DESIGN AND ANALYSIS OF CARBON FIBER REINFORCED PRESSURE VESSELS

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Abstract

This study presents a comprehensive investigation into the structural design and mechanical performance of carbon fiber-reinforced pressure vessels, which have become increasingly prominent in high performance engineering sectors due to their outstanding strength to weight ratio. The research primarily explores the effects of varying composite winding angles - specifically 30°, 45°, and 75°- along with different layer thickness configurations on the vessels' structural behaviour. These variables were examined through finite element analysis in terms of stress distribution, deformation response, and failure susceptibility under internal loading conditions. The von Mises stress analysis indicated that the configuration with a 75° winding angle exhibits the lowest stress concentration among all tested cases. This suggests that the 75° angle is the most structurally favourable, contributing to enhanced mechanical safety and durability. To further evaluate the failure behaviour, the study employed the Tsai-Hill, Tsai-Wu, and Maximum Stress failure criteria. These established composite failure theories were utilized to determine the optimal set of design parameters that would minimize the likelihood of structural failure. Moreover, the investigation extended to a comparative analysis of titanium and composite layer thickness combinations. The results revealed that layer thickness significantly influences not only the stress levels but also the displacement characteristics of the structure. Accordingly, the study proposes optimized thickness configurations that improve structural performance while maintaining safety margins. In conclusion, the findings confirm that carbon fiber-reinforced pressure vessels offer considerable advantages over traditional metal vessels, particularly in applications where weight reduction and mechanical efficiency are critical. The insights derived from this study contribute valuable knowledge toward the design of advanced, lightweight, and structurally reliable composite pressure vessels.

Keywords: Carbon fiber, pressure vessel, filament winding, composite materials

JEL Kodu: D24, L64, L60, L70

INTRODUCTION

Pressure vessels are engineering structures that safely store gases and liquids under high pressure. They are critical in various industries, including energy, chemicals, aerospace, food, and pharmaceuticals. Pressure vessels are designed using diverse materials and manufacturing techniques to ensure durable and safe operation in environments requiring high pressure and temperature (Fryer et al., 1998; Santos et al., 2025). Depending on the material utilized and the production method applied, pressure vessels are classified into four primary groups. These four types of pressure vessels, based on their structural properties, are presented in Table 1 (Yarrapragada, Mohan, & Kiran, n.d.).

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Table 1: Types of Pressure Vessels with Structural Details

Type-1	Type-2	Type-3	Type-4
All metal steel or aluminum	Stell or aluminum liner Composite material helical winding	Stell or aluminum liner Composite material full winding	Polymer Liner Composite material full winding

Type I vessels are entirely manufactured from metal (steel or aluminium) and represent the most straightforward and most economical model; however, due to their weight, they are primarily preferred for stationary applications (Barral & Barthélémy, 2006; Barthelemy et al., 2017). Type II vessels are reinforced by winding carbon fiber or glass fiber over a metal body, making them lighter and more resistant to high pressures than Type I vessels (Barthelemy et al., 2017). Type III vessels are produced by ultimately winding carbon fiber material over a metal liner and are widely used in the automotive industry (Zhang et al., 2015). Type IV vessels, representing the lightest design, are manufactured by fully winding carbon fiber material over a polymeric liner and are particularly preferred for applications such as hydrogen storage (Mori & Hirose, 2009).

Pressure vessels are utilized in various sectors: in the energy industry for steam boilers and nuclear reactors, in the chemical industry for chemical storage and separation processes, in the food industry for pasteurization and sterilization, and in the aerospace industry for fuel and gas storage (Tinita Engineering. (n.d.). The production of pressure vessels must be carried out following international standards, taking into account material properties and durability. In Turkey, standards such as ASME Sec. VIII Div 1 and EN 13445 are commonly applied (Aveskon, n.d.). In addition to traditional metal processing methods, the filament winding technique is a modern method employed to manufacture lightweight and durable vessels by winding carbon fiber materials at specific angles (Boon et al., 2018; Pandita et al., 2013).

This study investigated the design and analysis of carbon fiber-reinforced pressure vessels. It analyzed the effects of different winding angles and layer thicknesses on vessel strength to determine the optimal design parameters. Carbon fiber materials' superior strength-to-weight ratio compared to conventional metals provides a significant advantage in enhancing pressure vessels' performance.

