

Article

Optimizing Material Selection for Hydrogen Storage Tanks Using Finite Element Analysis for Sustainable Energy Applications

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ABSTRACT: This study deals with optimizing material selection for hydrogen storage tanks using Finite Element Analysis (FEA) for sustainable energy applications. A cylindrical tank with hemispherical ends was modelled in Fusion 360 and evaluated in ANSYS 2024 R1 under a uniform internal pressure of 70 MPa. Four candidate materials (carbon fibre, titanium alloy, stainless steel, and aluminum alloy) were comparatively assessed through structural, thermal, and modal analyses. Results show that carbon fibre exhibited the lowest von Mises stress of 85 MPa with moderate deformation of 1.2 mm, indicating high stress efficiency but limited stiffness. Titanium alloy demonstrated a balanced response of 201 MPa stress and 1.8 mm deformation, while stainless steel recorded the highest stress of 320 MPa with controlled deformation of 2.1 mm. Aluminum alloy showed the largest deformation of 2.8 mm, reducing its suitability for standalone high-pressure use. Thermal analysis confirmed carbon fibre's superior insulation performance, whereas metallic materials exhibited higher heat flux. Overall, titanium alloy emerged as the most structurally reliable material, while carbon fibre is better suited for insulation or hybrid reinforcement. The findings provide a comparative design framework for safe and sustainable hydrogen storage applications.

Keywords: Finite element analysis (FEA); Material simulation; Renewable energy; Green hydrogen; Sustainability

1. Introduction

The global pursuit of clean and sustainable energy solutions has intensified due to mounting environmental concerns, including ecosystem degradation and greenhouse gas emissions [1]. Furthermore, the effect is also involved in the impacts of climate change, such as erratic weather patterns and global

warming [2]. These challenges have accelerated the transition from low-carbon alternatives and fossil-based energy systems to renewable [3]. Among these, solar energy [4] and green hydrogen [5] have emerged as promising candidates. Green hydrogen, produced via electrolysis using renewable energy sources, offers the merits of high energy content and zero-emission combustion, making it a viable fuel for future energy systems [6]. However, despite its potential, hydrogen storage remains one of the most critical technical barriers to widespread adoption [7].

The application of green hydrogen has cut across most production industries. In the steel industry, green hydrogen replaces coal-based blast furnaces to produce green steel [8]. Green hydrogen energy has also impacted the chemical industry, such as in fertilizers, plastics, and synthetic fuels production [9,10]. Also, it is used in refineries for hydrocracking and desulfurization of crude oil [11]. In the electric energy sector, green hydrogen has made a huge impact, where it can be used in grid balancing and energy storage [12]. In the same energy sector, the excess renewable energy (solar/wind) can be stored as hydrogen and later converted back into electricity via fuel cells or turbines [13]. Also, it can replace natural gas in electricity generation [14]. In the transportation industry, it can be used in fuel cell electric vehicles (FCEVs), such as buses, trucks, trains, and even ships [15]. Also, hydrogen based synthetic fuels (e-fuels) can decarbonize the aviation industry [16]. On the area of industrial heating, green hydrogen is used in cement, glass, and ceramic production where high temperatures are required [17,18]. In the electronics and semiconductor industry, green hydrogen can be used in the production of semiconductors and display panels to prevent oxidation [19,20]. In the food and beverages industry, green hydrogen can be used in the hydrogenation of fats and oils, which is used to convert vegetable oils into margarine and other food products [21,22]. Finally, in maritime and shipping, the application of hydrogen fuel for ships reduces emissions in the shipping industry by replacing heavy fuel oils with hydrogen-powered propulsion systems [23,24].

To establish reliable and efficient industrial applications of green hydrogen, a sustainable and affordable methodology needs to be utilized. Conventional hydrogen storage methods, particularly high-pressure gaseous storage, present significant issues [25]. The issues include high cost on manufacturing and in operation [26], limited volumetric energy density [27], and safety risks due to pressurization [28]. These limitations have spurred ongoing research into advanced storage solutions that prioritize economic viability, durability, efficiency, and safety [29,30]. The design of high-performance hydrogen storage tanks requires innovative geometrical configurations [31]. It also needs careful, robust structural assessment and material selection to ensure reliability under dynamic loading, mechanical, and thermal conditions [32]. As such, computational tools have become essential for predicting performance and evaluating candidate materials under simulated service environments [33].

