

# Filament Winding Angle Optimization of Composite Shell Under Internal Load

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## Abstract

In this manuscript, filament winding angles are selected and enhanced utilizing various methodologies including optimization and numerical validation grounded on failure criteria of orthotropic characteristics. Initially, a composite shell is formulated utilizing the Ansys modeling module, followed by subjecting the shell to internal loading. The simulation is conducted employing ANSYS ACP (Pre/Post) and ANSYS Static Structural, with specific parameters specified for executing the optimization procedure. Upon completion of the optimization process, three potential points are selected based on meeting the optimization criteria. Various orthotropic criteria such as Maximum Strain, Maximum Stress, Hashin, Puck, among others, are integrated into the optimization process. Optimization of ply angles is performed, leading to the attainment of feasible points. Critical regions are depicted via contours for distinct plies and angles, demonstrating favorable agreement with existing literature in the obtained results.

**Keywords:** Filament Winding, Optimization, Composite, Winding Angle



## 1 Introduction

Filament winding angle optimization is key in composite material design, as it directly affects mechanical properties and performance of final material, strength, stiffness, and overall behavior of composite systems engineered by varying winding angles for specific fillings can meet design requirements and performance standards. In addition, the optimization of fiber winding angles can affect other important factors such as load distribution, fatigue resistance, and operating costs, making it an important consideration in the overall design as well. The selection of proper winding angle can significantly affect the overall structural integrity and durability of a composite component under different internal loading and environmental conditions. Longevity and reliability of the final product in real-world applications. Apart from that, research studies have shown that the optimum twist angle can vary depending on the specific application and desired performance characteristics of composite materials carried out, so the design phase. The importance of detailed analysis and testing over time is emphasized. Furthermore, the use of the design process to place cables at the selected bending point may affect equipment manufacturing processes and overall composite performance.

## 1-2 Literature Review

Filament winding angle optimization is a crucial aspect in the design of composite structures, as demonstrated in the research papers. The studies showcase methodologies for optimizing winding angles to enhance the performance of composite structures. By adjusting winding angles and tube ply thicknesses, the optimization process achieved desirable parameters such as displacement, strength, and weight requirements [1]. A hybrid method for optimizing the winding angle and fiber volume content of a composite cylinder under internal pressure considering the stability of strength ratio is proposed. However, the method is limited to the case of filament-wound cylinders. [2] Additionally, the use of variable-angle filament winding (VAFW) designs allowed for tailored thickness buildup and optimized tow-steered angles, resulting in higher buckling strength, stiffness, and energy absorption compared to constant-angle configurations [3]. The results prove the efficacy of the proposed framework and demonstrate the advantage of variable-stiffness designs over conventional ones for achieving a maximum load-carrying capacity while keeping the robustness of the design towards manufacturing uncertainties. [4] Furthermore, the finite element analysis of filament wound composite pressure vessels highlighted the importance of optimizing the fiber layer scheme, with the optimal angle and thickness obtained through iterative Nelder-Mead optimization functions [5]. The deformation and stresses of a thick-walled cylinder with multi-angle winding filament under uniform internal pressure are derived analytically, and two optimization methods are adopted to find the optimized winding angle sequence through different ways, and their combination led to the more efficient algorithm is suggested. [6] An analytical and optimization tool is provided to find the optimal winding parameters to obtain better mechanical performance of the filament wound composite internal pressure vessels accounting for the process-induced residual stresses. [7] Variable-angle filament-wound (VAFW) cylinders are optimized for minimum mass under manufacturing constraints and for various design loads using particle swarm optimization coupled with three Kriging-based metamodels. [8] The authors proposed a constant winding angle curve on the revolution ellipsoid showed that it is a special semi-geodesic, and provided a sufficient and necessary condition to make it on cone non-slip. [9] The effect of the two-layer angle ply [0/90]-55/-55]-75/-75] and implementation of different material testing to evaluate the toughness and stiffness of this vessel and compare the experimental result with the theoretical result. [10] A multi-angle filament wound (FW) model is proposed under pressure, torsion, and axial loads (multiple combined loads), which can calculate stresses and displacements of arbitrary multi-layers and bring more uniform strength through FW wall thickness based on orthotropic constitutive relation and axisymmetric thick-walled cylinder theory. [11] The optimal winding angle for laminated carbon fiber reinforced polymer (CFRP) composite pipes under patch loading was obtained by using a linear membrane shell theory to obtain the radial displacements along the radial direction. [12] The optimal fiber, matrix, volume fraction  $V_f$ , and winding angle  $\theta$  for a composite plain pipe are presented. However, the authors focus on the optimal design of a plain pipe, i.e., minimizing the wall thickness. [13] A linear finite element (FE) Eigenvalue and Eigenvector buckling model of thin-walled composite cylindrical shells using commercial software was developed and an optimization algorithm was used to find the highest Eigenvalue. [14] The effects of the wound angle on the strength of E-glass filament wound pipes were investigated under three different loading modes: hoop pressure loading, biaxial pressure loading, and axial compressive loading. [15] An orthotropic filament-wound glass-reinforced polyester (GRP) pipe with different fiber orientations ( $\pm 45^\circ$ ,  $\pm 55^\circ$ , and  $\pm 70^\circ$ ) was designed and manufactured to optimize the performance/cost ratio of these materials. [16] A multi-angle filament wound (FW) model is proposed under pressure, torsion, and axial loads (multiple combined loads), which can calculate stresses and displacements of arbitrary multi-layers and bring more uniform strength through FW wall thickness based on orthotropic constitutive relation and axisymmetric thick-walled cylinder theory. [17] The optimal winding angle for laminated carbon fiber reinforced polymer (CFRP) composite pipes under patch loading was obtained by using a linear membrane shell theory to obtain the radial displacements along the radial direction. [18] The optimal fiber, matrix, volume fraction  $V_f$ , and winding angle  $\theta$  for a composite plain pipe are presented. However, the authors focus on the optimal design of a plain pipe, i.e., minimizing the wall thickness. [19] A linear finite element (FE) Eigenvalue and Eigenvector buckling model of thin-walled composite cylindrical shells using commercial software was developed and an optimization algorithm was used to find the highest Eigenvalue. [20] The authors show that the optimum fiber winding angle can vary hugely with

