ANALYSIS AND OPTIMIZATION OF AUTOMATED FIBER PLACED ROTORCRAFT COMPOSITE TAIL BOOM

Sedat GULDU, Anil KOCKAR, Gokhan TURSUN
sguldu@tai.com.tr, akockar@tai.com.tr, gtursun@tai.com.tr

Turkish Aerospace Industries, Inc. (TAI),
Helicopter Group
Ankara, Turkey

Abstract

Automated Fiber Placement (AFP) is highly automated manufacturing process which allows for varying fiber orientations other than traditional orientation. A varying fiber angle might be favorable for structural performance of composite tail boom but it is almost not possible to analysis varying fiber placed structure and optimize fiber path by a commercial program. The purpose of this paper is to generate analysis and optimization tool for composite tail boom manufactured by AFP. Some of design parameters related to AFP manufacturing is also added to finite element model. The manufacturing constraint is also taken into account in optimization process. The tail boom is the primary structure of helicopter thus the structural performance is also investigated. Structural analysis is carried out by using MSC.Nastran. An interface algorithm is written in MATLAB to give input file for MSC.Nastran. Furthermore, tests are carried out in order to verify analysis. Particle Swarm Optimization (PSO), a robust stochastic optimization technique based on the movement and intelligence of swarms, is used and code generated by using MATLAB.

1. INTRODUCTION

Composite materials are used commonly in aerospace applications, where primary and secondary structures of aircrafts are manufactured. Traditional composite manufacturing methods and orientation (0^0, 90^0, $\pm45^0$.) limits to the design of composite structures since lamina properties are constant throughout the entire ply and generally it is not possible to use other orientations. The development of automated manufactured process gives a chance to alter some aircraft parts by an automated produced one. The fiber placement is an automated manufacturing process which combines the automated tape laying with the filament winding and a schematic representation of fiber placement process is given in Figure 1 [1,2,13]. It allows for varying fiber orientations other than traditional orientation and a variety of shapes from simple flat plates, to complex three dimensional form can be produced.

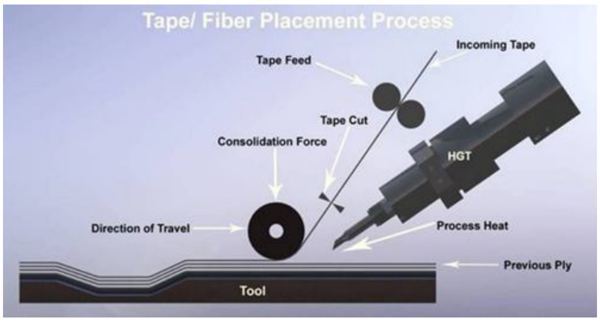

Figure 1 Fiber placement process (photo courtesy of Automated Dynamics)

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 hand lay-up method. AFP also has greater assurance of repeatability on free form surface. Advanced composite technologies, like AFP, give also some opportunities like increasing structural performance, decreasing cost and weight. To use the benefits and effectiveness of AFP, the new analysis and design tools are needed since AFP allows for fiber orientations other than 0^0, 90^0, and $\pm 45^0$.

The fiber orientation within a ply can be continuously varied as a function of position. This gives possibility to redistribute an applied loading so that a more favorable loading condition is encountered in a critical region. As a result, it can be used to improve the structural efficiency, weight and cost reduction of composite structures.

The tail boom is one of the primary structures of a helicopter. It houses portions of the tail drive mechanism, support for the tail rotor and give torque for the balance of main rotor. Aluminum tail booms are used mostly, but automated composite manufacturing is offering great corrosion resistance and stiffness properties. The composite tail boom can be one piece cone part, so that there is no need to fastener installation such as rivets and this reduces assembly time.

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 [2]. The laminate definition for varying fiber can be defined by using T_0, T_1. The fiber angle at the center of the laminate is T0, the fiber angle T1 is at a characteristic distance d from the panel center, and the direction angle Ø is determining the direction of variation [4]. These variables are illustrated in Figure 2 and Figure 3.

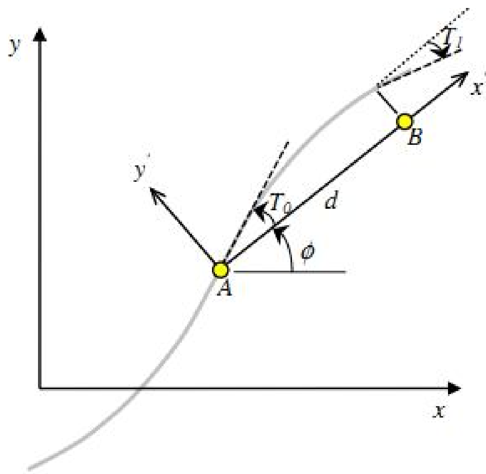

Figure 2 Fiber path parameters

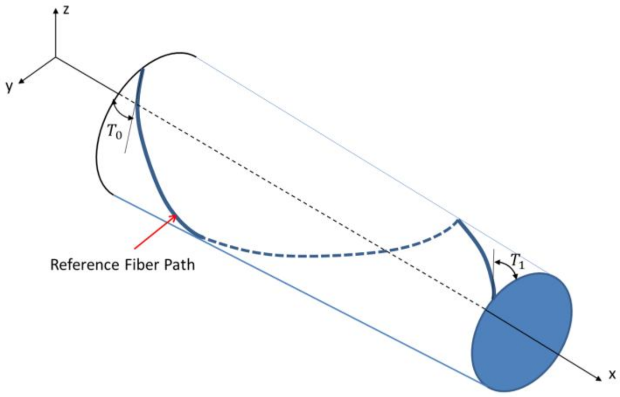

Figure 3 T_0 , T_1 and reference path

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 [5] 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 [5]. Buckling loads are also improved by using variable stiffness laminates. [6,10,11,12]

Conical shells can be assumed to symbolize a helicopter tail boom. To improve the structural performance of such structures, conical shell geometry can be used since the definition of reference fiber path on the conic geometry can be made analytically. This simplifies the fiber path definition over the complete conic.

