



## Optimization of Filament Winding variable angle for Pressure Vessels

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### Abstract

This scholarly work meticulously elucidates the substantial potential inherent in the manufacturing processes of variable-angle composite cylinders through the innovative technique known as filament winding (FW), which is herein referred to as Variable-Angle Filament Winding (VAFW). The design strategy that has been proposed facilitates the implementation of varying filament angles along the axial direction by segmenting the cylindrical structure into discrete regions characterized by a constant filament angle, which are designated as frames. In the current study, designs employing two, four, or eight distinct frames are rigorously investigated to assess their structural performance and viability. To enhance the performance of each design, a genetic algorithm is systematically applied with the objective of optimizing the structural integrity for achieving the maximum axial buckling load possible. Additionally, this comprehensive study incorporates an analysis of a design that adheres to the criterion of maintaining the minimum manufacturable filament angle, thereby providing a thorough exploration of the practical limits of this innovative manufacturing approach.

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



## Introduction

Pressure vessels hold significant importance due to the necessity of storing various liquids and gases under elevated pressure conditions. A particular focus is directed towards the structural integrity of the vessel to avert the potential for catastrophic explosions resulting from rupture. Regulatory codes have been established to ensure the safety of such vessels, delineating specific design parameters that must be adhered to under predetermined conditions. The majority of pressure vessels are designed to accommodate only low pressures, thereby being fabricated from rolled tubes and sheets to create cylindrical forms. Conversely, certain pressure vessels are required to withstand high-pressure environments, necessitating an increase in wall thickness to ensure sufficient structural strength. The interest in the study of shell structures emerged during the 1950s of the twentieth century. Assemblies that incorporate thin shells are extensively utilized in contemporary engineering applications, particularly within the maritime, aerospace, and space exploration industries. The analysis of shell vibrations and buckling phenomena is conducted using numerical methodologies to qualitatively elucidate the critical loads and various modes of buckling. In today's aerospace and aircraft industries, structural efficiency is the main concern. Due to their high specific strength and light weight, fiber reinforced composites find a wide range of applications. Light weight compression load carrying structures form part of all aircraft, and space vehicle fuel tanks, air cylinders are some of the many applications. In the present work, design analysis of fiber reinforced multi layered composite shell, with optimum fiber orientations; minimum mass under strength constraints for a cylinder with or without stiffeners under axial loading for static and buckling analysis on the pressure vessel has been studied. Cylindrical shells (see Fig.1.1) such as thin-walled laminated composite unstiffened vessels like deep submarine exploration housings and autonomous underwater vehicles are subjected to any combination of in plane, Out of plane and shear loads due to the high external hydrostatic pressure during their application. Due to the geometry of these structures, buckling is one of the most important failure criteria. Buckling failure mode of a stiffened cylindrical shell can further be subdivided into global buckling, local skin buckling and stiffener crippling. Global buckling is collapse of the whole structure, i.e. collapse of the stiffeners and the shell as one unit. Local skin buckling and the stiffeners crippling on the other hand are localized failure modes involving local failure of only the skin in the first case and the stiffeners in the second case. In the present work, an analytical model is developed for prediction of optimum fiber orientations for given layer thicknesses, and mainly minimum buckling load for with or without stiffener composite shell under multilayered continuous angle-ply loading condition is investigated. The model developed is more general in the sense that any configuration of stiffeners, on either one side or both sides of the shell can be modeled accurately. Stiffened shells having either symmetrical or unsymmetrical shell laminates can also be modeled with equal ease using this model. Grid stiffened cylindrical shells are the shells having a certain kind of stiffening structures either on inner, outer or both sides of the shell and significantly increases the load resistance without much increase in weight.

## 1-2 Literature Review

To further reduce the weight, both the shell and the stiffeners are made using fiber reinforced polymers. The promising future of stiffened composite cylinder has in turn led to an extensive research work in this area. Filament winding (FW) is one of the most suitable manufacturing processes for fiber-reinforced solids of revolution [1], such as composite overwrapped pressure vessels [2,3], tubes [4], pipelines [5,6], drive shafts [7], among others. The FW process is well-suited for automation, being fast, cost-effective and compatible with high fiber volume requirements of lightweight and high-performance structures [8]. There are numerous reports in the literature dealing with constant-angle (i.e. constant-stiffness) filament-wound structures, that is, when each layer has a nominal filament angle and a regular thickness distribution [9]. However, recently, Wang et al. [10] designed and optimized for the first time variable-angle filament-wound (VAFW) composite cylinders considering the uncertainties and characteristics of the FW process, and later focused on minimum-mass optimizations constrained by target design loads [11]. Based on that, the present investigation focuses on the innovative manufacturing and testing of VAFW cylinders, and the possibility of validating numerical models to investigate observed failure mechanisms. It is already well established that variable-angle configurations (also known as variable-axial [12], variable angle tow – VAT [13], towsteered [14] and variable-stiffness – VS [15]), in which stiffness can be tailored to follow load paths, are more effective than conventional laminates (e.g., quasi-isotropic laminates) in terms of weight savings, given the higher design freedom due to locally tailored fiber angles [16,17]. Since the establishment of VAT composites by Gürdal and Olmedo [15], this concept is under continuous development by the aerospace sector. For instance, Hao et al. [18] generated the fiber path through linear variation, cubic polynomial, contour lines of cubic function and flow field functions and optimized VS panels for maximum buckling load. The flow field method requires only a few variables to achieve complicated fiber paths, leading to designs that can be directly manufactured when curvature constraints are used in the optimization. Hao et al. [19–21] also developed integrated optimization frameworks based on isogeometric analysis for VS panels, providing an efficient numerical framework based on the isoparametric concept, which is similar to the finite element (FE) analysis and meshless method. They utilized non-uniform rational B-spline (NURBS) basis functions to discretize the geometric model. In brief, they developed efficient and reliable optimization frameworks at reasonable computational cost, whilst robust enough to generate complex fiber paths, which is hardly possible to reach in a single optimization step using gradient-based methods. In this context, the present work covers, for the first time, design,



modeling, optimization, of VAFW composite cylinders. First, the cylinders are optimized using a genetic algorithm for maximizing their axial compression buckling load by axially varying the angle.