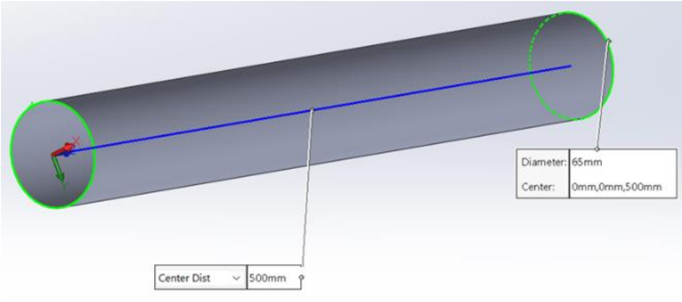
MATERIALS AND METHODS

The materials commonly used in the design of pressure vessels include titanium, steel, and carbon fiber composites. Titanium, due to its light weight and high strength, is particularly preferred in the aerospace and automotive industries (Elshaer & Ibrahim, 2022). Being 45% lighter than steel, titanium also offers high temperature resistance and corrosion durability, providing advantages in critical applications (Besisa & Yajima, 2024). On the other hand, carbon fiber-reinforced composite materials, although significantly lighter, offer five times the strength and twice the stiffness compared to steel (Khatib et al., 2024). These properties make composites more advantageous than traditional metal vessels.

In recent years, filament winding technology has been widely used in the production of pressure vessels. This method increases the strength of the vessels by winding composite materials at specific angles (Azeem et al., 2022). Filament winding is performed using three main techniques: polar, helical, and circumferential. In polar winding, fibers are placed along the axial length, while in helical winding, fibers are wound at angles ranging from 5° to 80°. Circumferential winding, wound at an approximately 90° angle, provides the highest strength. The winding angles significantly impact the mechanical strength of the vessels, and detailed analyses are carried out to determine the optimal angle. Therefore, to determine the optimal winding angle and layer thickness, pressure vessels' structural safety and durability are evaluated based on stress distribution, displacement, and damage criteria across different winding angles and layer thicknesses.

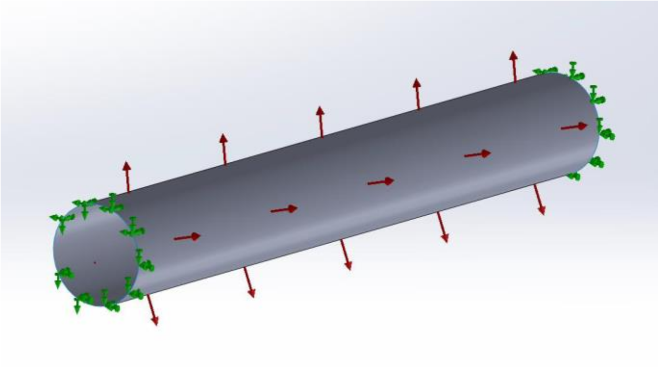
In Figure 1, a pipe liner has been designed according to the given dimensions, and a mandrel has been created for the pressure vessel.

Figure 1: Pressure Vessel Pipe Liner Dimensions.



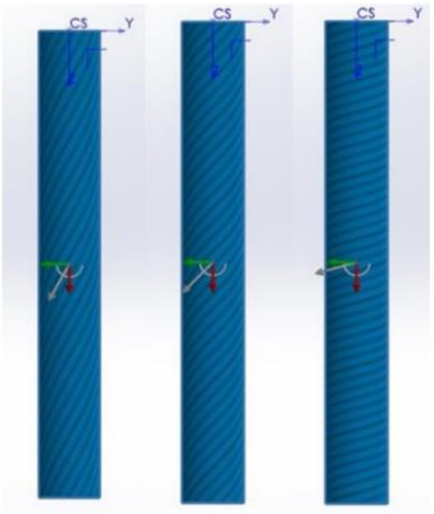
As shown in Figure 2, 38 MPa was applied to the mandrel, and both ends of the vessel were fixed to prevent movement along three axes.

Figure 2 The Pressure and Constraints Applied to the Pipe Liner.



