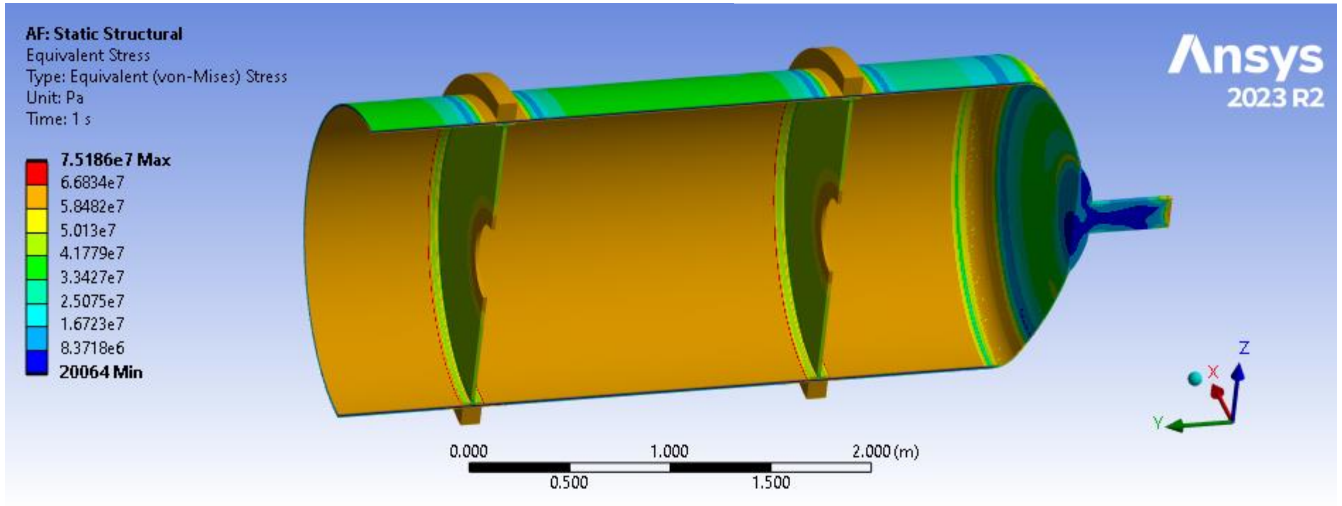


Thermo-mechanical static stress analysis

Anti-slosh internal walls

Total displacement

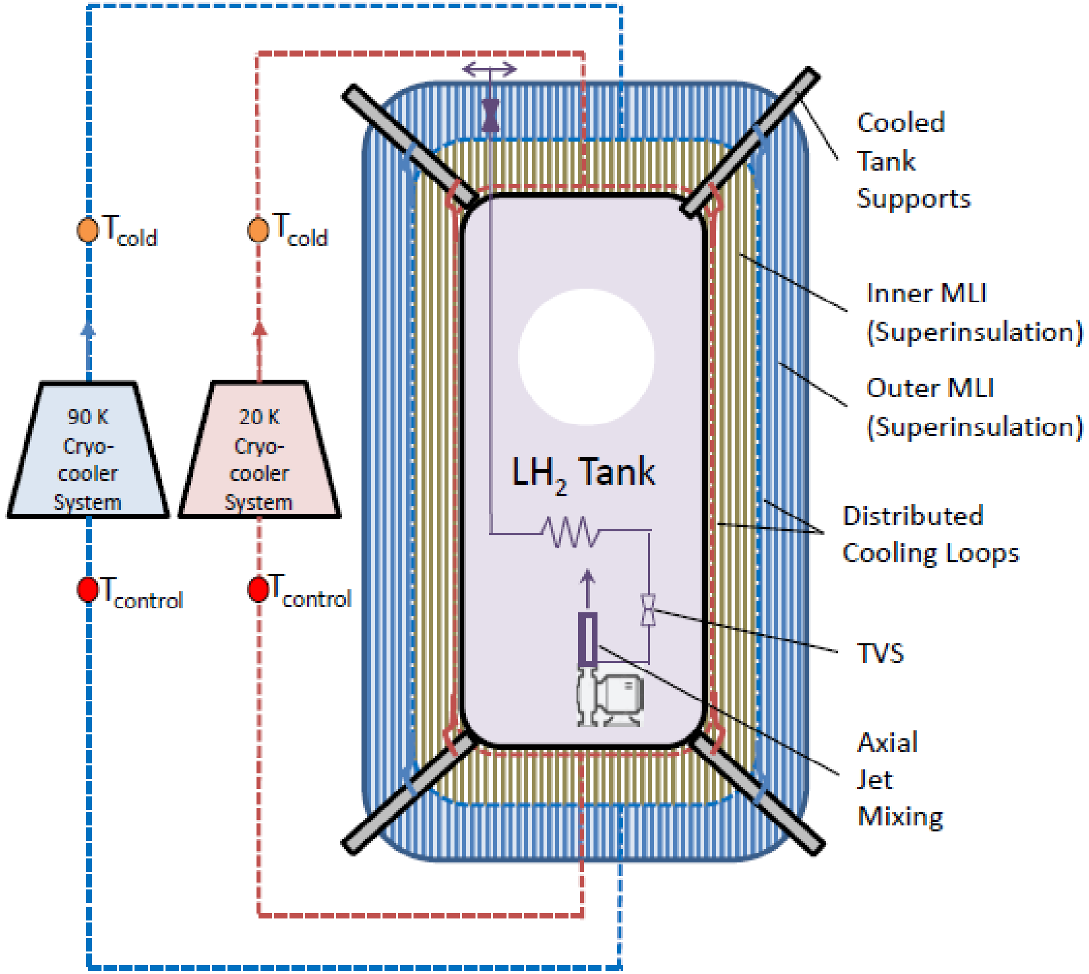