the scattering of some design variables, such as Young's modulus of the matrix and the transverse strength of the ply, and the amplitude of the applied pressure and the axial force also modifies the optimum winding angle.[21] a semi-geodesic path algorithm and verified finite element analysis method were used to predict the behavior of filament wound structures, and an optimal design algorithm was suggested using the genetic algorithm.[22] a comparison of multilabel filament wound pipe with traditional 54-degree wound pipe on various mechanical properties is presented. However, the comparison is limited to the case of multilevel wound pipe.[23] This paper provides a multi-level strategy to optimize the composite float system, which is manufactured from glass-reinforced plastic (GRP), and uses an efficient link between ANSYS Workbench and MATLAB through an in-house code that has been developed over 3 years.[24] a 3D finite element model of the filament wound tube was developed using NASTRAN in Unigraphics software to validate the results obtained from the experiments and the nonlinear behavior of the materials used in the experiments was incorporated into the FEA model by considering the appropriate stress-strain relationships.[25] a comparison of multilabel filament wound pipe with traditional 54-degree wound pipe on various mechanical properties is presented. However, the comparison is limited to the case of multilevel wound pipe.[26] the effect of the winding angle of the fiber reinforcements on the buckling and first-ply failure loads of the composite pipes has been examined and it was shown that the optimum winding angle varies according to the ratio of hoop-to-axial membrane stresses in the pipes.[27]

These findings underscore the significance of filament winding angle optimization in improving the overall performance of composite structures. In this paper, filament winding angles are chosen and optimized through various methodologies such as optimization and numerical validation based on failure criteria of orthotropic nature. First of all, a composite shell is designed using ansys modeling module then the shell is subjected to internal load. Simulation was done using ANSYS ACP (Pre/Post) and ANSYS Static Structural. Certain Parameters were defined to run the optimization process. After running the optimization, 3 candidate points are chosen based on the satisfaction of optimization criteria. Several orthotropic criteria such as Maximum Strain, Maximum Stress, Hashin, Puck, etc were integrated into the optimization process. Ply angles were optimized and feasible points were achieved. Critical areas are shown through contours for different plies and angles. Results show good agreement with the literature.

## 2 Materials and Theoretical Background:

The winding angle, i.e., the orientation of fibers, significantly influences the vessel's mechanical properties, resulting in varying stiffness and strength in different directions. The winding angle in a CPV can significantly affect the vessel's pressure load response. In a CPV, fibers can be organized in various configurations, as shown in Fig. 1, depicting the angular positioning of various winding configurations concerning the cylinder axis. The strength, stiffness, and general effectiveness of the vessel can all be affected by these orientations. The burst response is highly influenced by the fiber orientations as well as how the stresses are distributed throughout the vessel. Various fiber winding orientations are utilized in CPVs, including hoop, helical, and polar winding, each with potential advantages of their own. For instance, fibers wound at  $0^\circ$  (parallel to the vessel's axis) primarily resist axial loads, while fibers wound at  $90^\circ$  (perpendicular to the axis) primarily resist hoop stresses. Intermediate angles result in a combination of axial and hoop stress resistance. The exact needs and desired CPV characteristics will determine the fiber winding orientation to be used.[28]

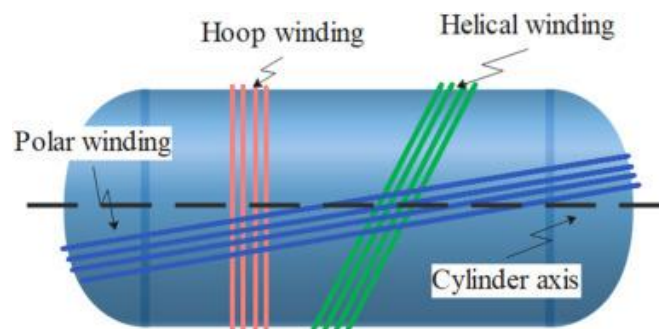


Fig. 1. Schematic details of various winding configurations, showing the angular orientation concerning the cylinder axis.