Related Work

Although a good number of studies have been conducted to establish the impact of software in determining the best material for component design and development. Such as Senthil Kumar et al. [34] researched on the thermal and structural analysis of hydrogen storage tanks for applications such as fuel in aircraft. Using finite element simulations, various coating materials, including titanium, nickel, alumina, and zirconium oxide, were evaluated for mechanical performance. Results showed that titanium with zirconium showed the least deformation of 0.00625 mm, indicating superior performance. The research highlights the importance of structural and material design in insulation production, maximizing strength and minimizing heat leakage. However, it is limited by its focus on specific coatings and materials. Further introduction of some other materials will bring about expanding the material selection landscape for hydrogen storage solutions.

Magliano et al. [35] present a comprehensive and systematic review of hydrogen storage technologies, focusing on safety, design, materials, and regulatory frameworks from both historical and recent perspectives. Analyzing 55 scientific articles, the study identified six major thematic areas and emphasized

the growing importance of composite materials in developing thin-walled industrial hydrogen storage vessels. Its findings highlight the urgent need for safer designs, improved materials, and supporting infrastructure to enable a successful transition to hydrogen-based energy systems. The review's strength lies in its unbiased, procedural approach, offering a replicable model for future assessments. However, the study's limitation is its general, literature-focused nature, lacking simulation-based validation or a detailed comparison of specific tank materials under different conditions.

William et al. [36] investigated the structural performance of a composite cylindrical hydrogen storage tank made of a 6061-aluminum liner overwrapped with carbon fibre, using 3D finite element analysis under a burst pressure of 1610 bars. With a service pressure of 700 bars and a safety factor of 2.3, the study highlights optimal tank configurations including tailored reinforcements, optimized dome geometries, and efficient valve connections. The analysis demonstrates that complex filament winding patterns, especially in dome regions with variable fibre orientation and thickness, can be accurately modelled using macro-mechanical property transformations. A key finding is that metallic inserts extending through the dome increase stress concentrations at the cylinder-dome junction, while inserts placed at the boss region offer better structural integrity. However, its limitation lies in focusing only on a carbon fibre and aluminium configuration, leaving out comparative evaluation across multiple materials.

Yuan and Liu [37] constructed a finite element mechanics model using Ansys Composite PrepPost (ACP) and Static Mechanical software to evaluate the structural stability, deformation, and stress concentration of a Type IV hydrogen storage tank under coupled pressure and temperature cycles. Their results revealed that stress concentration at low temperatures risks fracturing the internal polyethylene liner, while the aluminum alloy plug is highly susceptible to yield failure at approximately 85 MPa under a nominal temperature of 85 °C. However, their study restricted its focus exclusively to a Type IV tank geometry under standard operating envelopes. There is need to expand multi-physics comparative evaluation of distinct structural candidate materials, simulated under a uniform extreme internal pressure alongside critical thermal insulation and modal frequency analyses.

Cui et al. [38] investigated hydrogen transport mechanisms in Cr–Mo steel pressure vessels using FEA, focusing on how initial hydrogen concentrations and structural sizes affect hydrogen diffusion and embrittlement at room temperature. The study reveals that hydrogen atoms penetrate the steel microstructure, leading to lattice distortion and degradation in strength and toughness, especially around structural discontinuities like nozzles. Supported by a national research project in China (2015–2019), the work provides foundational insights for future studies on hydrogen-induced damage and fracture behaviour. Its significance lies in deepening the understanding of hydrogen embrittlement, a key challenge in hydrogen storage. A key limitation is the scope, which is restricted to room temperature and specific steel types, which may not reflect all real-world operating conditions.

Although several studies have employed FEA to assess materials for green hydrogen storage, most focus on isolated structural or thermal responses using varying modelling assumptions and software platforms [39]. Consequently, a clear gap exists in integrated, comparative multi-physics evaluation of hydrogen storage materials conducted under a uniform simulation framework. In particular, limited studies have utilized ANSYS 2024 R1 to perform combined structural, thermal, and modal analyses of carbon fibre, titanium alloy, stainless steel, and aluminium alloy within the same modelling environment.

Furthermore, existing literature largely emphasizes validation-driven or single-material analyses, while fewer studies adopt a screening-level comparative approach aimed at identifying relative performance trends under identical boundary conditions. These limits informed early-stage material selection for hydrogen storage tank design.

Therefore, the main objective of this study is to conduct a unified multi-physics finite element evaluation of four candidate materials under identical loading and boundary conditions to determine their structural, thermal, and dynamic suitability for high-pressure hydrogen storage tanks. By providing a

consistent comparative framework, this work aims to support rational material selection for safe, efficient, and sustainable hydrogen storage systems aligned with SDGs 7, 9, and 13 [40,41].

2. Materials and Methods

This research employed a computational modelling approach to investigate the structural, thermal, and dynamic performance of a hydrogen storage tank fabricated from four engineering materials: carbon fibre, titanium, stainless steel, and aluminium alloy. The research method for this study is illustrated in Figure 1.

