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Glass & Jute Fiber Composites Pressure Vessel Design and Optimization Using Finite Element Analysis

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ABSTRACT
This study focuses on maintaining the structural strength of composite pressure vessels (CPVs) used to store highly pressurized liquids and gases. CPVs are employed across multiple industries to store or transport substances under pressure. They find applications in sectors such as oil & gas, chemicals, and petrochemicals. CPVs offer a significant advantage over traditional metal vessels due to their lighter weight. However, their design, manufacturing, and testing processes require more specialized techniques. This research utilizes finite element analysis (FEA) software, specifically ABAQUS, to perform a design optimization of a CPV. The optimization of the CPV involved considering lamina sequences, thickness variations, and fiber winding angles to determine their impact on the vessel's maximum burst pressure capacity. The CPVs under investigation are constructed from glass fiber and jute fiber, with a specific lay-up configuration of six plies oriented at 0, 45, 60, -45, -60, and 90 degrees. The study investigates several key aspects. Firstly, it examines variations in different types of stresses—such as circumferential, axial, and radial—due to different meshing techniques. Secondly, it analyzes the maximum burst pressure under specific internal pressures. Finally, it applies failure criteria including Maximum stress (MSTRS), Tsai-Wu (TSAIW), and Tsai Hill (TSAIH) to predict the burst strength of the composite pressure vessel. Overall, this work aims to enhance the performance and reliability of CPVs through advanced numerical simulations and testing methodologies, ensuring their suitability for critical applications in demanding environments.

Keywords: Burst Pressure, Abaqus, Glass & Jute Fiber, MSTRS, TSAIW, TSAIH

1. Introduction

Recently, some sectors like automotive, energy storage, and aircraft are demanded for lightweight, high-performance materials which has guided to major advancements in composite materials technology. Composite pressure vessels (CPVs), which are highly valued for their capacity to store highly pressurized gases and liquids while drastically lowering weight in comparison to traditional metal containers, have surfaced as a crucial option. Nowadays, CPVs are widely used in sectors where safe and effective pressurized material transportation and containment are critical to operational effectiveness, including as petrochemicals, energy storage systems, and the oil and gas industry.

The remarkable mechanical qualities, corrosion resistance, and lightweight nature of composite materials—which include glass and natural fibers like jute—make them a popular choice for pressure vessel designs [1]. Because of its exceptional stiffness and tensile strength, glass fiber-reinforced composites are highly prized for demanding, high-performance applications. Conversely, natural fibers such as jute are becoming more and more popular because of their affordability, biodegradability, and sustainability, which makes them a viable substitute for some applications where environmental factors are crucial [2]. A cost-effective solution for lightweight, high-pressure containers can be achieved by combining glass and jute fibers to create hybrid composites that balance strength, stiffness, and sustainability [3]. Several design criteria, like fiber orientation, stacking order, as well as the composite material's capacity to tolerate internal pressures, have a significant impact on the structural integrity and performance of CPVs [4]. FEA, also known as finite element analysis, has emerged as a crucial method for optimizing the mechanical behavior of these vessels. It gives engineers the ability to forecast failure spots, examine stress distributions, and maximize material consumption [5]. In particular, the popular FEA application Abaqus makes it possible to build and simulate intricate composite structures and analyze the behavior of stresses under different load scenarios, such as radial, axial, and circumferential stresses.

Additionally, failure criteria like Maximum Stress (MSTRS) and Tsai Wu (TSAIW) are essential for forecasting the maximum load-bearing capacity and burst strength of CPVs. By evaluating the material's failure point under given stress conditions, these criteria aid in maintaining the pressure vessel's dependability and safety. The best design for high-pressure applications can be determined by analyzing the performance of jute and glass fiber composites in detail, considering different lamination angles and meshing methods [6].