## 2-1 Layer Stresses as Controlled by the Winding Angle

The winding process results in a  $\{+\alpha, -\alpha\}$  angle ply laminate with thickness  $t$ . The stiffness matrix of a single layer is:

$$\mathbf{S}_0 = \begin{bmatrix} \frac{E_1}{1 - \nu_{12}\nu_{21}} & \frac{\nu_{12}E_1}{1 - \nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{12}E_1}{1 - \nu_{12}\nu_{21}} & \frac{E_2}{1 - \nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix}$$

where  $\nu_{12}E_2 = \nu_{21}E_1$ , and  $E_1$  is the elasticity modulus in the fiber direction. The stiffness of the shell wall (angle ply laminate) is:

$$\underline{\mathbf{S}} = \frac{1}{2} [\mathbf{S}(\alpha) + \mathbf{S}(-\alpha)]$$

$$\mathbf{S}(\alpha) = \mathbf{M}(\alpha) \mathbf{S}_0 \mathbf{M}^T(\alpha)$$

in which:

$$\mathbf{M}(\alpha) = \begin{bmatrix} \cos^2 \alpha & \sin^2 \alpha & \sin(2\alpha) \\ \sin^2 \alpha & \cos^2 \alpha & -\sin(2\alpha) \\ -\cos \alpha \sin \alpha & \cos \alpha \sin \alpha & \cos(2\alpha) \end{bmatrix}$$

As a result of the shell stress vector  $\underline{\sigma} = \{\sigma_m, \sigma_p, 0\}^T$ , the stresses in the individual layers are:

$$\sigma(\alpha) = \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \mathbf{S}_0 \cdot (\mathbf{M}^T)^{-1} \cdot \underline{\mathbf{C}} \cdot \underline{\sigma}$$

where  $\underline{\mathbf{S}} = \underline{\mathbf{C}}^{-1}$ . The performance of a pressure vessel is defined as the ratio of the stored volumetric energy (pressure  $\times$  volume) divided by the weight of the structure. Vasiliev (Ref 3.8) and de Jong (Ref 3.3) have shown that for maximizing the performance of a pressure vessel, the shear stress  $\tau_{12}$  must be zero. Setting  $\tau_{12} = 0$  in Eq 3.11 results in:

$$\frac{\sigma_p}{\sigma_m} = \frac{\sin^2 \alpha + k_e \cos^2 \alpha}{\cos^2 \alpha + k_e \sin^2 \alpha}$$

where

$$k_e = \frac{E_2(1 + \nu_{12})}{E_1(1 + \nu_{21})}$$

For maximum strength (not necessarily performance),  $k_e$  should be replaced with  $k_s$ , which is the ratio of the transverse to the longitudinal (fiber direction) strength of a single layer (Ref 3.8). For the netting case (matrix stiffness negligible),  $k_e = 0$ ; for isotropic materials,  $k_e$  becomes equal to 1.

It can also be shown that optimally reinforced composite pressure vessels rely on geodesic fiber trajectories (Ref 3.3, 3.8):

$$\sin \alpha = \frac{1}{Y}$$

Plugging this in, Eq 3.12 gives:

$$\frac{\sigma_p}{\sigma_m} = \frac{1 + k_e(Y^2 - 1)}{(Y^2 - 1) + k_e}$$

For a given fiber-matrix combination ( $k_e$ ) and geodesic winding ( $Y$ ), this expression provides the optimal shell stress ratio.

## 2-2 Problem Statement:

A composite shell consists of several layers and plays with different angles stacked up together. The ply angles are {0,30,45,60,90} each ply consists of 3 layers. The composite shell is subject to 100 Mpa pressure from the inside. To achieve maximum performance, the Optimization process must be done on filament winding angles. Optimization parameters and constraints are listed below:

Name	Parameter	Objective	Objective	Objective	Constraint	Constraint	Constraint
Minimize P13; P13 ≤ 0.74 mm	P13 - Total Deformation Maximum	Type	Target	Tolerance	Type	Upper Bound	Tolerance
Maximize P7; P7 ≤ 1	P7 - Inverse Reserve Factor Maximum	Minimize	0		Values ≤ Upper Bound	0.74	0.001
Seek P1 = 0	P1 ModelingPly.1.ply_angle	Maximize	1		Values ≤ Upper Bound	1	0.001
Seek P2 = 30	P2 ModelingPly.2.ply_angle	Seek Target	0	10	No Constraint		
Seek P3 = 45	P3 ModelingPly.3.ply_angle	Seek Target	30	10	No Constraint		
Seek P4 = 60	P4 ModelingPly.4.ply_angle	Seek Target	45	10	No Constraint		
Seek P5 = 90	P5 ModelingPly.5.ply_angle	Seek Target	60	10	No Constraint		

Table 1. Objectives and Parameters

## 2-3 Methodology:

We used two methods, the complex method (CM) and the steepest descent (SD) to find the optimization solution.

