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TWO LEVEL OPTIMIZATION OF FIBER-PLACED LAMINATED CYLINDRICAL SHELLS OF REVOLUTION

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ABSTRACT

Automated Fiber Placement (AFP) is highly automated manufacturing process which allows for varying fiber orientations resulting in variable stiffness structures. Variable fiber orientation can be sought in an optimization framework for favorable structural response. The purpose of this paper is to show how the structural behavior of cylindrical shells changes through the use of fiber placement in the manufacturing of layers of the cylindrical shell of revolution instead of using constant angle straight fiber layers. For this purpose, two level optimization of fiber placed cylindrical shell of revolution is performed. The first step is the stacking sequence optimization. The second step is the optimization of the parameters of the reference fiber path considering the manufacturing constraints. In this study, to define the fiber path, two methods are tried and results are compared. In the first method, fiber path definition is made that fiber orientation angle changes linearly in the axial direction. In the second method, fiber angle is made to change linearly in the circumferential direction of the cylindrical shell. Structural response results are also compared for the constant stiffness laminate and the variable stiffness laminate. For the optimization purposes, Particle Swarm Optimization (PSO), a robust stochastic optimization technique based on the movement and intelligence of swarms, is used in both steps. PSO algorithm is written by using MATLAB®. Structural analyses are carried out using the finite element program MSC.NASTRAN®. Sample results presented show that the developed PSO algorithm is very successful in optimizing fiber paths of the laminated cylindrical shell of revolution that is studied in the present study.

INTRODUCTION

Composite materials are used commonly in aerospace applications, where primary and secondary structures of aircraft are manufactured with these materials. In the traditional composite manufacturing methods fiber orientation angles are set to some discrete values which limits the design of composite structures because lamina properties are constant throughout the entire ply. The development of automated manufactured process gives a chance to change the stiffness of the composite aircraft parts at the ply level. The fiber placement is an automated manufacturing process which combines the automated tape laying with the filament winding. Fiber placement process and machine which performs the laying up, is seen at Figure 1. Fiber placement machine allows for varying fiber orientations other than traditional orientation and a variety of shapes from simple flat plates, to complex three dimensional forms can be produced.

Knowledge and experience for the fiber placement process is limited, but potential of automated systems gives opportunity to decrease scrap ratio from 100%-50% to 15%-2% when compared to the hand lay-up method, AFP also has greater assurance of repeatability on the free form surface. Advanced composite technologies, like AFP, give also some opportunities like increasing structural

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performance, decreasing cost and weight through the variable stiffness concept that it presents. To use the benefits and effectiveness of AFP, the new analysis and design tools are needed because AFP allows varying fiber orientations other than constant straight fiber paths.

In constant stiffness laminates, orientation angle in a layer is constant, the distance between fibers is constant and layer thickness is constant, whereas in variable stiffness laminates, orientation angle, distance between fibers and layer thicknesses change as a function of position. This variability offers the possibility of redistributing the applied loading so that a more favorable loading condition is encountered in a critical region. As a result, variable stiffness concept offered by the automated fiber placement can be used to improve the structural efficiency, weight and cost of the composite structure.

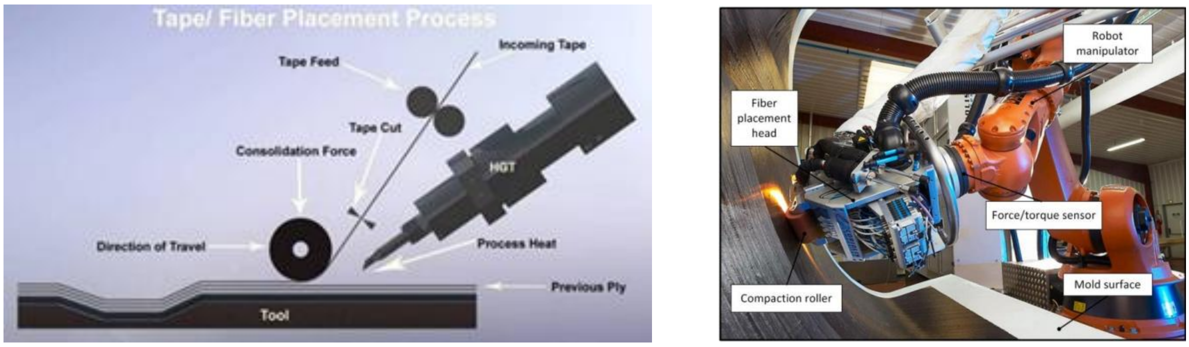

Figure 1 Fiber placement process (Automated Dynamics) and AFP machine

Cylindrical shells can be assumed as a full cylindrical part to symbolize a center fuselage section of an airplane or a D-shaped like cylindrical section to symbolize a helicopter blade spar. To improve the structural performance of such structures, cylindrical shell geometry can be used since the definition of reference fiber path on the cylindrical geometry can be made analytically which simplifies the fiber path definition over the complete cylinder. The composite cylinder can be one piece structural part, so that there is no need for fastener installation such as rivets.