This project aims to use Abaqus' finite element analysis to build and optimize composite pressure vessels constructed by jute and glass fibers. The main motive of the study is to investigate how the thickness variations, lamination order, and fiber orientation affect the vessels' maximum burst pressure and structural strength. Additionally, the study will assess the structural performance of these composite vessels under various stress conditions by applying the Maximum stress (MSTRS), Tsai-Wu (TSAIW), and Tsai Hill (TSAIH) failure criteria, adding to the expanding body of knowledge on

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environmentally friendly, high-strength materials for industrial applications [7].

2. Computational Method

2.1 Methodology

Finite Element Method (FEM) analysis is a computational approach that engages finite element formulas and techniques to break down a component into numerous small nodes and elements. The ABAQUS software was used to conduct a static structural analysis of the composite pressure vessel.

First, fix the geometry of the pressure vessel. For a composite pressure vessel, operate the 3D shell revolution command to model the vessel shape. Construct a fixed number of composite layers as required by the vessel design, making sure that the dimensions and thicknesses.

Appropriate materials are selected for composite layers. Commonly used materials include fiber-reinforced epoxy for the composite layers. Material properties are defined such as density, modulus of elasticity, Poisson's ratio, tensile strength, compressive strength, and shear strength based on data from material. Different orientations are assigned to each composite layer to optimize for maximum load-bearing capacity.

Internal pressure and boundary conditions are defined, and then different mesh sizes are generated and chosen the optimized one to get a better accuracy. Failure criteria and distribution of Von Mises stress are studied and determined the blast pressure.[8]

2.2 Geometry Part

In this study, a cylindrical shell revolution model of a pressure vessel was analyzed. The component features an internal diameter of 200 mm and a length of 550 mm, and it is subjected to an internal pressure of 6.1 MPa.

2.3 Material Selection & Properties Definition

The use of lightweight materials is becoming increasingly common as vehicle manufacturers aim to reduce the weight of automobiles to boost performance, decrease fuel and oil consumption, and cut down emissions. Reducing mass, optimizing the manufacturing process, and focusing on recyclability are crucial factors in lowering CO_2 and other pollutant emissions within the transport industry. This is because fuel combustion generates the force needed for motion, and a lighter mass results in lower acceleration, as explained by Newton's second law of motion. Weight reduction serves as an effective strategy for cutting CO_2 emissions regardless of the energy source, be it oil (gasoline, diesel, etc.), electricity, biofuels, or fuel cells. The latest polymer composite materials offer significant advantages for the transport sector, making them well-suited for modern applications [9]. Materials engineers can produce structures that are lighter and stronger than those made of bulk materials thanks to composite materials. Engineers can design pressure vessels that are highly customizable to meet specific requirements by adjusting the orientation of the fiber angles. Another advantage of composites is their extended lifespan, as they are resistant to corrosion [10].

The vessel consists of an S-glass fiber-reinforced epoxy composite layer & jute fiber-reinforced epoxy composite layer. 6 layers are sequencing GJGJGJ. Each of the layer thicknesses is 0.2 and the rotation angle is 0, 45, 60, -45, -60, and 90 respectively. Specific material properties and strength parameters of the vessel are listed in Table 1 & Table 2 [11,12].