## Composite Theory:

### 2.1 Introduction to Thin Composite Shells

The structural element characterized by a wall thickness that is minimal in comparison to its radius of curvature and the associated radius of twist is classified as a thin shell. Plate and shell structures are employed in lightweight load-bearing components for a diverse array of contemporary aerospace, offshore, nuclear, automotive, and civil engineering applications. These shells experience compressive forces. In the context of aircraft, they encounter variable flight loads, which concurrently generate compressive components. These compressive forces can induce buckling within the shell structure. The assessment of composite shell structures necessitates the consideration of multiple failure modes. Frequently, analytical programs are unable to forecast all potential failure modes utilizing a singular analysis model, thereby compelling structural designers to employ a spectrum of analytical tools. It is also prevalent that for a specific failure mode, achieving consistent results across different programs proves to be challenging. It is unequivocal that composite shells hold significant importance in contemporary technological advancements.

### 2.2 Composite Materials

In addition, low-order elements with complete integration are prone to volumetric, membrane, or shear locking, necessitating a fine mesh which hinders computational efficiency. To apply loads and boundary conditions, reference points are established at the center of each cylindrical shell's free edge, interconnected via multi-point constraints. This constraint ensures uniform displacement distribution across all nodes linked to the free edges. Nodes at the bottom edge are fully constrained, while top nodes can only translate axially. A buckling load is applied at the top reference point. The refined mesh comprises 152 axial elements and 213 circumferential elements, totaling 32,376 elements and 32,589 nodes. A linear buckling analysis is conducted utilizing the Lanczos Eigensolver. The buckling analysis rests on the principle of neutral equilibrium. This study addresses a constrained optimization problem with discrete design variables. The genetic algorithm (GA) is identified as effective for locating the global optimum, outperforming gradient-based methods prone to local minima. Design variables are represented as genes encoded in integers and organized into chromosomes. Populations of potential optimal designs are generated through evolutionary reproduction. Sufficient search points mitigate the risk of local minima. Chromosomes are evaluated based on a fitness function indicative of their phenotype. The GA initiates with a random population, followed by fitness assessment, procreation of superior individuals, and gene exchanges via crossovers. Offspring selection is based on fitness metrics. The optimization achieves convergence with parameters of 50 individuals, 50 generations, 20% mutation probability, and 50% crossover probability using two-point crossover. Upon specifying GA parameters, the optimization problem is formally established. Flaws like cracks against load direction critically impair material strength. Non-polymeric materials exhibit superior tensile strength along longitudinal axes due to small cross-sectional fibers that reduce defects. For polymeric materials, molecular architecture alignment is essential for enhanced strength and rigidity. Fibers, due to their small size, are not typically utilized in engineering. They are embedded in matrix materials to form fibrous composites. The matrix consolidates fibers, aids load transfer, and protects against environmental and mechanical harm. The shell consists of a multi-layered fibrous composite structure. Each layer or lamina is a single-layer composite, with orientation adjusted per design specifications. Each layer is very thin (0.4 mm to 0.7 mm) and cannot function alone. Identical or varied layers are bonded to form a multi-layered composite shell. Layers may differ in (a) material volumes, (b) reinforcement form, and (c) fiber orientation relative to a reference axis. Thus, the properties of individual layers can vary significantly. A common fabrication technique for matrix composites is the hot pressing method. Continuous glass fibers pass through a slurry of matrix material, solvent, and binder, as illustrated in figure 1.2. The tow is wound onto a drum and dried to produce prepreg tapes. These prepreg tapes can be layered to create the laminate; heating to approximately 932°F (500°C) burns off the binder. Hot pressing occurs at high temperatures around 1832°F (1000°C) and pressures from 7 to 14 MPa. A thorough design analysis of composite structural elements requires an understanding of individual layer properties. Each layer is a continuous angle-ply composite laminate, containing parallel fibers in a matrix. Multiple unidirectional layers can be arranged in a specific orientation to meet design strength and stiffness requirements. A unidirectional composite layer may be termed a layer ply or lamina. The relative proportions of matrix and reinforcement materials are critical to composite properties. These proportions can be expressed as weight fractions or determined through various post-fabrication experimental methods. Volume fractions are mainly used in theoretical studies of composite materials. Most synthetic composites comprise two materials: a reinforcing fiber and a foundational matrix material. For example, in concrete columns, concrete serves as the matrix, while iron rods act as reinforcement fibers.

Three primary types of composites exist:

1. Fibrous Composites: It consists of fibers of one material in a matrix material of another material.
2. Particulate Composites: These are composed of particles of one material in a matrix of another material.



3. **Laminate Composites:** These are made of layers in which fibers and matrix are made of different materials, including the composites.

The purpose of matrix is to transfer loads and protect them against environmental attack and damage due to handling. Based upon the properties required, the matrix and fiber materials are selected.

### 2.2.1. Fiber

Fibers are principal constituents in fiber reinforced composite material. They occupy the large volume fraction in a composite laminate and share major portion of load acting on a composite.

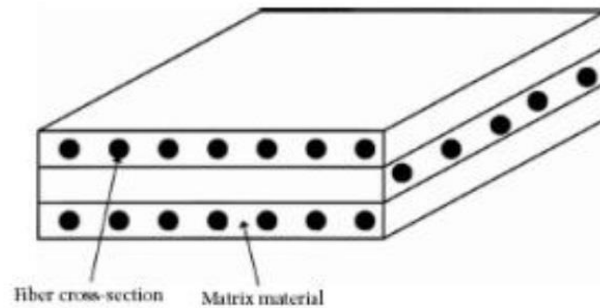


Figure 2.1 Typical Laminates made of three laminate

### 2.2.2 Matrix

Use of fibers by themselves as matrix is limited, because of smaller dimensions. Therefore fibers are used as reinforcement to matrices. The role of matrix in a fiber – reinforced composite material is:

- (1) To transfer stresses between the fiber.
- (2) To provide a barrier against an adverse environment.
- (3) To protect the surface of the fiber from mechanical abrasion.

