DESIGN AND SIMULATION OF HIGH STRENGTH VESSEL FOR COMPRESSED HYDROGEN GAS STORAGE

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CERTIFICATION

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DEDICATION

We dedicate this project to God, the source of wisdom, knowledge, and understanding, for His enabling support and assistance that allowed us to complete this program successfully. We extend our deepest appreciation to our parents for their endless love and support, acknowledging that we have reached this milestone because of their encouragement.

ABSTRACT

Over the years there've been need to transition from fossil fuel into cleaner forms of energy as a result of the detrimental effect the burning of fossil fuel has on the environment. The storage related issues of hydrogen are some of the challenges limiting its exploration as a cleaner energy source. Specifically, compressed form of hydrogen storage which is the most adopted method of storing hydrogen faces various challenges such as the hydrogen embrittlement of steel and loses of structural integrity over the course of usage.

This study is aimed at addressing this issue by exploring two configurations and comparing them to the conventional all alloy steel configuration. The two configurations (HDPE, Carbon fiber configuration(H-C) and carbon fiber, HDPE, carbon fiber configuration(C-H-C)). were investigated for performances characteristics at various pressure levels and compared to the all-alloy steel configuration. At a pressure of 15Mpa, the H-c configuration had a stress value of 7.89E+07N/mm while the C-H-C configurations had a stress value of 1.05E+08N/mm. various parameters including stress, displacement, strain, and factor of safety for the two configurations were investigated and compared to the all-alloy steel configuration. The two configurations should good performance for various pressure values. However, the carbon fiber, HDPE, carbon fiber configurations should the closest performance to the all-alloy steel configurations, with the factor of safety almost equal for pressure values above 35Mpa. Suggesting that the Carbon fiber, HDPE, Carbon fiber to be a good alternative to the all-alloy steel as it address the hydrogen embrittlement issue without compromising structural integrity.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND TO STUDY

Over the years, there has been a need to transition from fossil fuels into clean forms of energy because the burning of fossil fuels, such as coal, oil, and natural gas, for energy production releases greenhouse gases (such as carbon dioxide, methane, nitrous oxide, and water vapor) and other pollutants into the atmosphere (Panwar et al., 2011). These pollutants contribute to global warming, climate change, and air pollution, which have detrimental effects on the environment, ecosystems, and human health. For this reason, there is an increasing shift in energy production from fossil fuels to clean fuels(Perera, 2018). Hydrogen, which is a form of clean energy, plays a crucial role in the field of energy production, offering a wide range of applications and benefits. Its versatility, efficiency, and clean energy potential make it an attractive option for addressing various energy challenges.

Hydrogen functions as a means of energy storage and transportation. It can be produced through electrolysis, where electricity splits water into its constituents of hydrogen and oxygen. This process is done using energy from renewable sources, and the obtained hydrogen is stored for use when required. The stored hydrogen can then be used as a clean energy source, which helps reduce the need for fossil fuels as backup power sources, making the energy system more sustainable and reducing greenhouse gas emissions.

Since the application of hydrogen gas has been talked about and how it can be used for energy production that is safe, efficient, and versatile in this world of ours, there is a need to store this hydrogen, for which one of the major reasons is as a source of power. Aside from that, there are other benefits of storing this hydrogen, such as during grid disruptions, hydrogen storage can supply backup power, boosting the resilience and dependability of the energy system. It is especially useful for emergency services, vital infrastructure, and isolated locations with poor grid connections. Also, decentralized energy generation is made possible by hydrogen storage, offering businesses and consumers greater control over their energy supply. It can be combined with on-site renewable energy generation to lessen dependency on centralized power facilities.

However, there are challenges with storing hydrogen gas. Some of the challenges faced include the fact that hydrogen gas is less dense than many other gases, which means that it contains fewer molecules per unit volume (Manoharan et al., 2019). This lower density makes it harder to compress hydrogen to achieve high storage densities. Also, hydrogen has a high compressibility, meaning that it undergoes significant volume changes when subjected to pressure variations. This property makes it more difficult to achieve the desired compression levels without experiencing significant temperature and pressure changes, which can complicate the compression process (Manoharan et al., 2019). Concerns such as the embrittlement of steel materials by hydrogen are also noted. Considering the present storage methods, another limitation is the high energy requirement for the liquification of hydrogen for storage, as liquefying hydrogen usually consumes about 30% of the hydrogen's energy content. This reduces the overall energy efficiency (Senthil Kumar et al., 2020).

Building and designing a container is the primary goal of this project, a container that is especially made for storing hydrogen gas. This innovative concept seeks to address several common problems that now plague hydrogen storage techniques. In addition to addressing these issues, the project aims to improve the state of hydrogen storage technology and promote a more dependable, safe, and effective method of storing this essential energy source. It also aims to mitigate the issue with hydrogen's requirement for large storage by coming up with a vessel that will allow for the storage of compressed hydrogen.

1.2 STATEMENT OF PROBLEM.

The task at hand is to handle several issues concerning the storage of hydrogen gas. Concerns include the brittleness of steel materials from hydrogen exposure and the ability of the vessel to endure high pressures. Over the years, there have been catastrophic incidents in facilities that use hydrogen, ranging from explosions due to storage containment not being able to handle exerted pressure, to loss of structural integrity of the material as a result of hydrogen embrittlement (Rigas & Sklavounos, 2005). These problems, if not addressed, would further drawback the usage of hydrogen in a variety of processes as a clean energy substitute.

Becoming aware of the potential of hydrogen storage as a practical and sustainable energy source and progressing in hydrogen storage require finding comprehensive answers to these interconnected issues. This project addresses these issues by ensuring the preservation of the storage vessel's structural integrity and promotion of hydrogen adoption as an energy alternative in various processes.

1.3 SIGNIFICANCE.

From study and research, it has been demonstrated that there are numerous benefits to using hydrogen gas as fuel. The importance of storing hydrogen gas stems from its function as a clean energy source, facilitating the integration of renewable energy sources, and acting as a form of energy storage. In addition to supporting the development of hydrogen fuel cell cars and adding diversity to the energy mix, hydrogen is essential for industrial processes and space exploration. Effective hydrogen storage not only solves environmental problems but also enhances energy security and promotes a strong and sustainable energy infrastructure. This research aims to augment the current significance of hydrogen by designing a robust vessel capable of storing hydrogen in compressed form. Such a development would expand the accessibility of hydrogen gas for diverse applications whenever needed.

1.4 AIM/OBJECTIVE.

The purpose of this project is to simulate and create a high strength compressed hydrogen gas storage vessel. The project will be guided by the following objectives:

- Review existing hydrogen storage facilities.
- Design a high-strength vessel for compressed hydrogen storage.
- Simulate the designed vessel to ensure its structural integrity and performance.
- Address the issue of hydrogen embrittlement through proper material selection.
- Provide a comprehensive analysis of the simulated design, highlighting strengths and areas of improvement.

1.5 SCOPE OF PROJECT

The scope of this study entails the detailed design and simulation of a high-strength storage vessel tailored to address the current challenges associated with storing hydrogen, thereby bridging the storage-related gap associated with using hydrogen as a clean energy alternative. This study will achieve this in the following ways:

- The first is by creating various geometric designs that will mitigate the stress-related issues with the existing designs.

- Secondly, these designed storage geometries will be simulated against numerous materials with the aim of picking the most optimal in terms of cost, ease of fabrication, and general service conditions.

- Thirdly, expected operational conditions will be simulated for the selected design in terms of material and geometry.
- Finally, the obtained data will be analyzed and compared to the various existing storage forms and mediums, highlighting areas of improvement.

1.6 MATERIALS AND METHODOLOGY

1.6.1 DESIGN METHODOLOGY

Computer-aided design: Using Solidworks, different 3D models of the various storage tank concepts were designed, each time with a focus on different strength of material concepts for the various geometries designed, to arrive at a range of different concepts that were further analyzed using SolidWorks simulation. The methodology includes the various processes through which the various designs were analyzed to arrive at the final design concept.

1.6.2 MODELING AND ANALYSIS

Stress analysis: Various stress conditions, including pressure stress, longitudinal stress, hoop stress, axial stress, and thermal stress analysis, were carried out using SolidWorks simulation.

Finite element model: To evaluate each composite storage vessel's design, finite element models of the designs were created**.** The various parameters were applied to the inner and outer surfaces, the corresponding responses were evaluated, and the most optimal design was established.

CHAPTER 2

LITERATURE REVIEW

The universe's lightest and most prevalent element is hydrogen., with the chemical symbol "H" and atomic number 1. It consists of one proton and one electron and is the primary building block of the universe. On Earth, hydrogen is commonly found in compounds like water (H_2O) and organic materials. It is a colourless, odourless gas that is highly reactive and burns rapidly in the air. Hydrogen has significant industrial applications, including the production of ammonia and petroleum refining. It is also gaining attention as a clean energy carrier due to its potential to store and transport energy. Hydrogen can be utilized in fuel cells to produce energy, with the sole byproduct being water.

The increasing prominence of hydrogen on a global scale has sparked considerable research efforts aimed at enhancing its storage capabilities. This surge in interest is driven by the recognition of hydrogen's significant importance in the contemporary world. This chapter takes a review of the various works that have been done so far, ranging from the various storage mediums to discussing the merits of each while noting areas for improvement.

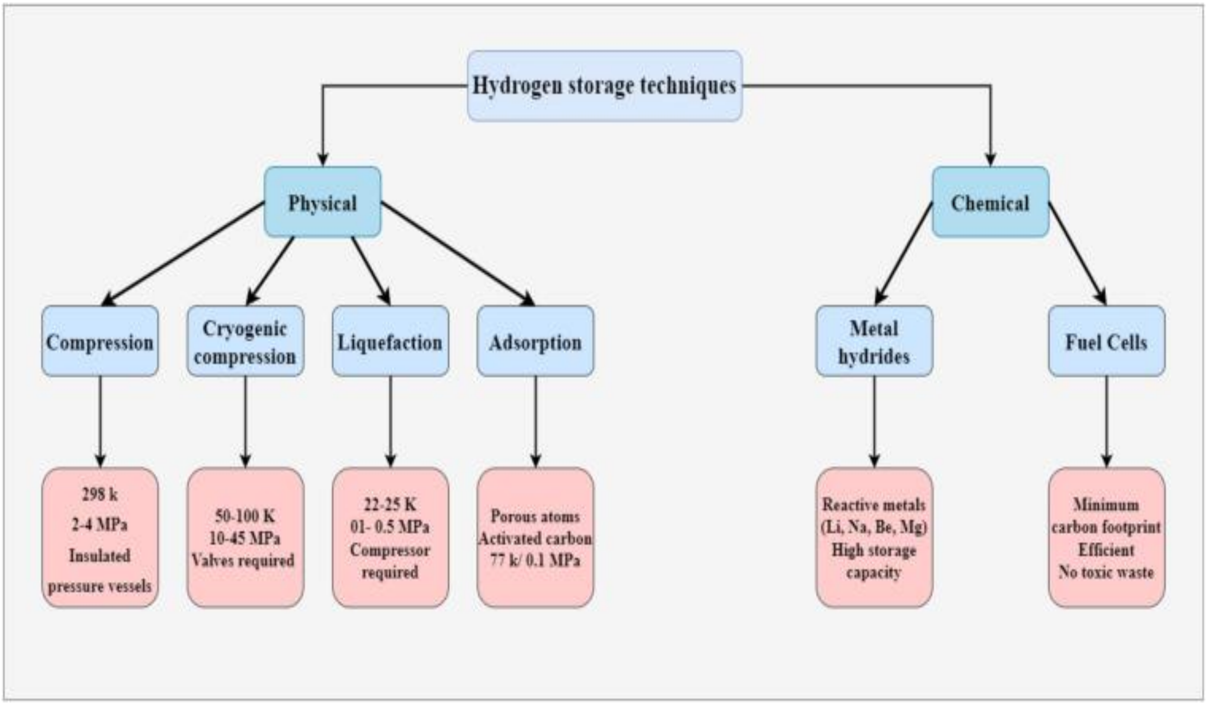


Figure 2.1 Hydrogen storage techniques

2.1 LIQUEFIED HYDROGEN STORAGE

Liquid hydrogen storage is one of the current ways for storing hydrogen. After being cooled to roughly -253 degrees Celsius, hydrogen is liquefied and kept in cryogenic tanks.

For low-temperature rockets—particularly large-scale, heavy-duty, low-temperature rockets like the CZ-7 series and CZ-8, as well as the upcoming generation of manned rockets—liquid hydrogen is the primary fuel. (Qiu et al., 2021). Considering the sensitivity of liquid hydrogen and its area of applications, special consideration is put into the design of these containers, ranging from geometry to material selection and understanding the different properties of these materials. It is thus important to use materials that meet certain requirements, such as maintaining plastic properties at operating temperatures and having low thermal expansion and conductivity.

The structural materials that can be used for LH2 storage applications are limited since hydrogen must be kept at temperatures below 20 K. Most of the applicable materials for compressed hydrogen gas storage, such as ferritic, are not applicable for use in LH2 storage due to reasons ranging from ductile to brittle transition temperatures above 20k, to incompatibility with hydrogen and limited behavioural data at 20 k.

Austenite stainless steel: Austenitic stainless steel is one of the four types of stainless steel, with others being martensitic, duplex, and ferritic. It is composed mainly of iron, nickel, carbon, magnases, and chromium. They possess distinct properties such as excellent corrosion resistance, being non-magnetic, high formability, and good weldability. Austenitic stainless steel is more stable at low temperatures than ferritic stainless steel because it is a member of the face-centered cubic crystal structure. It is non-magnetic because it normally contains 10% nickel and 18% chromium. There are several grades of austenitic stainless steel, with the most popularly used for liquid hydrogen storage (304 and 316). This is because of their good low-temperature performance and the lack of real ductile to brittle temperature challenges at the temperature required to liquify hydrogen.

304 austenitic stainless steel is also referred to as 18-8 strainless steel due to its main alloying constituencies of 18% chrominu and 8% nickel. Aside from the chromium and nickel contents, 304 also contains about 2% manganese and traces of carbon, silicon, sulfur, and phosphorus. Apart from being used for making cyrogenic containers for liquid hydrogen storage, it finds applications in other industries, including to produce storage tanks, sinks, cookware, tanks for surgical instruments, and piping.

The primary alloying elements of 316 austentic stainless steel are (16–18%) chromium, (2–3%) molybdenum, and (10–14%) nickel. It possesses enhanced corrosion resistance, especially in environments rich in chlorine, such as in marine and swimming pool equipment. Just like 304, the austentic structure of 316 allows it to maintain its mechanical properties, such as strength and ductility, at extremely low temperatures, which makes it suitable for cryogenic applications like liquid hydrogen storage. Aside from its cryogenic applications, it is also widely used in applications such as marine hardware, offshore structures, heat exchangers, surgical instruments, structural components, handrails, and storage tanks.

Aluminum alloy: Al alloy shares the same fcc structure as austenite stainless steel, which eliminates the need for ductile-to-brittle temperature challenges at the hydrogen liquification temperature. As such, it is an additional material for liquid hydrogen storage.. Various aluminum alloys used for this low-temperature Al-Mg, Al-Cu, Al-Mg, Al-Mg-Si, and Al-Zn-Mg alloys are among the alloys used.. Depending on the most desired property, the Mg content could range from 0.02-1.8% and the Zn content from 0.1–5.0%. Titanium alloys: Titanium alloys also possess desirable properties for cyrogenic applications, such as modest coefficient of expansion, low thermal conductivity, and excellent temperature resistance. They are widely used as structural materials in hydrogen storage tanks. However, the decreases in elongation, fracture toughness, and impact toughness with a decrease in temperature pose a challenge to the application of these alloys.

2.1.1 CHALLENGES ASSOCIATED WITH LH STORAGE

Aside from the material limitations, Liquid hydrogen storage is confronted with other obstacles as well, which include: Boil-off: this is a phenomena that occurs during storage where liquid hydrogen vaporizes to become gaseous. The evaporation of hydrogen during storage creates a significant challenge for the storage of hydrogen in its liquid form, with the major energy loss from liquification and hydrogen loss because of releasing the gas that has vaporized to prevent pressure from accumulating in the system (Aziz, 2021). When liquid hydrogen vaporizes, the inner pressure of the system increases. The vaporized hydrogen should thus be released to avoid the possibility of explosion. Boil-off occurs due to several factors, with the most prevalent being heat transferred from the surface environment to the liquid hydrogen. This is minimized by proper vessel insulation and increasing the size of the storage tank. Another prevalent cause of boil-off is as a result of sloshing. This is a phenomenon when kinetic energy is generated as a result of the motion of liquid hydrogen (Aziz, 2021). This kinetic energy that is built up is converted to heat energy, which further increases the vaporization of liquid hydrogen.