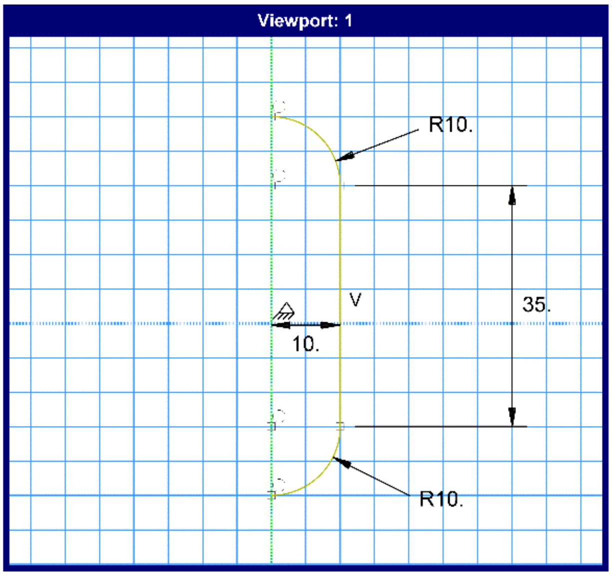


Fig.1 General parameters of the CPV: Dimensions

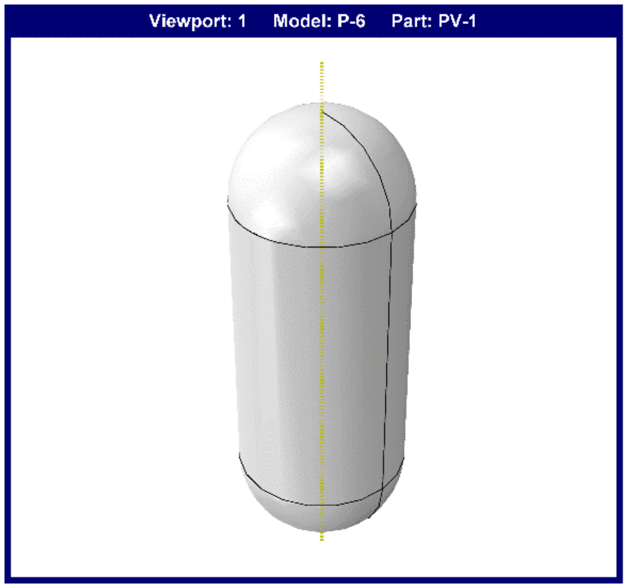


Fig.2 Shell cylinder

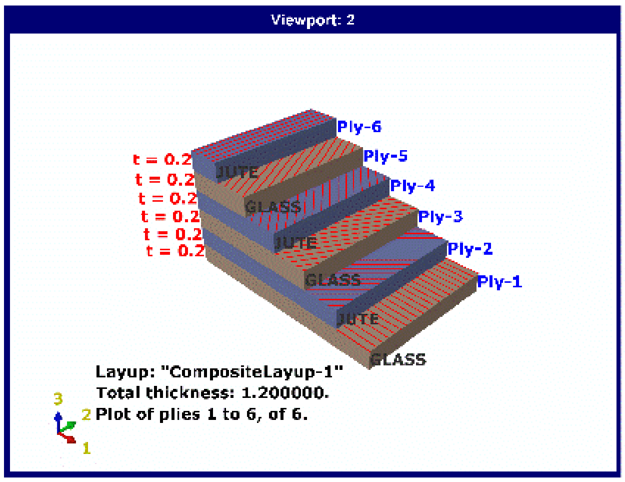


Fig.3 Ply stack plot.

Table 1 Material Properties

Material Properties	S-glass/Epoxy	Jute/Epoxy
Density (ρ, g/cm³)	2.0	1.38
Longitudinal modulus (E_1, GPa)	43	3.4
Transverse modulus (E_2, GPa)	8.9	3.2
In-plane shear modulus (G_{12}, GPa)	4.5	1.574
Major Poisson's ratio (ν_{12})	0.27	0.08
Minor Poisson's ratio (ν_{21})	0.06	0.32

Table 2 Strength Parameters

Strength Parameters	S-glass/Epoxy	Jute/Epoxy
Longitudinal tensile strength (F_{1t}, MPa)	1280	600
Transverse tensile strength (F_{2t}, MPa)	49	65
In-plane shear strength (F_6, MPa)	69	30
Longitudinal compressive strength (F_1c, MPa)	690	150
Transverse compressive strength (F_2c, MPa)	158	20

2.4 Internal Pressure & Boundary condition

The internal pressure of 6.1 MPa are applied for the pressure vessel and two boundary conditions are applied.