In the first stage, carbon fiber material was wound over a titanium liner with a winding angle of 30/90/-30/90 degrees, resulting in four layers. Then, three different winding angles 45/90/-45/90 degrees and 75/90/-75/90 degrees were examined. Figure 3 shows the visual representation of these winding angles.

Figure 3: (+, -) 30°, 45°, 75° Winding Angles.



30° winding angles 45° winding angles 75° winding angles

The titanium material used as the liner layer was selected as the Ti-3Al-8V-6Cr-4Mo-4Zr (MATWEB, 2025) titanium alloy available in the SolidWorks software. Table 2 provides the mechanical and structural properties of this material.

Table 2 Structural Properties Of The Titanium Alloy

Property	Value	Units
Elastic Modulus	104000,0002	N/mm^2
Poisson' Ratio	0,33	N/A
Shear Modulus	3999,99994	N/mm^2
Mass Density	4820,000081	kg/m^3
Tensile Strength	1220,0	N/mm^2
Compressive Strength	1089,999972	N/mm^2
Yield Strength	1034,213594	N/mm^2
Coefficient of Thermal Expansion	8,00E-06	1/K
Thermal Conductivity	6,2	W/(m.K)
Specific Heat	515,0	K/(kg.K)

Note: (MATWEB, 2025)

During the study, two different sets of data for carbon fiber material were examined. Firstly, the structural properties of the material, referred to as Composite, are shown in Table 3. The relevant data was obtained from previous studies (Solazzi & Buffoli, 2021).

Table 3: Structural Properties of the Composite Material.

Property	Value	Units
Elastic Modulus X	134000,0	N/mm^2
Elastic Modulus Y	7000,0	N/mm^2
Elastic Modulus Z	0,0	N/mm^2
Poisson' Ratio in XY	0,0	N/A
Poisson' Ratio in YZ	0,25	N/A
Poisson' Ratio in XZ	0,013	N/A
Shear Modulus in XY	0,0	N/mm^2
Shear Modulus in YZ	4200,0	N/mm^2
Shear Modulus in XZ	4200,0	N/mm^2
Mass Density	1530,0	kg/m^3
Tensile Strength in X	1270,0	N/mm^2
Tensile Strength in Y	42,0	N/mm^2
Compressive Strength in X	1130,0	N/mm^2

Compressive Strength in Y	141,0	N/mm^2
Shear Strength in XY	63,0	N/mm^2
Yield Strength	1270,0	N/mm^2

***Note**: (Solazzi & Buffoli, 2021)*

Secondly, the Epoxy Carbon UD (unidirectional) (230 GPa) material was selected from the ANSYS program, and its structural properties are presented in Table 4. The analyses conducted on these different materials aim to determine the optimal material and design parameters to enhance the mechanical strength of the pressure vessels.

Table 4: Structural Properties of Epoxy Carbon UD (230 Gpa) Material.

Property	Value	Units
Elastic Modulus X	121000	N/mm^2
Elastic Modulus Y	8600	N/mm^2
Elastic Modulus Z	0	N/mm^2
Poisson’ Ratio in XY	0	N/A
Poisson’ Ratio in YZ	0,4	N/A
Poisson’ Ratio in XZ	0,27	N/A
Shear Modulus in XY	0	N/mm^2
Shear Modulus in YZ	3100,0	N/mm^2
Shear Modulus in XZ	4700,0	N/mm^2
Mass Density	1490,0	kg/m^3
Tensile Strength in X	2231,0	N/mm^2
Tensile Strength in Y	29,0	N/mm^2
Compressive Strength in X	1089,0	N/mm^2
Compressive Strength in Y	100,0	N/mm^2
Shear Strength in XY	60,0	N/mm^2
Yield Strength	2231,0	N/mm^2

RESULT AND DISCUSSION

The analysis results show that the von-Mises stress distributions on the titanium layer for both Composite and Epoxy Carbon materials vary depending on the winding angle. As shown in Figure 4, at the 30°/90°/(-30°)/90° angle configuration, the composite material more effectively absorbed the stress in the titanium layer, resulting in a lower stress value. As shown in Figure 5, Epoxy Carbon attained a relatively higher stress value in comparison. At the 45°/90°/-45°/90° angle configuration, the Composite material provided a more balanced stress distribution, while Epoxy Carbon reached a higher stress value in comparison. At the 75°/90°/-75°/90° angle, the lowest stress values were observed, making this angle the most advantageous option in terms of structural safety. The results emphasize the critical impact of the winding angle on material strength and demonstrate that the Epoxy Carbon material offers a suitable alternative for applications requiring homogeneous stress distribution and high strength

Figure 4 von-Mises Analysis Results for Composite Material, Ply-1.