Heat inleak: heat inleak is another critical complication in liquid hydrogen storage. It's a phenomenon where there's unintended transfer of heat from the surrounding environment into the cryogenic storage system. Since liquid hydrogen is stored at extremely low temperatures, any external heat entering the storage system can cause the hydrogen to warm up, potentially leading to increased boil-off rates and other operational challenges. This phenomenon directly impacts the economic viability and efficiency of the storage system. The efficiency of liquid hydrogen storage systems is intricately tied to the minimization of boil-off losses. Heat inleak exacerbates this issue, as the introduced heat causes the liquid hydrogen to warm up and transition into a gaseous state more rapidly. In applications such as space exploration or hydrogen-powered transportation, where the stored liquid hydrogen serves as fuel, minimizing boil-off is crucial to maximizing the energy content available for use. Additionally, the efficiency of liquid hydrogen storage systems is intricately tied to the minimization of boil-off losses. Heat inleak exacerbates this issue, as the introduced heat causes the liquid hydrogen to warm up and transition into a gaseous state more rapidly. In applications such as space exploration or hydrogen-powered transportation, where the stored liquid hydrogen serves as fuel, minimizing boil-off is crucial to maximizing the energy content available for use.

2.2 CRYO-COMPRESSED HYDROGEN STORAGE

Cryo-compressed hydrogen storage is a hybrid storage technology that combines both cryogenic and compressed hydrogen methods. This method involves cooling the hydrogen gas to cryogenic temperatures, usually below -253 °C, where it becomes a liquid. This liquid hydrogen is then further compressed to higher pressures, resulting in a denser storage solution compared to either cryogenic or compressed storage alone. Cryo-compressed hydrogen storage systems aim to strike a balance between achieving high and gravimetric energy densities while minimizing storage complexities. This combination results in no phase shift and a larger hydrogen storage density than LH(Liquid Hydrogen)., a reduction in evaporation, an increase in pressure buildup time, and a reduction of boil-off losses. The tank can endure higher pressures before the hydrogen needs to be boiled out because of its ability to do so. When in use, these cryogenic pressure tanks greatly prolong the period of time before evaporative losses begin, increasing storage autonomy. The added advantage of a cryo-compressed storage system being able to store hydrogen either in liquid or gaseous form provides an additional advantage.

2.2.1 CHALLENGES ASSOCIATED WITH CRYO-COMPRESSED HYDROGEN STORAGE

Cryo-compressed hydrogen storage has several related issues, including material availability, system design, and costly refuelling infrastructure. Technologies for high-pressure compression and cryogenic cooling are combined to create cryo-compressed storage systems. This complexity can lead to challenges in system design, maintenance, and reliability. Additionally, the development and implementation of cryo-compressed hydrogen storage systems entail higher expenses than alternative storage techniques. The need for specialized materials, advanced insulation, and energy-intensive processes can impact the overall economic feasibility of the technology.

2.3 COMPRESSED HYDROGEN STORAGE

Compressed hydrogen storage is a technology that involves storing hydrogen gas under high pressure to reduce its volume and increase its energy density. A compressed gas storage system is the most adopted method for H2 storage technology (Bosu & Rajamohan, 2023). Hydrogen may be compressed into appropriate cylinders and kept as pressured gas in containers or even subterranean tunnels, at a pressure of up to 700 bar. Hydrogen provides the benefits of simplicity and rapid filling and release as a high-pressure gas. This method of storing fuel has the benefit of compact storage while preserving fuel's energy efficiencyThe most common and straightforward method for storing hydrogen is compression. The storage pressure has a significant impact on the density of hydrogen when it is compressed for storage. The compactness or density of the stored hydrogen is typically 7.8 kg-H2/m3 at a pressure of 10 MPa (at a temperature of 20 ◦C). It increases to 39 kg-H2/m3 when the pressure is increased to approximately 69 MPa (Bosu & Rajamohan, 2023). Compressed hydrogen storage is versatile and applicable across various industries, including transportation, industrial processes, and backup power systems. Its adaptability to different use cases makes it a practical choice for a wide range of applications, including vehicles, hydrogen refueling stations, and other industrial purposes.

2.3.1 HYDROGEN EMBRITTLEMENT

Hydrogen embrittlement is a phenomenon that occurs when hydrogen atoms diffuse into certain materials, causing a reduction in their mechanical properties, such as ductility and toughness, leading to an increased susceptibility to cracking and failure. Metallic materials such as precipitation hardening (PH) steels, low-alloy steels, super alloys, and aluminium alloys are the ones that get most affected by this phenomenon. High-strength materials like steel are more likely to HE(hydrogen embrittlement), which results in a decrease in strength. due to the interaction with the hydrogen atoms. It results from H atom dissolution and trap (stress corrosion cracking) (Meda et al., 2023). The hydrogen atoms become confined within the matrix of the metal, eventually causing the material to rupture and form cracks.

Metal components have traditionally deteriorated by a common process called hydrogen embrittlement, which is created when hydrogen encounters metal. In industries such as petrochemical, automobile, and aerospace, hydrogen-induced mechanical characteristics and corrosion resistance are important parameters related to the service safety of HSSs (Meda et al., 2023). This is a significant issue associated with compressed hydrogen storage. This prompted research into several kinds of pressure vessels for the storage of compressed hydrogen.

2.3.2 PRESSURE VESSELS

Pressure vessels of four different types can be used to store compressed hydrogen. The pressure vessels are generally cylinders, but they can also be polymorphs or toroids (Barthelemy et al., 2017). Type I is a pressure vessel that is entirely made of metal. This is the most common, least expensive, and heaviest variety, weighing about 1362 kg/m3 (Meda et al., 2023). They are typically constructed from steel or aluminum, these vessels can withstand pressures of up to 50 MPa. Type II vessels consist of steel with a glass fiber composite overwrap. The structural load is evenly distributed between the steel and the composite material. Type II vessels are about 50% more expensive to manufacture but usually 30–40% lighter than type I vessels. Another vessel configuration is a complete composite wrap with a metal liner. This is categorized under Type III. The composite carries the majority of the structural load, while the metal liner acts as a seal (Meda et al., 2023). The last configuration is a carbon fiber/carbon glass composite with a non-mental liner, usually a polymer. The structural load is sustained by the carbon fiber composite.

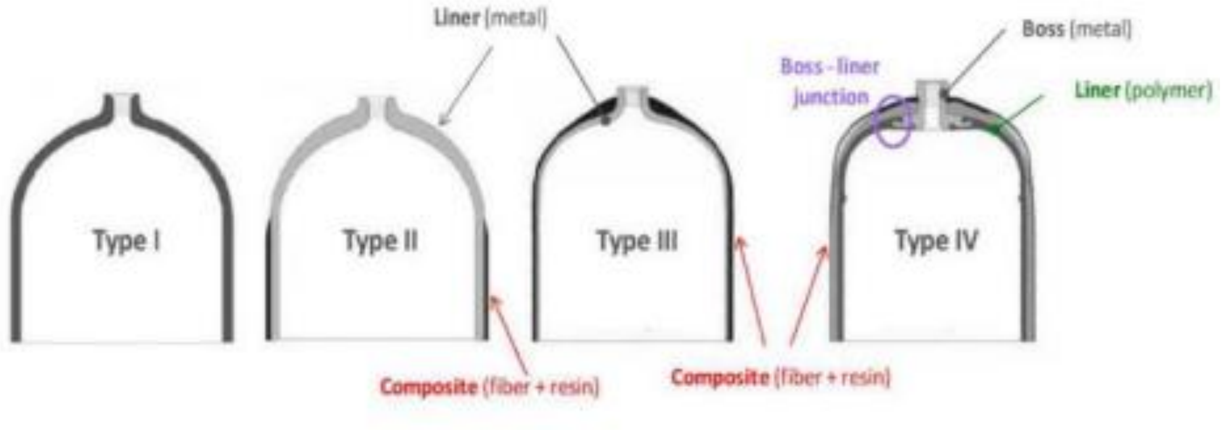


Figure 2.2 Pressure vessels

2.4 CHEMICAL STORAGE

For several decades, researchers have been investigating the chemical storage of hydrogen, and as interest in hydrogen as a clean energy source has grown, so too have their research efforts. But since it "began" gradually with a number of discoveries and developments, it's hard to say exactly when it did. Metal hydrides were discovered as possible storage materials, which was an important early development in chemical hydrogen storage. The mid-1900s is when this occurred. Studies on metal hydrides grew in the 1970s and 80s, especially because of the possibility of using them to store hydrogen for fuel cells and other hydrogen-powered vehicles.

Since then, scientists have looked into a number of additional chemical storage techniques, such as ammonia-based storage systems, chemical looping procedures, and the hydrogenation of organic molecules.

Chemical storage of hydrogen involves storing hydrogen within chemical compounds rather than as a pure gas or liquid. One common method of chemical storage is through hydrogenation, where hydrogen atoms are chemically bonded to other elements.

Utilizing materials as hydrogen transporters is the fundamental principle of chemical storage. The carrier regenerates and can be recycled when hydrogen is released. Some examples of chemical storage methods for hydrogen include:

- Ammonia (NH_3)
- Metal hydrides (MH)
- Liquid organic hydrogen carriers (LOHC)

2.4.1 AMMONIA

Ammonia is one of the most produced and used chemicals in the world. As a result, the sector is familiar with handling NH3, and there is existing infrastructure in place. Hydrogen can be stored in ammonia by the Haber-Bosch process, which mixes hydrogen gas with nitrogen gas to generate ammonia. Ammonia can then be heated to high temperatures in order to extract hydrogen when and where it is needed. Ammonia has several advantages over other materials for storing hydrogen, including a high hydrogen density, advanced synthesis and distribution technology, and simple catalytic breakdown. Its benefit over alcohols and hydrocarbons is that it emits no CO2 when used by the final consumer. The drawbacks are mainly the toxicity of liquid ammonia and the problems related to trace amounts of ammonia in the hydrogen after decomposition (Klerke et al., 2008). This is a major drawback when using ammonia for hydrogen gas storage.

2.4.2 METAL HYDRIDES (MH)

When some metals, such as lithium or magnesium, react with hydrogen gas, they can create metal hydrides. Atoms of hydrogen are bound to the metal lattice in these complexes. When heated, metal hydrides can release a sizable amount of hydrogen that is stored in their bulk. The two main techniques for releasing hydrogen from metal hydrides are hydrolysis (reacting with water) and thermolysis (heating). Hydrolysis and thermolysis are two very different processes: hydrolysis is usually in solution, while thermolysis is in the solid phase; hydrolysis can occur spontaneously at room temperature, while thermolysis requires higher temperatures; both processes can occasionally be reversible, but hydrolysis is always irreversible. Despite the large number of metal hydrides that have been developed and studied for thermolysis-based storage, very few of them have been used successfully for hydrolysis. The most well-known and promising metal hydride for hydrolysis is sodium borohydride (NaBH4), which will be the sole topic of this section.

Elemental hydrides, also known as binary compounds, are created when hydrogen combines with metallic elements. However, most systems are not suitable for hydrogen storage due to thermodynamics, hydrogen storage capacity, or both. Magnesium hydride (MgH2) and aluminum hydride (AlH3) are the elemental metal hydrides that are regarded to be the most promising for the large-scale storage of hydrogen. Two main factors make magnesium hydride, or MgH2, a desirable hydrogen storage solution: magnesium metal is widely available and reasonably priced, and it has a high theoretical hydrogen storage capacity of 7.6 percent (by weight). The hydrogen-magnesium bond, on the other hand, has a high enthalpy of dehydrogenation of around 75 kJ/mol. Moreover, the main reasons for the sluggish kinetics of the hydrogenation and dehydrogenation processes are the slow dissociation of molecular hydrogen on the magnesium surface and the slow diffusion of hydrogen through the hydride phase. As such, dehydrogenating pure MgH2 at a tolerable rate usually requires temperatures higher than 300 °C. Several tactics have been used to improve these reactions' kinetics. Although more advanced techniques, such as nanoconfinement, have seen some success in laboratory settings, ball milling is frequently used in the most promising pilot-scale storage systems to reduce particle size. To improve thermal conductivity, alloying, compaction with designed nanostructured materials, and the inclusion of transition metal additions are used. These methods together will enable the development of magnesium-based hydrogen storage materials with good kinetics, appropriate heat transfer properties, and long-term stability. Nonetheless, the principal drawback remains the high temperature requirements for both dehydrogenation and hydrogenation processes (Andersson & Grönkvist, 2019).

2.4.3 LIQUID ORGANIC HYDROGEN CARRIERS (LOHC)

Early in the 1980s, research on hydrogen storage in large-scale hydrogen storage cells (LOHCs) using hydrogenation and dehydrogenation processes began. The toluene/methyl cyclohexane (MCH) system was identified as the most important task based on the dehydrogenation processes. Many LOHC approaches have been evaluated considering the MCH system study, using hydrogenation and dehydrogenation criteria for hydrogen storage. (Rao & Yoon, 2020). Liquid organic hydrogen carriers are substances with the ability to bind and release hydrogen catalytically in a reversible manner. Unlike gaseous or cryogenic hydrogen, these chemicals are frequently liquid at ambient temperature, which simplifies storage and transportation. LOHCs offer a workable option for the delivery and storage of hydrogen by addressing some of the problems with existing storage methods.

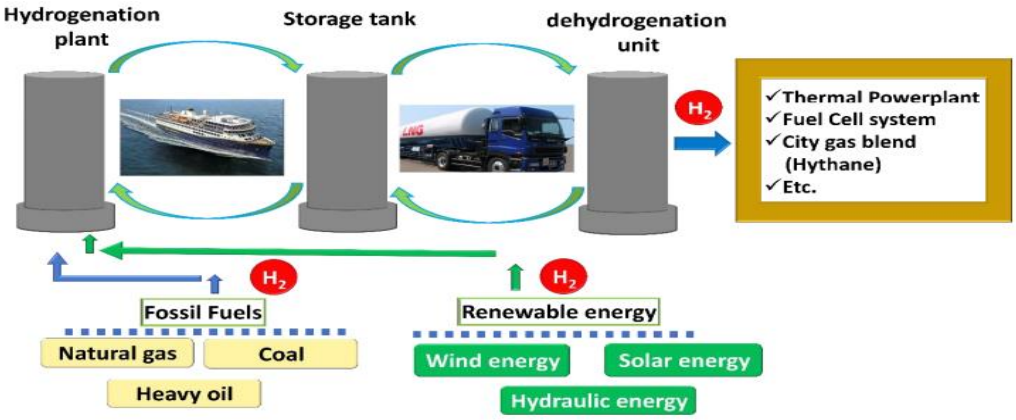


Figure 2.3 LOHC

The basic principle of LOHC systems involves hydrogenation and dehydrogenation cycles. During the hydrogenation process, the LOHC absorbs hydrogen to form a hydrogenated compound, storing the hydrogen. In the dehydrogenation process, the hydrogenated compound is heated, releasing hydrogen and regenerating the original LOHC.

Common examples of LOHCs include dibenzyltoluene (DBT) and perhydro-dibenzyltoluene (H18-DBT). Research and development efforts are ongoing to improve the efficiency, stability, and scalability of LOHC systems for commercial applications. When considering the practical use of liquid organic hydrogen carriers for hydrogen storage, it is important to evaluate the toxicity and biodegradability of the materials used. This assessment is essential for reducing adverse effects on human health and the environment. The Toxicity Potential Indicator (TPI) is used to rate the toxicity of molecules, with values ranging from "0" for non-toxic to "100" for extremely toxic. Generally, toxicity assessment is more common for the dehydrogenation counterparts of LOHC molecules than for the hydrogenated molecules (Rao & Yoon, 2020).

2.5 OVERVIEW OF MODELLING AND SIMULATION.

Modelling and simulation are integral to the engineering design process; they play a crucial role in engineering design by providing a systematic approach to design, refine, predict, analyse, and understand the behaviour of complex systems. These methodologies find application across diverse engineering disciplines to elevate the performance, efficiency, and overall functionality of varied systems. Modelling is based on the necessity of creating accurate representations of physical systems, allowing a better understanding of how these systems perform. Structural analysis, a key modeling approach, involves the use of finite element analysis to simulate stress distribution, deformation, and fatigue life within components. This aids in identifying weaknesses and optimizing structural designs for improved strength and durability.