Von Mises stress

Advanced solution for Liquid Hydrogen Tank

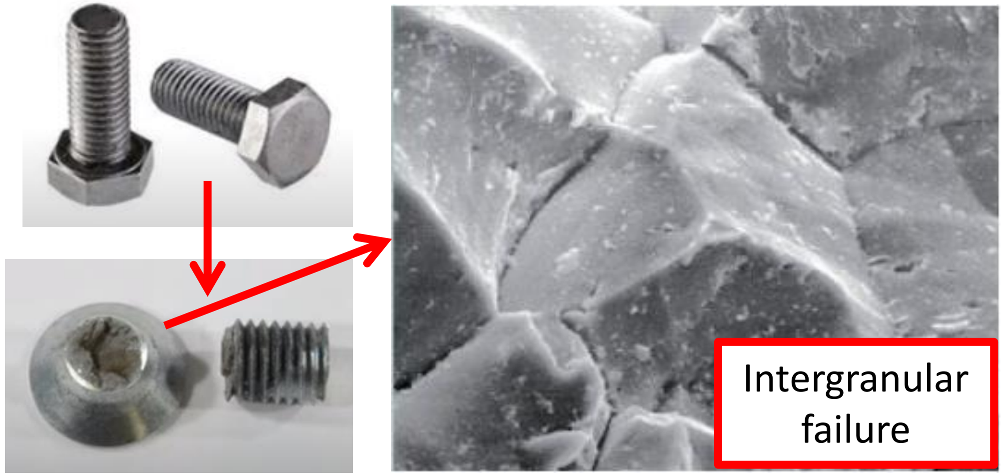
Double cryo-cooler system for control pressure