### 2-3-1 Complex method

CM is a development of the simplex method in constrained problems. In 1965, Box extended the simplex method of unconstrained minimization to solve constrained minimization problems of nonlinear programming:

$$\text{Minimize } f(X)$$

subject to

$$g_j(X) \leq 0, (j = 1, 2, \dots, m)$$

$$x_i^{(l)} \leq x_i \leq x_i^{(i)}, (i = 1, 2, \dots, n)$$

In general, the satisfaction of the side constraints (lower and upper bounds on the variables  $x_i$ ) may not correspond to the satisfaction of the constraints  $g_f(X) \leq 0$ . The formation of a sequence of geometric figures each having  $k = n + 1$  vertices in an  $n$ -dimensional space (called the simplex) is the basic idea, where a sequence of geometric figures each having  $k \geq n + 1$  vertices is formed to find the constrained minimum point. The method assumes that an initial feasible point  $X_1$  (which satisfies all the  $m$  constraints) is available. Iterative steps in the procedure:

- (1) Find  $k \geq n + 1$  points, satisfied all  $m$  constraints.
- (2) The objective function is evaluated at each of the  $k$  points (vertices). If the vertex  $X_h$  corresponds to the largest function value, the reflection is used to find a new point  $X_r$  as

$$X_r = X_0 + \alpha(X_0 - X_h)$$

where  $\alpha = 1.3$  and  $X_0$  is the centroid of all vertices except  $X_h$  :



$$X_0 = \frac{1}{k-1} \sum_{\substack{l=1 \\ l \neq k}}^k X_l$$

(3) If the point  $X_r$  is feasible and  $f(X_r) < f(X_h)$ , then point  $X_h$  is replaced by  $X_r$ , and turn to step 2. If  $f(X_r) \geq f(X_k)$ , a new trial point  $X_r$ , is found by reducing the value of  $\alpha$  in Eq. (16) by a factor of 2 and is tested for the satisfaction of the relation  $f(X_r) < f(X_k)$ . The procedure of finding a new point  $X_r$  with a reduced value of  $\alpha$  is repeated again. This procedure is repeated, until the value of  $\alpha$  becomes very small. If an improved point  $X_r$ , with  $f(X_r) < f(X_h)$ , cannot be obtained even with that small value of  $\alpha$ , the point  $X_r$  is discarded and the entire procedure of the reflection is restarted by using the point  $X_\rho$  (which has the second-highest function value) instead of  $X_h$ .

(4) If at any stage, the reflected point  $X_r$  (found in step 3) violates any of the constraints, it is moved halfway in toward the centroid until it becomes feasible. This method will progress toward the optimum point as long as the complex has not collapsed into its centroid.

(5) Each time the worst point  $X_h$  of the current complex is replaced by a new point, the complex gets modified, and we have to test for the convergence of the process. We assume convergence of the process whenever the following two conditions are satisfied:

- (a) The complex shrinks to a specified small size.
- (b) The standard deviation of the function value becomes sufficiently small.

### 2.3.2 Steepest descent method

SD is one of the simplest and the most fundamental minimization methods for unconstrained optimization. Since it uses the negative gradient as its descent direction, it is also called the gradient method. It can be summarized by the following steps:

- (1) Start with an arbitrary initial point  $X_1$ . Set the iteration number as  $i = 1$ .
- (2) Find the search direction  $\nabla f(X_i)$ .
- (3) Determine the optimal step length  $h_i$  in the direction  $\nabla f(X_i)$ , and set

$$X_{i+1} = X_i - h_i \nabla f(X_i)$$

- (4) Test the new point,  $X_{i+1}$ , for optimality. If  $X_{i+1}$  is optimum, stop the process. Otherwise, go to next step.
- (5) Set the new iteration number  $i = i + 1$ , and return to step 2.

### 3 Simulation and Optimization:

Filament winding is a popular manufacturing technique used in industries such as aerospace, automotive, and marine to produce composite structures. The winding angle plays a crucial role in determining the mechanical properties and performance of the final product. Simulation and optimization of filament winding angles using ANSYS Workbench have become essential tools in the design and manufacturing process. This advanced software allows engineers to model, analyze, and optimize the winding process to achieve the desired mechanical properties and structural integrity of the composite structure. In the next sections, we will explore the significance of simulation and optimization in determining the filament winding angle using ANSYS Workbench.

#### 3-1 Modelling:

Modeling a composite shell using ANSYS SpaceClaim encompasses a series of intricate steps that commence with the importation of the geometric data, followed by meticulous preparations of the model, subsequent creation of the shell element, meticulous generation of a mesh, detailed definition of boundary conditions, precise establishment of parameters for the analysis, execution of the simulation, and thorough examination of the results during the post-processing phase. This meticulous and systematic process culminates in the attainment of a profound and all-encompassing comprehension of the behavior exhibited by the composite shell when subjected to diverse and varying conditions.