In engineering, various types of modelling exist with the key ones being mathematical modelling, geometric modelling, and physical modelling.

Mathematical modelling involves using differential, algebraic and other mathematical equations to represent the behavior of a system. These equations are then solved, to understand and analyze the behavior of the system under various conditions.

Another type of modelling often used to analyze the behavior of system is physical modelling. It involves creating physical replica or scaled-down version of the actual system. It is commonly used for testing and validating concepts before full-scale implementation.

Simulation techniques encompass the utilization of mathematical models to replicate the behaviour of systems across diverse conditions. This enables the evaluation of system responses and performance without the necessity for physical prototypes. By taking into account aspects like fixtures/connections, material properties, and external loads, engineers can acquire insights into the dynamic response of a system. This proves especially beneficial for forecasting and enhancing system behaviour under varying operating conditions.

During the course of this project two forms of modelling were carried out; Geometric modelling and Mathematical modelling. Geometric modelling serves as a fundamental element within computer-aided design (CAD), playing a crucial role in the representation of physical objects, structures, or spaces within a digital environment. In CAD, geometric modelling is the cornerstone that enables the creation of virtual counterparts for real-world entities, allowing designers and engineers to visualize, analyze, and manipulate these digital representations before any physical implementation occurs. This method, vital in various industries, enables the visualization, analysis, and manipulation of intricate shapes and structures. Two main types of representations emerge from this process: 2D (two-dimensional) and 3D (three-dimensional). While 2D models find frequent use for simpler shapes and drawings, 3D models offer a more realistic and thorough portrayal of complex objects. Typically, these 3D models are obtained by "extruding" 2D geometries.

Mathematical modeling, commonly referred to as analytical modeling, utilizes mathematical equations, including simple algebraic equations or differential equations, to depict a system or a component of a system. The application of mathematical modelling in simulation offers a lot of advantages., with the main one being the ability to correctly and accurately represents systems regardless of their level of simplicity or complexity. This approach is highly cost effective as it provides a means to test and refine designs without the need for a physical prototype. Another important advantage of this approach lies in the ease with which various conditions can be explored by manipulating various parameters. Engineers can systematically vary the input parameters to observe their impact on the systems output.

While mathematical modelling is a powerful tool in simulation, it also comes with some disadvantages, starting with the inherent need for simplification and assumptions. In an attempt to render complex systems solvable, models often require simplifications that may not fully capture the intricacies of real-world phenomena. These simplifications, while aiding in mathematical tractability, can lead to deviations from actual system behavior, introducing inaccuracies and limiting the model's applicability. Furthermore, the validity of assumptions made in mathematical models poses a critical challenge. If the foundational assumptions do not align with the real-world conditions, the accuracy of the simulation is compromised. Additionally, parameter estimation adds another layer of complexity; obtaining accurate values for model parameters is often a non-trivial task, and inaccuracies in these parameters can propagate through the simulation, affecting the reliability of predictions. As a result, while mathematical modelling offers valuable insights, careful consideration of these challenges is essential to enhance the credibility and utility of the simulations.

2.6 OVERVIEW OF UTILIZED MODELLING AND SIMULATION SOFTWARE

The design and simulation of the high strength pressure vessel for compressed hydrogen storage was done using SolidWorks, a software package that comes with various computer aided design and computer aided engineering functionalities. It is utilized for various geometric and mathematical modelling.

Solidworks is a widely used CAD and CAE software developed by Dassault Systenes. It is a powerful 3D CAD software that enables engineers, designers, and architects to create detailed and precise models of mechanical and architectural structures. It provides a user-friendly interface with a wide range of tools for designing 3D models and simulating their behavior under various conditions.

Various functionalities of Solidworks that makes it a widely used design software include:

1. **Parametric Modeling:**
    - Parametric Modeling in SolidWorks allows users to create dynamic 3D models with ease by establishing parametric relationships. The flexibility of parametric modeling facilitates easy design modifications, as users can effortlessly adjust parameters, leading to automatic updates throughout the model.
2. **Part Modeling:**
    - Part Modeling in SolidWorks is a versatile and efficient process, thanks to its comprehensive set of tools tailored for creating detailed 3D parts. The software offers fundamental features such as extrusions, enabling the extension of 2D sketches into solid shapes, providing a foundational structure for components.
3. **Assembly Modeling:**
    - Assembly Modeling in SolidWorks allows users to efficiently create and manage complex assemblies with multiple parts, components, and sub-assemblies. The software provides tools for precise positioning, constraint management, and supports various mate types for defining component relationships. With a top-down design approach, users can create assemblies by defining relationships at the assembly level, enhancing design flexibility.
4. **Sheet Metal Design:**
    - SolidWorks is equipped with specialized tools tailored for precision in the creation of sheet metal components. These tools encompass features such as defining bend allowances, crafting flanges, and generating flat patterns.

5. **Surface Modeling:**

    - The software offers precise control over surface curvature and continuity, ensuring smooth transitions and high-quality aesthetics. Incorporating techniques such as blending and lofting, SolidWorks facilitates seamless integration of surfaces, enhancing the visual appeal and overall integrity of the design.

6. **Drawing and Detailing:**

    - SolidWorks encompasses a suite of powerful tools for the creation of precise 2D drawings enriched with annotations, dimensions, and various detailing features. Serving as a vital bridge between intricate 3D models and clear 2D representations, these tools enable effective communication within design processes.

7. **Motion Analysis:**

    - **SolidWorks** introduces dynamic simulation tools that play a pivotal role in evaluating the motion of assemblies. This functionality goes beyond basic kinematics, offering a comprehensive approach to design validation. The tools enable the identification and resolution of potential interferences by providing interference detection during assembly motion, ensuring a clash-free design.

8. **Bill of Materials (BOM) Functionality:**

    - SolidWorks includes tools for generating and managing Bill of Materials, providing a structured list of components, sub-assemblies, and quantities used in an assembly. The BOM functionality allows for customization, automatic updating, and exportation of BOM data for documentation and manufacturing purposes.

CHAPTER 3

MATERIALS AND METHOD

3.1 RESEARCH METHOD

i. Materials utilized.

ii. Evaluation of pressure vessel model components.

3.2 MATERIALS UTILIZED

3.2.1 HDPE LINER

High-Density Polyethylene (HDPE) liner is one type of geomembrane used in numerous applications such as environmental containment, landfill liners, pond liners, and mining applications. HDPE liners are manufactured from high-density polyethylene resins, which provide excellent chemical resistance, UV resistance, and durability. HDPE liners are typically installed in layers to create a barrier that prevents the leakage of liquids or gases into or out of a containment area.

The inner lining is made of HDPE (High-Density Polyethylene), High-strength HDPE liners are engineered to withstand significant stress and environmental pressures, making them suitable for demanding applications where standard liners may not provide adequate protection, this was used rather than the convectional steel lining because of problems associate with hydrogen embrittlement which causes loss of structural integrity of vessel.

3.2.2 CARBON FIBER

Made of carbon atoms together in a crystalline structure, carbon fiber is a robust and light material. It is well known for having an outstanding strength-to-weight ratio, which makes it perfect for many high-performance uses in a variety of sectors, including sporting goods, civil engineering, automotive, and aerospace.

3.2.3 STAINLESS STEEL

Known for its strength, resilience to corrosion, and visual appeal, stainless steel is a frequently used and adaptable alloy. Iron makes up the majority of its composition, with different grades containing varied quantities of chromium, nickel, and other metals.

3.3 EVALUATION OF PRESSURE VESSEL MODEL COMPONENTS

The model consists of HDPE liner, Carbon fiber outer body, valve, dome, Head boss, End boss.

3.3.1 HDPE LINER

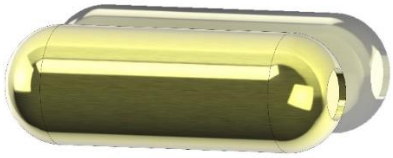


Figure 3.1 HDPE liner

Properties of HDPE liner

Mass = 2712.57 grams

Volume = 1356283.13 mm3

Surface area = 513300.86 mm2

Density = 0.00 g\mm3

Center of mass: (mm)

(X,Y,Z) = (-4.95,0.00,0.00)

Measured at centroid, the principal moments and axes of inertia are expressed as (g\mm2).

Ix = (1.00, 0.00, 0.00)	Px = 14109988.09
Iy = (0.00, 0.00, -1.00)	Py = 72899238.77
Iz = (0.00, 1.00, 0.00)	Pz = 72899238.77

Moments of inertia: (g\mm2)

Taken using positive tensor notation, centered at centroid, and aligned with the output coordinate system.

(Lxx,Lxy,Lxz) = (14109988.09,0.00,0.00)

(Lyx,Lyy,Lyz) = (0.00,72899238.77,0.00)

(Lzx,Lzy,Lzz) = (0.00,0.00,72899238.77)

Moments of inertia: (g\mm2)

Recorded in the output coordinate system with positive tensor notation

Ixx = 14109988.09	Ixy = 0.00	Ixz = 0.00
Iyx = 0.00	Iyy = 72965787.64	Iyz = 0.00
Izx = 0.00	Izy = 0.00	Izz = 72965787.64

3.3.2 CARBON FIBER OUTER BODY

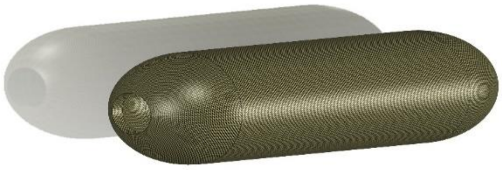


Figure 3.2 Carbon fiber outer body

Properties of carbon fiber body

Mass = 8137.67 grams

Volume = 4328549.92 mm3

Surface area = 585391.28 mm2

Density = 0.00 g\mm3

Center of mass: (mm)

(X,Y,Z) = (0.00,0.00,0.00)

Measured at centroid, the principal moments and axes of inertia are expressed as (g\mm2).

Ix = (1.00, 0.00, 0.00)	Px = 57322095.73
Iy = (0.00, 0.00, -1.00)	Py = 215958044.91
Iz = (0.00, 1.00, 0.00)	Pz = 215958044.91

Moments of inertia: (g\mm2)

Taken using positive tensor notation, centered at centroid, and aligned with the output coordinate system.

(Lxx,Lxy,Lxz) = (57322095.73,0.00,0.00)

(Lyx,Lyy,Lyz) = (0.00,215958044.91,0.00)

(Lzx,Lzy,Lzz) = (0.00,0.00,215958044.91)

Moments of inertia: (g\mm2)

Recorded in the output coordinate system with positive tensor notation.

Ixx = 57322095.73	Ixy = 0.00	Ixz = 0.00
Iyx = 0.00	Iyy = 215958044.91	Iyz = 0.00
Izx = 0.00	Izy = 0.00	Izz = 215958044.91

3.3.3 VALVE

Figure 3.3 Valve

Properties of Valve

Mass = 150.32 grams

Volume = 150322.40 mm3

Surface area = 28941.58 mm2

Density = 0.00 g\mm3

Center of mass: (mm)

(X,Y,Z) = (-47.62,1.33,-2.32)

Measured at centroid, the principal moments and axes of inertia are expressed as (g\mm2).

Ix = (1.00, -0.04, 0.08)	Px = 59447.67
Iy = (0.05, 0.98, -0.20)	Py = 184631.89
Iz = (-0.07, 0.20, 0.98)	Pz = 191182.48

Moments of inertia: (g\mm2)

Taken using positive tensor notation, centered at centroid, and aligned with the output coordinate system.

(Lxx,Lxy,Lxz) = (60540.12,-4752.72,10848.25)

(Lyx,Lyy,Lyz) = (-4752.72,184703.33,-1682.66)

(Lzx,Lzy,Lzz) = (10848.25,-1682.66,190018.60)

Moments of inertia: (g\mm2)

Recorded in the output coordinate system with positive tensor notation.

Ixx = 61612.57	Ixy = -14248.19	Ixz = 27445.77
Iyx = -14248.19	Iyy = 526449.46	Iyz = -2144.92
Izx = 27445.77	Izy = -2144.92	Izz = 531221.20

3.3.4 DOME

Figure 3.4 Dome

Properties of Dome

Mass = 269.05 grams

Volume = 269052.96 mm3

Surface area = 116229.33 mm2

Density = 0.00 g\mm3

Center of mass: (mm)

(X,Y,Z) = (-70.32,0.00,0.00)

Measured at centroid, the principal moments and axes of inertia are expressed as (g\mm2).

Ix = (0.00, 1.00, 0.00) Px = 1066292.93

Iy = (0.00, 0.00, 1.00) Py = 1066292.93

Iz = (1.00, 0.00, 0.00) Pz = 1749678.89

Moments of inertia: (g\mm2)

Taken using positive tensor notation, centered at centroid, and aligned with the output coordinate system.

(Lxx,Lxy,Lxz) = (1749678.89,0.00,0.00)

(Lyx,Lyy,Lyz) = (0.00,1066292.93,0.00)

(Lzx,Lzy,Lzz) = (0.00,0.00,1066292.93)

Moments of inertia: (g\mm2)

Recorded in the output coordinate system with positive tensor notation

Ixx = 1749678.89	Ixy = 0.00	Ixz = 0.00
Iyx = 0.00	Iyy = 2396714.76	Iyz = 0.00
Izx = 0.00	Izy = 0.00	Izz = 2396714.76

3.3.5 HEAD BOSS

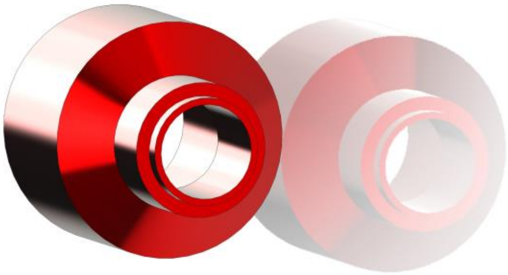


Figure 3.5 Head Boss

Properties of Head Boss

Mass = 146.42 grams

Volume = 146419.45 mm3

Surface area = 29164.55 mm2

Density = 0.00 g\mm3

Center of mass: (mm)

(X,Y,Z) = (-36.83,0.00,0.00)

Measured at centroid, the principal moments and axes of inertia are expressed as (g\mm2).

Ix = (0.00, 0.00, 1.00) Px = 107510.54

Iy = (0.00, -1.00, 0.00) Py = 107510.55

Iz = (1.00, 0.00, 0.00) Pz = 110211.70

Moments of inertia: (g\mm2)

Taken using positive tensor notation, centered at centroid, and aligned with the output coordinate system.

(Lxx,Lxy,Lxz) = (110211.70,0.00,0.00)

(Lyx,Lyy,Lyz) = (0.00,107510.55,0.00)

(Lzx,Lzy,Lzz) = (0.00,0.00,107510.55)

Moments of inertia: (g\mm2)

Recorded in the output coordinate system with positive tensor notation.

Ixx = 110211.70	Ixy = 0.00	Ixz = 0.00
Iyx = 0.00	Iyy = 306073.22	Iyz = 0.00
Izx = 0.00	Izy = 0.00	Izz = 306073.22

3.3.6 END BOSS

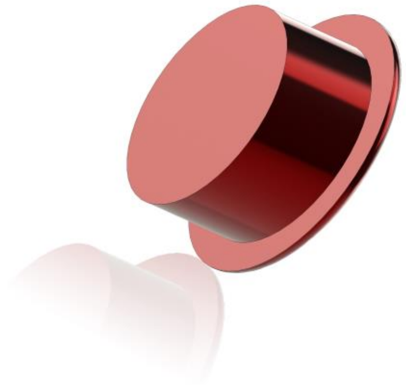


Figure 3.6 End Boss

Properties of End Boss

Mass = 134.97 grams

Volume = 134974.64 mm3

Surface area = 19724.70 mm2

Density = 0.00 g\mm3

Center of mass: (mm)

(X,Y,Z) = (17.31,0.00,0.00)

Measured at centroid, the principal moments and axes of inertia are expressed as (g\mm2).