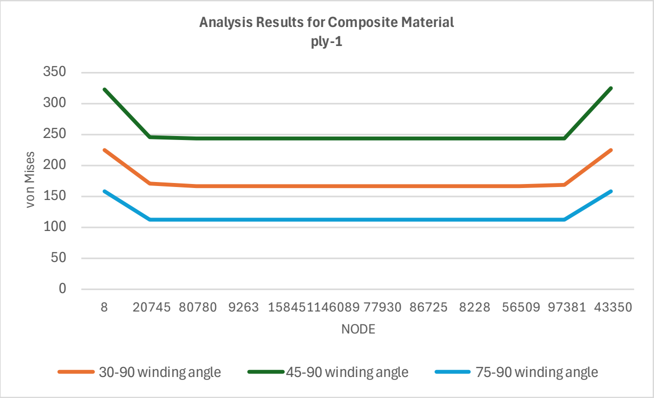
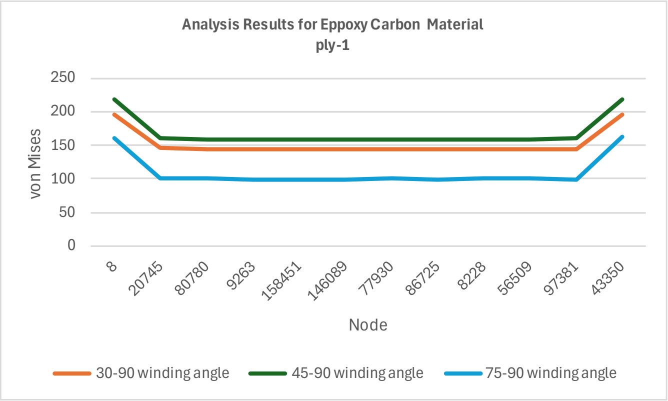


Figure 5 von-Mises Analysis Results for Epoxy Carbon Material, Ply-1.



The analysis results presented in Figures 6 and 7 indicate that the von Mises stress distributions in the top layer of the Composite and Epoxy Carbon materials vary depending on the winding angle. At the 30°/90°/-30°/90° and 45°/90°/-45°/90° angles, a more balanced value was observed for the Composite material. At the 75°/90°/-75°/90° angle, the lowest stress values were obtained, making this angle the most advantageous option in terms of safety. Furthermore, the Composite material is more beneficial in terms of these values. The results emphasize the critical impact of the winding angle on material strength.

Figure 6 von-Mises Analysis Results for the Composite Material, ply-5

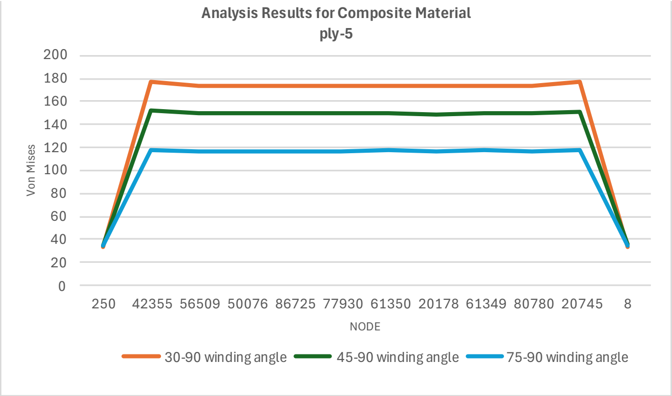
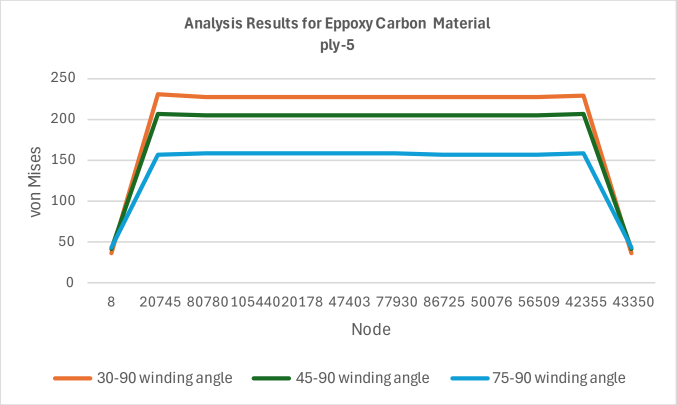


Figure 7 von-Mises Analysis Results for Epoxy Carbon Material, Ply-5.