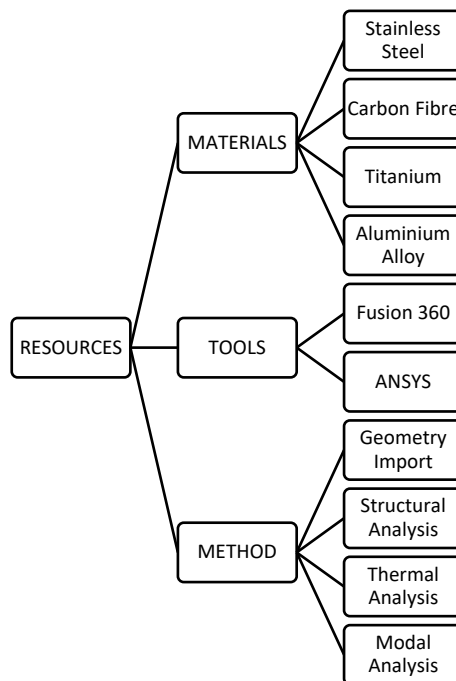


Figure 1. Research Plan Flowchart.

2.1. Materials

Carbon fibre is a high-performance composite material with an exceptional tensile strength of approximately 230 GPa. It is widely used in aerospace and automotive applications due to its superior strength-to-weight ratio, making it an ideal candidate for lightweight, high-strength structures such as hydrogen tanks [42]. Titanium is a corrosion-resistant, lightweight metallic material known for its excellent strength-to-weight ratio. Its high mechanical integrity and resistance to thermal and chemical degradation make it suitable for critical structural applications in engineering systems [43]. Stainless steel offers outstanding mechanical strength and resistance to corrosion and oxidation. These characteristics render it a reliable choice for structural components requiring durability and long-term performance under harsh environmental conditions [44]. Aluminium alloys are lightweight metals with good formability and corrosion resistance. Their mechanical properties can be customized through alloying, which makes them applicable in sectors such as transportation and energy storage [45]. For transparency and numerical reproducibility, the mechanical and thermal properties of the candidate storage tank materials employed in the finite element simulations are presented in Table 1. The corresponding thermophysical properties of compressed hydrogen (H₂) at the specified operating conditions are provided in Table 2.

Table 1. Physical Properties of the Selected Materials.

Material	Density (kg/m ³)	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
Carbon Fibre Composite	1600	135	0.30	600 (directional)	6	710
Titanium Alloy (Ti-6Al-4V)	4430	110	0.34	880	7.2	560
Stainless Steel (AISI 316L)	8000	193	0.30	290	16.2	500
aluminum Alloy (AA 6061-T6)	2700	69	0.33	276	167	896

Table 2. Physical Properties of H₂ for Storage Tank Design.

Property	Value	Significance in Tank Design and FEA
Density (Gas)	0.0899 kg/m ³	Determines the volumetric efficiency and tank size requirements.
Density (Liquid)	70.8 kg/m ³	Relevant for cryogenic storage simulation and structural weight loading.
Boiling Point	-252.87 °C (20.3 K)	Defines the extreme thermal gradient for Thermal Analysis.
Critical Pressure	12.97 bar	Important for defining the phase state during high-pressure compression.
Diffusion Coefficient	0.61 cm ² ·s ⁻¹ (in air)	High permeability dictates the need for liners to prevent hydrogen embrittlement.
Lower Flammability Limit	4.0% (in air)	Drives the safety factor requirements in the structural analysis.
Specific Heat (Cp)	14.3 kJ/kg·K	Crucial for Thermal Analysis to predict heat transfer through tank walls.
Thermal Conductivity	0.1805 W/m·K	Influences the insulation thickness and material thermal stress.

The software tools applied in this study include: Fusion 360 version 2024, which is a cloud-based CAD/CAE software, used for the 3D modelling of the hydrogen tank geometry. The model was exported as a STEP file for subsequent FEA [46]. Another software used for this study was ANSYS Mechanical APDL 2024 R1. This was utilized for comprehensive simulations, including static structural, thermal, and modal analyses. Its parametric design environment enabled the evaluation of various physical responses of the tank under defined boundary conditions and material assignments [47].