Ix = (0.00, 1.00, 0.00)   Px = 58866.17

Iy = (0.00, 0.00, 1.00)   Py = 58866.17

Iz = (1.00, 0.00, 0.00)   Pz = 91869.07

Moments of inertia: (g\mm2)

Taken using positive tensor notation, centered at centroid, and aligned with the output coordinate system.

(Lxx,Lxy,Lxz) = (91869.07,0.00,0.00)

(Lyx,Lyy,Lyz) = (0.00,58866.17,0.00)

(Lzx,Lzy,Lzz) = (0.00,0.00,58866.17)

Moments of inertia: (g\mm2)

Recorded in the output coordinate system with positive tensor notation

Ixx = 91869.07	Ixy = 0.00	Ixz = 0.00
Iyx = 0.00	Iyy = 99299.49	Iyz = 0.00
Izx = 0.00	Izy = 0.00	Izz = 99299.49

3.4 PRESSURE VESSEL ASSEMBLY

Figure 3.7 Pressure vessel assembly

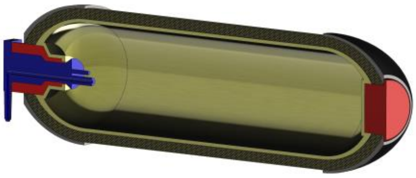


Figure 3.8 Sectional view of assembly

Properties of Pressure vessel

Mass = 11820.06 grams

Volume = 6654655.46 mm3

Surface area = 1408981.62 mm2

Center of mass: (mm)

(X,Y,Z) = (140.78,-0.03,-3250.17)

Measured at centroid, the principal moments and axes of inertia are expressed as (g\mm2).

Ix = (1.00, 0.00, 0.00)	Px = 75195071.74
Iy = (0.00, -0.35, -0.94)	Py = 349302864.02
Iz = (0.00, 0.94, -0.35)	Pz = 349309269.32

Moments of inertia: (g\mm2)

Taken using positive tensor notation, centered at centroid, and aligned with the output coordinate system.

(Lxx,Lxy,Lxz) = (75195121.32,101804.73,56789.07)

(Lyx,Lyy,Lyz) = (101804.73,349308431.21,2139.04)

(Lzx,Lzy,Lzz) = (556789.07,2139.04,349303652.56)

Moments of inertia: (g\mm2)

Recorded in the output coordinate system with positive tensor notation

Ixx = 124937423583.67	Ixy = 52742.75	Ixz = -5408149955.93
Iyx = 52742.75	Iyy = 125445784666.29	Iyz = 1134859.78
Izx = -5408149955.93	Izy = 1134859.78	Izz = 583551445.85

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapters presents the results obtained from running simulations of the various concepts, including the HDPE-Carbon fiber combination, Carbon fiber-HDPE-Carbon fiber combination, and all alloy steel combination. One form if simulation us used: static stress simulation used to simulate the stress distribution across components when the pressure vessel is subjected to different values of pressure, using SolidWorks simulation. The goal is to analyze the stress, strain, deformation and factor of safety these results are then compared for the three configurations of the designed pressure vessel which include the conventional all steel vessel.

4.1 SIMULATION REPORT FOR THE VARIOUS CONFIGURATIONS.

Assumptions (The same for every simulation carried out in this report)

- The material properties of the vessel are assumed to be uniform and isotropic throughout.
- The material is assumed to behave linear elastically, meaning that stress is directly proportional to strain within the elastic limit.
- Connections between components are assumed to be perfectly rigid.
- Loading conditions are assumed to be uniform and evenly distributed.
- The geometry of the vessel is idealized to simplify the simulation. Complex features or manufacturing details are neglected.
- The loading is assumed to be static only. Dynamic effects, such as vibration or impact, are neglected.

4.2 SIMULATION REPORT FOR ALL ALLOY STEEL COMBINATION

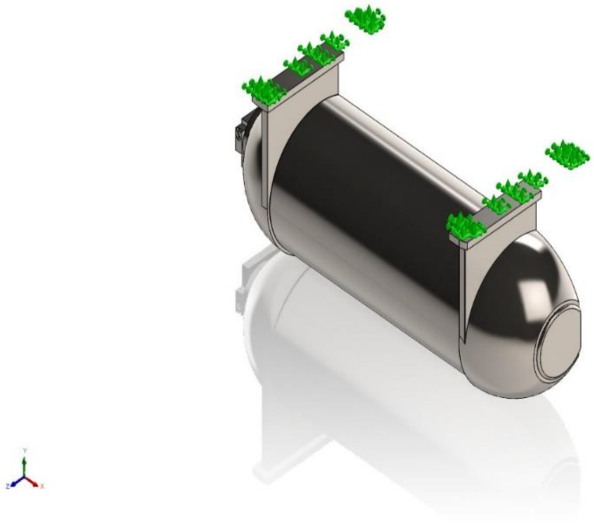
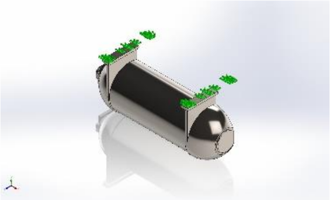
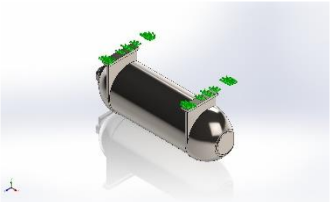
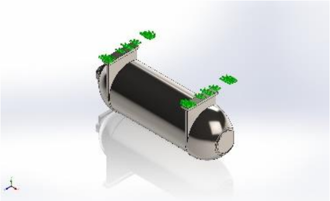
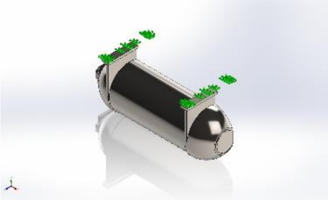
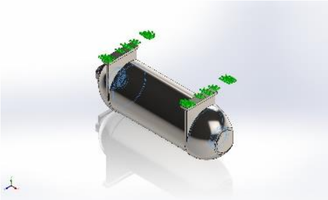
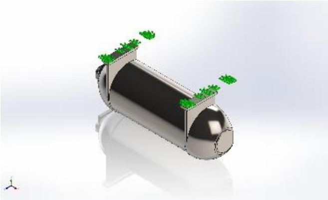
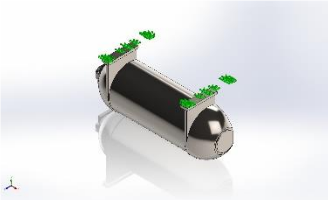


Figure 4.1 Alloy steel combination

Document Name and Reference	**Treated As**	**Properties**	**File location/Date Modified**
Revolve1 	**Solid**	**Mass:1.12743 kg** **Volume:0.000146419 m^3** **Density:7,700 kg/m^3** **Weight:11.0488 N**	**Zee3ez\Hydrogen Storage Project\Boss.SLDPRT** **Apr 16 11:22:52 2024**
Revolve1 	**Solid**	**Mass:1.0393 kg** **Volume:0.000134975 m^3** **Density:7,700 kg/m^3** **Weight:10.1852 N**	**Zee3ez\Hydrogen Storage Project\Boss Cover.SLDPRT** **Apr 16 11:22:50 2024**
Revolve1 	**Solid**	**Mass:33.3298 kg** **Volume:0.00432855 m^3** **Density:7,700 kg/m^3** **Weight:326.632 N**	**Zee3ez\H22\Hydrogen Storage Project\Carbon fibre outter plating.SLDPRT** **Apr 30 14:18:41 2024**

Boss-Extrude3 	**Solid**	**Mass:3.65709 kg** **Volume:0.000474947 m^3** **Density:7,700 kg/m^3** **Weight:35.8395 N**	**Zee3ez\Hydrogen Storage Project\Head Dome.SLDPRT** **Apr 16 11:20:50 2024**
Revolve1 	**Solid**	**Mass:10.4434 kg** **Volume:0.00135628 m^3** **Density:7,700 kg/m^3** **Weight:102.345 N**	**Zee3ez\Hydrogen Storage Project\Carbon Fibre inner plating.SLDPRT** **May 1 11:13:14 2024**
Boss-Extrude4 	**Solid**	**Mass:1.15685 kg** **Volume:0.00015024 m^3** **Density:7,700 kg/m^3** **Weight:11.3371 N**	**Zee3ez\Hydrogen Storage Project\Valve.SLDPRT** **Apr 30 18:00:38 2024**
Boss-Extrude3 	**Solid**	**Mass:3.65709 kg** **Volume:0.000474947 m^3** **Density:7,700 kg/m^3** **Weight:35.8395 N**	**Zee3ez\Hydrogen Storage Project\Head Dome.SLDPRT** **Apr 16 11:20:50 2024**

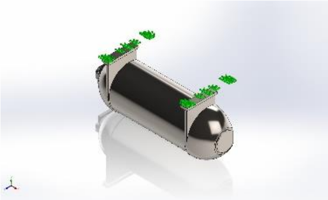
Fillet1 	**Solid**	**Mass:0.000632276 kg** **Volume:8.21137e-08 m^3** **Density:7,700 kg/m^3** **Weight:0.0061963 N**	**Zee3ez\Hydrogen Storage Project\Valve.SLDPRT** **Apr 30 18:00:38 2024**

TABLE 1 PROPERTIES USED IN STUDY

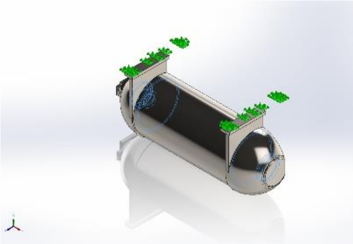
Name	**Conventional**
Type of	**Static analysis**
Thermal effect	**Nil**
Type of mesh	**Solid mesh**
Zero strain temperature	**298K**
Thermal option	**Temperature loads included**
Inplane effect	**Nil**
Type of solver	**Automatic**
Inertial relief	**Nil**
Large displacement	**Nil**
Soft spring	**Nil**
Friction	**Nil**
Free body forces	**Computed**
Adaptive method	**Unused**

UNITS

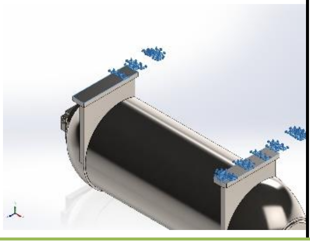
Length/Displacement	Mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/stress	N/m^2

Table 2 Properties of materials

Material Properties

Reference	Properties	Components
	Name: Alloy Steel Model type: Linear Elastic Isotropic Strength at yield: 6.20422e+08 N/m^2 Default failure criterion: Max von Mises Stress Elastic modulus: 2.1e+11 N/m^2 Tensile strength: 7.23826e+08 N/m^2 Poisson's ratio: 0.28 Mass density: 7,700 kg/m^3 Thermal expansion coefficient: 1.3e-05 /Kelvin Shear modulus: 7.9e+10 N/m^2	SolidBody 1(Revolve1)(Boss Cover-1), SolidBody 1(Revolve1)(Boss-1), SolidBody 1(Revolve1)(Carbon Fibre inner plating-1), SolidBody 1(Revolve1)(Carbon fibre outter plating-1), SolidBody 1(Boss-Extrude3)(Head Dome-1), SolidBody 1(Boss-Extrude3)(Head Dome-2), SolidBody 1(Boss-Extrude4)(Valve-1), SolidBody 2(Fillet1)(Valve-1)

Loads and Fixtures

Name	Image	Details
Fixed-1		Entities: 2 face(s) Type: Fixed Geometry

Name	**Image**	**Details**

Resultant Forces

Components	**X**	**Y**	**Z**	**Resultant**
Reaction force(N)	**-20,426.8**	**-2.38013**	**25.3833**	**20,426.8**
Moment(N.m) of Reaction	**-**	**-**	**-**	**-**

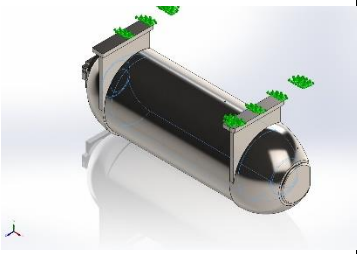
Load name	**Load Image**	**Load Details**
Pressure-1		**Entities: 5 face(s)** **Type: Normal to selected face** **Value: 10** **Units: N/mm^2 (MPa)** **Phase Angle: 0** **Units: deg**

Table 3 Details of mesh

Information

Type	Solid Mesh
Jacobian points for High quality mesh	16 Points
Mesher Used:	Blended curvature-based mesh
Min element size	2.62432 mm
Max element size	52.4864 mm
Remesh failed parts independently	Nil
Quality	High

Details

Total Nodes	22370
Max Aspect Ratio	66.619
Total Elements	11697
Percentage of elements with Aspect Ratio > 10	2.9
% of elements with Aspect Ratio < 3	70

% of distorted elements	0
Time to complete mesh(hh;mm;ss):	00:00:09

Resultant Forces

Reaction forces

Selection set	Units	X	Y	Z	Resultant
Entire Model	N	-20,426.8	-2.38013	25.3833	20,426.8

Reaction Moments

Selection set	Units	X	Y	Z	Resultant
Entire Model	N.m	-	-	-	-

Free body forces

Selection set	Units	X	Y	Z	Resultant
Entire Model	N	13.3631	73.619	-16.9642	76.721

Free body moments

Selection set	Units	X	Y	Z	Resultant
Entire Model	N.m	-	-	-	1e-33

Name	Type	Min	Max
Stress	VON: von Mises Stress	1.066e+02N/m^2 Node: 22315	5.257e+07N/m^2 Node: 7914

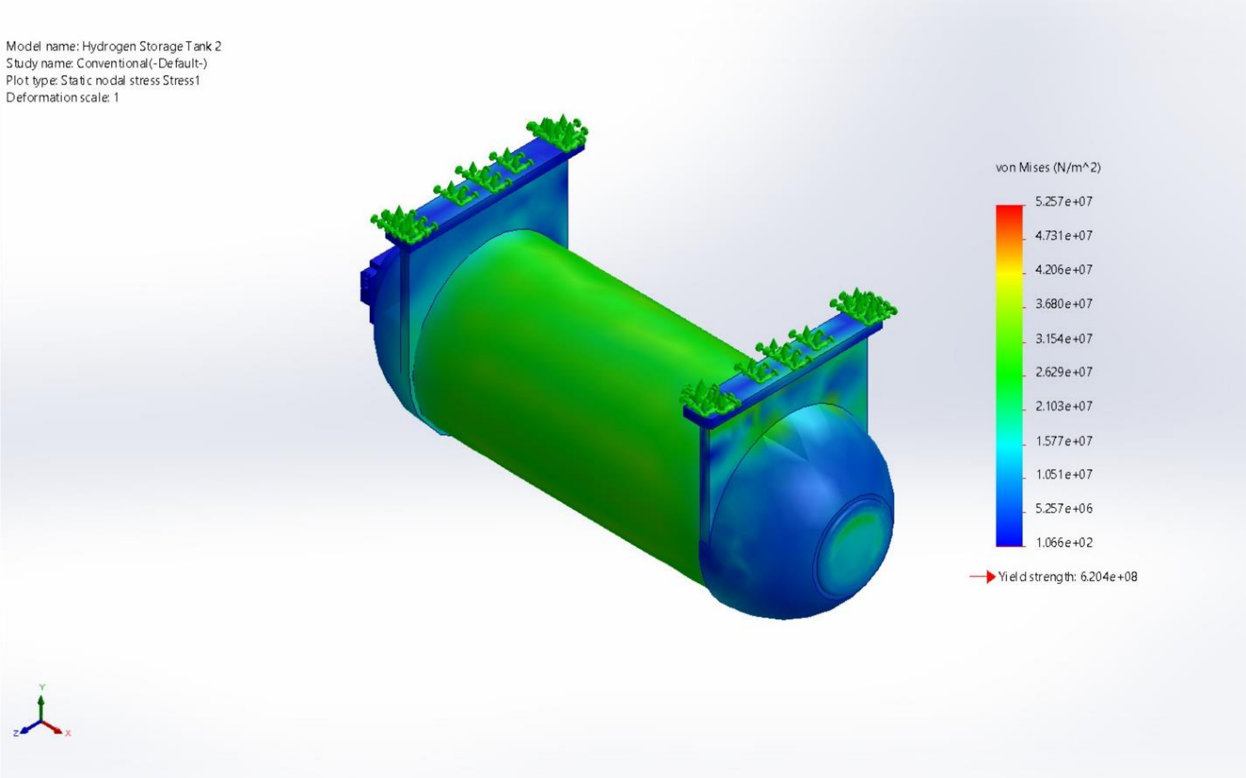


Figure 4.2 Stress distribution

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0.000e+00mm Node: 9924	3.559e-02mm Node: 11329