The concept of a continuous, linear fiber angle variation along one direction within a ply to tailor the stiffness of a composite laminate was introduced by Gürdal and Olmedo. The laminate definition for varying fiber can be defined by using parameters denoted by T_0 and T_1 [2]. In this representation, the fiber angle at the center of the laminate is denoted by T_0, T_1 is the fiber angle at a characteristic distance d from the panel center, and the direction angle ∅ determines the direction of variation.[5] These variables are illustrated in Figure 2 and 3.

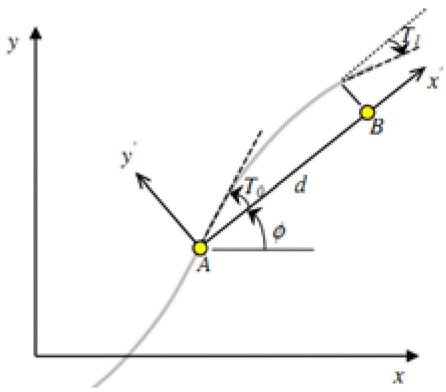

Figure 2 Parameters $\boldsymbol{T_0}$, $\boldsymbol{T_1}$ and ∅ which account for linear change of fiber angle [5]

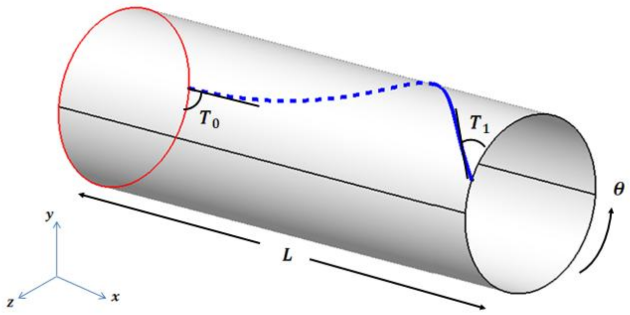

Figure 3 Parameters $\boldsymbol{T_0}$ and $\boldsymbol{T_1}$ on cylinder which accounts for linear change of fiber angle

There have been various studies in the literature on the variable stiffness concept achieved by fiber placement technology. As sample studies in the area of variable stiffness concept, Hyer and Lee [7] have developed finite element models of panels with curvilinear fiber format. The response of laminates composed of layers with fiber orientation varying along a direction has been studied by Tatting and Gürdal[6]. Bloom, et al [1] maximized the overall bending stiffness of circular cylinders by changing the fiber orientation with location in circumferential direction. Buckling loads are also improved by using variable stiffness laminates. [7,11,12,13]

In this study, a cylindrical shell of revolution with clamped edge condition is taken and different in-plane and out-of-plane loads such as pressure, bending and bending with torsion loads are applied to the cylindrical shell structure. The aim is to optimize the fiber placed laminated cylindrical shell in a two level optimization scheme. In the first step, discrete fiber orientation angle optimization is performed assuming that each ply is manufactured by straight fiber composite. In the second step, two reference fiber path definitions are made with two design parameters which account for the linear variation of the fiber angle. In the study, manufacturing constraint of the fiber placement machine is also included in the optimization process. In order to define the fiber path, two methods are tried and results are compared. In the first method, fiber path definition is made that fiber orientation angle changes linearly in the axial direction. In the second method, fiber angle is made to change linearly in the circumferential direction of the cylindrical shell. While optimizing the cylindrical shell structure, it is also aimed to see the difference between the constant ply angle laminates and the variable fiber angle ply laminates in terms of structural response. For the structural analysis MSC.NASTRAN® is used. For the optimization purposes, Particle Swarm Optimization (PSO), a robust stochastic optimization technique based on the movement and intelligence of swarms, is used in both steps. All codes used in the study are written in MATLAB® and codes are integrated again in the MATLAB® environment. Results presented show that the developed PSO algorithm is very successful in optimizing the fiber paths of the laminated cylindrical shell of revolution that is studied in the present study.

OPTIMIZATION PARAMETERS

Different approaches have been used to the model fiber placed laminate and to study its response. Gürdal and Olmeda developed a method, which is based on the variation of the the fiber orientation angle spatially throughout the structure as a function of position[2,3,5]. A limited number of design variables are used to define a reference path. The formulation with the minimum parameters decreases the time consumed for the optimization and the design. After the reference path is defined, other plies are constructed by shifting paths in the direction perpendicular to the direction of variation. Shifted paths essentially are identical to the reference path. In the first method, the direction of variation changes along the axial direction and reference path is shifted along the circumferential direction. Therefore, the cylinder manufactured using the first method is called as axially varying variable stiffness cylinder, as seen in Figure 4. If the direction of variation is circumferential and reference path is shifted along axial direction, then the cylinder manufactured is called as circumferential varying variable stiffness cylinder, as seen in Figure 5.