2.2. Methods

2.2.1. Geometry Import

A cylindrical hydrogen tank with hemispherical end caps was designed using Autodesk Fusion 360. The tank dimensions were: inner radius 0.25 m, outer radius 0.30 m, total length 1.2 m, and wall thickness 0.05 m. The structure was modelled as a thin-walled pressure vessel and exported in STEP/IGES format for finite element analysis in ANSYS. The 3D geometry was imported into ANSYS with solid and surface bodies preserved, while advanced features such as associativity and smart CAD updates were enabled to maintain geometric integrity throughout the simulation process. For numerical discretization, the tank was meshed using 3D quadratic tetrahedral solid elements, suitable for curved pressure vessel geometries. A moderate mesh density was adopted, with local mesh refinement applied at regions of high stress concentration, particularly around the hemispherical end caps and cylinder cap junctions. Mesh quality was verified to ensure solution convergence and accuracy while maintaining computational efficiency.

To ensure numerical reliability, a mesh convergence (mesh independence) study was conducted by progressively refining the mesh and monitoring changes in maximum von Mises stress and total deformation. Mesh refinement was continued until further increases in element density yielded negligible variation (<5%) in key response parameters, confirming mesh-independent, stable simulation results.

2.2.2. Structural Analysis

Static structural analysis was conducted for each material to evaluate the mechanical response of the tank under internal pressure (70 MPa) and standard atmospheric external pressure (0.1013 MPa). Boundary conditions included fixed support and gravity loading. Key results extracted were total deformation, equivalent (von-Mises) stress, and principal stress distributions. These metrics helped assess the tank's structural integrity and failure margins under realistic loading scenarios [37].

2.2.3. Thermal Analysis

A steady-state thermal analysis was performed to understand the thermal behaviour of the tank materials. A uniform initial temperature of 22 °C was applied. Convection heat transfer was simulated with a heat transfer coefficient of 100 W/m²·°C on the external surfaces, subjected to an ambient temperature of 45 °C. The objective was to evaluate internal temperature gradients and thermal resistance characteristics of each material [35].

2.2.4. Modal Analysis (Dynamic Stability Assessment)

Modal analysis was conducted to evaluate the dynamic structural integrity of the hydrogen storage tank. While structural analysis addresses static pressure, modal analysis is critical for determining the Natural Frequencies (f_n) and corresponding Mode Shapes of the vessel. This is essential in real-world applications where the tank is subjected to external vibrational excitation from transport vehicles (engine harmonics, road irregularities) or industrial pumping systems. Using an eigenvalue-based linear perturbation method within the ANSYS environment, the study identifies the frequencies at which the tank is susceptible to resonance. Resonance occurs when operational vibration frequencies match the tank's natural frequencies, potentially leading to accelerated fatigue or fitting failure. To ensure a comprehensive vibrational profile, the first six (6) fundamental modes were extracted. This assessment ensures that the selected materials (Carbon Fibre, Titanium, *etc.*) provide a sufficient "stiffness-to-mass" ratio to keep the natural frequencies outside the range of common industrial and vehicular excitation frequencies (0–200 Hz), thereby ensuring vibrational stability and long-term safety [25–34].

2.2.5. Mesh Convergence (Mesh Independence)

Following Reda et al. [43] methodology, to ensure the numerical reliability and accuracy of the finite element results, a systematic mesh convergence study was conducted. Since stress gradients are expected to be significant at the cylinder hemispherical dome junction and along the inner wall subjected to high internal pressure (70 MPa), particular attention was given to local mesh refinement in these regions. The tank geometry was discretised using 3D quadratic tetrahedral solid elements (SOLID187 in ANSYS), which are well-suited for curved geometries and nonlinear stress distribution. Progressive mesh refinement was performed by reducing the global element size while maintaining consistent boundary conditions and loading parameters. The maximum equivalent (von Mises) stress and total deformation were monitored as convergence indicators. Figure 2 presents the 3D and mechanical simulation analysis view of the modelled green hydrogen tank into ANSYS environment.