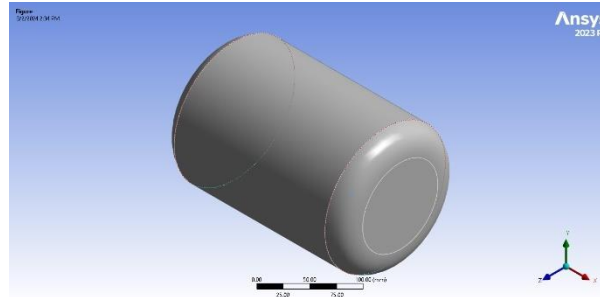


Fig 2. Composite Shell Designed in SpaceClaim

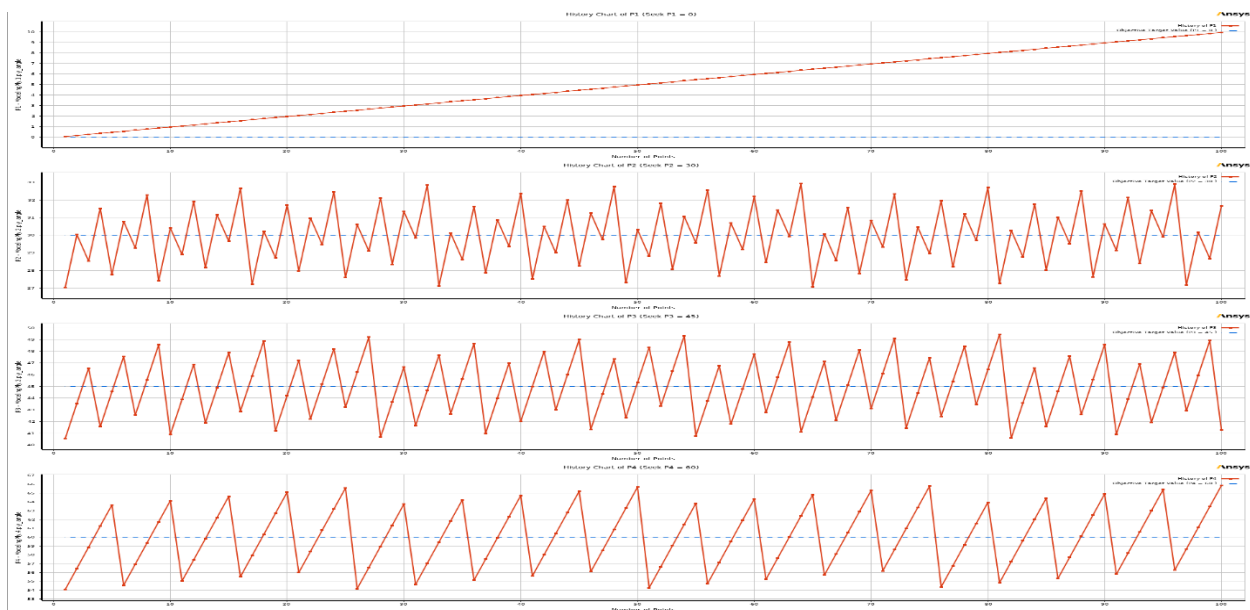
### 3-2 Simulation of Composite Shell Under Internal Load:

After Designing the Composite shell, the model is meshed. The mesh consists of 6536 elements. The shell then goes under -100 MPa pressure from the inside. The whole simulation is run by ANSYS Static Structural. After applying internal pressure on the composite shell, a displacement constraint is defined on the cap of the composite shell. Simulation results consist of total deformation of different plys/layers and Composite Failure Tool. ANSYS Composite PrepPost provides all necessary functionalities for the analysis of layered composite structures. The Composite Failure tool in ANSYS allows engineers to predict failure in composite materials by utilizing various failure criteria such as Tsai-Wu, Hashin, and Puck. This tool helps in understanding how and where a composite structure may fail under different loading conditions, enabling engineers to optimize designs and ensure structural integrity.

### 3-3 Optimization Process:

Optimization methodology in ANSYS Workbench involves utilizing advanced algorithms and tools to iteratively improve the performance of a design based on specified objectives and constraints. The process typically includes defining design variables, setting optimization goals, selecting appropriate algorithms such as genetic algorithms or gradient-based methods, running simulations to evaluate design performance, and automatically adjusting the design parameters to optimize the desired outcomes. By leveraging the optimization capabilities in ANSYS Workbench, engineers can efficiently explore a wide range of design options, identify the most optimal solutions, and ultimately enhance the overall performance and efficiency of their products or systems.

In this study, the ANSYS Direct Optimization module is used to optimize parameters extracted from ANSYS Static Structural and ANSYS ACP. By defining Objectives and Constraints importing Parameters from other modules setting up Optimization methods and adjusting them, the evaluation of design variables can begin. After Optimization is done ANSYS Direct Optimization gives 3 candidate points. These 3 candidate points are from 100 points that Ansys computed and solved. Furthermore, ANSYS Direct Optimization gives an enormous amount of data such as Feasible and Infeasible points, schematics of different candidate points, etc. figures below represent cycles of each design angle.