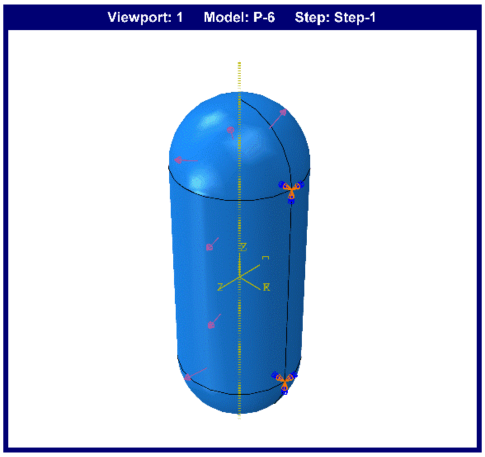


Fig.4 Boundary Condition 1

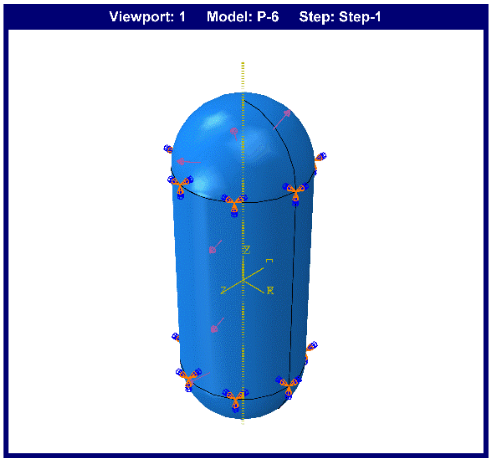
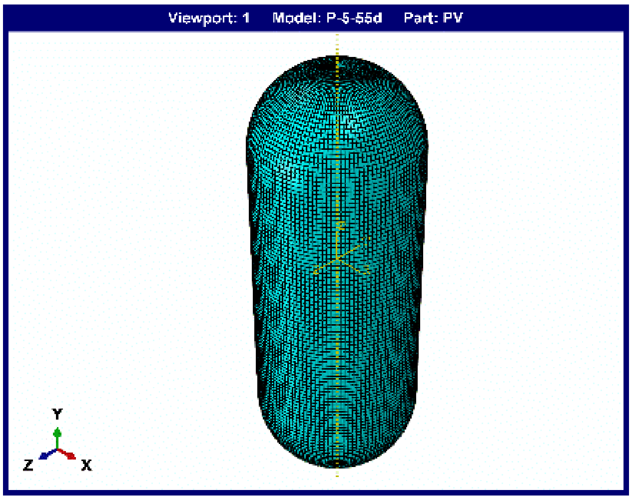


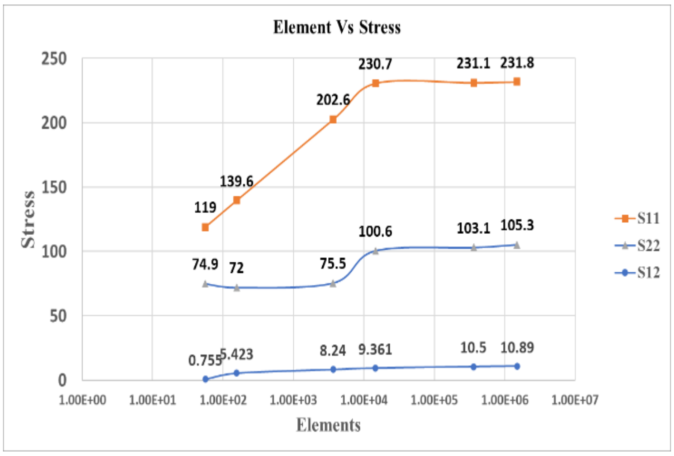
Fig.5 Boundary Condition 2

2.4 Optimum Mesh Size for The Study

The mesh analysis is very crucial to improve the accuracy of the FEA simulation. Six meshes including 10, 5, 1, 0.5, 0.1, and 0.05 are conducted and observed in S11, S22, and S12. From 10 to 0.5, the value of the S11, S22, and S12 are increased, and then from 0.5 to 0.05, the value of the S11, S22, and S12 are almost the same. The mesh size of 0.5 including 16632 elements was chosen for simulation, as the mesh converged after these numbers of elements.



(a)



(b)

Fig.6 (a) Meshed pressure vessel with mesh size 0.5 (16632 elements), (b) Mesh Convergence.