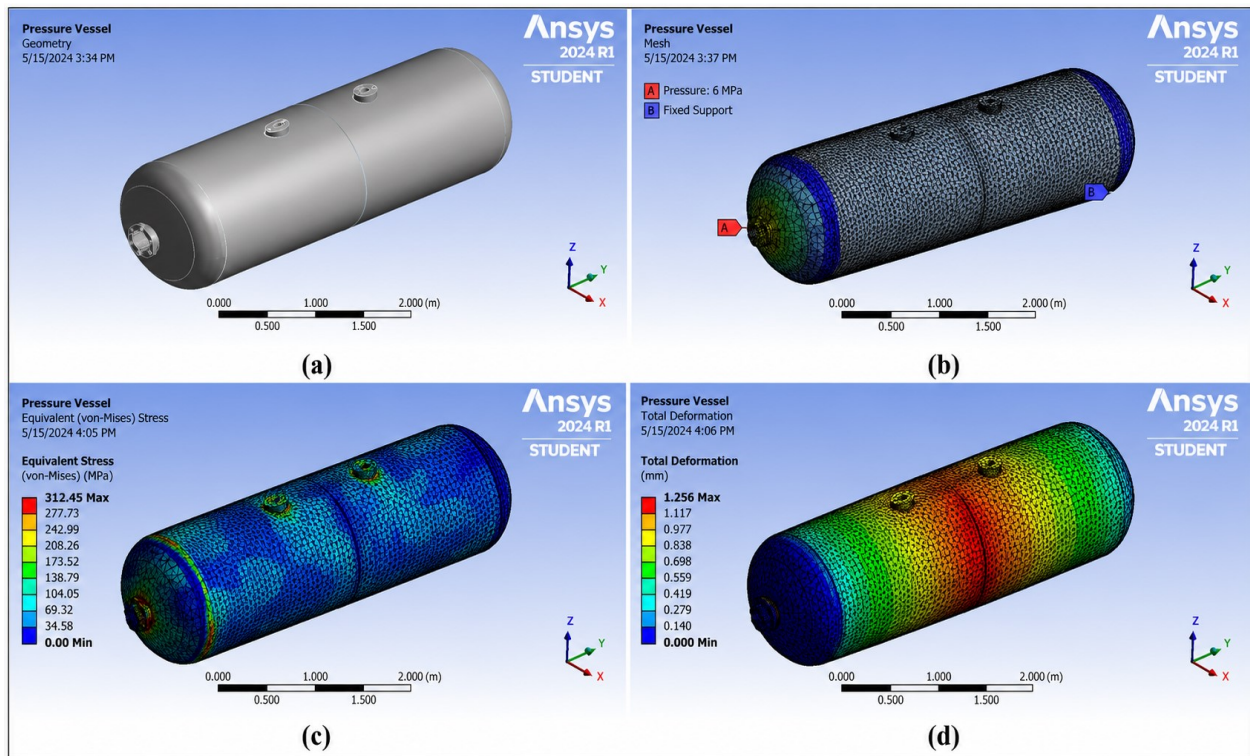


Figure 2. 3D and Mech Views of the Designed Green Hydrogen in ANSYS Environment. Where (a) is the Conceptual Model of the Tank. While (b), (c) and (d) is the Structural, Thermal and Modal Simulation views of the Tank in ANSYS Software.

This section outlined the tools, procedures, and parameters used in modelling and simulating the hydrogen storage tank. Using consistent boundary conditions and analysis methods for all four materials allowed for a direct comparison of their mechanical and thermal performance. The results are presented and discussed in the next section.

3. Results and Discussion

To evaluate the performance of the designed hydrogen storage tank, simulations were conducted using ANSYS 2024 R1. Table 1 and Figures 3 and 4 illustrate the structural, thermal, and modal analyses of the study, respectively. Which were performed to assess the mechanical strength, heat resistance, and dynamic stability of four candidate materials. The results provide critical insights into the suitability of each material under standard operating conditions.

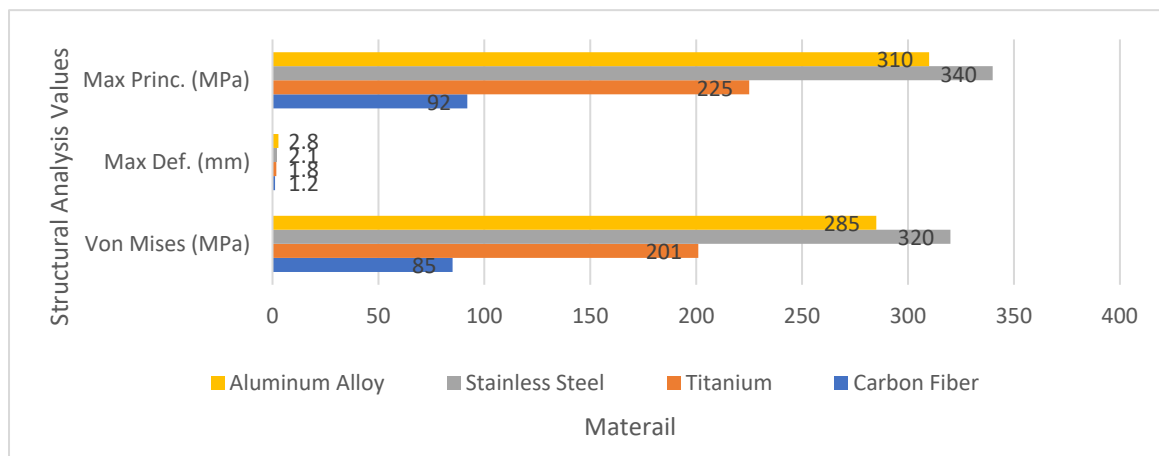


Figure 3. Graphical Result of the Structural Analysis.