The analysis results compare the displacement distributions of Composite and Epoxy Carbon materials based on different winding angles. As presented in Table 5, the displacement values varied for both materials depending on the winding angles. At the 30°/90°/-30°/90° winding angle, the displacement value for both materials was calculated to be 0.6 mm, indicating that both materials exhibit similar deformation behaviour at this angle combination. At the 45°/90°/-45°/90° winding angle, the displacement values decreased slightly for both materials, showing a more balanced distribution. This angle resulted in a structure that reduced the deformation level. At the 75°/90°/-75°/90° winding angle, the displacement values reached their minimum level. This shows that the 75° winding angle provides the lowest displacement values for both materials, enhancing their resistance to deformation.

Table 5 Displacement Analysis Results.

Displacement	**30° Winding Angle**	**45° Winding Angle**	**75° Winding Angle**
Composite Material	0,06 mm	0,05 mm	0,04 mm
Epoxy Carbon Material	0,06 mm	0,05 mm	0,04 mm

The Tsai-Hill, Tsai-Wu, and Maximum Stress (Max-Stress) criteria for damage prediction in composite materials were evaluated under different winding angles. The Tsai-Hill criterion predicts initial damage nonlinearly, while Tsai-Wu considers tensile and compressive loads for a more detailed analysis. The Maximum Stress criterion is the simplest method.

According to the damage analysis results presented in Table 6, the safety factor is low at a 30° winding angle, and damage risk is higher. At 45°, the safety factor is more balanced, increasing the material's load-bearing capacity. At 75°, the highest safety factors are achieved, offering the most durable structure. The Tsai-Wu criterion provides a broad safety range, while the Maximum Stress criterion gives the highest safety level.

Table 6 Damage criterion analysis results.

	30° Winding Angle		**45° Winding Angle**		**75° Winding Angle**	
	Composite Material	**Epoxy Carbon Material**	**Composite Material**	**Epoxy Carbon Material**	**Composite Material**	**Epoxy Carbon Material**
Tsai-Hill (worst)	3,80	2,30	4,10	3,10	4,40	2,80
Tsai-Wu (worst)	3,80	2,30	4,60	3,30	4,50	2,90
FOS max Stress (worst)	4,10	2,60	4,40	3,60	4,60	2,90

In the scope of design optimization, the 75° winding angle was chosen, and improvements were made in terms of cost and strength. In the first scenario, the titanium layer was kept constant, and the carbon fiber layer thickness was set to 1 mm. In the second scenario, the titanium layer was reduced to 1 mm, and the carbon fiber layer thickness was set to 2 mm. The effects of these modifications were analysed and based on the analysis results presented in Figure 8 and Figure 9, optimal design recommendations were proposed.