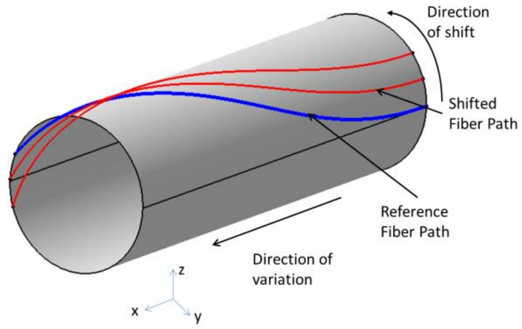

Figure 4 Axial angle variation on the cylinder

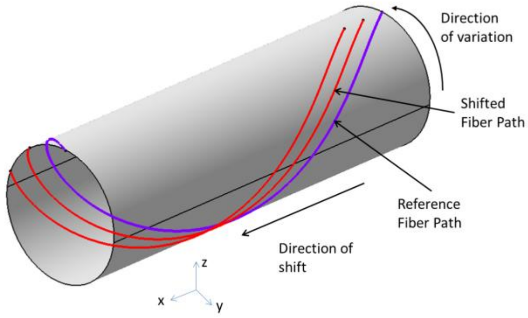

Figure 5 Circumferential angle variation on the cylinder

Mathematical expressions are derived to define the fiber paths with varying fiber angles to generate the fiber placed cylinders, and to determine the laminate stacking sequence as function of location for both axially and circumferentially varying fiber orientation angle. The laminate definition for varying fiber can be defined by using two design parameters T_0 and T_1 as illustrated before in Figure 2 and 3. The fiber angle at the root section of the laminate is denoted by T_0 , the fiber angle T_1 is defined at a characteristic distance from the root section. In this study, direction angle Ø is optimized in the first level optimization and the parameters T_0 and T_1 are optimized in the second level using particle swarm optimization algorithm. In the first approach, the orientation angle $\varphi(x)$ changes linearly in the axial direction, and $\theta(x)$ changes throughout the circumferential direction for the axially varying stiffness laminate as described by Eqs. (1) and (2). On the other hand, in the second approach, the orientation for the fiber path with a circumferentially varying fiber orientation is defined by $\varphi(\theta)$ and $\boldsymbol{x}(\theta)$ as given Eqn. (3) and (4).

$$\varphi(x) = T_0 + (T_1 - T_0)x/L \qquad (1)$$

$$\theta = \frac{L}{R(T_1 - T_0)}(In(\cos(T_0) - \ In(\cos(\varphi) \qquad (2)$$

$$\varphi(\theta) = T_0 + (T_1 - T_0)\theta/2\pi \qquad (3)$$

$$x = \frac{2\pi R}{(T_1 - T_0)}(In(\sin(\varphi) - \ In(\cos(T_0)) \qquad (4)$$

OPTIMIZATION METHOD

The optimization method used is Particle Swarm Optimization which is a robust stochastic optimization technique based on the movement and the intelligence of swarms [8]. PSO optimizes a problem by having a population of candidate solutions, here dubbed particles, and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity. Each particle's movement is influenced by its local best known position and is also guided toward the best known positions in the search-space. The particles are updated as better positions are found by other particles. This is expected to move the swarm toward the best solutions.

The PSO algorithm and other algorithms, which are coded in MATLAB®, provide the optimization calculation along with the writing and reading of input and output files and calling for Nastran to run within the MATLAB® environment.

Optimization Methodology

A general optimization problem is about determining design variables, x, to minimize the function.

F(x) and subject to a set of inequality constraints g(x) and equality constraints h(x). The mathematical expression of this problem is expressed as;

$$Minimize \;\; F(x) \tag{5}$$

$$Subject\ to; \qquad g_i(x) \geq 0 \qquad i = 1,2, \dots n_g \tag{6}$$

$$h_i(x) = 0 \qquad i = 1,2, \dots n_h \tag{7}$$

$$x_i^L \leq x_i \leq x_i^U \quad i = 1,2, \dots \tag{8}$$

The penalty function method is the modification of objective function F(x), such that the new objective function now includes the constraints. Once the objective function is modified through the penalty function method, then, the optimization problem can be solved as an unconstrained problem. Modification of the objective function is achieved by adding penalty function P(x) to objective function and defining r_h and r_g which are penalty function multiplier.

$$F(x, r_h, r_g) = F(x) + P(x, r_h, r_g) \tag{9}$$

$$P(x, r_h, r_g) = r_h * \sum_{i=1}^{l} h_i(x)^2 + r_g * \sum_{i=1}^{m} \max(0, g_i(x))^2 \tag{10}$$