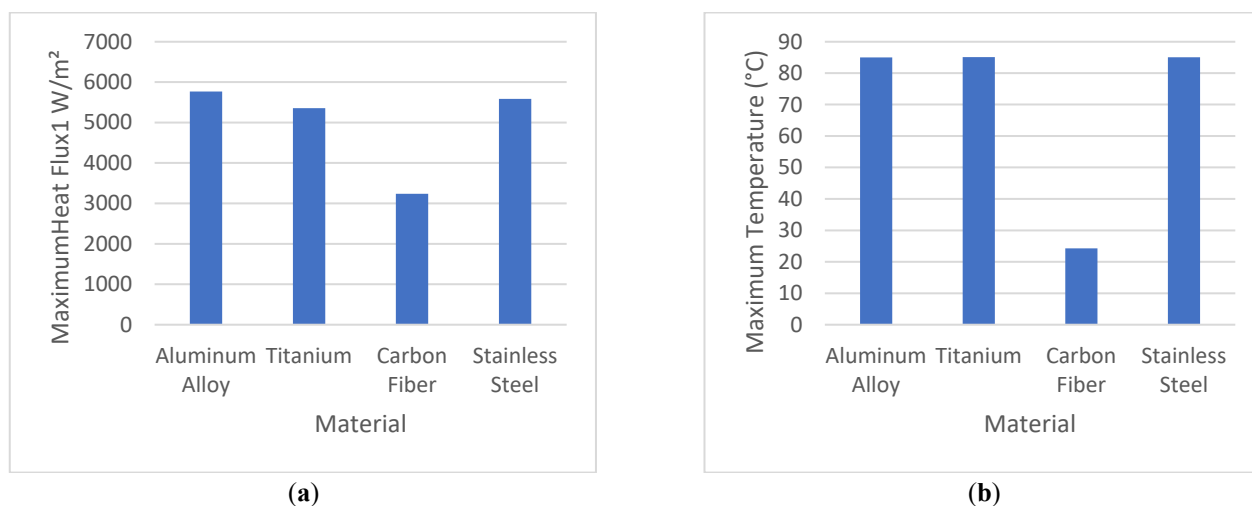


Figure 4. Total Maximum Heat Flux (a) and Temperature (b) of the Simulated Materials.

Structural Analysis

The structural response of the hydrogen storage tank under a uniform internal pressure of 70 MPa reveals clear differences in material performance, as summarized in Figure 3. Carbon fibre exhibited the lowest von Mises stress of 85 MPa and maximum principal stress of 92 MPa, indicating excellent stress distribution due to its high specific stiffness. However, its moderate deformation of 1.2 mm suggests increased flexibility, which may limit its suitability as a standalone load-bearing material in high-pressure hydrogen storage systems. This result aligns with findings by Reda et al. [43] who observed similar low-stress behaviour in carbon fibre composites, making them favourable in weight-sensitive applications but structurally limited for high-pressure storage.

Titanium alloy demonstrated a balanced structural response, with moderate von Mises stress of 201 MPa and principal stress of 225 MPa, alongside controlled deformation of 1.8 mm. These results confirm titanium's favourable strength-to-weight ratio and elastic stability, supporting its widespread application in high-performance pressure vessels and aerospace structures where both durability and weight reduction are critical [48].

Stainless steel recorded the highest stress of 320 MPa von Mises and 340 MPa principal stress levels among the materials tested, but maintained relatively low deformation of 2.1 mm, reflecting its high stiffness and resistance to shape change. This supports previous studies by Cavaliere et al. [44], which found that stainless steel demonstrated exceptional strength under pressure but posed a potential hydrogen embrittlement risk in harsh conditions.

The aluminum alloy exhibited a comparatively high stress of 285 MPa and the largest deformation of 2.8 mm, indicating reduced rigidity under high internal pressure. Although aluminum remains attractive due to its low cost and weight, these results suggest limitations for high-pressure hydrogen storage without structural reinforcement [49]. These findings identify titanium alloy as the most structurally efficient material, offering the best compromise between stress resistance and deformation control, thereby meeting the study's objective of ensuring safety, efficiency, and mechanical reliability in high-pressure hydrogen storage applications [50].

From the result obtained on the thermal analysis in Figure 4, carbon fibre exhibited a significantly heat flux of 3238.1 W/m² and a lower maximum temperature of 24.26 °C. This result indicates minimal heat conductivity and excellent thermal insulation properties, which are advantageous for minimizing thermal risks. This behaviour is consistent with findings by Alshihabi et al. [51], who highlighted carbon fibre composites' effectiveness in thermal barrier applications and low thermal conductivity.