Figure 8 Von-Mises Result for Ply-1

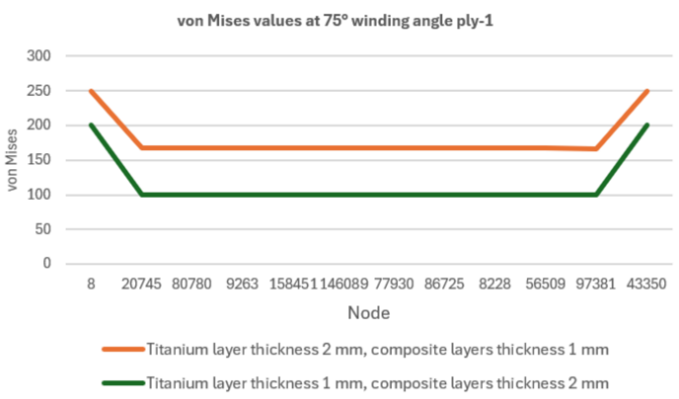
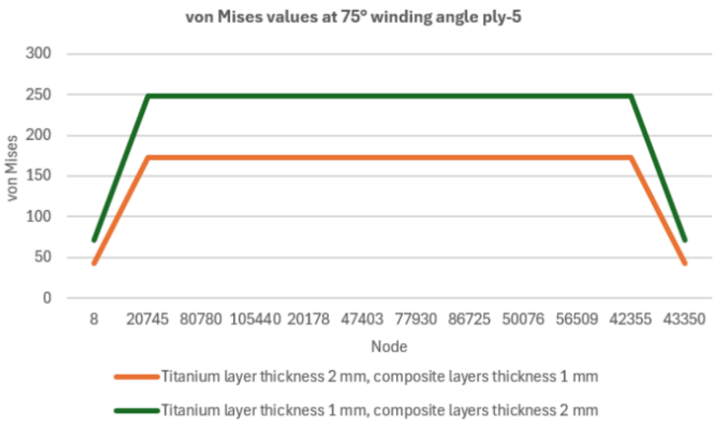


Figure 9 Von-Mises Result for Ply-5



The results of the optimization analysis show that the thicknesses of the titanium and composite layers significantly impact the stress, displacement, and damage criteria. When the titanium layer is 2 mm and the composite layers are 1 mm, the von Mises stress values are calculated to be 187.2 MPa on the titanium and 214.1 MPa on the top layer. The displacement is 0.06 mm, and the Tsai-Hill and Tsai-Wu criteria are 2.3 and 2.3, respectively. In this scenario, the stress on the titanium is low, while the stress in the composite layers is higher.

When the titanium layer is reduced to 1 mm and the composite layers are increased to 2 mm, the von Mises stress on the top layer decreases to 134 MPa, while the stress on the titanium increases to 247.6

MPa. The displacement reduces to 0.04 mm, and the Tsai-Hill and Tsai-Wu criteria are considered 4.2 and 4.3, respectively.

As shown in Table 7, the results indicate that layer thicknesses have a direct impact on stress distribution and damage risk. A thicker titanium layer increases deformation while decreasing safety factors, whereas a thinner titanium layer reduces deformation but increases stress on the titanium. This highlights the critical nature of selecting the optimal layer thickness based on the specific application.

Table 7 Damage Criterion Analysis Results.

	75° Winding Angle	
	Titanium Layer Thickness 2 mm, Composite Layers Thickness 1 mm	**Titanium Layer Thickness 1 mm, Composite Layers Thickness 2 mm**
Displacement	0,06 mm	0,04 mm
Tsai-Hill (worst)	4,40	2,80
Tsai-Wu (worst)	4,50	2,90
FOS max Stress (worst)	4,60	2,90

CONCLUSION

The current study aimed to improve the strength of pressure vessels, commonly used in various fields from aerospace to automotive industries, by using composite materials instead of traditional steel materials. In this context, finite element analyses were conducted using the SolidWorks software to evaluate design types with different winding angles and layer thicknesses of composite materials. Static analysis was performed in SolidWorks software, where composite layers were defined over a titanium liner, and under fluid pressure, stress, strain, and safety factors were obtained. The advantages and disadvantages of the pressure vessels designed with these configurations were then assessed. In evaluating the results, in addition to the values in the previous study, two separate evaluations were made according to different composite strength values (Guler & Genc, 2025). In addition, this study includes the results obtained by reducing the thickness of titanium and composite materials.

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Author Contributions

All authors contributed equally to all stages of this study, including conceptualization, data collection, analysis, writing, and final revision. All authors have read and approved the final manuscript.

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Ethical Approval Statement

This study was conducted in accordance with ethical standards and does not require ethical approval as it does not involve human or animal subjects.

Conflict of Interest Statement

The authors declare that there are no financial or personal conflicts of interest related to this study.