The matrix plays a minor role in load carrying capacity. The matrix has a major influence on Inter laminar shear as well as in plane shear properties of the composite. Inter laminar shear strength is important in design under bending loads. In plane shear, strength is important in design under tensional loads. The matrix provides lateral support against the possibility of fiber buckling under compressive loads. Among the matrix materials epoxies are used because of commercial availability and ease of processing. More than two-thirds of the polymer matrices used in aerospace applications are epoxy based. The main reason why epoxy is the most used polymer matrix material is due to its Advantages over the other matrix:

- (1) Wide variety of properties available.
- (2) Absence of volatile matters during cure.
- (3) Low shrinkage during cure.
- (4) Excellent resistance to chemical and solvents.
- (5) Excellent adhesion to fibers.
- (6) The disadvantages are relatively high cost and long curing time.

### 2.2.3 Characteristics of Composites

Fiber reinforced composite materials offer a combination of strength and elasticity that are better than conventional metallic materials. Composites are superior because of their low specific gravities, high strength-weight ratios and high modulus-weight ratio's. Structural materials such as steel and aluminum alloys are considered isotropic since they exhibit nearly equal properties irrespective of the direction of measurement. In case of composites, properties depend strongly on the direction of measurement. Many fiber reinforced composites have high internal damping which leads to better vibration energy absorption within the material and results in reduced transmission of noise and vibrations to neighboring structures. There are several distinct characteristics that make composites different from many conventional materials.

1.2.4. Applications of Composite Materials The aircraft industry uses composites to meet performance requirements beyond the capabilities of metals. The Boeing 757, for example, uses approximately 760ft<sup>3</sup> of composites in the body and wing components, with an additional 361 ft<sup>3</sup> used in rubber, elevator, edge panels and tip fairings. The B-2 bomber contains carbon and glass fibers, epoxy resin matrices, and high temperature polyimide as well as other material in more than 10,000 composite components. Composites are also used in race cars, tennis rackets, golf clubs, and other sports and leisure products. Few more applications are given as below

- Aircraft and military applications



- Space applications
- Automotive applications
- Sporting goods applications
- Marine applications Medical applications
- Commercial goods

## 2.2.4 Lamina and Laminate Analysis

A lamina (considered a unidirectional composite) is characterized by having all fibers (either a single ply or multiple plies) oriented in the same direction. This model allows one to treat lamina as an orthotropic material. A lamina is a collection of laminates arranged in a specified manner as shown in fig.2.1. Adjacent lamina may be of the same or different materials and their orientations with respect to a reference axis may be arbitrary.

- Single-layered laminates: A single layered laminate is a unidirectional lamina with multiple layers.
- Symmetric Laminates: A symmetric laminates has both geometric and material symmetry with respect to the mid-surface. Geometric symmetry results from having identical lamina orientations above and below the mid surface. Material symmetry can result from either having all lamina the same material, or requiring different lamina to be symmetrically disposed about the mid-surface.
- Antisymmetric Laminates: This laminate is characterized by having its layers arranged in an ant symmetric fashion with respect to the mid surface. There must be even number of plies for a laminate to be ant symmetric.

Cross-ply Laminates: A cross-ply laminate contains an arbitrary number of plies, each with a fiber orientation of either  $0^\circ$  or  $90^\circ$ , and can be either symmetric or anti symmetric. Angle-Ply Laminates: Angle-ply laminates have an arbitrary number of layers (n). Each ply has the same thickness and is the same material. The plies halt can be either symmetric or antisymmetric (see fig 2.1)

In Filament winding as shown in fig2.2, fibers are impregnated with a resin by drawing them through an in-line resin bath, Depending on the desired properties of the product; winding patterns such as hoop, helical can be developed. The product is then cured with or without heat & pressure. Each ply is pressed to remove any entrapped air & wrinkles; the lay-up is sealed at the edges to form a vacuum seal.

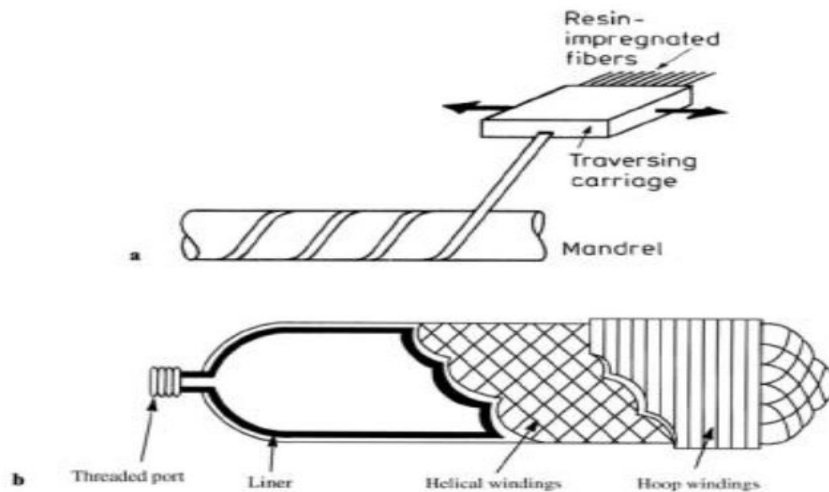
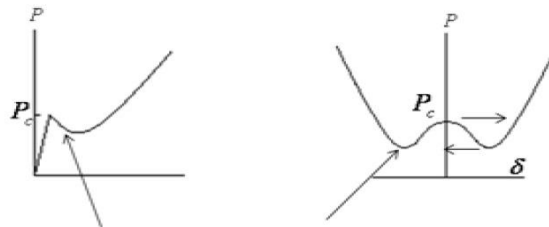


