Cryogenic Structural Analysis of LH2 Fuel Tanks in ANSYS Static Structural

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Abstract

This paper provides a comparative structural comparison of cryogenic Liquid Hydrogen (LH_2) tanks for aerospace use, where the aim is to maximize weight, strength, and deformation against harsh cryogenic conditions. The study examines six potential materials—Aluminium 6061, Aluminium 7075, Structural Steel, Stainless Steel 304, Titanium alloy Ti-5Al-2.5Sn, and Magnesium alloy AZ31—via finite element simulations in ANSYS Static Structural at 77 K, subjected to an internal pressure of 5 MPa and an 80% fill. Results indicate that although Stainless Steel 304 and Structural Steel have minimum deformation, the excessive weight and high induced stresses limit their applications in aerospace. Aluminium alloys yield moderate strength and deformation at lower weight, making Al6061 a practical lightweight candidate. Magnesium AZ31 has minimum weight and comparable mechanical performance, although it poses a flammability risk as a design issue. Titanium alloy Ti-5Al-2.5Sn performs better than all other materials, with lowest stress and deformation and optimum strength-to-weight ratio and is, therefore, the best choice for aerospace-quality LH_2 containment. The results emphasize the necessity for expanded research on dynamic loading, thermal flux behavior, and multi-material hybrid configurations to optimize the safety and efficiency of next-generation cryogenic propulsion systems.

Key words: Cryogenic tank, Liquid Hydrogen (LH_2), Aerospace applications, Finite Element Analysis (FEA), Material selection, Aluminum alloys, Titanium alloys, Magnesium alloys, Stainless steel, Structural integrity, Cryogenic temperatures, Stress analysis, Deformation, Lightweight design

Introduction

One of the most critical components of a rocket is its propulsion system. Modern aerospace manufacturers increasingly use cryogenic propulsion systems due to their superior energy efficiency. For instance, Liquid Oxygen (LOX) and Liquid Hydrogen (LH2) offer the highest energy storage capacity in rocket engines [1]

A typical LH2 storage tank consists of an inner vessel containing the cryogenic liquid, an insulating layer, and a vacuum between the inner and outer vessels to minimize heat transfer. The inner vessel is structurally supported either by its inlet and outlet at the top or by a skirt at the bottom. These tanks, which store LOX and LH2 propellants, must withstand both mechanical and thermal loads at cryogenic temperatures while minimizing heat flux.

Cryogenic tanks are widely used not only in aerospace applications but also in the transportation of green energy sources such as liquefied methane. In its liquid form, methane occupies less than 1/580th of its gaseous volume [2], making cryogenic storage crucial to the green energy revolution. Beyond aerospace, cryogenics has applications in medical science, high-volume technology, biological research, food processing, cryophysics, manufacturing, and material recycling .

Optimizing the inner vessel's weight can significantly enhance overall efficiency, reducing both production costs and operational performance [3] Previous studies have identified a research gap in the mechanical characterization of inner tanks[4].Therefore, this study aims to design a structurally sound cryogenic tank using materials capable of withstanding extreme mechanical and thermal loads while optimizing weight and wall thickness.

Literature Review

Cryogenic storage vessels, such as for liquid hydrogen (LH_2), are one of the most vital pieces of equipment in aerospace and advanced energy technologies, demanding serious consideration of material behavior, structural integrity, and operational performance. One of the main issues facing LH_2 storage is embrittlement because the very small size of hydrogen atoms allows them to penetrate materials and lower ductility. These are mitigated with metals that have face-centered cubic (FCC) crystal structures, supplemented with specialized insulation, double-walled vacuum enclosures, and multi-layer thermal protective systems. Hybrid tanks made of combinations of metals and composites, although lighter, pose interface stresses in the form of mismatched thermal expansion coefficients, heightening the susceptibility to structural failure under cryogenic conditions. [5], [6] Therefore, materials used in LH_2 tanks should have high ductility, good fracture resistance, and adequate safety factors to support combined mechanical, thermal, and dynamic loads. [4]