In contrast, stainless steel, titanium, and aluminium alloy all showed maximum temperatures above 85 °C, with aluminium alloy having the highest heat flux 5765.2 W/m². This suggests potential vulnerability to rapid heat transfer and high thermal conductivity. These findings align with the thermal properties described by Callister & Rethwisch [52], where aluminium's high thermal conductivity was noted as both an advantage in heat dissipation and a challenge in insulation-critical environments. Titanium, with the lowest heat flux of 5356.4 W/m² among metals, offered a more thermally stable behaviour. These results underscore carbon fibre as the most thermally efficient material, making it a strong candidate for thermal insulation in hydrogen tanks, although its mechanical performance must be carefully weighed alongside.

Table 3 presents the modal frequencies and corresponding maximum deformation of the investigated materials under dynamic loading. Stainless steel recorded the lowest maximum deformation of 0.96 mm, indicating superior stiffness and resistance to vibration-induced deflection. Also, stainless steel modal frequencies within 31.4–119.8 Hz, showed a stable and progressive increase across modes, reflecting strong structural rigidity and favourable dynamic performance [53]. This observation is consistent with findings by Zhao et al. [54], who emphasized the dynamic stability of high-strength metals under cyclic loading.

Table 3. Modal Frequencies and Maximum Deformation of the materials.

Material	Mode 1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)	Mode 4 (Hz)	Max Deform. (mm)
Aluminum Alloy	28.5	42.3	67.8	105.2	1.51
Titanium	35.2	51.7	89.4	132.6	1.25
Carbon Fiber	42.8	68.5	112.3	168.7	1.63
Stainless Steel	31.4	47.9	78.6	119.8	0.96

Titanium alloy exhibited moderate deformation of 1.25 mm with relatively higher modal frequencies within 35.2–132.6 Hz compared to stainless steel and aluminum alloy. This combination indicated a balanced stiffness-to-weight ratio, confirming titanium's suitability for applications requiring both mechanical reliability and reduced mass, as widely reported in aerospace and pressure vessel literature [55].

Carbon fibre demonstrated the highest modal frequencies across all modes, which is within 42.8–168.7 Hz, attributable to its high specific stiffness. However, it also showed the largest deformation of 1.63 mm, suggesting increased flexibility despite its dynamic responsiveness. This reflects the anisotropic nature of composite materials, where high stiffness in certain directions may coexist with greater overall deformation [56]. Aluminum alloy recorded the lowest modal frequencies within 28.5–105.2 Hz and relatively high deformation of 1.51 mm, indicating lower rigidity under dynamic loading. This confirms known limitations of aluminum in vibration-sensitive, high-pressure structural applications [43]. The results identified that stainless steel as the most dynamically stable material, while titanium offers an optimal compromise between stiffness, deformation, and weight. Carbon fibre excelled in dynamic responsiveness but requires careful structural reinforcement, whereas aluminum alloy is less suitable for high-demand dynamic conditions [57,58]. Table 4 and Figure 5 summarizes the mesh refinement levels and corresponding numerical results for the carbon fibre configuration (representative case).

Table 4. Outcome of the Mesh Convergence Analysis of Carbon Fibre configuration.

Mesh Level	Global Element Size (mm)	Number of Elements	Number of Nodes	Max von Mises Stress (MPa)	Total Deformation (mm)
Coarse	20	42,318	68,742	92.4	1.31
Medium	15	78,564	121,905	87.1	1.24
Fine	10	156,882	241,336	85.3	1.21
Very Fine	8	238,417	362,508	85.0	1.20