3. Result & Discussion

3.1 Distribution of Von Mises Stress

In this study, the distribution of Von Mises stress can be observed in relation to burst pressure, providing insight into the specific locations where maximum stress is located. This distribution also highlights the areas of the pressure vessel that will bear the greatest load, as well as the load-bearing profile of other regions. Fig. 4 displays the Von Mises stress distribution at burst pressure.

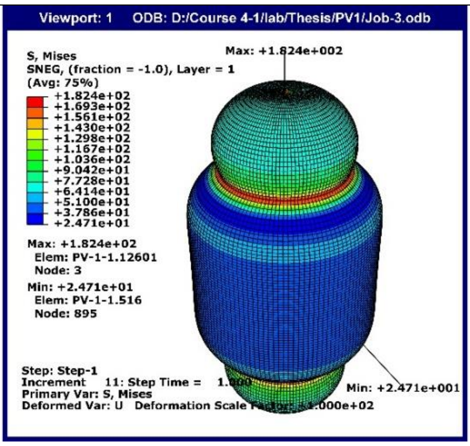


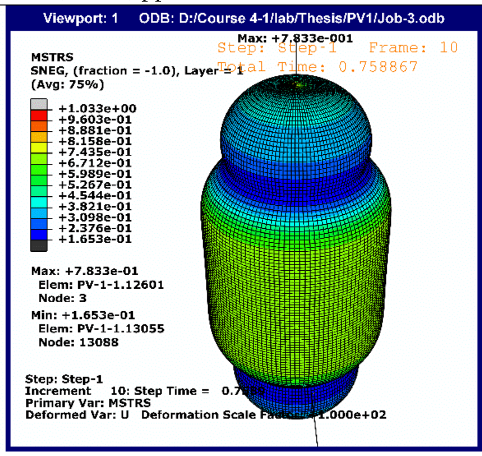
Fig.4 Von Mises stress distribution at burst pressure

3.2 Failure Criteria Analysis

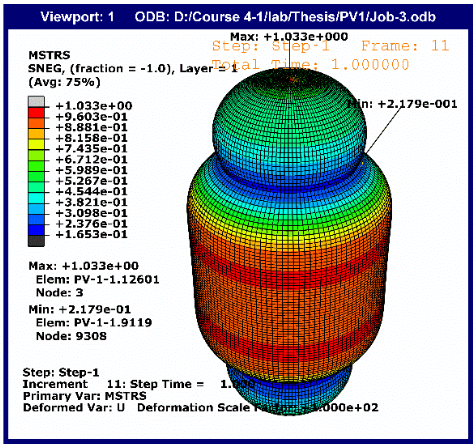
The failure criteria included in this analysis include Maximum Stress, Maximum Strain, Tsai-Hill, Tsai-Wu, and Hashin criterion. In this following study, the focus is on three of these criteria: Maximum Stress, Tsai-Hill, and Tsai-Wu, to determine the resulting burst pressure. The internal pressure is applied incrementally (using boundary condition settings) in very small load steps, and the failure index is observed. If the failure index exceeds 1, the corresponding load is identified as the burst pressure, indicating the pressure at which the composite pressure vessel (CPV) fails. The boundary conditions are defined using a local cylindrical coordinate system, with radial and circumferential displacements being constrained [13]. The internal surface of the model is exposed to a uniform pressure of 6.1 MPa.