Extensive research reveals that metallic tanks have a definitive edge over composite tanks under cryogenic loads. Aluminum alloys, for instance, display little overall deformation relative to aluminum-carbon fiber composites for similar internal pressures, indicating higher load-carrying ability in cryogenic conditions. [7] Properties of metals' mechanical are still further improved at low temperatures: aluminum alloys like AA2195 and EN AW 1085 exhibit very high yield and ultimate tensile strength increases, with low reduction in ductility, while titanium alloys like Ti-5Al-2.5Sn and Ti-6Al-4V exhibit nearly twofold increase in yield and tensile strength at cryogenic temperatures. Alpha-phase titanium alloys, specifically, possess adequate strength coupled with excellent fracture toughness to be ideally suited for LH_2 containment in the aerospace industry.[8], [9], [10] Magnesium alloys such as AZ31 and ZK60 possess high strength-to-density ratios and acceptable thermal conductivity but some compositions (e.g., AZ80) suffer ductile-to-brittle transitions at very low temperatures, emphasizing careful selection of alloy. [11], [12], [13] Stainless steels like SS304 and duplex grades retain ductile fracture modes and have good strength-elongation balance at cryogenic temperatures, and lower residual stresses minimize the possibility of micro-crack generation and hydrogen permeability. [14], [15]

Structural and design considerations are also important. Simulations project that maximum deformation in vertical tanks takes place at the opposite end of fixed constraints, while horizontal tanks undergo circumferential stress distributions where maximum stress concentration is at mounting locations. [16] Dynamic loading in terms of dead weight, internal pressure, seismic forces, and wind loads also need to be considered, especially in aerospace environments. [17] Experiments with support systems show that well-designed fastening rings and support pads can satisfy specified safety factors and support adequate rigidity, indicating the need for harmonizing material selection with geometric and boundary condition issues. [18]

Aside from ground applications, the design of railway and mobile cryogenic tanks has uncovered the same structural issues. For instance, impact tests on LNG tanks for rail transport identified that conventional frame structures would fail under standard vehicle-induced loads, and frame redesign or elimination of side rails may be recommended to achieve safety. [19] The results support the significance of assessing static and dynamic parameters, deformation mode, and long-term performance in cryogenic tank design.

Overall, the literature emphasizes that peak cryogenic tank performance results from the skillful coordination of material characteristics, structural design, and operating conditions. Of the metallic contenders, titanium alloys, aluminum alloys, magnesium alloys, and some stainless steels exhibit the best balance of strength, ductility, and cryogenic performance. Yet, the reinforcement needs, heat insulation, fire risk reduction (for magnesium), and dynamic loading aspects continue to be essential in ensuring safety and efficiency. Advanced compositions of alloys, hybrid material concepts, and dynamic loading behavior should remain subjects of investigation in the future to further improve LH_2 cryogenic tanks for aerospace and green energy use.

Methodology

For the purposes of this research, an internal vertical vessel with hemispherical heads with dimensions 2504mm dome radius, 4894mm total length and thickness 15 mm, constrained by all the external surfaces as the assumption of this design is the presence of a secondary structural shell made from composite materials. The secondary shell is not a part of the simulations as the extent of this research is with respect to the inner vessel and its structural integrity at cryogenic temperatures. . The materials used in the simulation are Aluminium 6061, Aluminium 7075, Structural steel, Ti-5Al-2.5Sn, Austenitic annealed steel 304 and Magnesium alloy az31 . The simulation was conducted assuming an 80% full tank with LH2 propellant.

Criteria	Value
Temperature	77K
Internal Pressure	5 MPa
Fluid load	178 kg

Table 1: Simulation parameters

Material	Density (g/cm^3)	Youngs Modulus (GPa)	Coefficient of thermal Expansion

			(C^-1)
Al6061	2.7	68.9	2.3x10^-5
Al7075	2.81	71.7	2.5x10^-5
Ti-5Al-2.5Sn	4.48	125	9.4x10^-6
Steel 304	7.88	193	1.69x10^-5
Structural Steel	7.85	200	1.2x10^-5
Magnesium AZ31	1.77	44.8	2.6x10^-5

Table 2 : Simulation Material Characteristics

For the extent of this research the criterion of analysis will be the maximum deformation and the maximum stress induced in the inner vessel. The simulation was performed in ANSYS static structural. The model of the tank was developed in ANSYS design modeler.