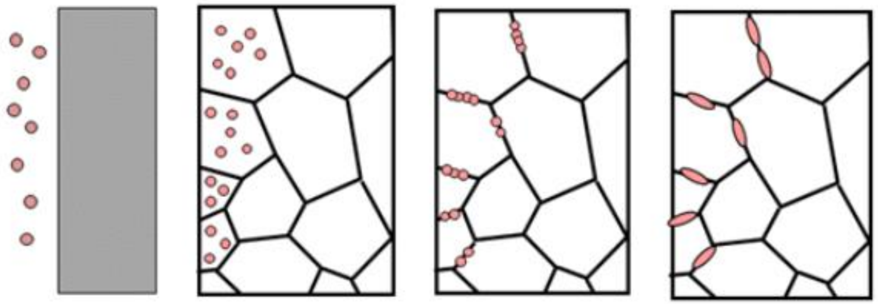
Recent interests for the Hydrogen Tank Failure Analysis :

Hydrogen embrittlement modelling

Background for Hydrogen embrittlement modelling



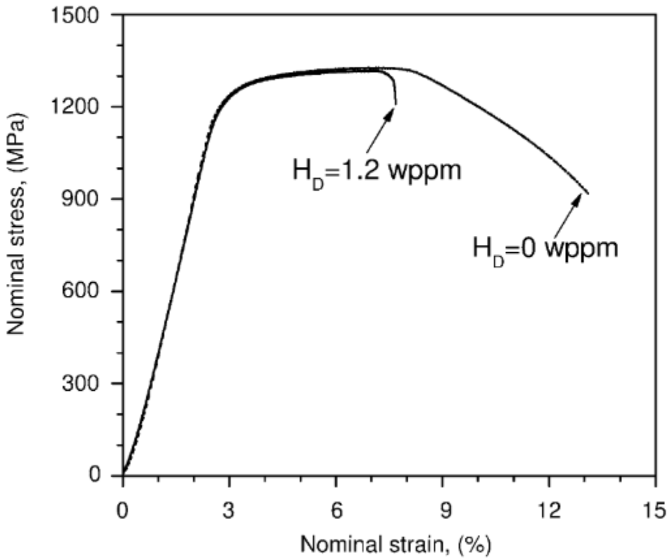
H-enhanced localized plasticity (HELP)
Interface-enhanced decohesion (HEDE)
Other mechanisms (slip bands)