The maximum stress failure indices (MSTRS) are presented in Fig. 5(a) at a step time of 0. 7589. In this model, all maximum stress failure index values are below 1, indicating that this load step is not considered the burst pressure. Fig. 5(b) shows the maximum stress failure indices (MSTRS) at a step time 1 just after 0.8600, where the index reaches 1.072. In this case, the failure indices exceed 1 in the large hoop regions (indicated in red), so this load step is taken as the burst pressure. Since the maximum stress is calculated by multiplying the failure time step with the applied stress, the burst pressure at this step is (6.1 × 1.0), resulting in 6.1 MPa. In Fig. 5(c), the Tsai-Hill failure index (TSAIH) distribution is displayed at a step time of 0. 7589. Here, all areas of the model have TSAIH indices below 1, so this load step does not determine the burst pressure. Fig. 5(d) illustrates the Tsai-Wu failure index distribution at a step time of 1.0, where values greater than 1 are observed in the large hoop regions (in red), marking this load step as the burst pressure. At this point, the burst pressure is also 6.1 MPa (6.1 × 1). Next Fig. 5(e) shows the Tsai-Wu failure index (TSAIW) contour at a step time of 0. 7589, with TSAIW values across all model regions being less than 1. Thus, this load step does not represent the burst pressure. In Fig. 5(f), the Tsai-Wu indices (TSAIW) at a step time of 1.0 exceed 1 in the large hoop sections (in red), indicating that the burst pressure is reached at this load step, resulting in a burst pressure of 6.1 MPa (6.1 × 1).

The analysis notices that both the MSTRS and Tsai-Hill indices are impactful in determining the failure of the pressure vessel, while the Tsai-Wu criterion appears less impactful, as it provides lower values.



(a)



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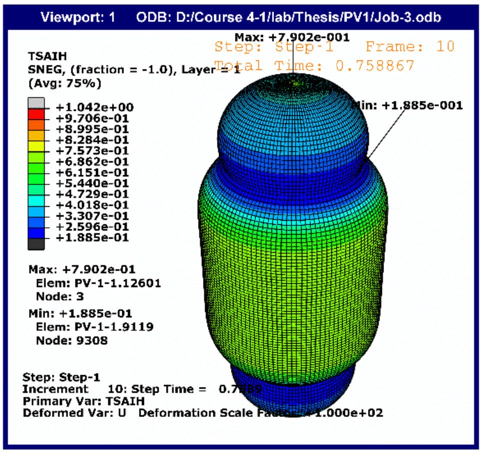

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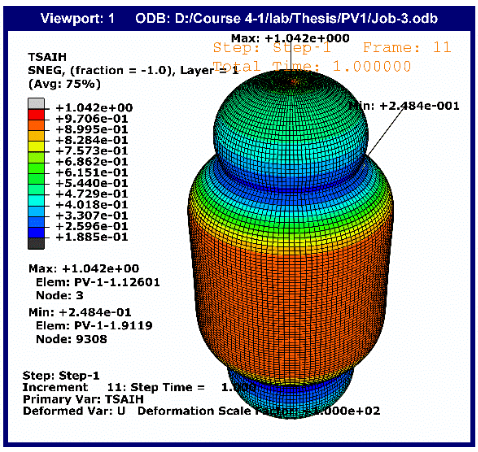
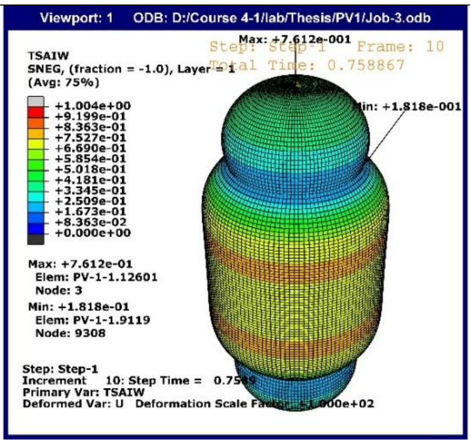
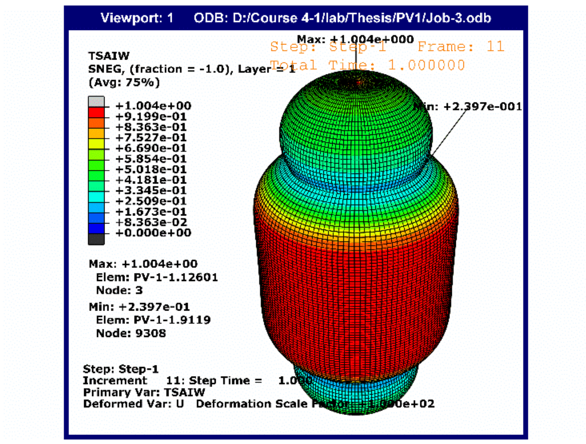