Figure 2.2 Filament wound Pressure Vessel

Buckling denotes the failure of a structural element under axial compressive forces. The load at which a shell structure becomes unstable and buckles is known as the buckling load. A structural system may fail to support imposed loads due to connection failure, excessive deformation, tensile separation or fracture, compressive crushing, or lateral displacement exceeding its capacity. Among structural failure modes, buckling is particularly significant and catastrophic. The buckling factor is defined as the ratio of critical stress to operational stress. Buckling in thin shells can be classified into three types based on membrane stresses: axial, circumferential, and shear stresses. For buckling to occur, axial and circumferential stresses must both be compressive. A structure experiences buckling when large displacements occur perpendicular to compressive forces. An example of buckling is compressing the edges of a cardboard sheet towards each other. At low loads, this remains elastic as displacements revert to zero upon load removal. Localized buckling is indicated by bulges or ripples in slender structural member plates. Buckling occurs in two modes: Stable, where regulated displacement increases with load, and Unstable, where sudden deformation leads to structural failure. Neutral equilibrium is a theoretical state during buckling where deformation increases without



changing the applied load. Buckling and bending share similarities due to bending moments present in both phenomena. In bending, moments are independent of resultant deflections, whereas in buckling, they are interdependent, affecting moments, deflections, and stresses. Excessive buckling deflections compromise structural integrity, highlighting a geometric dependency unrelated to material strength. Design must ensure strength and buckling safety criteria for any component vulnerable to buckling. The behavior exhibited by a compressed shell post-buckling diverges significantly from that of a plate; in this scenario, an unstable (negative) stiffness is concomitant with a drastic decrease in load-carrying capacity, as illustrated in figure 2.3.



Unstable post-buckling path (snap)

Figure 2.3 Buckling Curve

The uncontrolled displacements in practical systems lead to snap-buckling behavior in shells, requiring instantaneous deflection increases under escalating loads. Upon load reduction, buckling deflection diminishes until a snap occurs, reverting to the primary trajectory. This behavior underscores the necessity of substantial safety factors in the design of compressed cylinder buckling loads. Mathematical modeling of composite shells requires the application of lamina and laminate analysis theory. A laminate is an arrangement of lamina in a designated configuration. To analyze laminated composites effectively, predicting individual lamina behavior is crucial. Buckling load calculations for unstiffened shells involve load-strain and moment-curvature relationships through laminate analysis, while stiffened shells require assessing force and moment interactions to determine stiffeners' stiffness contributions. The buckling analysis aims to estimate the maximum pressure a composite shell can withstand before elastically destabilizing, using the "Windenburg and Trilling Equation" to determine critical buckling pressure. The primary design philosophy for composite shells is to prevent failure over a designated service lifespan. Failure occurrence in a shell largely depends on its specific application context. Composite laminates with fiber-reinforced thermosetting polymers exhibit minimal yielding but do not fit traditional brittle material definitions. Many laminates display non-linear behavior under static tensile loading due to progressive ply failures. Current design methodologies in aerospace and marine applications primarily follow the first-ply failure paradigm. A crack in a failed ply can compromise adjacent plies' integrity against mechanical and environmental deterioration. The design parameters for fiber-reinforced composite shells conform to the same standards as those for metallic materials, including specific criteria. The design parameters for fiber-reinforced composite shells adhere to the same standards as those applicable to metallic materials. These parameters include the following:

- 1) The structure must withstand the ultimate design load during static testing.
- 2) The fatigue life must be equal to or exceed the anticipated lifespan of the vehicle.
- 3) Deformations arising from the application of repeated loads and the limits of design load must not impede the mechanical functionality of the system.

2.1 General Design Guide Lines The principal steps in designing a composite laminates are

- 1) Selection of fiber, resin and fiber volume fraction.
  - 2) Selection of optimum fiber orientation in each ply and the lamina stacking sequence.
  - 3) Selection of number of plies needed in each orientation which also determines the final thickness of the component.
- In general symmetric laminates are commonly preferred over unsymmetrical laminates. This eliminates the extension – bending coupling represented by the B-matrix. The presence of extension – bending coupling is also undesirable from the stiffness stand point. Since it reduces the effective stiffness of the laminate and thereby increases its deflection, reduces the critical buckling loads and decreases the natural frequency of vibration. Similar but lesser effects are observed if the laminate has bending – twisting coupling due to presence of D16 and D26 terms. If the angle of ply laminates are used the layers with  $+\theta$  and  $-\theta$  orientations should be altered instead of in clustered configuration. Thus for example an fourteen layer laminate with 7 of  $+\theta$  orientations and 7 of  $-\theta$  orientations should be designed as  $[+\theta/-\theta/+\theta/-\theta]_s$  instead of  $[+\theta/+\theta/-\theta/-\theta]_s$  or  $[+\theta/+\theta/-\theta/-\theta]_s$ .

Longitudinal Modulus	$E_{22} = \frac{E_f E_m}{E_m V_f + E_f V_m}$
Transverse Modulus	$E_{11} = E_f V_f + E_m V_m$
Major Poisson's Ratio	$\mu_{12} = \mu_f V_f + \mu_m V_m$
Minor Poisson's Ratio	$\mu_{21} = \frac{E_{22}}{E_{11}} \mu_{12}$

Shear Modulus

$$G_{12} = \frac{G_f G_m}{G_f V_m + G_m V_f}$$

### Windenburg and Trilling Equation:

The equation can be used for thin wall filament wound structures with conventional sheet materials. “Windenburg and Trilling Equation” is used to determine composite shell critical buckling pressure  $P_{cr}$  = Critical Pressure,  $t$  = Thickness of the Shell,  $d$  = Diameter of the cylindrical shell  $L$  = length (spacing) between the stiffeners,  $E$  = Young’s Modulus,  $\mu$  = Poisson’s Ratio

$$P_{cr} = \frac{2.42E \left[ \frac{t}{d} \right]}{[1 - \mu^2] \left[ \frac{L}{d} - 0.45 \left[ \frac{t}{d} \right]^{0.5} \right]}$$

$$E_x = \frac{E_L}{\cos^4 \theta + \frac{E_L}{E_T} \sin^4 \theta + 0.25 \left[ \frac{E_L}{E_T} - 2\mu \right] \sin^2 2\theta}$$

$$E_y = \frac{E_L}{\cos^4 \theta + \frac{E_L}{E_T} \sin^4 \theta + 0.25 \left[ \frac{E_L}{E_T} - 2\mu \right] \sin^2 2\theta}$$

## Static Analysis of FEM

### 3.1 Introduction to FEM

The finite element method is a numerical procedure for analyzing structures and continua. Usually problem addressed is too complicated to solve satisfactorily by classical analytical methods. The finite element procedure develops many simultaneous algebraic equations, which are generated and solved on a digital computer. The results obtainable are accurate enough for engineering purposes at reasonable cost. In addition it is an efficient design tool by which designers can perform parametric design studies by considering various design cases (different shapes, materials, loads, etc.), analyze them and choose the optimum design. Hence the method has increasingly gained popularity among both researchers and practitioners.