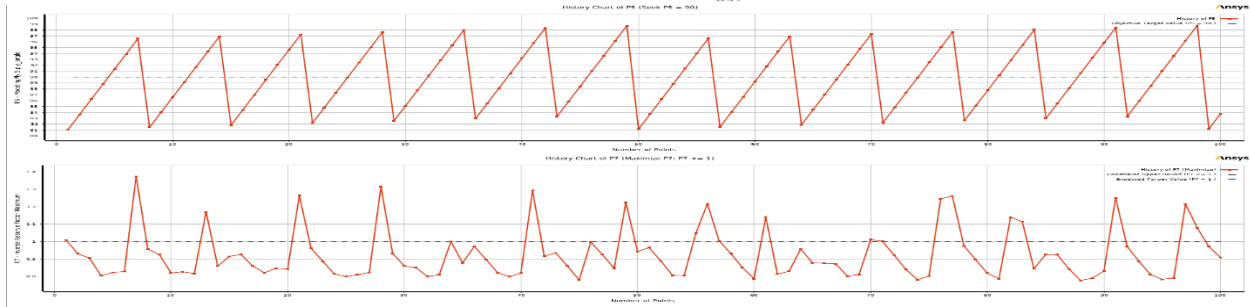


Figure 3. Number of cycles for each angle

#### 4 Results and Discussion

The numerical simulation shows the shell can operate with better performance with the winding angle around 55 degrees. The goal of this paper is the acquisition of better performance and superior ultimate failure strength through the means of Optimizing Filament winding Angles based on widely accepted criteria such as Tsai-Wu, Tsai-Hill, Hashin, etc. The Optimization process shows 3 candidate points shown in the Table Below:

Name	P1	P2	P3	P4	P5	P8	P9	P10	P11	P12	P7	P13
Candidate Point 1	3.35	30.123	42.656	61.836	95.416	3	3	3	3	3	1.000051	0.6848
Candidate Point 2	4.55	31.248	41.322	56.076	91.008	3	3	3	3	3	0.996837	0.6528
Candidate Point 3	7.75	31.201	48.433	59.148	82.611	3	3	3	3	3	0.974702	0.5991

Table 2. Candidate Points

Different Contours of different angles of plies and layers show different areas that are prone to failure. Ansys direct optimization shows candidate point 2 as the best choice to achieve superior performance and strength. As mentioned before stipulated candidate point contains pressure better due to the winding angle of 56 degrees which is near 55 degrees. A 55-degree winding angle is considered the ultimate winding angle by a lot of scholars in literature.[15][18][28][29]

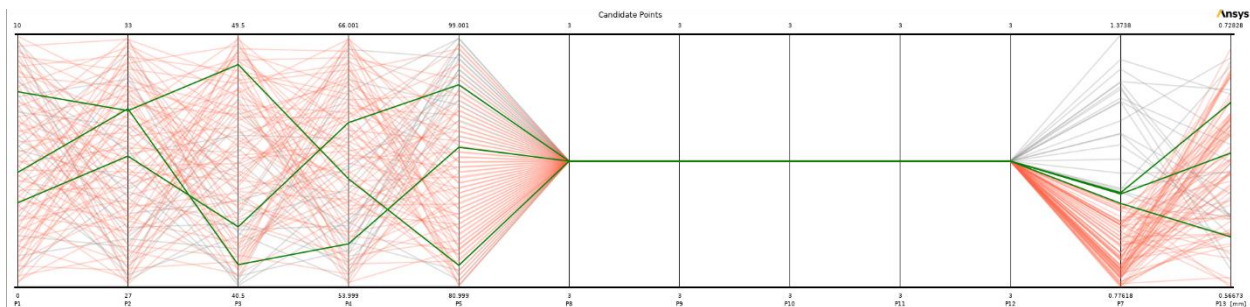


Figure 4. Candidate Points(Green) & Samples(Other colors)

Through the process of exporting a two-dimensional graph that showcases both feasible and infeasible points, it can be deduced that the sequence of winding angles emerges as a pivotal determinant in the attainment of the desired outcomes.