(d)



(e)



(f)

Fig.7 (a) Maximum stress failure index (MSTRS) less than 1 at load step 0. 7589, (b) Maximum stress failure index (MSTRS) greater than 1 at load step 1.0, (c) Tsai Hill failure index (TSAIH) smaller than 1 at load step 0.7589, (d) Tsai Hill failure index (TSAIH) greater than 1 at load step 1.0, (e) Tsai Wu failure index (TSAIW) smaller than 1 at load step 0. 7589, (f) Tsai Wu failure index (TSAIW) greater than 1 at load step 1.0.

3.3 Effect of Layer Number & Winding Angle

To validate the work, the influence of ply stacking and winding angle on burst pressure was evaluated. Measurements were conducted across different ply numbers and winding angles given in Table 3 & Table 4.

Table 3 Effect of Layer Number

Ply number	Winding angle	Burst pressure (MPa)
5	[55, -55]	8
8	[55, -55]	7.4
14	[55, -55]	7.5
20	[55, -55]	7.6
21	[55, -55]	7.6
27	[55, -55]	7.4

Table 4 Effect of Winding Angle

Ply number	Winding angle	Burst pressure (MPa)
5	[55, -55]	8
5	[60, -60]	7.5
5	[75, -75]	7
5	[85, -85]	7

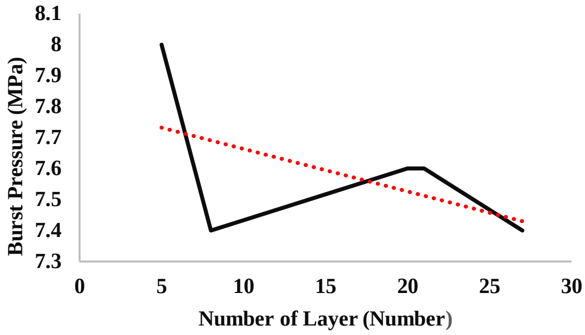


Fig.8 Impact of increasing the number of layers on burst pressure.

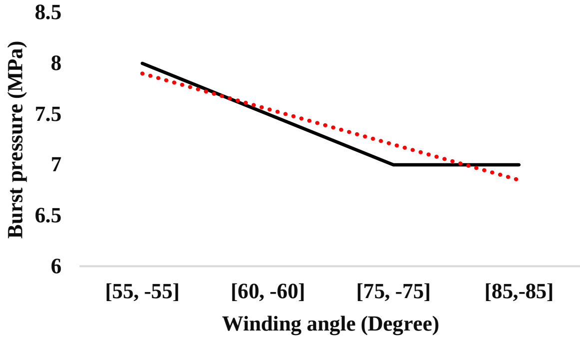


Fig.9 Impact of increasing the winding angle on burst pressure.

The results indicate that the maximum burst strength of 8 MPa occurs at a winding angle of [55, -55] with 5 plies. The analysis reveals a trend: as the number of plies and the winding angle increase, the burst pressure decreases [10].

4. Conclusion

The ABAQUS FEA model is utilized to simulate various conditions, including the effects of gravity, temperature, and getting the optimal mesh values to be employed in the construction of a specific pressure vessel. The accuracy was affected for particularly small mesh size values due to the shifting mesh variables, but a compromise was made to obtain the optimum values at a manageable running time. The goal was the current work is to observe the burst pressure of composite pressure vessels of a certain design. For this study, S-glass/Epoxy and Jute/Epoxy are used. Six plies with alternating glass and jute sequencing GJGJGJ and a combination of rotation angle (0, 45, 60, -45. -60, 90) are used to build the CPV body having light weight & strong. Key findings of this experiment are the distribution of burst pressure with a certain fixed parameter, the burst pressure from MSTRS criterion is greater than the Tsai-Wu criterion, burst pressure distribution changes a slight with mesh refinement and failure is observed in the areas in most cases.

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