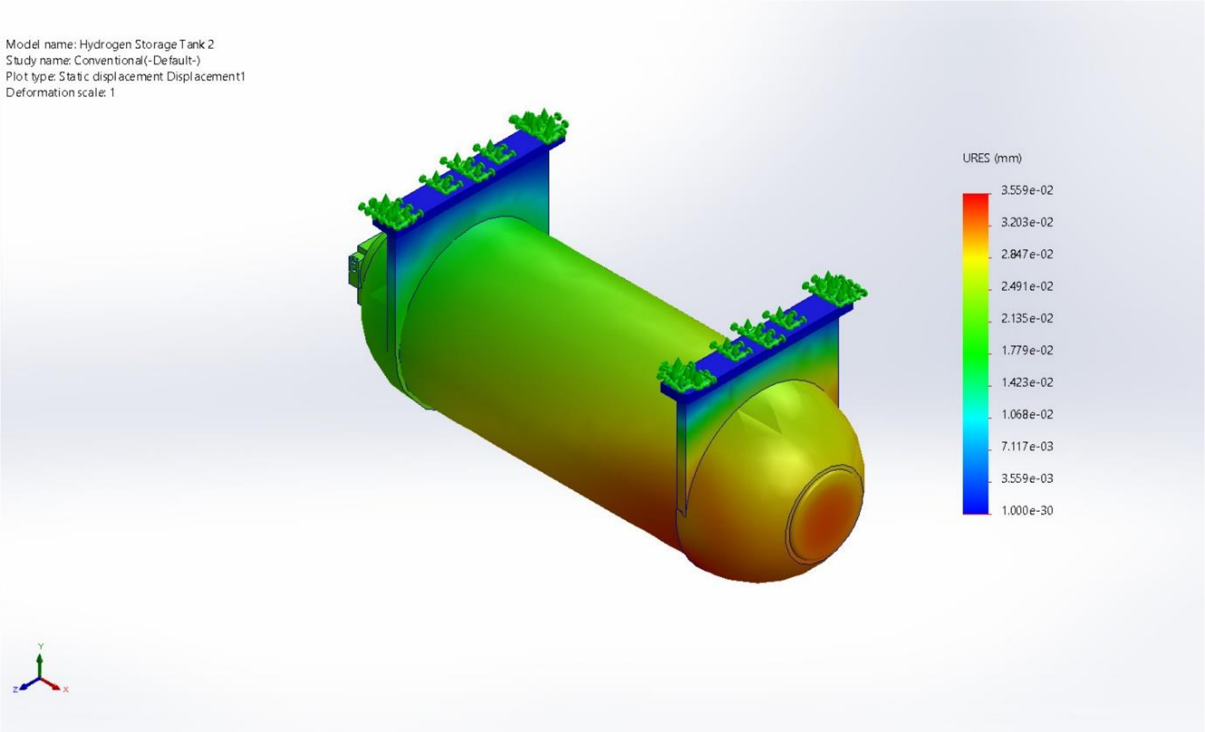
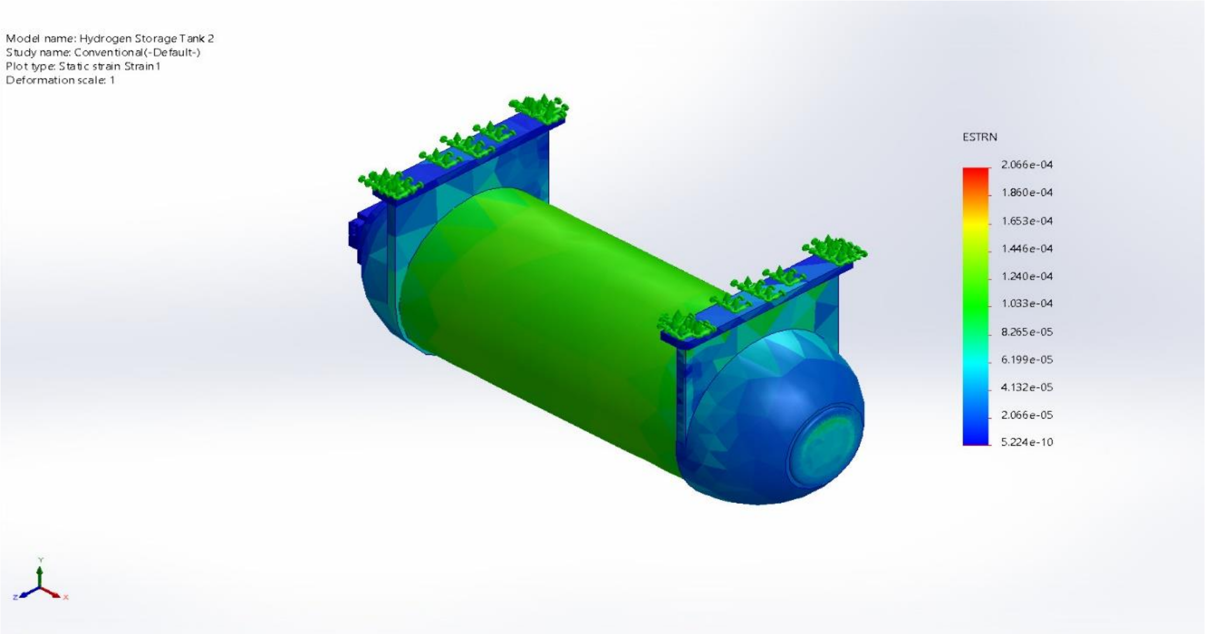


Figure 4.3 Displacement

Name	Type	Min	Max
Strain	ESTRN: Equivalent Strain	5.224e-10 Element: 11675	2.066e-04 Element: 3327



Name	Type	Min	Max
Factor of Safety	Automatic	1.180e+01 Node: 7914	5.818e+06 Node: 22315

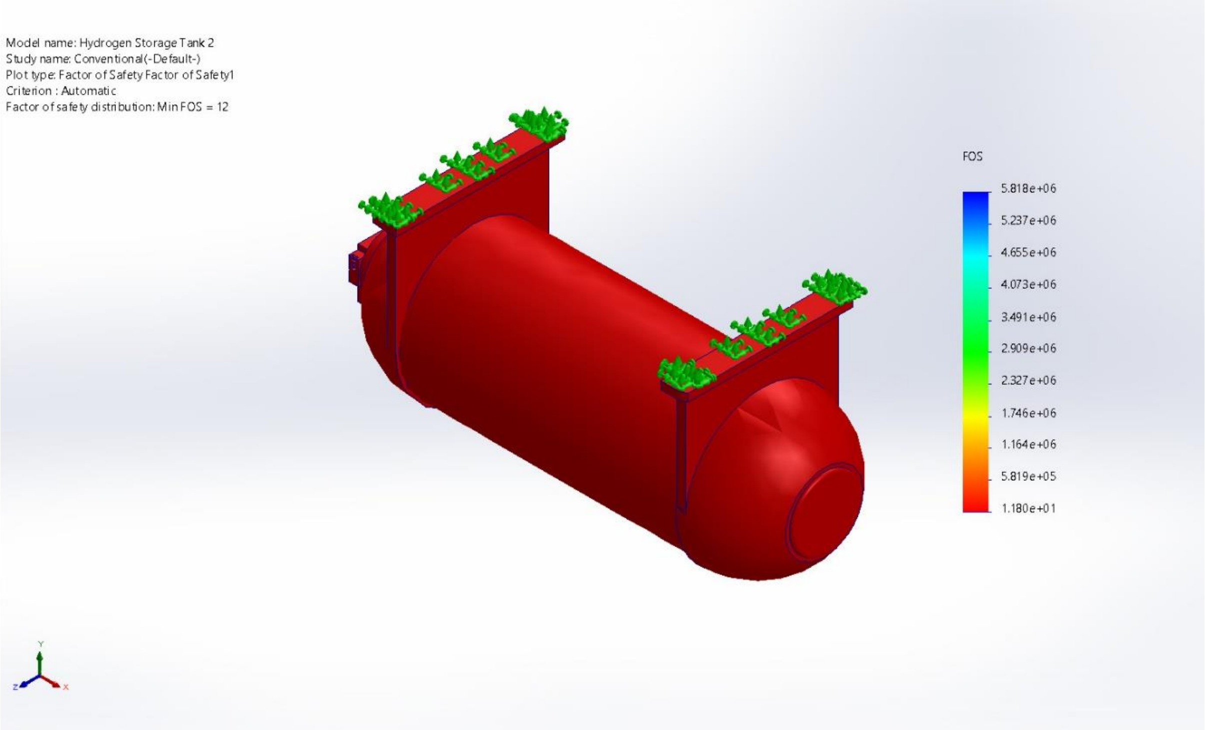


Figure 4.4 Factor of safety

4.3 SIMULATION REPORT FOR HDPE CARBON FIBER COMBINATION

Model Information

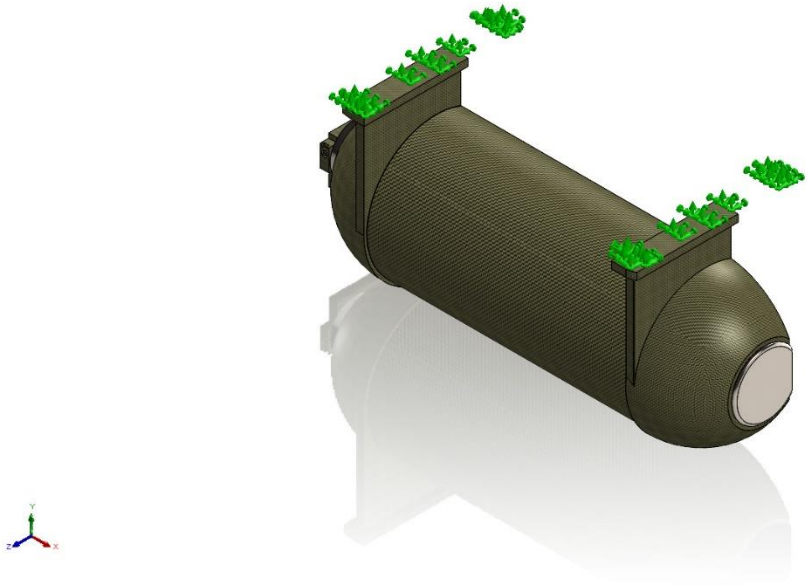
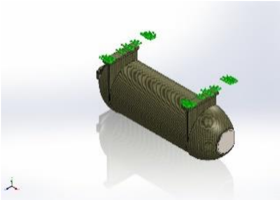
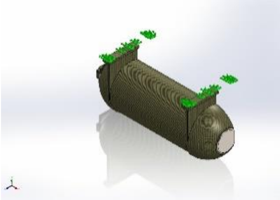
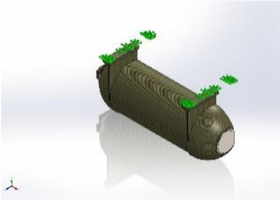
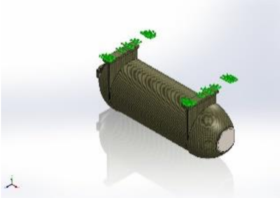
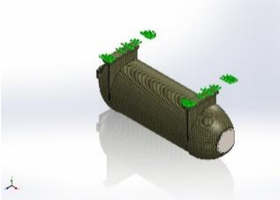
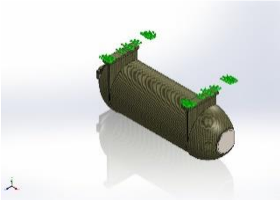


Figure 4.5 HDPE Carbon fiber combination

Model name: Hydrogen Storage Tank 2
Current Configuration: Default

Solid Bodies			
Document Name and Reference	**Treated As**	**Properties**	**File location**
Revolve1 	**Solid**	**Mass:1.0393 kg** **Volume:0.000134975 m^3** **Density:7,700 kg/m^3** **Weight:10.1852 N**	**Zee3ez\Hydrogen Storage Project\Boss Cover.SLDPRT**
Revolve1 	**Solid**	**Mass:1.12743 kg** **Volume:0.000146419 m^3** **Density:7,700 kg/m^3** **Weight:11.0488 N**	**Zee3ez\Hydrogen Storage Project\Boss.SLDPRT**
Revolve1 	**Solid**	**Mass:1.29118 kg** **Volume:0.00135628 m^3** **Density:952 kg/m^3** **Weight:12.6536 N**	**Zee3ez\Hydrogen Storage Project\Carbon Fibre inner plating.SLDPRT**
Revolve1 	**Solid**	**Mass:6.92568 kg** **Volume:0.00432855 m^3** **Density:1,600 kg/m^3** **Weight:67.8717 N**	**Zee3ez\H22\Hydrogen Storage Project\Carbon fibre outter plating.SLDPRT**
Extrude3 	**Solid**	**Mass:0.759915 kg** **Volume:0.000474947 m^3** **Density:1,600 kg/m^3** **Weight:7.44716 N**	**Zee3ez\Hydrogen Storage Project\Head Dome.SLDPRT**
Extrude3 	**Solid**	**Mass:0.759915 kg** **Volume:0.000474947 m^3** **Density:1,600 kg/m^3** **Weight:7.44716 N**	**Zee3ez\Hydrogen Storage Project\Head Dome.SLDPRT**

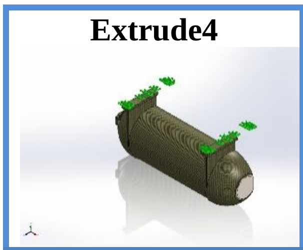
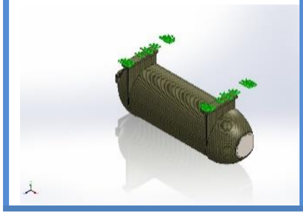
Extrude4 	**Solid**	**Mass:0.240384 kg Volume:0.00015024 m^3 Density:1,600 kg/m^3 Weight:2.35577 N**	**Zee3ez\Hydrogen Storage Project\Valve.SLDPRT**
Fillet1 	**Solid**	**Mass:0.000131382 kg Volume:8.21137e-08 m^3 Density:1,600 kg/m^3 Weight:0.00128754 N**	**Zee3ez\Hydrogen Storage Project\Valve.SLDPRT**

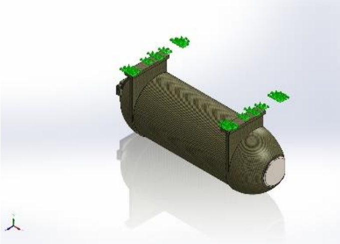
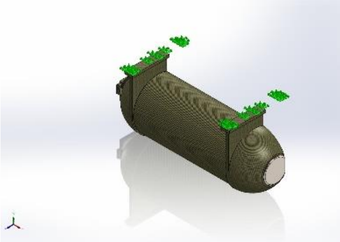
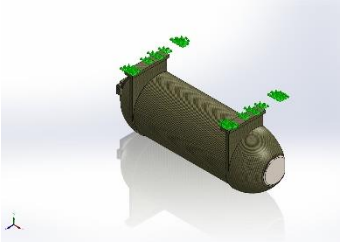
Table 4 Properties of Study

Name	**Conventional**
Type of	**Static analysis**
Thermal effect	**Nil**
Type of mesh	**Solid mesh**
Zero strain temperature	**298K**
Thermal option	**Temperature loads included**
Inplane effect	**Nil**
Type of solver	**Automatic**
Inertial relief	**Nil**
Large displacement	**Nil**
Soft spring	**Nil**
Friction	**Nil**
Free body forces	**Computed**
Adaptive method	**Unused**

UNITS

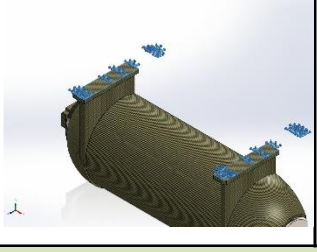
Length/Displacement	Mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/stress	N/m^2