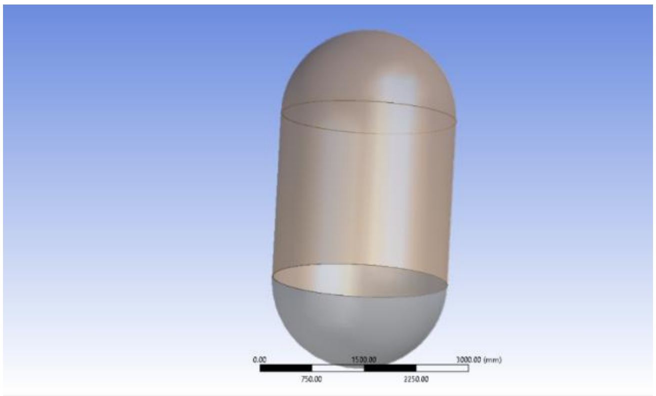

Fig 1: Model of Vessel

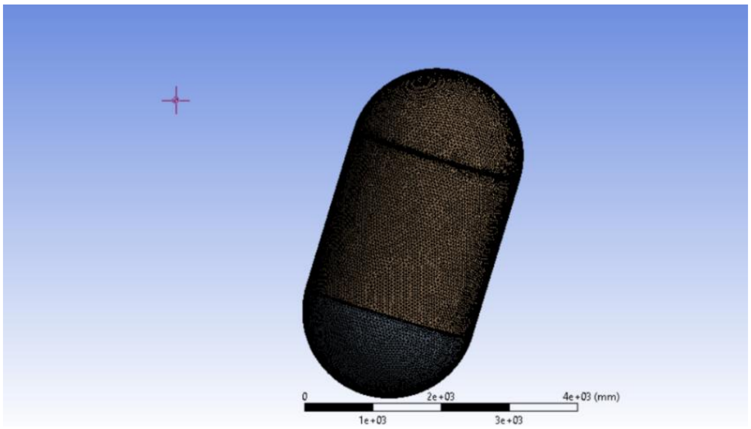

Fig 2 : Meshed Vessel

A mesh was developed within ANSYS with tetrahedrons . A total of 256825 nodes and 128593 elements were generated.