### 3.2 General Design Guide Lines

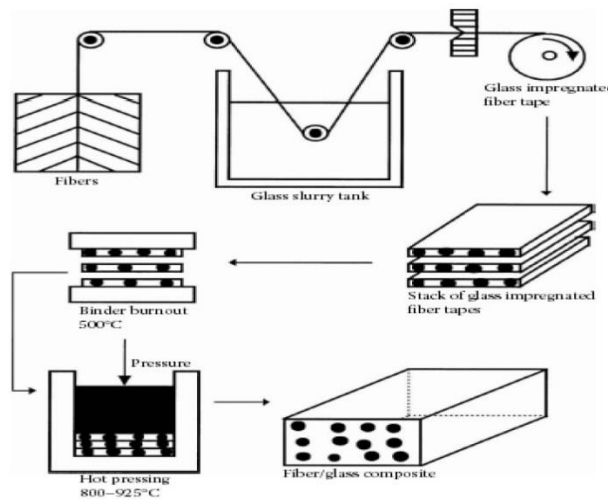
The principal steps in designing a composite laminates are

- 1) Selection of fiber, resin and fiber volume fraction.
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In general symmetric laminates are commonly preferred over unsymmetrical laminates. This eliminates the extension – bending coupling represented by the B-matrix. The presence of extension – bending coupling is also undesirable from the stiffness stand point. Since it reduces the effective stiffness of the laminate and thereby increases its deflection, reduces the critical buckling loads and decreases the natural frequency of vibration. Similar but lesser effects are observed if the laminate has bending – twisting coupling due to presence of D16 and D26 terms. If the angle of ply laminates are used the layers with  $+\theta$  and  $-\theta$  orientations should be altered instead of in clustered configuration. Thus for example an fourteen layer laminate with 7 of  $+\theta$  orientations and 7 of  $-\theta$  orientations should be designed as  $[+\theta/-\theta/+ \theta/-\theta]_s$  instead of  $[+\theta/+ \theta/-\theta/-\theta]_s$  or  $[+\theta/+ \theta/-\theta/-\theta]_s$ .

### General Description Of Finite Element Analysis

In the finite element method, matter is modeled as a collection of finite elements. These elements connect at specific points known as nodes. Nodes typically reside at element boundaries, linking adjacent elements. As the precise variation of field variables within the continuum is unknown, it is presumed that such variations can be approximated by simple functions within finite elements. These approximating functions, or interpolation models, are expressed in terms of nodal values. Field equations for the continuum yield unknown nodal values of the field variable. By solving these equations, often in matrix form, the nodal values become discernible. Once established, the approximating function delineates the field variable across the entire assembly of elements.



**Figure 3.1 Schematic Matrix Composite Laminates Manufacturing**

One of the most common methods to manufacture matrix composites is called the hot pressing method. Glass fibers in continuous tow are passed through slurry consisting of powdered matrix material, Solvent such as alcohol, and an organic binder as shown in fig 1.2. The tow is then wound on a drum and dried to form Prepreg tapes. The prepreg tapes can now be stacked to make a required laminate; heating at about 932°F (500°C) burns out the binder. Hot pressing at high temperatures of about 1832°F (1000°C) and pressures of 7 to 14Mpa. Design analysis of any composite structural element would require a complete knowledge of properties of individual layers. Each layer is a continuous angle-ply composite laminate consists of parallel fibers embedded in a matrix. Several unidirectional layers can be stacked in a specified sequence of orientation to fabricate a laminate that will meet design strength and stiffness requirements. Each layer of a unidirectional composite may be referred to as simple a layer ply or lamina. One of the most important factors for determining the properties of composites is relative proportions of the matrix and reinforced materials. The relative proportionate can be given as the weight fractions or by one of the experimental methods after fabrication. The volume fractions are exclusively used in the theoretical analysis of composite materials. Most manmade composite materials made from two materials, these are a reinforced material called fiber and a base material called matrix. For example in concrete columns the concrete is base material which is called matrix and the iron rods come under fibers for reinforcement. Their existing three types of composites.

1. **Fibrous Composites:** It consists of fibers of one material in a matrix material of another material.
2. **Particulate Composites:** These are composed of particles of one material in a matrix of another material.
3. **Laminate Composites:** These are made of layers in which fibers and matrix are made of different materials, including the composites.

The purpose of matrix is to transfer loads and protect them against environmental attack and damage due to handling. Based upon the properties required, the matrix and fiber materials are selected. Fibers are principal constituents in fiber reinforced composite material. They occupy the large volume fraction in a composite laminate and share major portion of load acting on a composite.