The optimization method consists of two steps. For those steps, modifications are done by using penalty function. The first step of the optimization is the stacking sequence optimization. Optimum direction angle ∅ is determined for each ply in the laminate. First, the geometry, mesh, loads, boundary conditions and the material information are given as input to the main Matlab code. Another input data comes from Matlab code, which performs the Particle Swarm Optimization (PSO). After the processing of the input files, the main code prepares the input file for MSC.NASTRAN®. The structural analyses are carried out using the finite element program MSC.NASTRAN®. After the completion of the structural analysis, the output file of MSC.NASTRAN® is read by another Matlab subroutine and the results are evaluated by the PSO subroutine. If the optimum results are obtained based on a criterion, the program terminates, or else the program continues to perform design iterations in a cyclic form as shown in Fig.6. The stopping criterion of the optimization process is defined as getting the same result by two times after two consecutive runs of the whole optimization process. After the first optimization cycle, the optimum results are obtained, but program is not stopped to prevent getting the local optimum results and to be sure if the results are global optimum or not. Second optimization cycle starts with using the first results in a new population. If the same results are found in the second cycle, then the program stops, if not, program continues until the same results are determined for the two consecutive complete optimization runs.

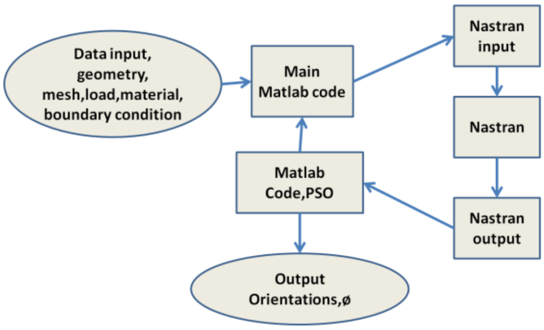

Figure 6 Optimization cycle

In the second level of the optimization process, the reference fiber path is defined in terms of two parameters T_0 and T_1 which are the design variables to be optimized for the reference fiber path definition. Like the first level optimization, the geometry, mesh, loads, boundary conditions and the material information are given as input to the main Matlab code and the second level starts. The same steps of the optimization are followed in the second level as illustrated Figure 6. The aim is to find the optimum values of parameters which define the reference fiber path. To assign the shell properties to the finite element model, the center of a given finite element is located as a first step. Then, the distance between the center of element and the shifted paths are calculated. If the distance is less than half of the tow width for any shifted path, the thickness of the tow is assigned to the element. This process is repeated for all elements in the analysis model. It should be noted that an element may get thickness contribution from more than one shifted path resulting in thickness overlap. The sample discretized laminate with overlap distribution for the finite element model is shown in Figure7. In Figure 7, overlap distribution is given by the red colored elements which are 1.5 times thicker than the elements with white color. Main MATLAB code is used to organize the preparation and writing of the input and the output files. Particle swarm optimization routine is used as the optimizer MSC.NASTRAN® is used as the structural solver until optimum T_0 and T_1 are obtained utilizing the same stopping criteria that is used in the first level optimization. For the first level and second level optimizations, the orientation angles are discretized and discrete design variables are used for $\emptyset$, T_0 and T_1. The discretization interval is taken as 3 degrees in the design space for $\emptyset$, T_0 and T_1 .

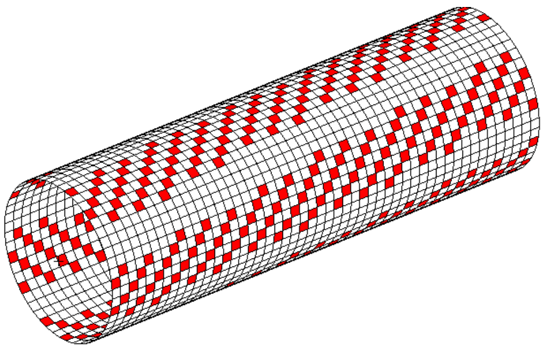

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Figure 7 Finite element model, overlap distribution

In both levels of the optimization process, the cylinder structure is analyzed using the commercially available finite element program MSC.NASTRAN®. The element properties are implemented using a user subroutine written in MATLAB®. The subroutine writes the laminate properties for each element to the Nastran input file and the output file of Nastran is again read by Matlab code as illustrated in Fig. 6.

MANUFACTURING CONSTRAINT

In fiber placement method, manufacturing constraint is dominant to be considered during the optimization and analysis process. In this study, manufacturing constraints are also considered. Specifically, curvature constraint is imposed during the optimization process to prevent the local wrinkling of the tow. Curvature is the minimum turning radius of a central fiber path. When the curvature constraint is violated, local fiber buckling may occur as seen in Figure 8. A minimum turning

radius of 635 mm is suggested by Nagendra et al.[14] to prevent local fiber buckling for a tow width of3.175mm .
In the present study, curvature constraint is implemented by calculating the radius of the curvature for the reference path and checking it against the turning radius constraint imposed. After one reference curve is defined which does not violate the curvature constraint, by shifting the reference path in the direction perpendicular to the axis of fiber orientation variation, the remaining of the ply can be constructed utilizing the shifted paths.