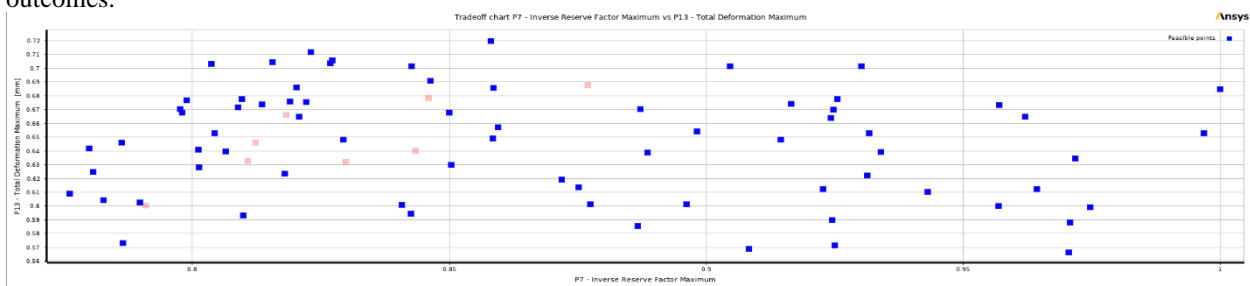


Figure 5. Feasible Points



Different plots of deformation and stress contours below show that optimization works around decreasing the concentration of tension in the areas prone to failure by checking the range of winding angles and choosing the optimum winding angle as the candidate optimal point. Inverse Reverse Factor (IRF) is the parameter used in composite failure. The failure load can be defined as the load value divided by IRF. Thus when  $IRF > 1$  the composite fails and if  $IRF < 1$  it is safe. But to avoid unnecessary bulky structure IRF must be maintained between 0.9 and 1. The IRF of Optimal Point Found by the authors of this paper is 0.99. Contour plots of the composite shell with different failure criteria are shown below:

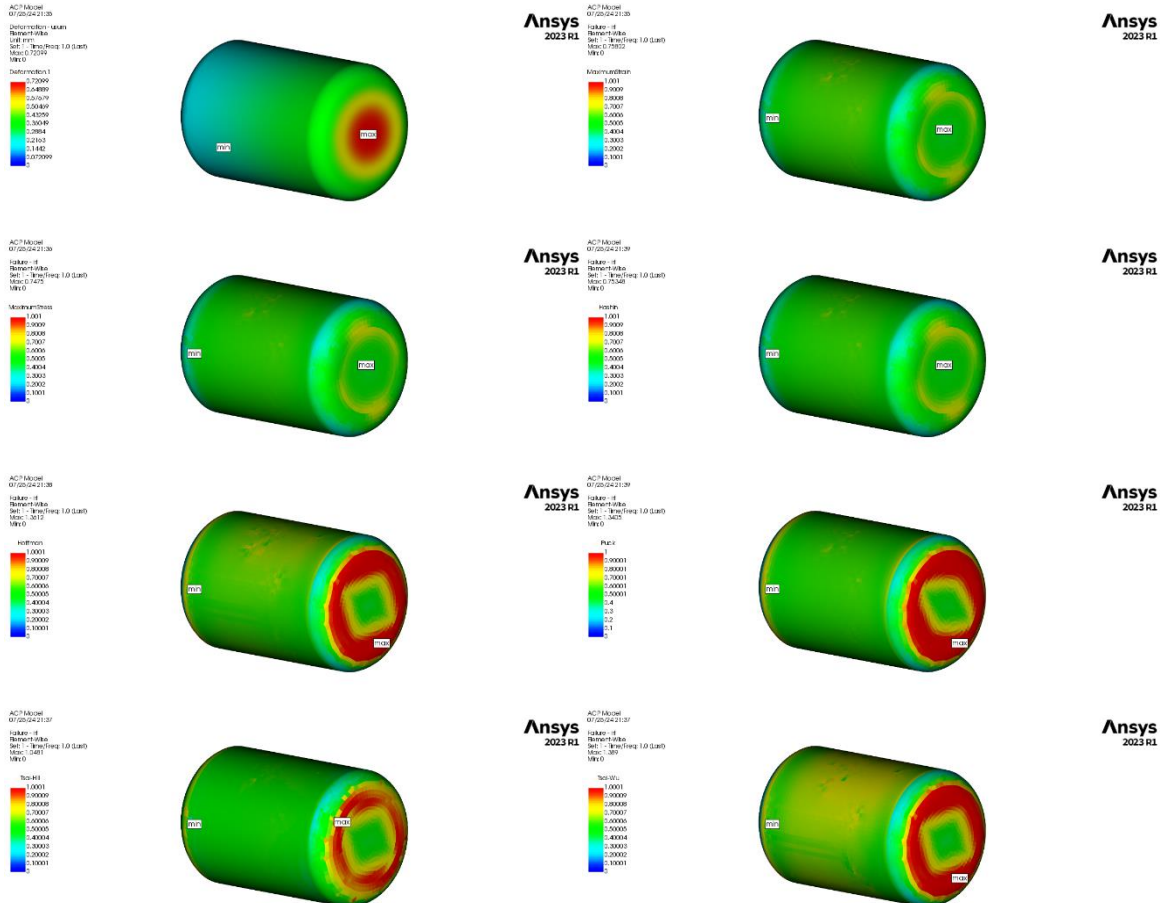


Figure 6. Contour plots of the composite shell (a-Deformation, b-Maximum strain, c-Maximum stress, d-Hashin, e-Hoffman, f-Puck, g-Tsai-Hill, h-Tsai-Wu)

Moreover, the subsequent illustrations display contour plots delineating various configurations of ply orientations and layers, each characterized by distinct angles. These graphical representations serve to visually depict the spatial distribution of material properties across the composite structure. Particularly noteworthy are the regions identified as susceptible to failure, namely the vicinity surrounding the composite shell caps. These critical zones necessitate immediate attention and remedial actions to mitigate the likelihood of structural failure. Additionally, the visualizations also include plots illustrating the distribution of deformation and stress within the composite material. These graphical representations offer valuable insights into the mechanical behavior of the structure under varying loading conditions.