Table 5 Material Properties

Reference	Properties	Components
	**Name:** Alloy Steel **Model type:** Linear Elastic Isotropic **Default failure criterion:** Max von Mises Stress **Yield strength:** 6.20422e+08 N/m^2 **Tensile strength:** 7.23826e+08 N/m^2 **Elastic modulus:** 2.1e+11 N/m^2 **Poisson's ratio:** 0.28 **Mass density:** 7,700 kg/m^3 **Shear modulus:** 7.9e+10 N/m^2 **Thermal expansion coefficient:** 1.3e-05 /Kelvin	SolidBody 1(Revolve1)(Boss Cover-1), SolidBody 1(Revolve1)(Boss-1)
	**Name:** PE High Density **Model type:** Linear Elastic Isotropic **Default failure criterion:** Unknown **Tensile strength:** 2.21e+07 N/m^2 **Elastic modulus:** 1.07e+09 N/m^2 **Poisson's ratio:** 0.4101 **Mass density:** 952 kg/m^3 **Shear modulus:** 3.772e+08 N/m^2	SolidBody 1(Revolve1)(Carbon Fibre inner plating-1)
	**Name:** Thornel VCB-20 Carbon Cloth/Epoxy composite **Model type:** Linear Elastic Isotropic **Default failure criterion:** Max von Mises Stress **Yield strength:** 3.8e+08 N/m^2	SolidBody 1(Revolve1)(Carbon fibre outter plating-1), SolidBody 1(Boss-Extrude3)(Head Dome-1), SolidBody 1(Boss-Extrude3)(Head Dome-2),

	Tensile strength: 1.38e+09 N/m^2 **Compressive strength:** 3.45e+08 N/m^2 **Elastic modulus:** 4.1e+10 N/m^2 **Poisson's ratio:** 0.28 **Mass density:** 1,600 kg/m^3	SolidBody 1(Boss-Extrude4)(Valve-1), SolidBody 2(Fillet1)(Valve-1)

Loads and Fixtures

Name	Image	Details
Fixed-1		**Entities:** 2 face(s) **Type:** Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-949.971	16.9045	-6.97253	950.147
Reaction Moment(N.m)	-	-	-	-

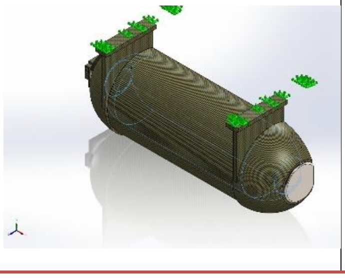
Load name	Load Image	Load Details
Pressure		**Entities:** 5 face(s) **Type:** Normal to selected face **Value:** 10 **Units:** N/mm^2 (MPa) **Phase Angle:** 0 **Units:** deg

Table 6 Information of mesh

Type	Solid Mesh
Mesher Used:	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points
Min element size	2.44123 mm
Max element size	48.8245 mm
Mesh Quality	High
Remesh failed parts independently	-

Details

Total Nodes	23463
Max Aspect Ratio	117.82
Total Elements	12351
% of elements with Aspect Ratio < 3	70.8
Percentage of distorted elements	0
% of elements with Aspect Ratio > 10	2.43
Time to complete mesh(hh;mm;ss):	00:00:10

Resultant Forces

Reaction forces

Selection set	Units	X	Y	Z	Resultant
Entire Model	N	-949.971	16.9045	-6.97253	950.147

Reaction Moments

Selection set	Units	X	Y	Z	Resultant
Entire Model	N.m	-	-	-	-

Free body forces

Selection set	Units	X	Y	Z	Resultant
Entire Model	N	11.2007	11.6655	16.5808	23.1617

Free body moments

Selection set	Units	X	Y	Z	Resultant
Entire Model	N.m	-	-	-	1e-33

Result of Study

Name	Type	Min	Max
Stress1	VON: von Mises Stress	1.773e+02N/m^2 Node: 16011	1.050e+08N/m^2 Node: 8135

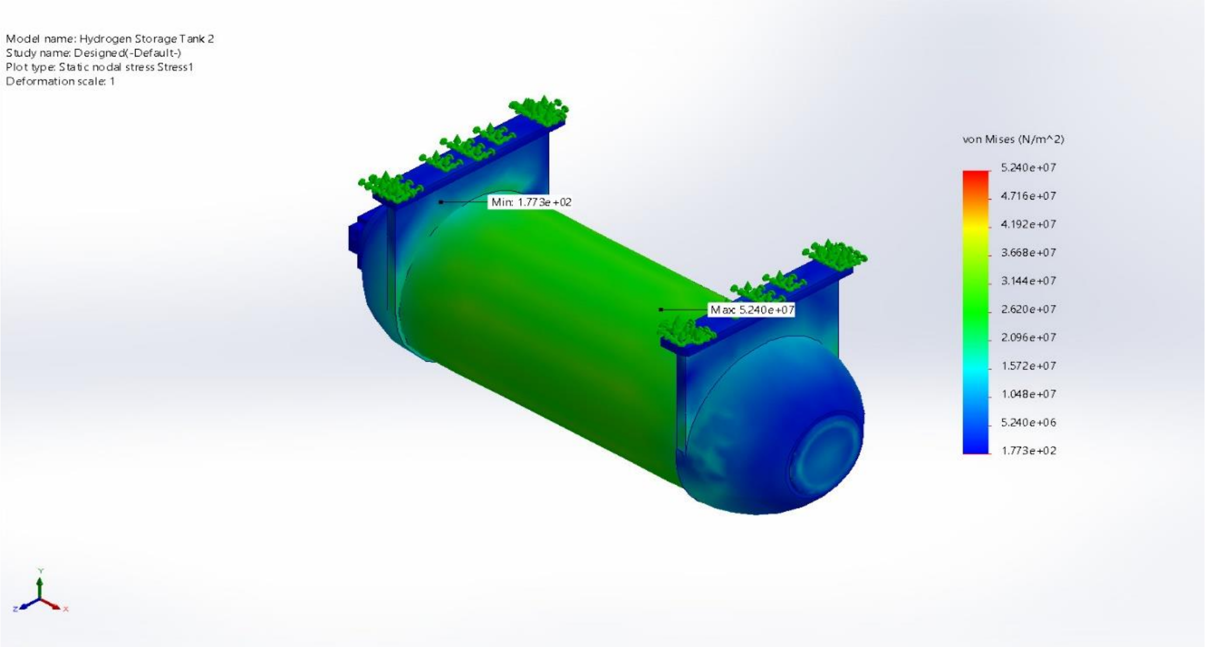
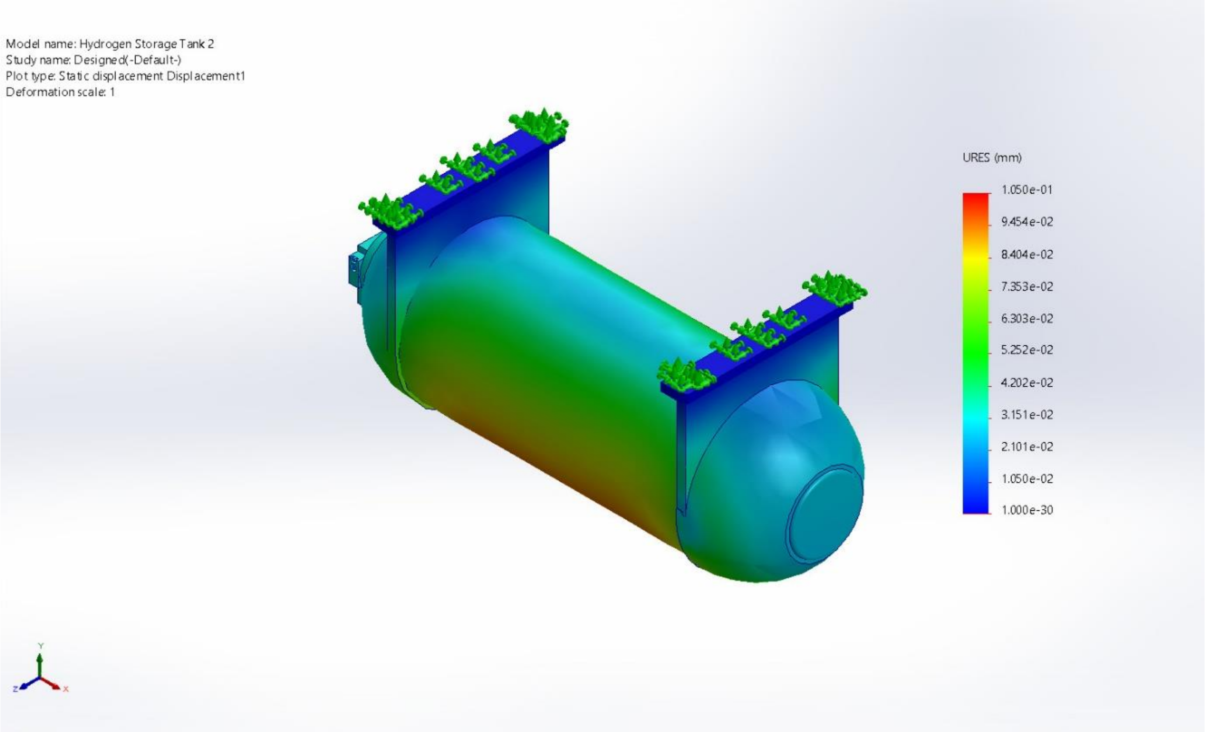


Figure 4.6 Stress distribution

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0.000e+00mm Node: 10156	2.64e-01mm Node: 6398



Name	Type	Min	Max
Strain	ESTRN: Equivalent Strain	2.414e-09 Element: 12348	5.50e-04 Element: 4065

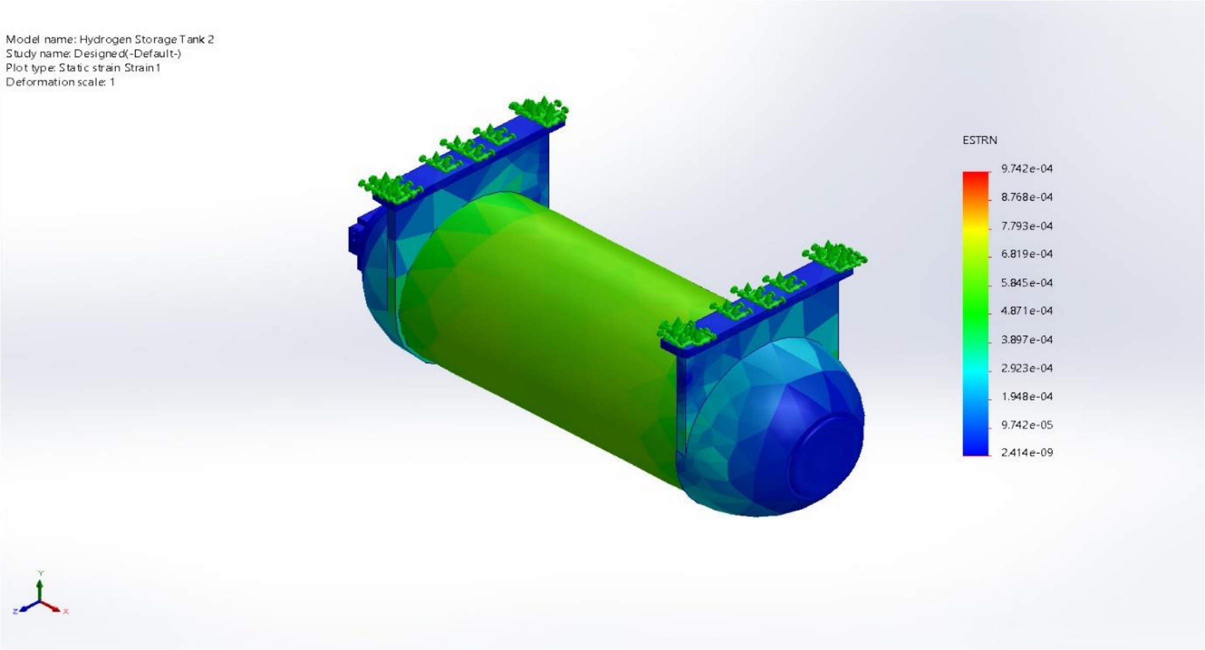


Figure 4.7 Strain distribution

Name	Type	Min	Max
Factor of Safety1	Automatic	5.93e+00 Node: 8482	2.143e+06 Node: 16011

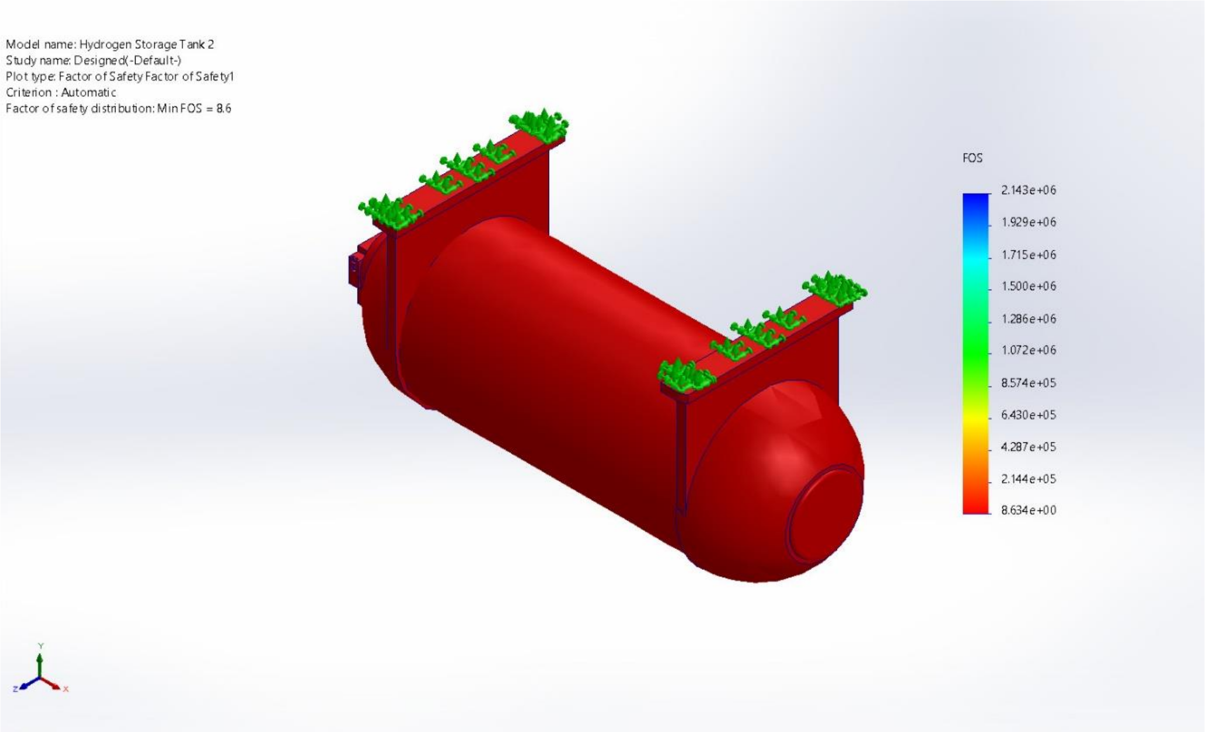


Figure 4.8 Factor of safety

4.4 SIMULATION REPORT FOR CARBON FIBER, HDPE, CARBON FIBER COMBINATION

Model Information

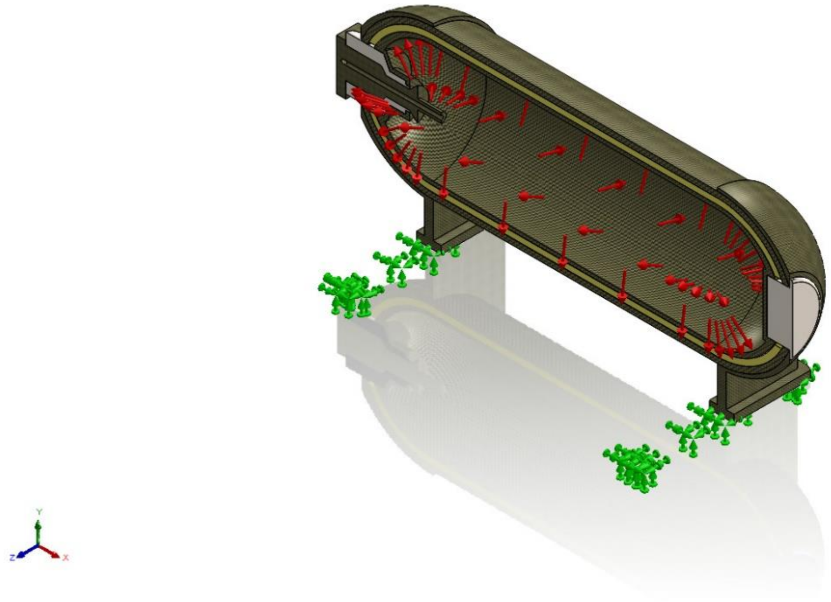
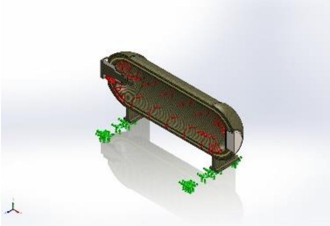
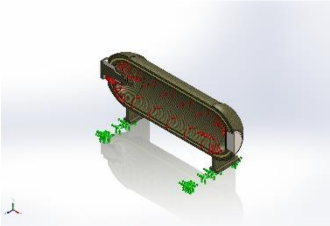
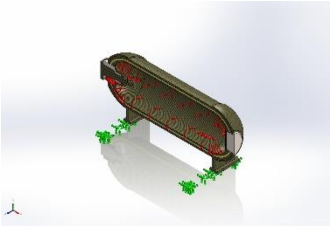
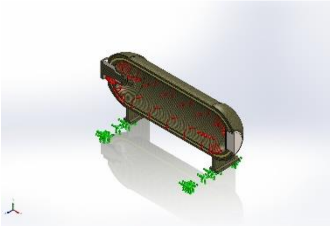
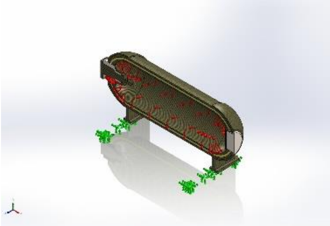
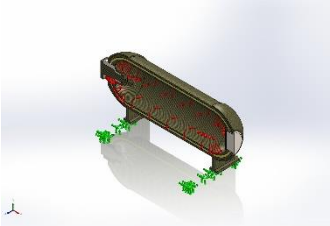