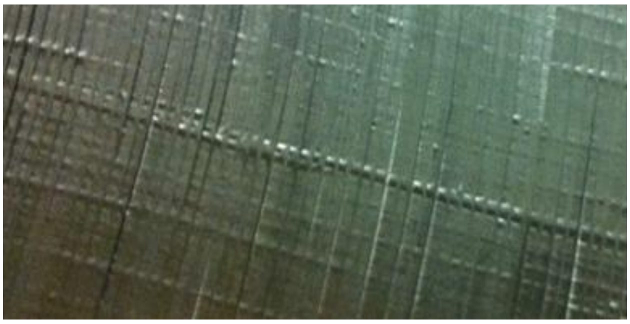

Figure 8 Local fiber buckling

Gaps and overlaps between tows must be simulated correctly by doing analysis. Figure 9 and 10 show the gap and the overlap of two courses. In the finite element analysis, if overlap exists between two curved courses, the shell element gets thickness contribution of overlapping tows. If the surface is not covered by tow and there is a gap between tows, the shell element does not take the thickness of tows. While the constant stiffness laminate thickness is constant, thickness of the variable stiffness laminate changes because of the gap and overlaps. Therefore, to compare the weight of constant and variable stiffness laminates, mean thickness is used. The mean thickness is calculated by summing element thicknesses and dividing the sum by the total number of elements.

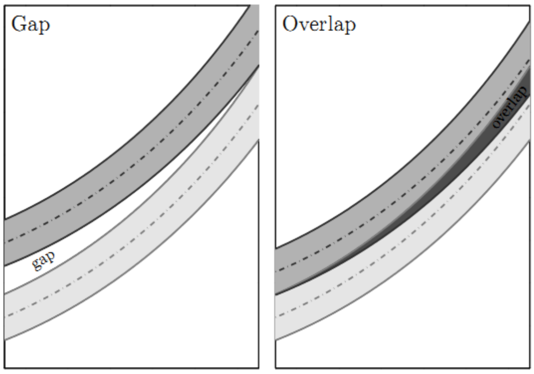

Figure 9 Gap and overlap between two courses[1]

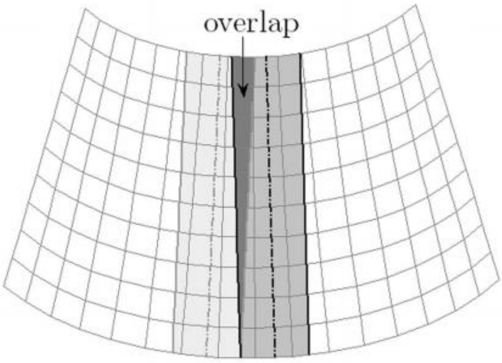

Figure 10 Overlapping courses on curved surface[1]

If overlap or gap is not wanted in the ply, the fiber placement machine's overlap/gap parameters can be used. If the overlap ratio is 0%, the machine is not let overlap between two courses as shown Figure 11, white areas are the gaps, and if the overlap ratio were 100%, there will be no gap between the courses but then overlaps would exists.

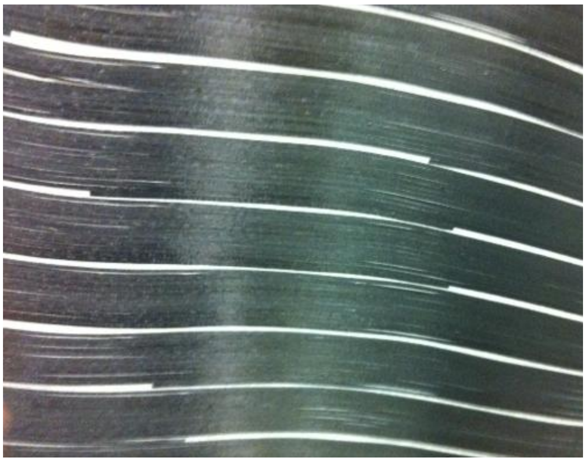

Figure 11 Ply lay-up with 0% overlap ratio

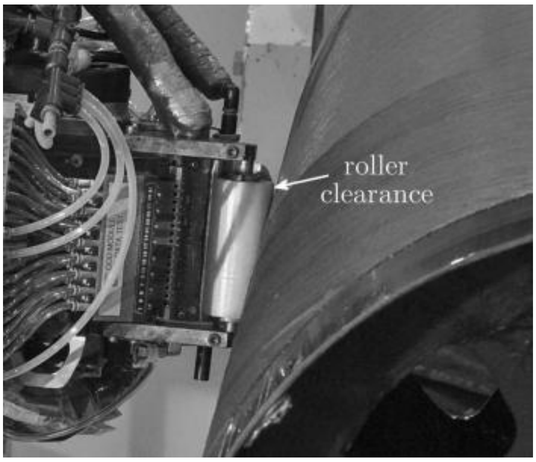

Figure 12 Roller clearance on the cylinder surface [1]

The cylinder tool surface for lay-up is contoured so that the rigid compaction roller leads to non-uniform pressure distribution to tows. The centers of tows are exposed higher pressure than sides because of the roller clearance as seen at Figure 12. For the contoured surface, tow number for the lay-up must be taken into account for design consideration. In the present study, in one pass 12 tows are placed on the mold surface and each tow has a width of 3.175 mm. Other design considerations for the manufacturing are the heat flux, head pressure and lay-up speed parameters. These parameters are depends on the fiber placement machine. In this study, the effect of these parameters are not taken into account, but as a future work, they can be investigated by performing tests on specimens manufactured by changing process parameters and the effect of these parameters can be better understood, and optimum combination of parameters can be defined for the manufacturing.