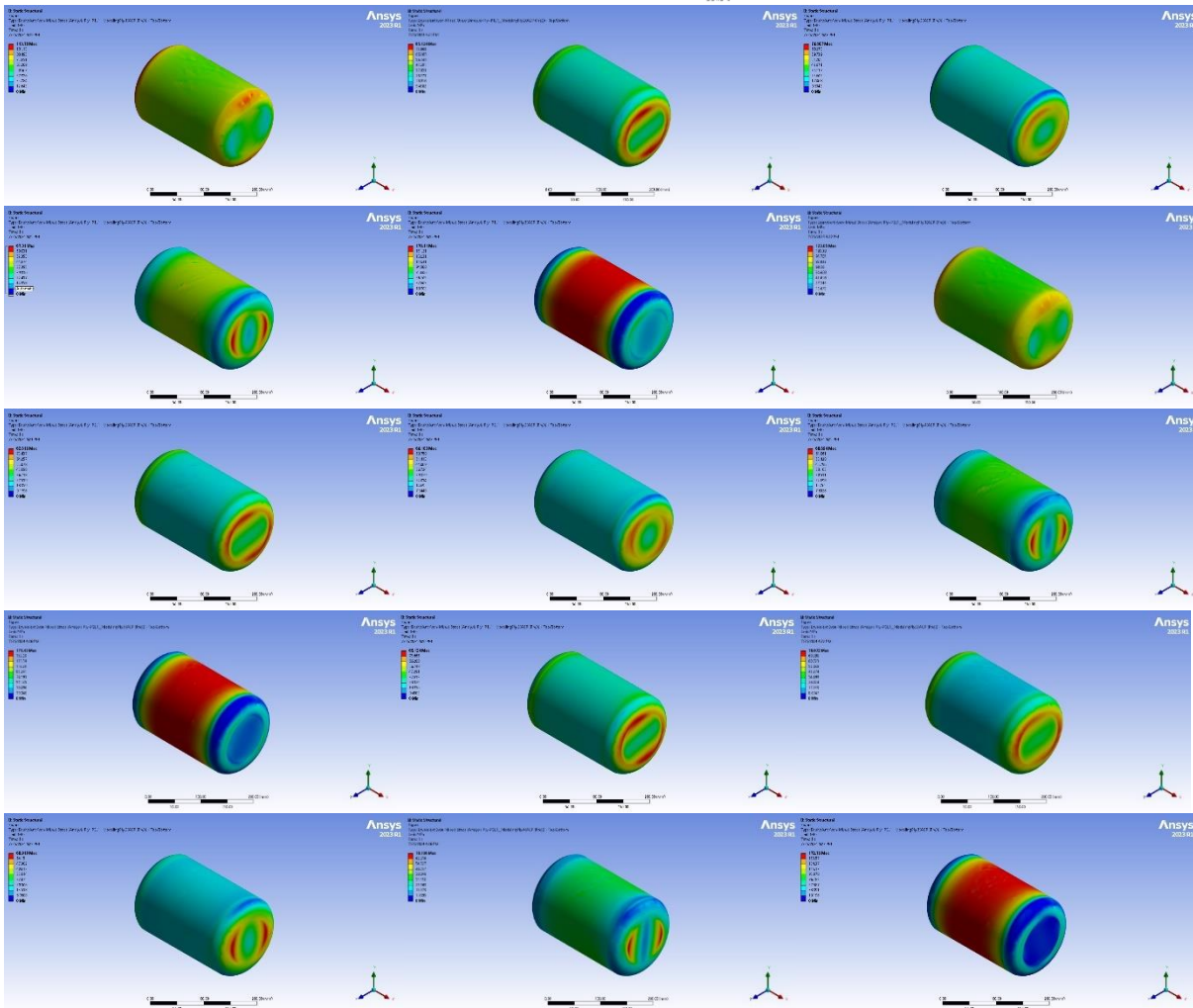


Figure 7. Contour Plots of Stress in each layer of different ply

## 5 Conclusion

Winding angle sequence and how to stack up different layers and plies are regarded as the most important factor in optimizing the composite shell filament winding angle. Ply angles are considered the only tool present to alleviate structure situations in the winding process. This paper emphasizes on optimizing winding angles using finite element modeling and direct optimization methods. The stacking sequence that contains a degree near 55 degrees that is considered optimal degree is the most desirable stacking sequence. The methodology used in this work is the most reliable and swiftest way to optimize composite shells. The stipulated methodology is to optimize the winding angle based on constraints and optimization criteria and test each candidate point in ANSYS ACP and Static Structural to validate the best choice for filament winding stacking sequence and angles. The methodology proved to be one of the most authentic ways to optimize filament winding angle.



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