Figure 4.9 Carbon fiber HDPE Carbon fiber

Name: **TEST2**

Configuration: **Default**

Solid Bodies			
Document Name and Reference	Treated As	Properties	File location
Revolve1 	Solid	Mass:2.17005 kg Volume:0.00135628 m^3 Density:1,600 kg/m^3 Weight:21.2665 N	Zee3ez\Hydrogen Storage Project\Carbon Fibre inner plating.SLDPRT
Revolve1 	Solid	Mass:1.0393 kg Volume:0.000134975 m^3 Density:7,700 kg/m^3 Weight:10.1852 N	Zee3ez\Hydrogen Storage Project\Boss Cover.SLDPRT
Revolve1 	Solid	Mass:1.12743 kg Volume:0.000146419 m^3 Density:7,700 kg/m^3 Weight:11.0488 N	Zee3ez\Hydrogen Storage Project\Boss.SLDPRT
Revolve1 	Solid	Mass:3.66527 kg Volume:0.0022908 m^3 Density:1,600 kg/m^3 Weight:35.9197 N	Zee3ez\Hydrogen Storage Project\Carbon fibre outter plating3.SLDPRT
Extrude3 	Solid	Mass:0.759915 kg Volume:0.000474947 m^3 Density:1,600 kg/m^3 Weight:7.44716 N	Zee3ez\Hydrogen Storage Project\Head Dome.SLDPRT
Revolve1 	Solid	Mass:1.92674 kg Volume:0.00202388 m^3 Density:952 kg/m^3 Weight:18.882 N	Zee3ez\Hydrogen Storage Project\Carbon fibre outter plating4.SLDPRT

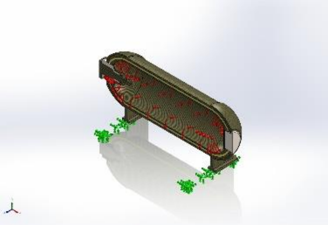
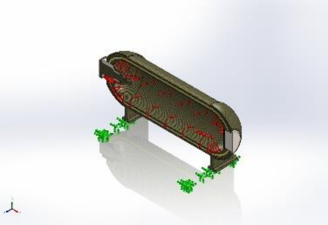
Extrude3 	**Solid**	**Mass:0.759915 kg** **Volume:0.000474947 m^3** **Density:1,600 kg/m^3** **Weight:7.44716 N**	**Zee3ez\Hydrogen Storage Project\Head Dome.SLDPRT**
Fillet1 	**Solid**	**Mass:0.000131382 kg** **Volume:8.21137e-08 m^3** **Density:1,600 kg/m^3** **Weight:0.00128754 N**	**Zee3ez\Hydrogen Storage Project\Valve.SLDPRT**
Extrude4 	**Solid**	**Mass:0.240384 kg** **Volume:0.00015024 m^3** **Density:1,600 kg/m^3** **Weight:2.35577 N**	**Zee3ez\Hydrogen Storage Project\Valve.SLDPRT**

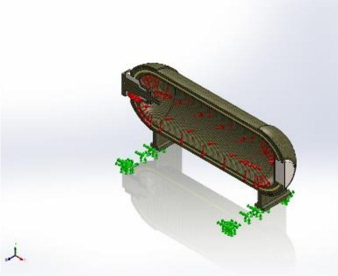
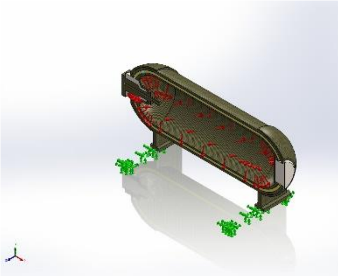
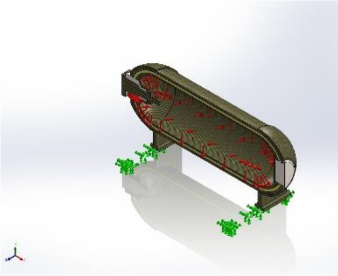
Table 7 Study Properties

Name	**Conventional**
Type of	**Static analysis**
Thermal effect	**Nil**
Type of mesh	**Solid mesh**
Zero strain temperature	**298K**
Thermal option	**Temperature loads included**
Inplane effect	**Nil**
Type of solver	**Automatic**
Inertial relief	**Nil**
Large displacement	**Nil**
Soft spring	**Nil**
Friction	**Nil**
Free body forces	**Computed**
Adaptive method	**Unused**

Units

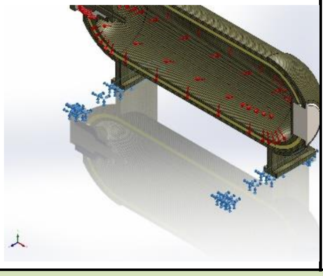
Length/Displacement	Mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/stress	N/m^2

Properties of material

Reference	Properties	Components
	Name: **Alloy Steel** Model type: **Linear Elastic Isotropic** Default failure criterion: **Max von Mises Stress** Yield strength: **6.20422e+08 N/m^2** Tensile strength: **7.23826e+08 N/m^2** Elastic modulus: **2.1e+11 N/m^2** Mass density: **7,700 kg/m^3** Poisson's ratio: **0.28** Shear modulus: **7.9e+10 N/m^2** Thermal expansion coefficient: **1.3e-05 /Kelvin**	**SolidBody 1(Revolve1)(Boss Cover-1),** **SolidBody 1(Revolve1)(Boss-1)**
	Name: **Thornel VCB-20 Carbon Cloth/Epoxy composite** Model type: **Linear Elastic Isotropic** Default failure criterion: **Max von Mises Stress** Yield strength: **4.5e+09 N/m^2** Tensile strength: **1.38e+09 N/m^2** Elastic modulus: **4.1e+10 N/m^2** Compressive strength: **3.45e+08 N/m^2** Poisson's ratio: **0.28** Mass density: **1,600 kg/m^3**	**SolidBody 1(Revolve1)(Carbon Fibre inner plating-1),** **SolidBody 1(Revolve1)(Carbon fibre outter plating3-1),** **SolidBody 1(Boss-Extrude3)(Head Dome-1),** **SolidBody 1(Boss-Extrude3)(Head Dome-2),** **SolidBody 1(Boss-Extrude4)(Valve-1),** **SolidBody 2(Fillet1)(Valve-1)**
	Name: **PE High Density** Model type: **Linear Elastic Isotropic** Default failure criterion: **Unknown** Tensile strength: **2.21e+07 N/m^2** Poisson's ratio: **0.4101** Elastic modulus: **1.07e+09 N/m^2**	**SolidBody 1(Revolve1)(Carbon fibre outter plating4-1)**

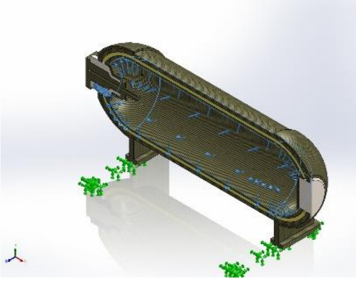
	Mass density: **952 kg/m^3** Shear modulus: **3.772e+08 N/m^2**	

Loads and Fixtures

Name	Image	Details
Fixed		**Entities: 2 face(s)** **Type: Fixed Geometry**

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	**-1,881.74**	**-18.7157**	**8.35218**	**1,881.86**
Reaction Moment(N.m)	**0**	**0**	**0**	**0**

Load name	Load Image	Load Details
Pressure		**Entities:** 3 face(s) **Type:** Normal to selected face **Value:** 10 **Units:** N/mm^2 (MPa) **Phase Angle:** 0 **Units:** deg

Information of mesh

Mesh type	Solid Mesh
Mesher Used:	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points
Min element size	2.87287 mm
Max element size	57.4574 mm
Remesh failed parts independently	Off
Mesh Quality	High

Details

Total Nodes	22180
Total Elements	11644
Max Aspect Ratio	5,837.9
% of elements with Aspect Ratio > 10	8.1
% of distorted elements	0
% of elements with Aspect Ratio < 3	57.1

Table 8 Mesh information

Resultant Forces

Reaction forces

Selection set	Units	X	Y	Z	Resultant
Entire Model	N	-1,881.74	-18.7157	8.35218	1,881.86

Reaction Moments

Selection set	Units	X	Y	Z	Resultant
Entire Model	N.m	-	-	-	-

Free body forces

Selection set	Units	X	Y	Z	Resultant
Entire Model	N	-0.426072	92.3462	61.552	110.98

Free body moments

Selection set	Units	X	Y	Z	Resultant
Entire Model	N.m	-	-	-	1e-33

Results

Name	Type	Min	Max
Stress	VON: von Mises Stress	9.017e+01N/m^2 Node: 22128	8.215e+07N/m^2 Node: 5859

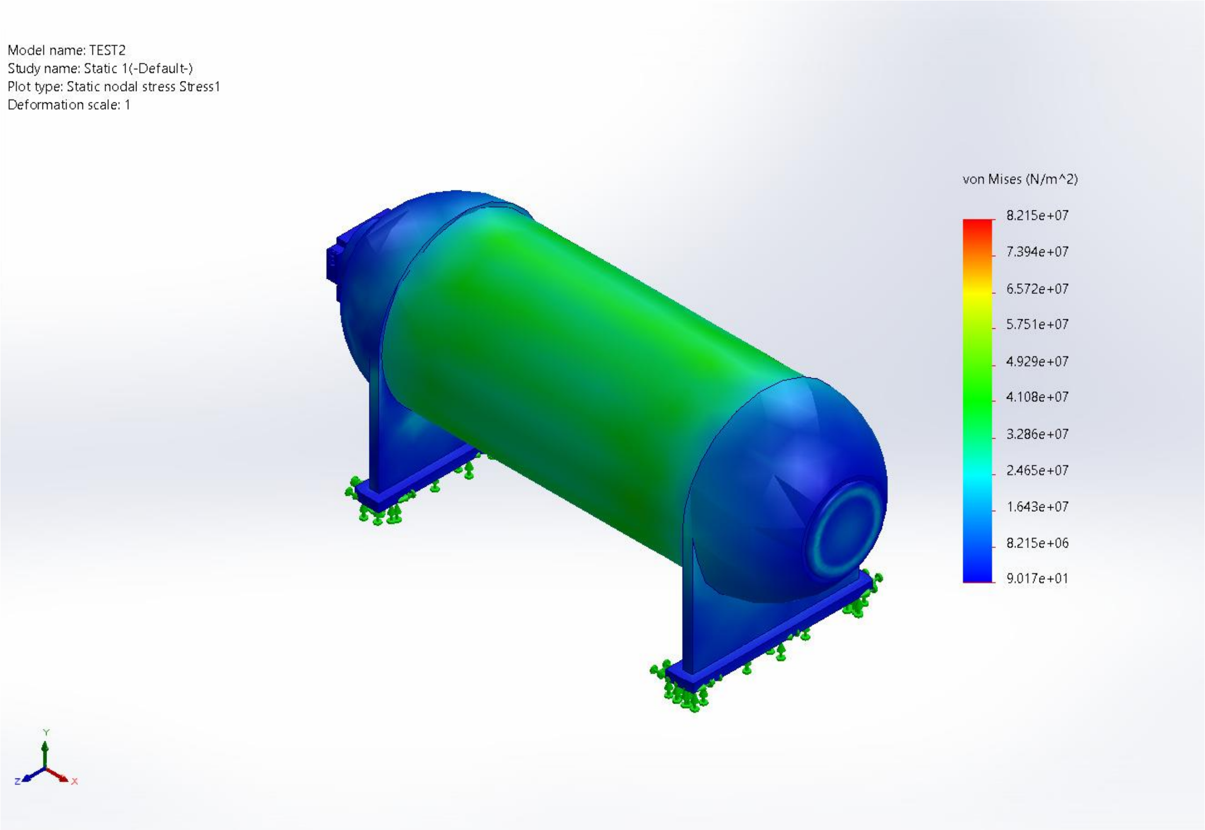
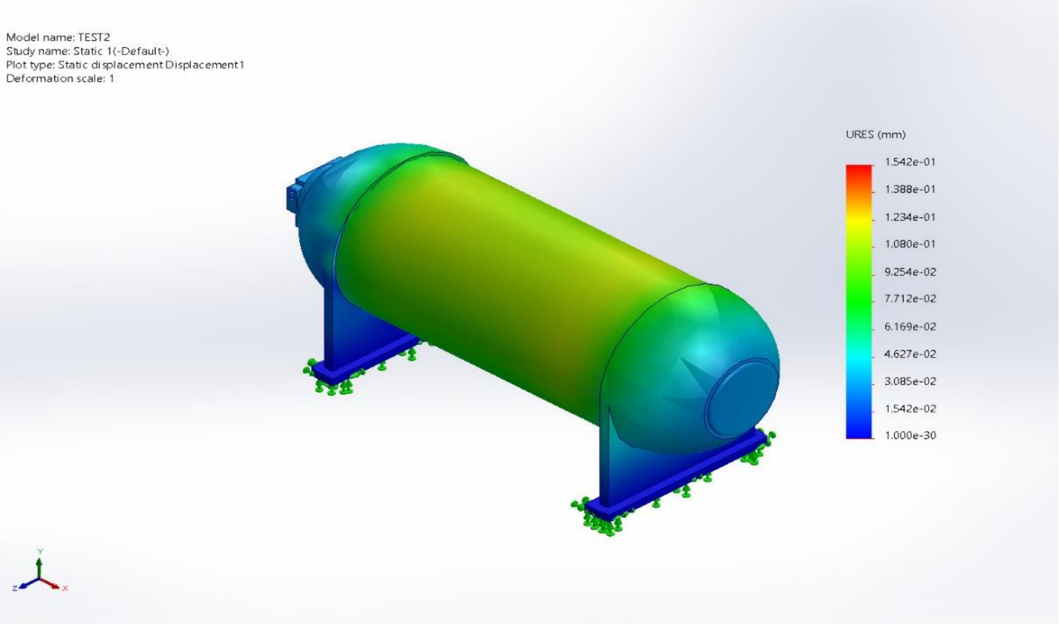


Figure 4.10 Stress distribution

Name	**Type**	**Min**	**Max**
Displacement	URES: Resultant Displacement	0.000e+00mm Node: 11594	1.542e-01mm Node: 6061



Name	**Type**	**Min**	**Max**
Strain	ESTRN: Equivalent Strain	2.207e-09 Element: 11642	4.309e-03 Element: 5555