RESULTS AND DISCUSSION

Before demonstrating the PSO code for structural optimization purposes, the PSO code is verified by a benchmark problem to test the convergence and accuracy. After the benchmark problem, the structural optimization problems are performed and the results which are obtained are presented.

Verification problem

The verification case is defined in Figure 13. The objective is to minimize the function defined in Eq.(11) subject to the constraint defined in Eq.(12). The design variables are X_1 and X_2.

$$f(X_1, X_2) = 0.25 * X_1^4 - 3 * X_1^3 + 11 * X_1^2 - 13 * X_1 + 0.25 * X_2^4 - 3 * X_2^3 + 11 * X_2^2 - 13 * \ X_2 \quad (11)$$

$$g_1(X) = 4 - X_1 - X_2 \leq 0 \quad (12)$$

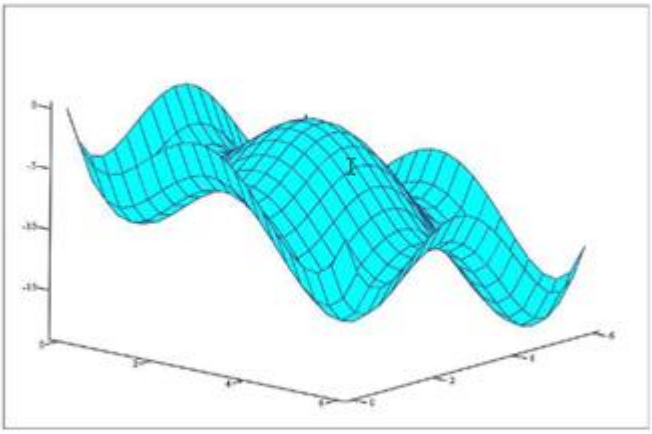

Figure 13 Verification Problem

The PSO algorithm gives the minimum at point $(X_1, X_2\,)$ at $(5.3145,5.2643)$ with $f(X_1, X_2\,) = 18.55$. The exact minimum is 18.568 for this problem. Error is determined as 0.09 % compared to the exact minimum of the function. The search space is composed of 10^8 elements, and the convergence is obtained in less than 0.03 % of the search space.

For the cylinder optimization problem, the objective function of all optimization problems is taken as maximizing the buckling load subjected to the constraints given by Eqs. (14) and (15) for the constant stiffness laminate optimization problem and Eqs.(17)-(19) for the laminate optimization with fiber orientation angle variation in the axial and circumferential directions. In all problems, Tsai-Hill failure criteria is applied to calculate failure index. The cylinder studied has a length of 635 mm (25”) and radius of 101mm (4”). To construct the cylinder structure, intermediate modulus carbon fiber material is used for this study.

For the constant stiffness laminate optimization;

$$Objective; \quad Maximize \quad Buckling\ Load\ Factor \quad (13)$$

$$Maximum\ Failure\ Index \leq 1 \quad (14)$$

$$Maximum\ Deflection \leq \frac{L}{200} \quad (15)$$

For the laminate optimization with fiber orientation angle variation in the axial and circumferential directions:

$$Objective; \quad Maximize \quad Buckling\ Load\ Factor \quad (16)$$

$$Maximum\ Failure\ Index \leq 1 \quad (17)$$

$$Maximum\ Deflection \leq \frac{L}{200} \quad (18)$$

$$Maximum\ Curvature \leq \frac{1}{635} \quad (19)$$

In the results tables of optimized solutions corresponding to different load cases, optimum orientation angles are given in the first column. The maximum deflection, maximum failure index, mean thickness and the buckling load factor are given column by column. The mean thickness is calculated by summing the thickness of all elements and dividing the sum by element number as shown in Eq.(20). The tow thickness is taken 0.13 mm and it is assumed to be constant. Symmetric and balanced 8 ply laminate is used for the constant and variable stiffness laminates. The mean thickness is constant and 1,04 mm for the constant stiffness and 8 ply symmetric balanced laminate. However, for variable stiffness laminates, although the tow thickness is constant, the laminate thickness changes because of the overlaps and the gaps. The weight increase in laminate can be compared by calculating mean thickness, so the results of constant stiffness and variable stiffness laminate can be compared easily.

$$Mean\ Thickness = \frac{\sum_{m=1}^{Element\ number} Element\ Thickness(m)}{Element\ Number} \tag{20}$$

The buckling load factor (BLF) is the factor of safety against buckling, in other words it is the ratio of the buckling load to the applied loads.