## Design and optimization

### 4.1 Design

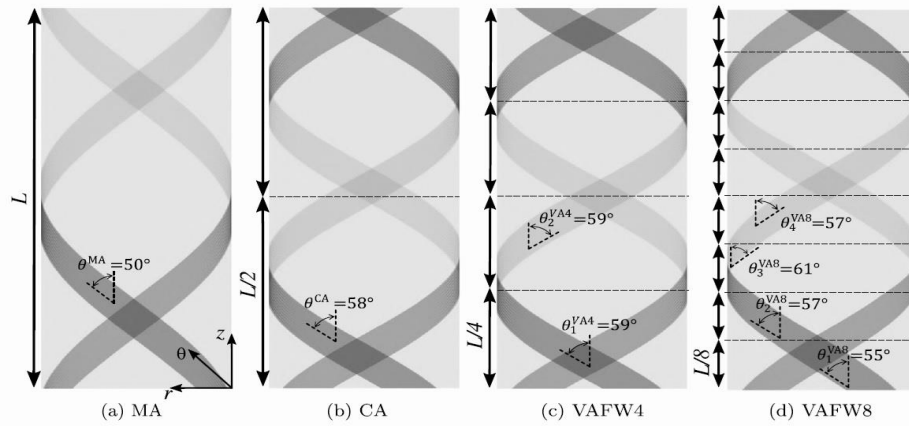
Throughout this article, the novel cylinders herein studied are called VAFW. Four designs are investigated: MA: non-optimized constant-angle cylinder with a winding angle of  $\pm 50^\circ$ , which is the minimum angle (MA) for the utilized mandrel to avoid fiber slippage –Fig. 4.1 (a);

CA: constant-angle with two frames, design variable  $\theta_1^{CA}$  - Fig 4.1(b)

VAFW4: variable-angle with four frames, design variables  $\theta_1^{V A4}, \theta_2^{V A4}$  Fig. 4.1(c)

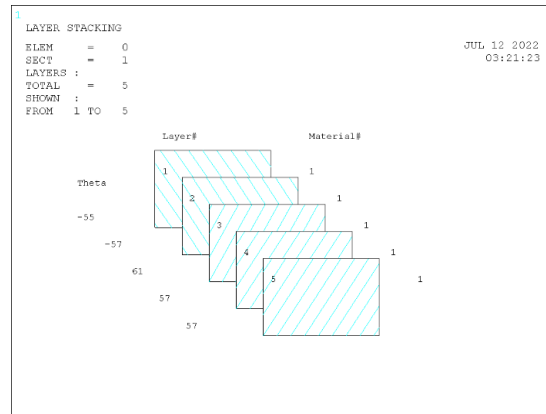
VAFW8: variable-angle with eight frames, design variables  $\theta_1^{V A8}, \theta_2^{V A8}, \theta_3^{V A8}, \theta_4^{V A8}$  Fig. 4.1(d)





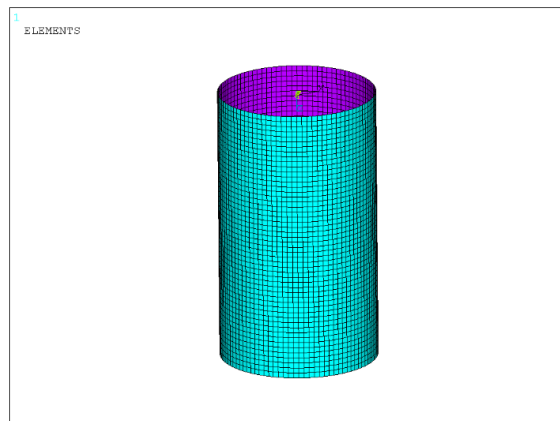
**Fig. 4.1.** The filament-wound designs along with the optimum fiber path for each case: side view of the cylinders highlighting the non-optimized design variable(s) for each case, control points (dotted lines) along the shell length ( $L$ ), and winding trajectories. The shift direction is along the  $Z$  (axial) axis.

## 4.2 Linear finite element modeling



**Figure 4.2 Composite Layers**

In this Section, the linear finite element modeling (FEM) is presented in detail. The composite cylinders under investigation here are 300mm long with a diameter of 136 mm, whose layup consists of an angle-ply layer,  $\pm\theta$ , nominal thickness of 0.8 mm, i.e. a radius-to-thickness ratio of 85. The experimentally-measured material properties used in all simulations are listed in Table 1, which are representative of towpregs with Toray T700-12K-50C carbon fibers and UF3369 epoxy resin. The FE models are generated using ANSYS APDL and the models are parameterized via Macro Code. The cylinders are meshed using four-node reduced integration general purpose shell elements (S4R), with three integration points through-thickness for each layer. Previous simulations with full integration were carried out and as the results were the same, elements with reduced integration were chosen given their lower computational costs, crucial for an optimization procedure in which several simulations need to be run.



**Figure 4.3 Cylinder model mesh**

In addition, low-order elements with full integration exhibit increased vulnerability to volumetric, membrane, or shear locking, necessitating fine mesh for efficiency. A reference point is established at each cylindrical shell's free edge for load application and boundary condition enforcement via multi-point constraint. This constraint ensures uniform displacement across nodes linked to the free edges. Degrees-of-freedom are constrained at the bottom edge, while top nodes are restricted to axial movement. A buckling load is administered at the top reference point. The converged mesh contains 152 axial elements and 213 circumferential elements, totaling 32,376 elements and 32,589 nodes. A linear buckling analysis utilizes the Lanczos Eigensolver. The optimization approach is constrained with discrete design variables. Genetic algorithms (GA) are effective in locating the global optimum compared to gradient-based methods. Design variables are represented as genes, organized into chromosomes. The GA generates diverse populations of potential optimal designs through reproductive evolution. With sufficient search points, the algorithm minimizes the risk of local minima. Chromosomes are evaluated based on a fitness function, indicating their effectiveness. The GA initiates with a random population, selecting the fittest individuals for reproduction through genetic crossover. The solution offspring are determined by fitness metrics. The optimization process converges with specified parameters: a population of 50, 50 generations, a 20% mutation rate, and a 50% crossover rate using two-point crossover. After establishing the GA parameters, the optimization problem is formally defined.:

$$\text{Fitness function: } \min \frac{1}{P_{cr}}$$

$$\text{subject to : } \theta_L \leq \theta \leq \theta_U$$

where the fitness function goal is to maximize the first buckling load,  $P_{cr}$  (obtained by linear FE analysis - Section 2.2), and the design variables are  $\theta$ , whose lower and upper bounds are represented by  $\theta_L$  and  $\theta_U$ , respectively. The former is defined as the minimum winding angle to avoid fiber slippage for the current mandrel system [40], whereas the latter is defined by  $\text{Arc cos}(w/r) = 86.6^\circ$ , where  $w$  is the tow bandwidth and  $r$  is the mandrel radius. To ensure a smooth winding angle transition between adjacent mandrel frames, preventing tow slippage, a maximum angle variation between consecutive control points (represented by dotted lines in Fig. 1) is set, being represented as:

$$|\theta_K - \theta_{K-1}| < 10^\circ$$

in which  $k$  is a control point.