Results and Discussion

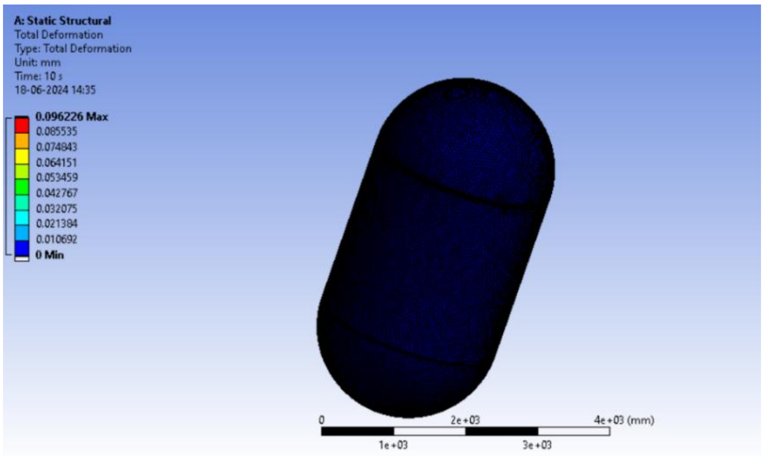

Fig 3: Total Deformation with SS304

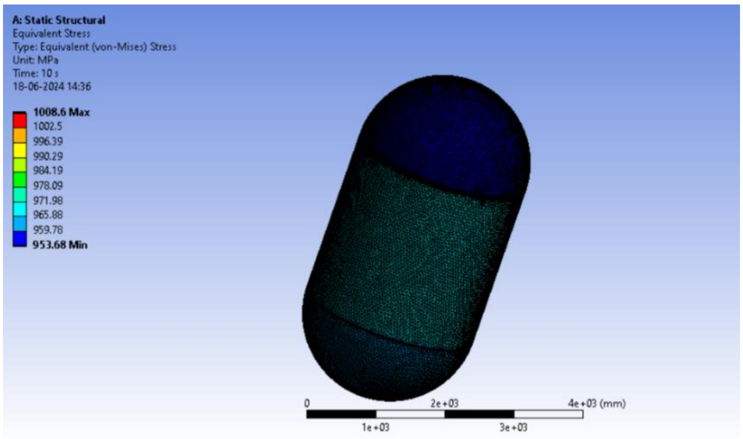

Fig 4: Stress with SS304

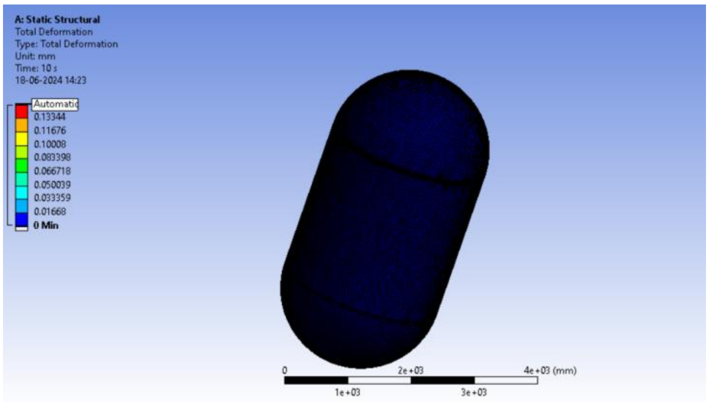

Fig 5 : Total Deformation with Al6061

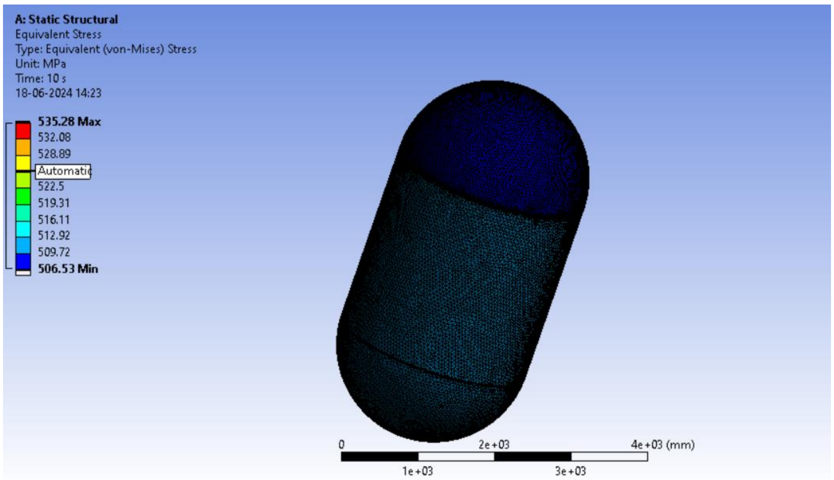

Fig 6 : Stress with Al6061

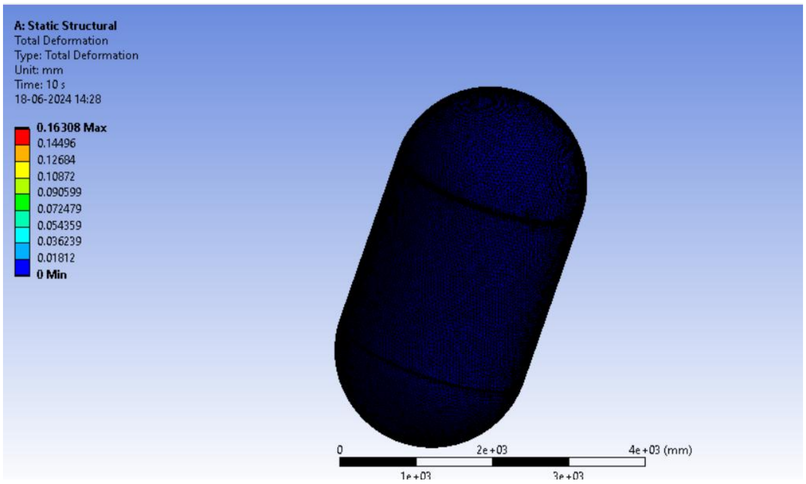

Fig 7 : Total Deformation with Al 7075

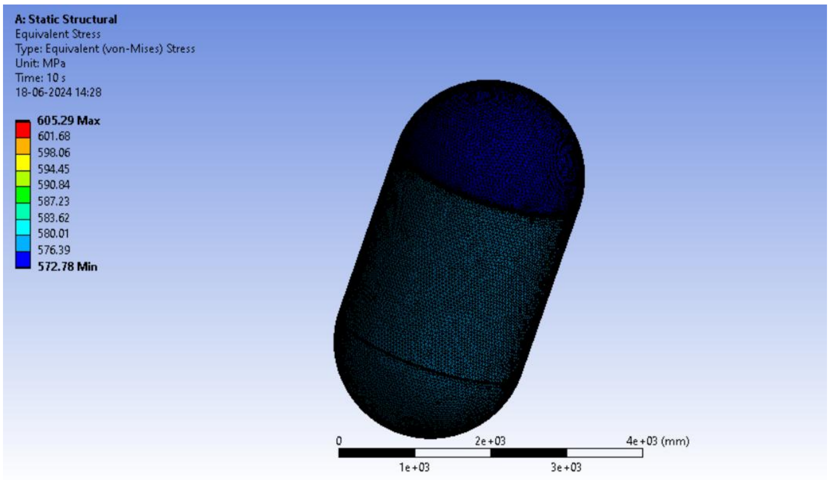

Fig 8 : Stress with Al7075

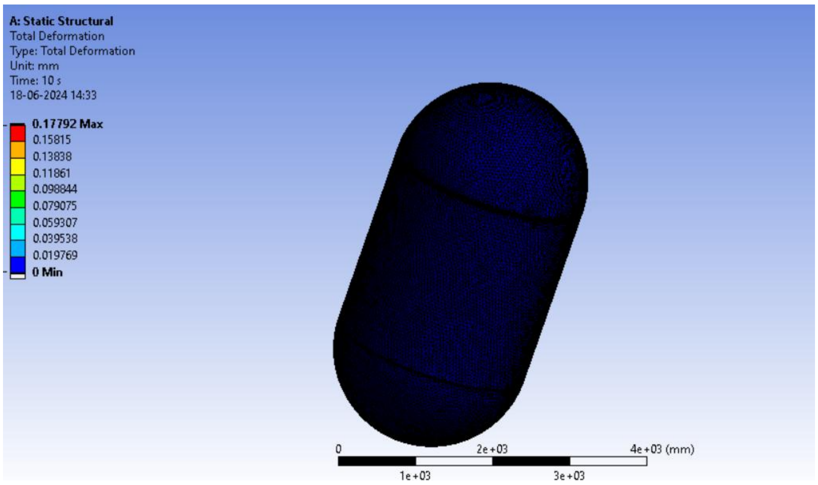

Fig 9 : Total Deformation with AZ31 Magnesium alloy

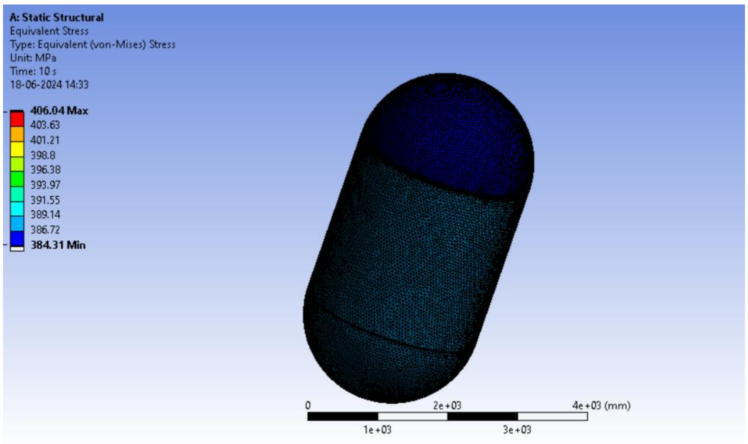

Fig 10 : Stress with AZ31 Magnesium alloy

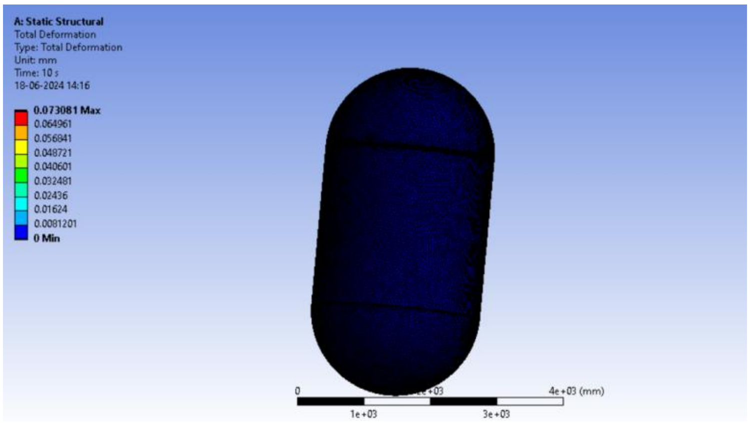

Fig 11 : Total Deformation with Structural Steel

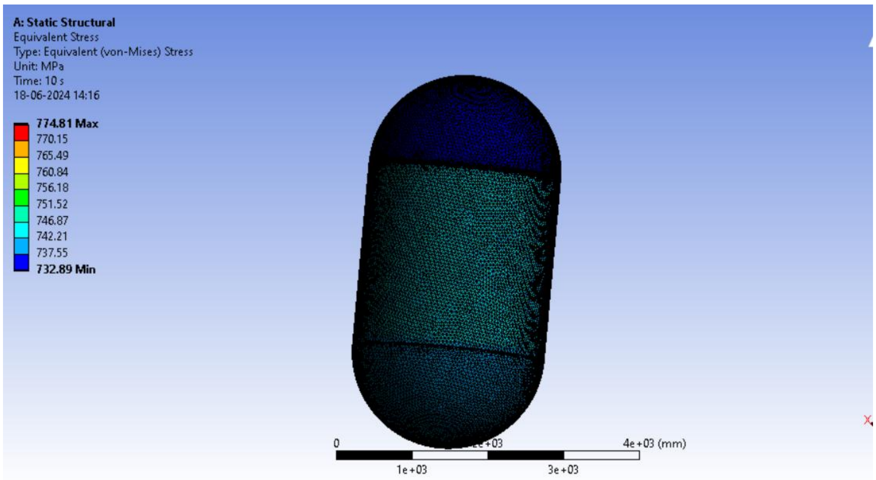

Fig 12 : Stress with Structural Steel

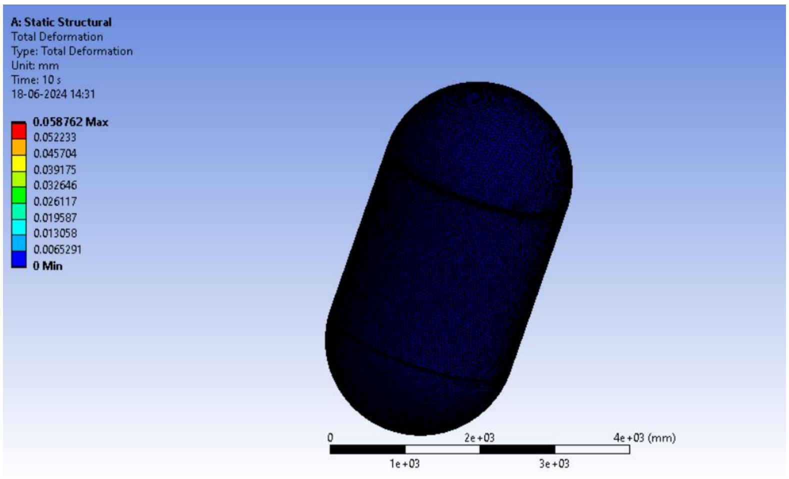

Fig 13 : Total Deformation with Ti-5Al-2.5Sn Alloy

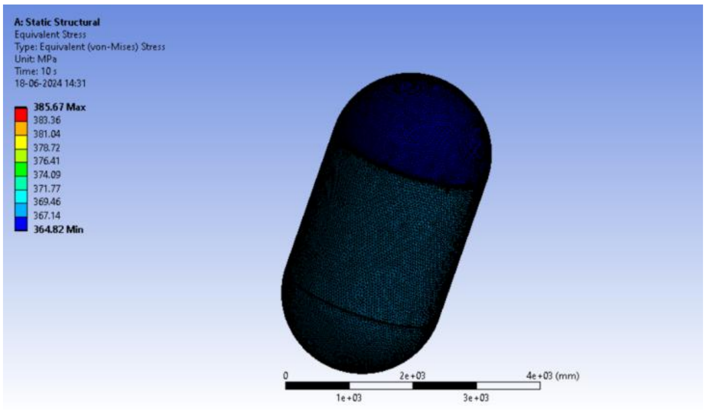

Fig 14 : Stress with Ti-5Al-2.5Sn Alloy

The results of the simulation display interesting properties of the materials under load at cryogenic temperatures. The maximum stress of 1008MPa was induced is Stainless Steel 301 which produced a deformation of .096. The least deformation and the least stress induced was in the titanium alloy Ti-5Al-2.5Sn. Structural