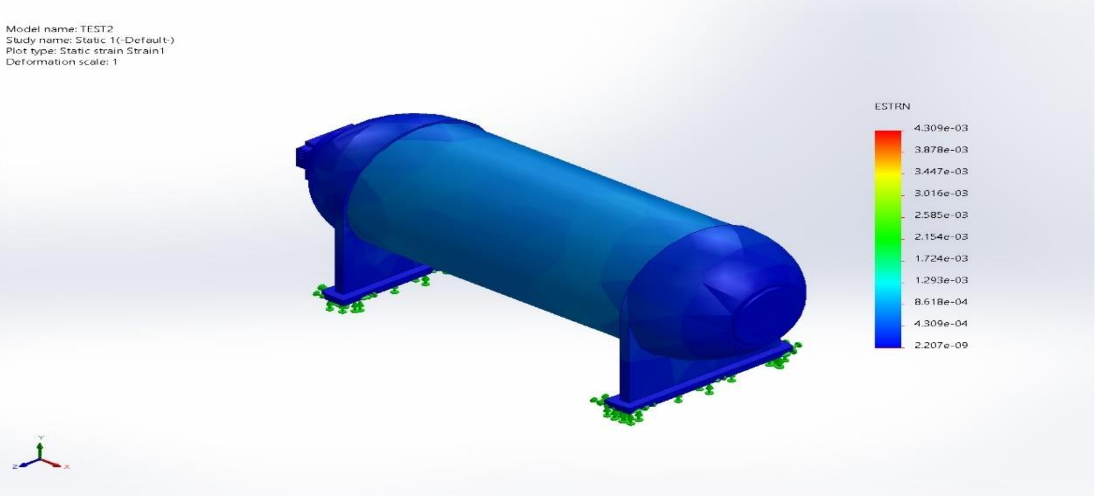


Figure 4.11 Strain distribution

Name	**Type**	**Min**	**Max**
Factor of Safety	Automatic	1.123e+01 Node: 937	4.991e+07 Node: 22128

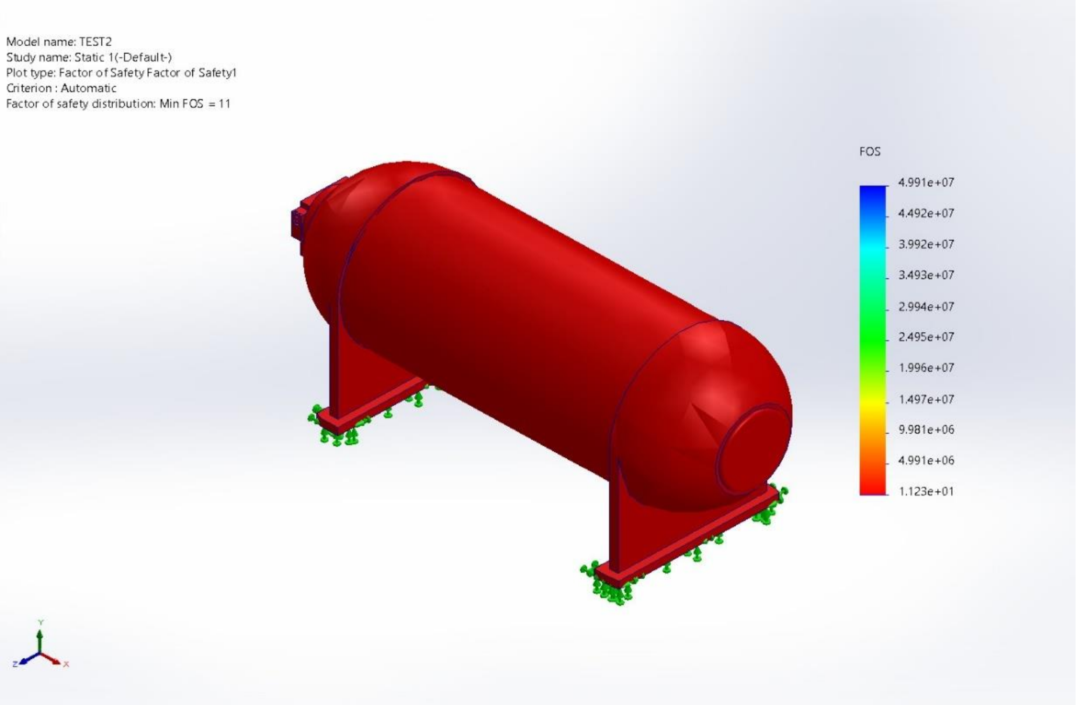


Figure 4.12 Factor of safety

4.5 ANALYSIS OF RESULTS

The simulation report provides us with key insight into the behaviour of the various pressure vessel configuration. These data include maximum (von mises) stress, displacement, strain, and factor of safety for different pressure conditions of the various configuration.

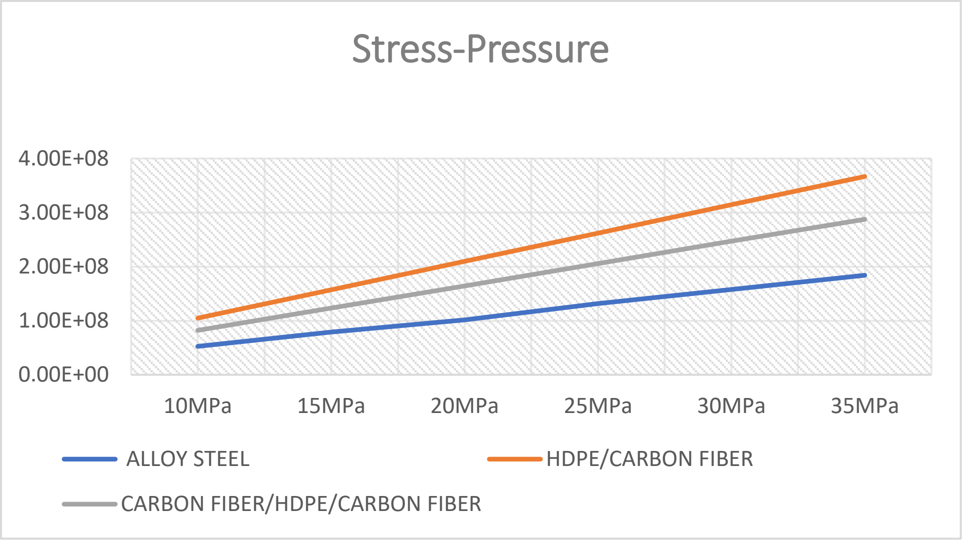
These data have been curated for the a number of pressure conditions for the various pressure vessel configurations as shown in the table below.

Table 9 Simulation results

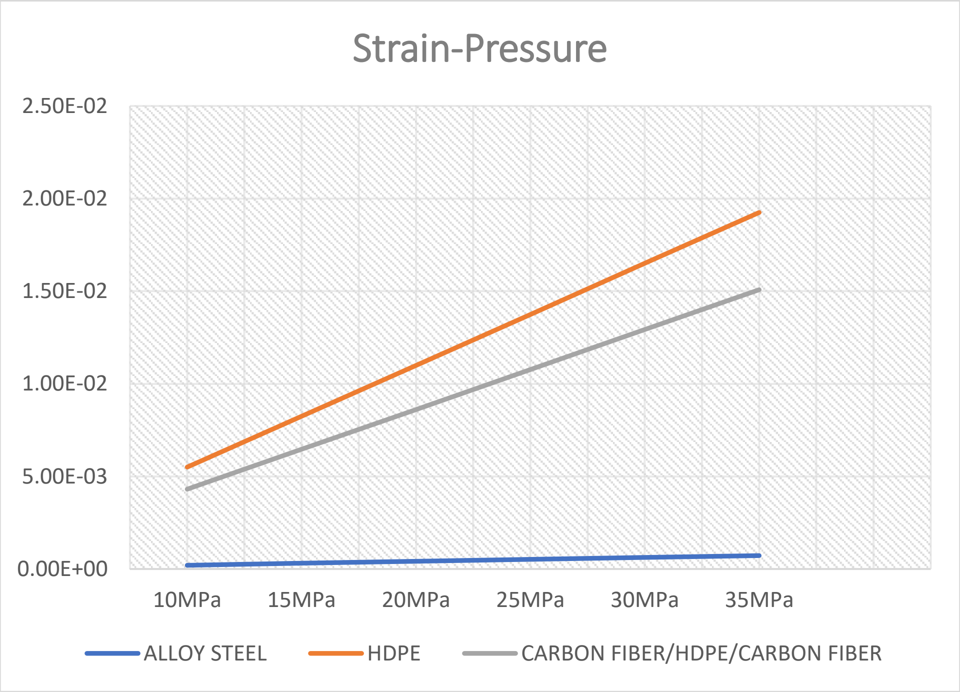
PRESSURE	PARAMETER	ALLOY STEEL	HDPE/CARBON FIBER	CARBON FIBER/HDPE/CARBON FIBER
10MPa	STRESS(N/mm2)	5.26E+07	1.05E+08	8.22E+07
	DISPLACEMENT (mm)	3.34E-02	2.64E-01	1.54E-01
	STRAIN	2.01E-04	5.50E-03	4.31E-03
	FACTOR OF SAFETY	11.8	5.9	11.23
15MPa	STRESS(N/mm2)	7.89E+07	1.57E+08	1.23E+08
	DISPLACEMENT (mm)	5.34E-02	3.97E-01	2.31E-01
	STRAIN	3.10E-04	8.25E-03	6.46E-03
	FACTOR OF SAFETY	7.86	3.94	7.49
20MPa	STRESS(N/mm2)	1.02E+08	2.10E+08	1.64E+08
	DISPLACEMENT (mm)	7.12E-02	5.29E-01	3.09E-01
	STRAIN	4.13E-04	1.10E-02	8.62E-03
	FACTOR OF SAFETY	5.9	2.91	5.61
25MPa	STRESS(N/mm2)	1.31E+08	2.62E+08	2.05E+08
	DISPLACEMENT (mm)	8.90E-02	6.61E-01	3.86E-01

	STRAIN	5.17E-04	1.38E-02	1.08E-02
	FACTOR OF SAFETY	4.72	2.33	4.49
30MPa	STRESS(N/mm2)	1.58E+08	3.15E+08	2.47E+08
	DISPLACEMENT (mm)	1.07E-01	7.93E-01	4.63E-01
	STRAIN	6.20E-04	1.65E-02	1.29E-02
	FACTOR OF SAFETY	3.93	1.97	3.74
35MPa	STRESS(N/mm2)	1.84E+08	3.67E+08	2.88E+08
	DISPLACEMENT (mm)	1.25E-01	9.25E-01	5.40E-01
	STRAIN	7.23E-04	1.93E-02	1.51E-02
	FACTOR OF SAFETY	3.37	1.69	3.21

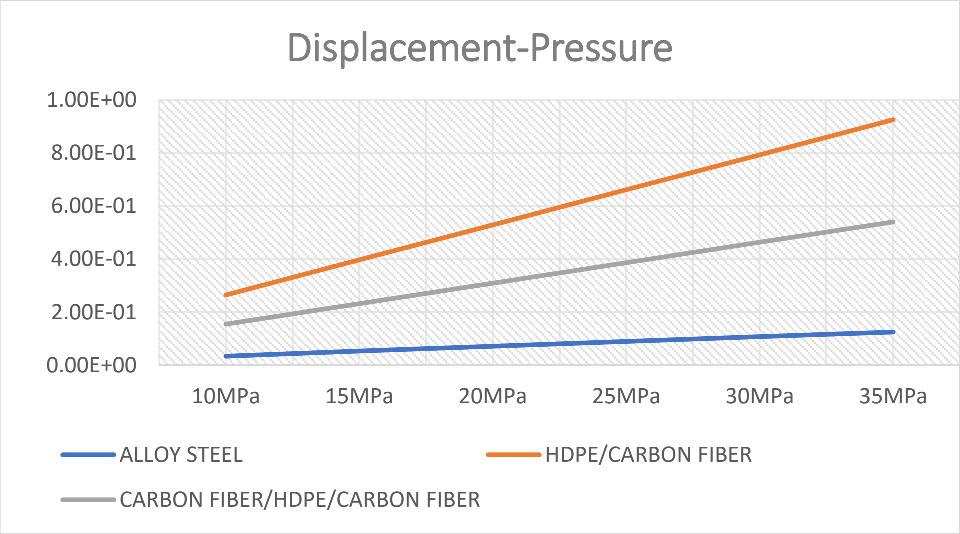
4.5.1 GRAPH OF STRESS AGAINST PRESSURE FOR THE THREE CONFIGURATIONS



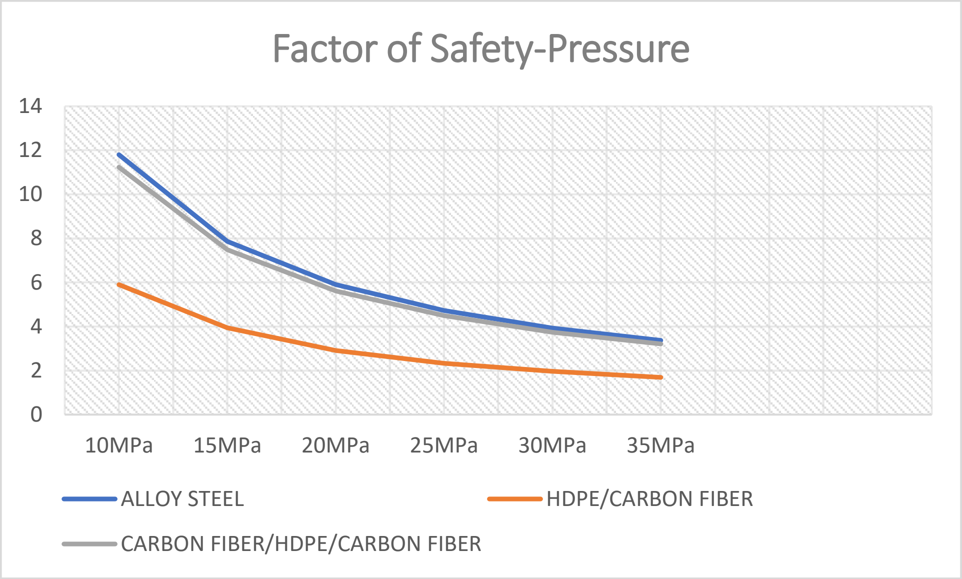
4.5.2 GRAPH OF STRAIN AGAINST PRESSURE FOR THE THREE CONFIGURATIONS



4.5.3 GRAPH OF DISPLACEMENT AGAINST PRESSURE FOR THE THREE CONFIGURATIONS.



4.5.4 GRAPH OF FACTOR OF SAFETY AGAINST PRESSURE FOR THE THREE CONFIGURATIONS.



The following interpretation can be made from the data presented the above:

- The three configurations present a stress response >1e7 N/mm^2 with the all-alloy steel presenting the lowest stress for given pressure values.
- The displacement response for the three configurations is in the range of 3.3e-02 mm with the all-alloy steel combination presenting the least displacement for given pressure values.
- The HDPE Carbon fiber configuration presents the highest strain response value for the various pressure conditions.
- The factor of safety response for the three configurations are well above 1 for pressure values even up to 35Mpa with the carbon fiber/HDPE/Carbon fiber combination presenting almost equal factor of safety at these pressure value.

From the results, it can be noted that the Carbon fiber/HDPE/Carbon fiber configuration presents the closest performance characteristics to the all-alloy steel configuration, with the factor of safety for both design equalizing for pressure values approximately greater than 35 megapascals.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The simulation result showed that the three-pressure vessel configuration showed great performance, with the conventional all-alloy steel pressure vessel presenting the least average stress, maximum factor of safety and least strain for various pressure values. The other two configurations simulated showed equally great performance.

The HDPE/Carbon Fiber configuration showed equally great performance with significant factor of safety for various pressure values. However, the carbon fiber/HDPE/carbon fiber configuration, showed the closest performance to an all-alloy steel configuration, with the factor of safety for pressure values above 35MPa almost equal.

It is therefore suggested to adopt the carbon fiber/HDPE/carbon fiber configuration as it solves the hydrogen embrittlement issue associated, while also exhibiting same performance characteristics as the all-alloy steel configuration.

In addition to the structural consideration, further studies should be carried out to ascertain other performance characteristics. Further research may also be carried out to determine the on-field performance of the concept before full implementation/adoption is carried out.

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