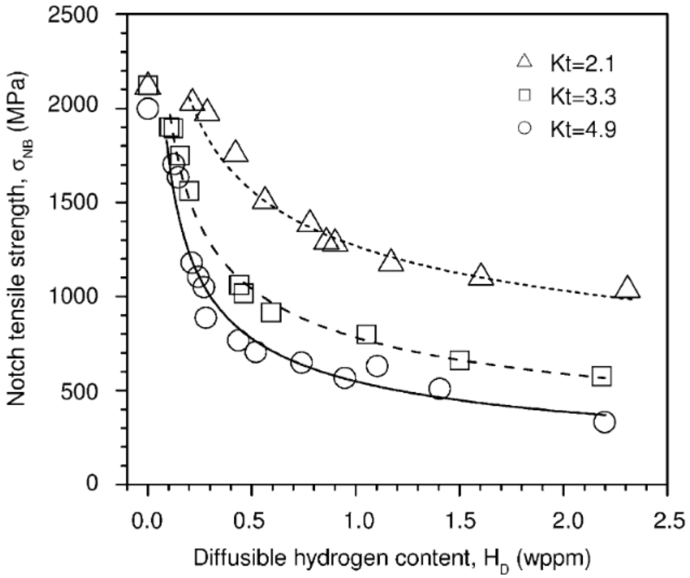


1st: H diffuses into the grains

2nd: H diffuses into the grain boundaries

Change of mechanical properties (due to H) in steels





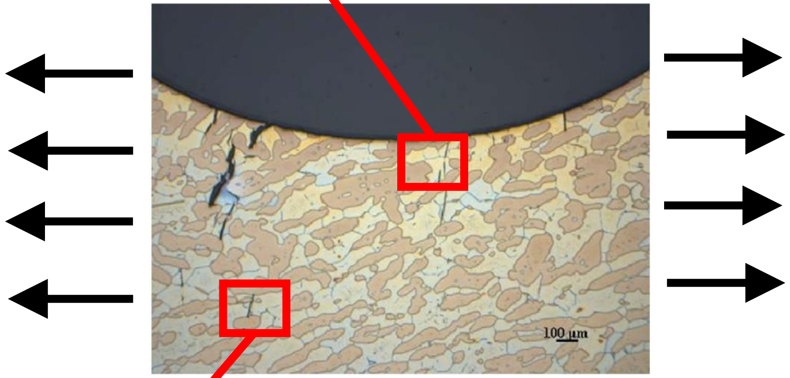
Loss of ductility

Loss of toughness

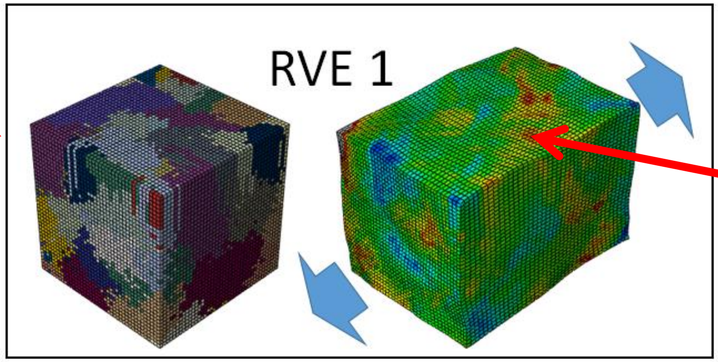
M. Wang et al. / Materials Science and Engineering A 398 (2005) 37–46

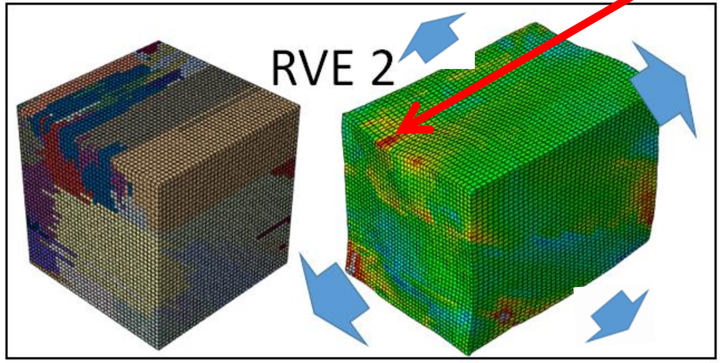
Hydrogen embrittlement Modelling strategy

Failure driven by the maximum principal at the notch route



Failure driven by the build-up of hydrostatic stress (σ_H) subsurface, crack initiations reported subsurface





Strain localisation led to damaged elements.

Elastic modulus lowers with the concentration of H:
E(H)