### 5.1 Results and Discussion:

The optimization results are presented in Fig. 3, where the evolution of fitness is plotted against the generations. As can be seen, all three optimization cases are convergence-free and the global optimum for each case is certainly reached. The magnitude of the linear buckling loads follows the sequence  $\text{VAFW8} > \text{VAFW4} > \text{CA}$ .

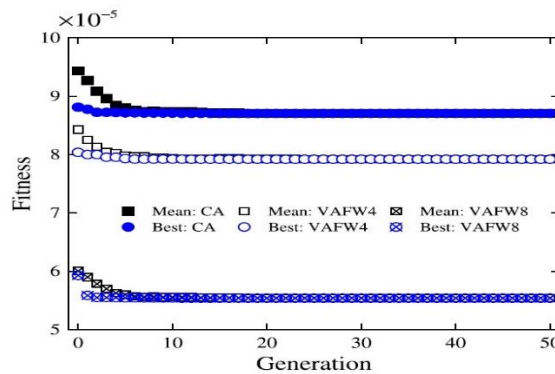


Figure 5.1 Convergence plot of the genetic algorithm highlighting the mean and best individuals of each population over the generations for the three optimization cases.

Table 1 – Elastic , Strength and damage properties used in the simulations

Property	Description	Value
Elastic	Longitudinal elastic modulus ( $E_1$ )	90.0 Gpa
	Transverse elastic modulus ( $E_2$ )	8.5 Gpa
	Poisson's ratio in planes 1-2/2-3 ( $\nu_{12} = \nu_{23}$ )	0.32
	Shear moduli in planes 1-2 and 1-3 ( $G_{12} = G_{13}$ )	4.3 Gpa
	Shear modulus in-plane 2-3 ( $G_{23}$ )	2.1 Gpa

Table 2 - Optimal design variables and eigenvalues for each cylinder.

Design	Optimum angles (in degrees)	$P_{cr}[N]$
MA	50	36,748
CA	58	40,198
VAFW4	<59 59 59 59>	39,874
VAFW8	<55 57 61 57 57 61 57 55>	40,363

The optimum winding angles for every cylinder is presented in Table 2, and the respective fiber paths are shown in Fig. 4.1 (a) shows the design with minimum winding angle (MA) and Fig. 4.1(b) shows the optimized design with constant angle (CA). The first VAFW optimization result for VAFW4 is illustrated in Fig. 4.1 (c), showing a constant winding angle throughout the shell length, meaning that with only two design variables, that geometry and number of layers do not represent a design space large enough to generate a cylinder with variable stiffness. A similar result was reported in a recent study with VAFW cylinders using an enhanced Kriging metamodel for the optimization [10]. The second VAFW optimized design VAFW8, given in Fig 4.1(d), reached the best combination of variable angles to increase the axial buckling capacity. In the optimization procedure, the fiber angles have one decimal place, but the optimal angles reported in Table 2 are rounded. Pressure vessels are vital for storing liquids and gases at high pressures. The vessel's strength is crucial to avert explosive ruptures. Safety codes dictate the design of these containers under specific conditions. Typically, pressure vessels operate at low pressures, constructed from rolled tubes and sheets into cylinders. However, high-pressure vessels necessitate thicker walls for sufficient strength. Interest in shell studies emerged in the mid-twentieth century. Thin shell assemblies are extensively utilized in modern engineering, notably in the aerospace sector. Numerical methods analyze shell vibrations and buckling modes to elucidate critical loads and buckling behaviors. In aerospace and aircraft industries, structural efficiency is paramount. Fiber reinforced composites, prized for their high specific strength and light weight, have diverse applications. Lightweight structures such as aircraft and space vehicle fuel tanks exemplify their use. This study analyzes the design of fiber reinforced multi-layered composite shells, optimizing fiber orientations while minimizing mass under strength constraints for static and buckling assessments. Cylindrical shells, like thin-walled laminated composites, endure various loads from external hydrostatic pressure. Buckling emerges as a critical failure criterion due to these structures' geometry. Stiffened cylindrical shell buckling can be categorized into global, local skin, and stiffener crippling modes. Global buckling involves the simultaneous collapse of the entire structure, whereas local skin and stiffener failures pertain to localized issues in specific components. This work presents an analytical model to predict optimum fiber orientations for given layer thicknesses, focusing on minimizing buckling loads in composite shells with and without stiffeners under continuous angle-ply conditions. The model accommodates various stiffener configurations, ensuring accurate representation on one or both sides of the shell. Stiffened shells having either symmetrical or unsymmetrical shell laminates can also be modeled with equal ease using this model. Grid stiffened cylindrical shells are the shells having a certain kind of stiffening structures either on inner, outer or both sides of the shell and significantly increases the load resistance without much increase in weight. To further reduce the weight, both the shell and the stiffeners are made using fiber reinforced polymers. The promising future of stiffened composite cylinder has in turn led to an extensive research work in this area.

## Conclusion:

The methodologies involve altering fiber orientation in the shell's axial dimension. Optimization was achieved through a genetic algorithm. To maximize VAFW cylinder potential, it is essential to tailor stiffness and buckling traits by adjusting design parameters and optimizing winding angles and tow overlaps to postpone buckling and enhance material strength, as demonstrated in this research. Future studies should quantify the effects of manufacturing variability and material properties on VAFW cylinder performance, while also investigating reliability-centered design under such variability. Finally, the potential of VAFW designs for imperfection-insensitive aerospace structures is under-researched, and the design strategies discussed herein present numerous opportunities for developing less conservative design methodologies.