REFERENCES

Aveskon. (n.d.). Welded manufacturing in pressure vessels. Retrieved April 5, 2025, from https://www.aveskon.com

Azeem, M., Ya, H. H., Alam, M. A., Kumar, M., Stabla, P., Smolnicki, M., Gemi, L., Khan, R., Ahmed, T., Ma, Q., Sadique, M. R., Mokhtar, A. A., & Mustapha, M. (2022). Application of Filament Winding Technology in Composite Pressure Vessels and Challenges: A Review. *Journal of Energy Storage*, *49*, 103468. https://doi.org/https://doi.org/10.1016/j.est.2021.103468

Barral, K., & Barthélémy, H. (2006). Hydrogen high pressure tanks storages: overview and new trends due to H2 Energy specifications and constraints. *June*. https://www.cder.dz/A2H2/Medias/Download/Proc%20PDF/PARALLEL%20SESSIONS/%5BS12%5D%20Storage%20-%20Gaseous%20Hydrogen/15-06-06/331.pdf*[S12], 20*.

Barthelemy, H., Weber, M., & Barbier, F. (2017). Hydrogen storage: Recent improvements and industrial perspectives. *International Journal of Hydrogen Energy*, *42*(11), 7254-7262. https://doi.org/https://doi.org/10.1016/j.ijhydene.2016.03.178

Boon, Y. D., Joshi, S. C., & Ong, L. S. (2018). Interfacial bonding between CFRP and mechanically-treated aluminum liner surfaces for risers. *Composite Structures*, *188*, 374-386. https://doi.org/https://doi.org/10.1016/j.compstruct.2018.01.047

Elshaer, R. N., & Ibrahim, K. M. (2022). Applications of titanium alloys in aerospace manufacturing: a brief review. *The bulletin tabbin institute for metallurgical studies (TIMS)*, *111*(1), 60-69.

Fryer, D. M., Harvey, J. F., Fryer, D. M., & Harvey, J. F. (1998). *High pressure vessels*. Springer.

Gascylinder Supplier. (2025, January 3). High pressure 70MPa hydrogen storage tank. Retrieved from https://www.gascylindersupplier.com/high-pressure-70mpa-hydrogen-storage-tank

Guler, Z., & Genc, G. (2025). Design and analysis of composite hydraulic cylinders developed for aerospace applications [Havacılık ve uzay uygulamalarına yönelik geliştirilen kompozit hidrolik silindirlerin tasarımı ve analizi]. *International Journal of New Findings in Engineering, Science and Technology*, *3*(1), 25-31. https://doi.org/10.61150/ijonfest.2025030103

Khatib, M., Shaik, M., Kumar, R., & Imad, M. (2024). Carbon Fiber Reinforced Polymer (CFRP): A New Alternative to Steel and Aluminium for Lightweight Materials for Automotive Applications.

MatWeb. (2025, April 5). Material property data: [Specific material]. Retrieved from https://www.matweb.com/search/DataSheet.aspx?MatGUID=17287d9bb9ee4887a6e3da0294c905e7

Mori, D., & Hirose, K. (2009). Recent challenges of hydrogen storage technologies for fuel cell vehicles. *International Journal of Hydrogen Energy*, *34*(10), 4569-4574.

Pandita, S., Irfan, M. S., Machavaram, V., Shotton-Gale, N., Wait, C., Paget, M., Harris, D., Leek, C., & Fernando, G. (2013). Clean wet-filament winding - Part 1: Design concept and simulations. *Journal of Composite Materials*, *47*, 379-390. https://doi.org/10.1177/0021998312440474

Santos, R., Vandepitte, D., & Moens, D. (2025). Prediction of composite pressure vessels' burst strength through machine learning. *Composite Structures*, *351*, 118617. https://doi.org/https://doi.org/10.1016/j.compstruct.2024.118617

Solazzi, L., & Buffoli, A. (2021). Fatigue design of hydraulic cylinder made of composite material. *Composite Structures*, *277*, 114647. https://doi.org/https://doi.org/10.1016/j.compstruct.2021.114647

Tinita Engineering. (n.d.). *Types and applications of pressure vessels in industrial sectors*. Retrieved April 5, 2025, from https://www.tinita.in

Yarrapragada, R., Mohan, R. K., & Kiran, B. V. (n.d.). *Composite pressure vessels*. Academia.edu. https://www.academia.edu/6934184/COMPOSITE_PRESSURE_VESSELS

Zhang, Y.-h., Jia, Z.-c., Yuan, Z.-m., Yang, T., Qi, Y., & Zhao, D.-l. (2015). Development and application of hydrogen storage. *Journal of Iron and Steel Research International*, *22*(9), 757-770.