Pressure Load Case

Composite cylinder structure is investigated under pressure loading. Maximizing the buckling load factor is specified as the objective of the optimization study. As for the load case, one side fixed and pressure load is applied from other side to compress the structure as seen in Figure 14. Results of the PSO optimization are summarized in Table 1.

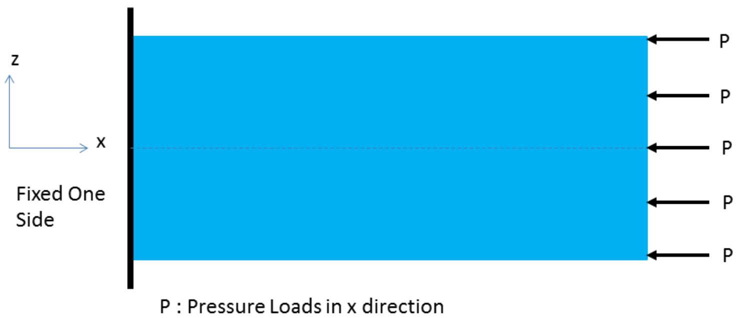

Figure 14 Pressure Load Case

Table 1 Optimization results under pressure loading

	Optimum Orientation (degree)	Max. Def (mm)	Max. FI	Mean Thickness(mm)	BLF
Quasi-İsotropic Laminate	$[<0/90/\pm45>]_s$	0,6818	0,0953	1,04	0,8385
Constant Stiffness Laminate	$[<\pm3/\pm75>]_s$	0,702	0,0931	1,04	1,0194
Axial Variable Stiffness Laminate	$[<0/30><51/69>]_s$	0,7323	0,2934	1,4531	1,9116
Circumferential Variable Laminate	$[<39/36><90/51>]_s$	2,385	0,1816	1,4595	1,1716

In the results Table 1, the first row is the structural response of the quasi isotropic laminate. The orientation angle $\emptyset$ is optimized in the first level optimization and the results are given in the second row. So, for the end pressure load case, optimum direction angles are determined as 3^0 and 75^0 in the 8 ply symmetric balanced laminate. T_0 and T_1 angles are optimized by using axial variable stiffness laminate approach, and the orientation angle $\emptyset$ is taken zero degree for this case.). The third row of Table 1 shows the structural response for the cylinder with axially variable stiffness case. The last row of Table 1 shows the structural response of the circumferentially variable stiffness laminate and again optimization parameters are T_0 and T_1 and the direction angle $\emptyset$ is again taken as zero degree.

Comparing the results line by line, firstly it is seen that using different orientation other than $0^0, 90^0$ and $\pm45^0$ increases the buckling load factor. It is seen that although the thickness of the constant stiffness laminate is the same as that of quasi-isotropic laminate, BLF of the constant stiffness laminate is 22% higher than the BLF of the quasi-isotropic laminate. For the laminate with axially varying stiffness, BLF is approximately twice of the BLF for the constant stiffness laminate. When using circumferential and axial variable stiffness laminate, the thickness change approximately the same, but laminate performance is not same. Other structural performance, maximum deflection and maximum failure index results both satisfy the constraints.

Bending Load Case

Under bending loading as seen Figure 15, the loads are applied to center of the cylinder by applying multi point constraint (MPC) to node at the section. In this load case, one side of cylinder is under compression and the other side is under tension, and buckling load is critical for the compression side. Again the objective of the optimization is stated as the maximization of the buckling load. Results of the optimization performed by the PSO algorithm are summarized in Table 2.

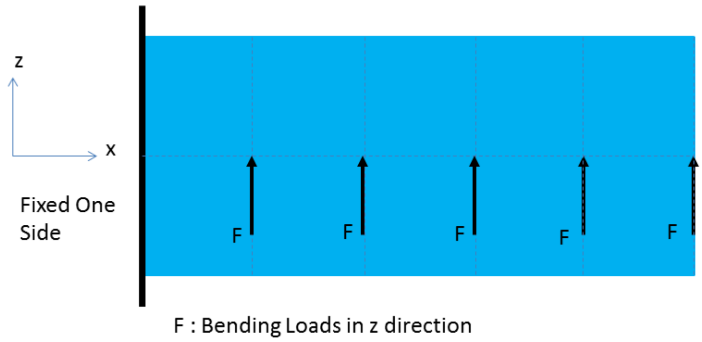

Figure 15 Bending Load Case

Table 2 Optimization results under bending loading

	Optimum Orientation (degree)	Max. Def (mm)	Max. FI	Mean Thickness(mm)	BLF
Quasi-İsotropic Laminate	$[<0/90/\pm45>]_s$	0,6199	0,0116	1,04	13,2984
Constant Stiffness Laminate	$[<0/90/\pm33>]_s$	0,7056	0,0158	1,04	14,2
Axial Variable Stiffness Laminate	$[<75/21><51/75>]_s$	0,3175	0,0047	1,8	28,3836
Circumferential Variable Laminate	$[<45/45><51/21>]_s$	0,94	0,0256	1,83	20,93

Looking at the results, axial stiffness laminate results are the best compared to the other cases. The overlaps improve the buckling load factor of the cylinder. It is noted that for the cylinder with the axially variable stiffness laminate while the thickness change is 80%, the buckling load change is 100% when compared to the cylinder with constant stiffness.