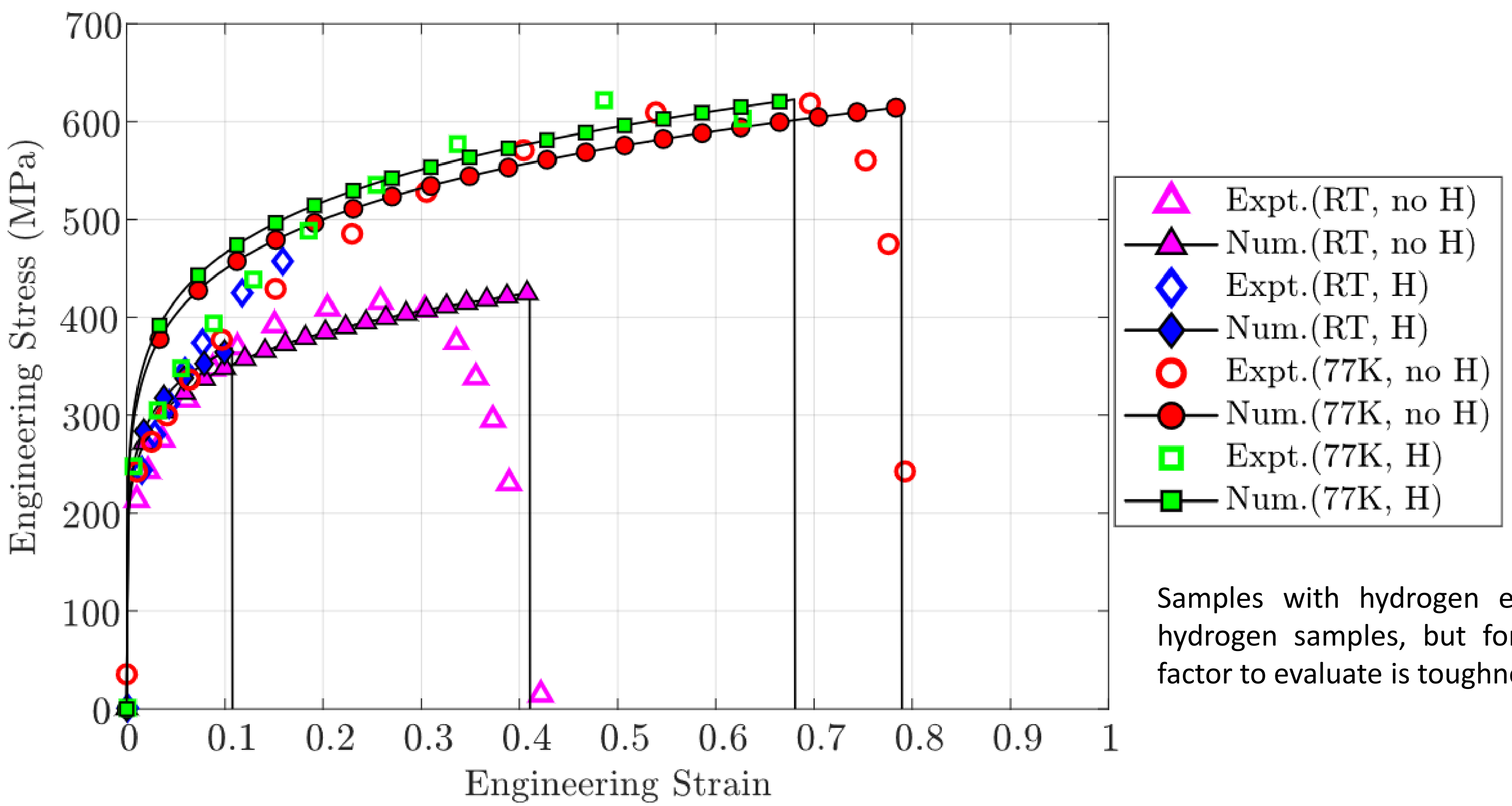
H concentration = f(σ_H)

$$H = H_D \exp\left[\frac{-V_H(\sigma_h - \sigma_{h,min})}{RT}\right]$$

Mass conservation

$$f = \frac{H_D \sum_i V_i}{\sum_i (V_i H_i)}$$

Loss of toughness in H-charged samples



Samples with hydrogen exposure appear harder than non-hydrogen samples, but for hydrogen embrittlement, the key factor to evaluate is toughness, not just hardness.

Valverde-González, A., et al. "Computational modelling of hydrogen assisted fracture in polycrystalline materials." *international journal of hydrogen energy* 47.75 (2022): 32235-32251.

Conclusions

- Thin-walled hydrogen tanks are employed in different industrial applications with different working conditions. Therefore, multilayered design of hydrogen tanks will be more requested in the coming years.
- The use of hydrogen in aeronautics transportation systems is very challenging. Complex and advanced solutions are under investigation.
- The use of liquid hydrogen (LH2) at low pressure leads to the design of tanks working at cryogenic temperature (lower than 30 K).
- To reduce the cooling costs during operations, it is necessary to design tanks with effective isolation solutions.
- It is mandatory to study the filling process of tanks in order to capture the thermal shock faced by the structure.
- A proper thermal-stress analysis has to be conducted to choose the optimal stacking sequence for the tank wall.
- The embrittlement effect has to be considered into a multiscale campaign analysis to prevent possible hydrogen leaks during operations.

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