steel also performed relatively on par with SS301 with 774MPa of maximum stress and .073 maximum deformation. Both aluminium 6061 alloy and 7075 alloy performed comparably with moderate values in stress and deformation. Magnesium AZ31 alloy performed comparatively better than the aluminium alloys with a lower stress value and relatively similar deformation values.

Material	Deformation(mm)	Stress (MPa)	Mass (kg)
SS304	.096	1008.6	1938480
Structural Steel	.073	774.81	1931100
Al6061	.14	535.28	664200
Al7075	.16	605.29	691260
AZ31	.17	406.04	435420
Ti-5Al-2.5Sn	.058	385.67	1102080

Table 3 : Summarized Results

It is clear from the table that Magnesium AZ31 seems to be the best choice that balances mass, stress induced and total deformation. A vessel made from AZ31 would require much less reinforcing external structure when compared to steel. Both the steel alloys performed with excellent results in terms of deformation but the maximum stress induced requires very aggressive reinforcement and the mass of the tank also makes them unviable for aerospace applications. Titanium alloy displays an efficient balance between very low deformation, stress and mass. A titanium vessel would require minimal reinforcement. Aluminium alloys 6061 and 7075 display similar deformation and similar mass. Al7075 would require more aggressive reinforcement when compared to Al6061. Alternatively the thickness of the vessel can be increased to compensate for the induced stress in the case of both aluminium alloys 6061 and 7075.

Conclusion

The study conducted assessed the research conducted in the design, material selection and analysis of LH2 cryogenic containment tanks. The literature review shows that ample amount of study was conducted for terrestrial vessels with minimal design and analysis performed for aerospace applications. The key aim of the research intended to validate the structural performance of an optimal tank design with varying materials.

- As referenced by Naik et al [7] metal vessels performed with greater safety at cryogenic loads when compared to Composite tanks
- Magnesium , Aluminium and Titanium alloys all displayed excellent tensile properties at cryogenic temperatures making them lucrative for LH2 tanks
- Steel 304 performance at cryogenic temperatures makes the material also a viable option for cryogenic vessels.
- Titanium alloy Ti-5Al-2.5Sn is an alpha phase alloy which displays excellent properties at cryogenic temperatures.

These materials were analysed for an aerospace vessel design in ansys static structural. The results of the study conclude

- Steel is a viable option for terrestrial applications due to it extremely high mass and the need for external reinforcement. Steel alloys displayed the lowest deformation under the loading conditions.
- Aluminium alloys 6061 and 7075 both displayed similar deformations under the load, with Al6061 with the lower mass and induced stress. Al6061 would be a viable option for an aerospace cryogenic vessel when compared to steel.
- Magnesium AZ31 showed relatively similar values in deformation with respect to both the aluminium alloys , the stress induced on the other hand was lower than both. The mass of the AZ31 vessel was the lowest amongst the chosen study materials. AZ31 is also a very viable option for aerospace applications, but magnesium alloys are at risk for a fire hazard requiring stronger insulation and protective measures.
- Titanium alloy Ti-5Al-2.5Sn displayed deformation in the relative range of steel alloys with the induced stress being the lowest amongst all. Titanium alloys seem to be the best option for cryogenic LH2 aerospace tanks due to its requirement of minimal structural reinforcement.

Future research in the area of cryogenic LH2 vessels for aerospace applications must be performed in the areas of dynamic loading, heat flux and secondary vessel design.

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