Combined Bending and Torsion Load Case

Combining bending and torsion loads, the loads are applied the cylinder center section by section by applying MPC to nodes at the sections, and other side is fixed again as seen in Figure 16. Under torsional loading for tubular structure, buckling is a critical case, and affects the design of structure.

The aim of this optimization is to get optimum laminate under combined loading. Results are summarized in Table 3.

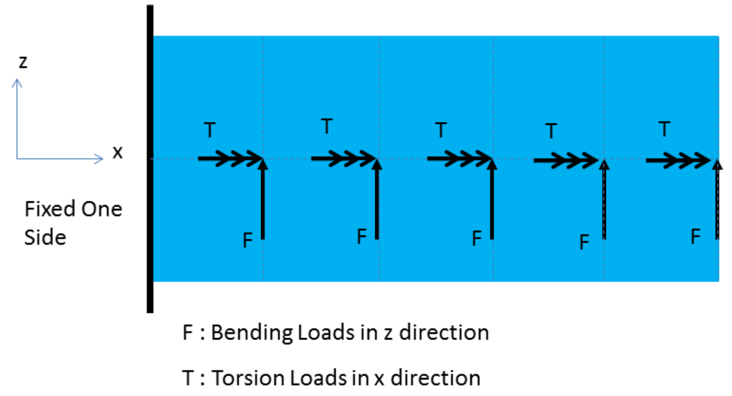

Figure 16 Combined Load Case

Table 3 Optimization results under combined loading

	Optimum Orientation (degree)	Max. Def (mm)	Max. FI	Mean Thickness(mm)	BLF
Quasi-İsotropic Laminate	$[<0/90/\pm45>]_s$	0,8075	0,143	1,04	12
Constant Stiffness Laminate	$[<0/90/\pm33>]_s$	0,64	0,09	1,04	13,1
Axial Variable Stiffness Laminate	$[<33/3><66/21>]_s$	0,85	0,0091	1,1893	18,27
Circumferential Variable Laminate	$[<48/42><75/90>]_s$	0,5835	0,0044	1,2823	12,9

The results of the combined load case again shows that by using variable stiffness laminate, buckling load factors can be improved compared to the buckling load factors of cylinders with quasi-isotropic laminate and optimized constant stiffness laminate.

CONCLUSION

Automated fiber placement is an innovative technique for manufacturing of composite structures. The analysis of composite structure manufactured by AFP needs a different approach, therefore in the present study, analysis and optimization code for AFP is developed. Manufacturing constraints of AFP is also added to the optimization process. The manufacturing of the variable stiffness laminates is not possible when the curvature constraint is not taken into account. The curvature constraint is imposed because the fiber placement machines which are used in manufacturing have limitations on the minimum radius of curvature. In addition, in order to prevent the wrinkling of the fiber, a constraint must be applied on the minimum radius of curvature.

AFP allows varying fiber orientation and the fiber orientation angle is one of the most significant variables affecting the mechanical behavior of the composite laminates. Therefore, to see how fiber placed structure response changes with the fiber orientation under some load cases, MSC.NASTRAN® finite element solver and MATLAB PSO algorithm are coupled. For this purpose, an interface code is developed in MATLAB environment.

In the present study, the stiffness and the buckling capacity of the fiber placed laminated cylindrical shell of revolution is studied. This study aims to generate an output for the design and the manufacturing of the composite cylinder structure manufactured with AFP. In the first step, the optimum constant stiffness laminate is obtained. For the constant stiffness case, ply angle is constant throughout the laminate in each ply. In the second step, the optimum fiber placed variable stiffness laminate is obtained. With the curvilinear fiber paths more favorable stress distributions and improved laminate performances are obtained. Two different fiber path definitions were used to lay-up the fibers on the laminate. The results of the present study shows that laminate with axial variation of the fiber orientation angle gives better buckling load factor values compared to laminate with circumferential variation of the fiber orientation angle.

At this point, there appears to exist enough potential benefits in the variable-stiffness design. The stiffness values are generally improved compared to the quasi-isotropic and constant stiffness laminate. It shown that variable stiffness concept can be applied to improve structural response of the cylindrical shell of revolution. More experimental researches of tow-placed variable-stiffness laminates are also necessary to validate the theoretical models. The manufacturing of the laminates similar to those modeled in this research is necessary to determine how the tow-placement machines perform on such complex parts. An experimental research could also give more insight into the effects of changes on thickness. Similarly, the investigation of the failure behavior of the tow-placed variable-stiffness composite laminates should also be performed and comparison with theoretical results should be made.

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