## Reference:

- [1] Huang Z, Qian X, Su Z, Pham DC, Sridhar N. Experimental investigation and damage simulation of large-scaled filament wound composite pipes. *Composites B* 2020;184:107639. <http://dx.doi.org/10.1016/j.compositesb.2019.107639>.
- [2] Almeida Jr JHS, Faria H, Marques A, Amico S. Load sharing ability of the liner in type III composite pressure vessels under internal pressure. *J Reinf Plast Compos* 2014;33(24). <http://dx.doi.org/10.1177/0731684414560221>.
- [3] Perillo G, Grytten F, Šrbć S, Delhaye V. Numerical/experimental impact events on filament wound composite pressure vessel. *Composites B* 2015;69:406–17. <http://dx.doi.org/10.1016/j.compositesb.2014.10.030>.
- [4] Cui Z, Liu Q, Sun Y, Li Q. On crushing responses of filament winding CFRP/aluminum and GFRP/CFRP/aluminum hybrid structures. *Composites B*



- 2020;200:108341. <http://dx.doi.org/10.1016/j.compositesb.2020.108341>.
- [5] Almeida Jr JHS, Tonatto ML, Ribeiro ML, Tita V, Amico SC. Buckling and postbuckling of filament wound composite tubes under axial compression: Linear, nonlinear, damage and experimental analyses. *Composites B* 2018;149:227–39. <http://dx.doi.org/10.1016/j.compositesb.2018.05.004>.
- [6] Gemi L, K̇klü U, Yazman Ş, Morkavuk S. The effects of stacking sequence on drilling machinability of filament wound hybrid composite pipes: Part-1 mechanical characterization and drilling tests. *Composites B* 2020;186:107787. <http://dx.doi.org/10.1016/j.compositesb.2020.107787>.
- [7] Stedile Filho P, Almeida Jr JHS, Amico SC. Carbon/epoxy filament wound composite drive shafts under torsion and compression. *J Compos Mater* 2018;52(8):1103–11. <http://dx.doi.org/10.1177/0021998317722043>.
- [8] Wang Q, Li T, Wang B, Liu C, Huang Q, Ren M. Prediction of void growth and fiber volume fraction based on filament winding process mechanics. *Compos Struct* 2020;246:112432. <http://dx.doi.org/10.1016/j.compstruct.2020.112432>.
- [9] Rafiee R. On the mechanical performance of glass-fibre-reinforced thermosettingresin pipes: A review. *Compos Struct* 2016;143:151–64. <http://dx.doi.org/10.1016/j.compstruct.2016.02.037>.
- [10] Wang Z, Almeida Jr JHS, St-Pierre L, Wang Z, Castro SGP. Reliability-based buckling optimization with an accelerated kriging metamodel for filament-wound variable angle tow composite cylinders. *Compos Struct* 2020;254:112821. <http://dx.doi.org/10.1016/j.compstruct.2020.112821>.
- [11] Wang Z, Almeida, Jr. JHS, Ashok A, Wang Z, Castro SGP. Lightweight design of variable-angle filament-wound cylinders combining kriging-based metamodels with particle swarm optimization. 2021, <http://dx.doi.org/10.31224/osf.io/3ym95>, Preprint.
- [12] Almeida Jr JHS, Bittrich L, Spickenheuer A. Improving the open-hole tension characteristics with variable-axial composite laminates: Optimization, progressive damage modeling and experimental observations. *Compos Sci Technol* 2020;185:107889. <http://dx.doi.org/10.1016/j.compscitech.2019.107889>.
- [13] Kim BC, Potter K, Weaver PM. Continuous tow shearing for manufacturing variable angle tow composites. *Composites A* 2012;43(8):1347–56. <http://dx.doi.org/10.1016/j.compositesa.2012.02.024>.
- [14] Chauncey Wu K, Turpin JD, Gardner NW, Stanford BK, Martin RA. Structural characterization of advanced composite tow-steered shells with large cutouts. In: 56th AIAA/ASCE/AHS/ASC structures, structural dynamics, and materials conference. American Institute of Aeronautics and Astronautics Inc.; 2015, <http://dx.doi.org/10.2514/6.2015-0966>.
- [15] Gürdal Z, Olmedo R. In-plane response of laminates with spatially varying fiber orientations: Variable stiffness concept. *AIAA J* 1993;31(4):751–8. <http://dx.doi.org/10.2514/3.11613>.
- [16] Guimarães TAM, Castro SGP, Cesnik CES, Rade DA. Supersonic flutter and buckling optimization of tow-steered composite plates. *AIAA J* 2018;57(1):397–407. <http://dx.doi.org/10.2514/1.J057282>.
- [17] Castro SGP, Donadon MV, Guimarães TA. ES-PIM applied to buckling of variable angle tow laminates. *Compos Struct* 2019;209:67–78. <http://dx.doi.org/10.1016/j.compstruct.2018.10.058>.
- [18] Hao P, Liu C, Yuan X, Wang B, Li G, Zhu T, et al. Buckling optimization of variable-stiffness composite panels based on flow field function. *Compos Struct* 2017;181:240–55. <http://dx.doi.org/10.1016/j.compstruct.2017.08.081>.
- [19] Hao P, Yuan X, Liu C, Wang B, Liu H, Li G, et al. An integrated framework of exact modeling, isogeometric analysis and optimization for variable-stiffness composite panels. *Comput Methods Appl Mech Engrg* 2018;339:205–38. <http://dx.doi.org/10.1016/j.cma.2018.04.046>.
- [20] Hao P, Wang Y, Ma R, Liu H, Wang B, Li G. A new reliability-based design optimization framework using isogeometric analysis. *Comput Methods Appl Mech Engrg* 2019;345:476–501. <http://dx.doi.org/10.1016/j.cma.2018.11.008>.
- [21] Hao P, Liu D, Wang Y, Liu X, Wang B, Li G, et al. Design of manufacturable fiber path for variable-stiffness panels based on lamination parameters. *Comp Struct* 2019;219:158–69. <http://dx.doi.org/10.1016/j.compstruct.2019.03.075>.