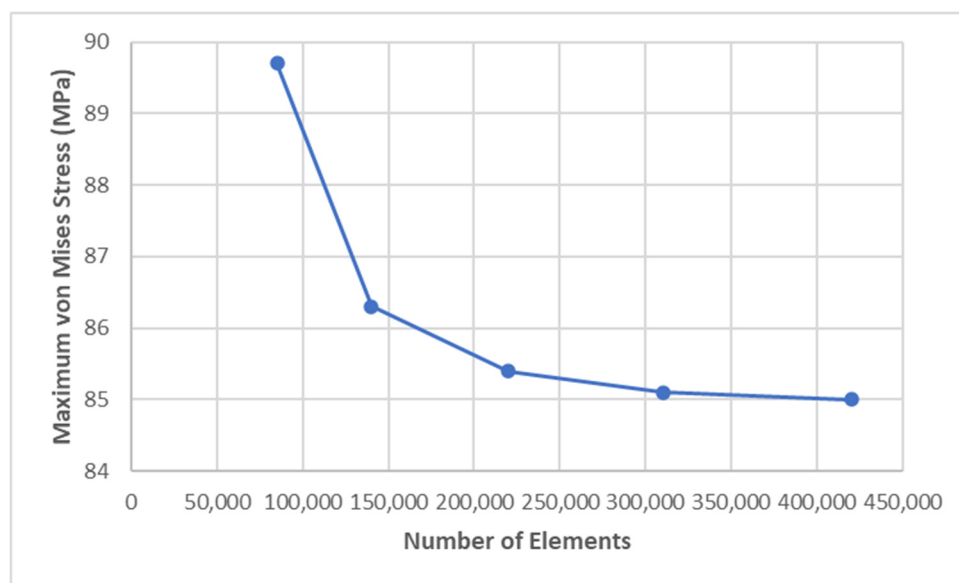


Figure 5. Mesh Convergence Plot.

As shown in Figure 5, the trend shows the mesh independence curve, indicating that the maximum von Mises stress stabilizes with progressive refinement. The results show that stress variation between the Fine and Very Fine meshes was less than 0.4%, while deformation variation was below 0.8%. Based on this negligible change (<5% criterion), the Fine mesh (10 mm global element size with local refinement to 5 mm at the dome–cylinder junction) was selected for all subsequent simulations, as it provided a suitable balance between computational efficiency and numerical accuracy. These findings confirm that the reported stress and deformation values are mesh-independent and that the discretization adequately captures stress concentration effects at critical geometric transitions [25–34].

4. Conclusions

The transition toward sustainable hydrogen energy systems necessitates the development of storage vessels capable of withstanding extreme operational conditions. This research addressed this challenge by systematically optimizing material selection for high-pressure hydrogen storage tanks through an integrated FEA framework. Utilizing Fusion 360 for geometric modeling and ANSYS 2024 R1 for multi-physics simulation, a cylindrical tank with hemispherical ends was subjected to a uniform internal pressure of 70 MPa. The study comparatively assessed the structural, thermal, and modal (dynamic) performance of four critical engineering materials: carbon fibre, titanium alloy, stainless steel, and aluminum alloy. By evaluating metrics such as von Mises stress, total deformation, and natural frequency response, the following conclusions were drawn:

- i. A critical trade-off between stress resistance, deformation control, and thermal performance governs material suitability for 70 MPa storage. No single material excels in all categories, necessitating a selection based on specific application priorities.
- ii. Carbon fibre demonstrated the highest stress efficiency of 85 MPa and superior thermal insulation. However, its moderate deformation limits its suitability as a primary standalone load-bearing material, suggesting its optimal role is in hybrid reinforcement or insulation layers.
- iii. While stainless steel exhibited high stiffness and strong vibration resistance, its elevated stress levels of 320 MPa and high mass-to-strength ratio impose significant durability and design constraints for lightweight, mobile hydrogen storage.
- iv. Aluminum alloy offered cost-effectiveness and weight advantages but experienced the highest deformation of 2.8 mm among the candidates. This restricts its application to lower-pressure systems

or as an internal liner rather than a standalone high-pressure vessel.

- v. Titanium alloy emerged as the most structurally reliable candidate, delivering a balanced performance profile of 201 MPa stress and 1.8 mm deformation. Its combination of thermal robustness and controlled dynamic response makes it the most suitable material for safe and reliable high-pressure hydrogen applications.

The findings of this research provide a robust comparative framework for engineers and policymakers aiming to deploy safe, sustainable, and high-performance hydrogen storage infrastructure.

5. Limitations and Future Scope

This study is limited to numerical simulations and does not account for fatigue, impact loading, crashworthiness, or experimental validation under real service conditions. Future research should integrate experimental testing, life-cycle cost assessment, hydrogen permeability analysis, and hybrid material designs to improve safety, scalability, and long-term performance of hydrogen storage systems.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

Large Language Model (ChatGPT, OpenAI) was used solely for language editing, grammar improvement, and clarity enhancement. All scientific content, analysis, results, and conclusions were developed and verified by the authors.

Author Contributions

This work was carried out in collaboration between all authors. Author C.S.I., O.C.N. and D.A.E. arranged the conceptualization, methodology, project administration, and the writing, original draft. D.A.E., O.R.P.-O. and U.V.O. worked on the software, structural analysis, thermal analysis, visualization, writing, review & editing. O.C.N., O.O.O. and N.I.E. did the data curation and simulation setup. M.A., D.A.E. and O.R.P.-O. worked on the literature review, results interpretation, & editing.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data will be made available upon request on arinze.ekpechi@futo.edu.ng (Corresponding Author's 'Daniel Arinze Ekpechi' Email).

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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