This study is presented in two sections. First section consists of manufacturing considerations; which parameters and how they can be added to analysis model is investigated. In the second section, analysis and optimization results are represented. Structural analysis is carried out by MSC.Nastran. Stress, displacement, buckling, natural frequencies, etc. are found by FEM analysis. The fiber path can be defined mathematically on conical shells [1]. Conical shells can be representative of a tail boom and the path can be optimized by using PSO.

For this purpose, a conical shell with clamped boundary condition at root condition is modeled. Intermediate modulus carbon fiber material are used for the analysis. The most critical case is chosen and the shear, bending and torque loads which are coming from tail rotor blade system are applied at the tip section. The conical shell geometry is seen at Figure 4:

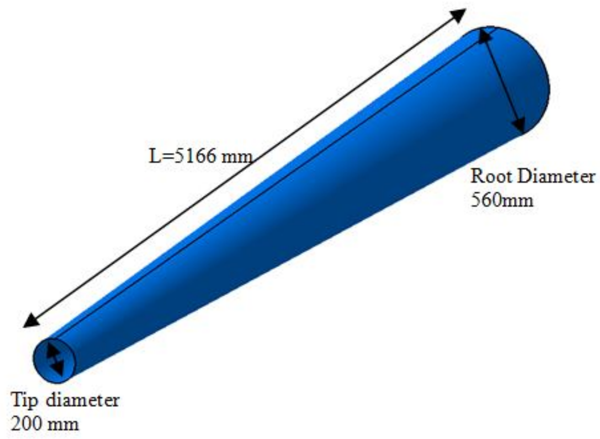

Figure 4 Conical shell dimension

While optimizing the conical shell structure, it is also aimed to see the difference between the constant ply angle laminates and variable fiber angle ply laminates in terms of structural response. For the structural analysis MSC.NASTRAN® is used. All optimization codes used in the study are written in MATLAB® and codes are integrated in MATLAB® environment. Results presented show that the developed PSO algorithm is very successful in optimizing fiber paths of the laminated shell of revolution that is studied in the present study.

2. ANALYSIS OF FIBER PLACED STRUCTURE

In the analysis of a tail boom, the conical shell can be used. The element properties on shell, varies in the axial direction linearly. It is not possible to give property for all elements one by one as the element thicknesses are changing because of overlaps and gaps. Owing to cone geometry, cross sectional area decreases from root to tip, the overlaps increase at the tip. The overlaps can be observed apparently in Figure 5. To decrease overlaps at tip, the cone is separated by 3 section.

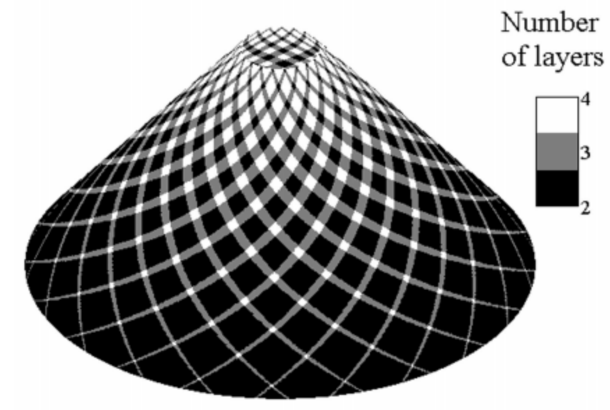

Figure 5 Overlap distribution over conical surface [1]

A special code is needed so as to generate properties for all elements by using fiber path definition. The code is capable of reading the element location, and determines element properties. By using information about materials, thickness, orientation, the input file for MSC. Nastran® is prepared.

3. OPTIMIZATION TOOL

The Particle Swarm Optimization method which is a robust stochastic optimization technique based on the movement and intelligence of swarms is used in this study [7]. 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, which 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 another algorithms that are generated by MATLAB®, provide the optimization calculation along with the writing and reading of input and output files and calling for Nastran runs from MATLAB® environment.

4. OPTIMIZATION METHODOLOGY

The optimization methodology for fiber path starts with parameter optimization. Fiber path parameters T_0 and T_1 will be optimized. Firstly, previously defined data input for main Matlab code is generated. The data consists of geometry, mesh, loads and boundary conditions. Another input data is coming from another Matlab code, which is Particle Swarm Optimization (PSO) subroutine. After processing input files, the main code generates the input file for MSC.Nastran and solves it. Subsequently, the output file of MSC. Nastran is read by another Matlab subroutine and the results are evaluated by PSO subroutine. If the optimum results are obtained, the program terminates, else the program is going on the cycle like Figure 6. 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 Figure 6. The stopping criterion is getting the same result by two times. After the first optimization cycle, the optimum results are obtained, but program is not stopped to prevent getting local optimum results and to be sure about results are global optimum or not.

After one path is defined, other paths are defined by shifting the reference path.

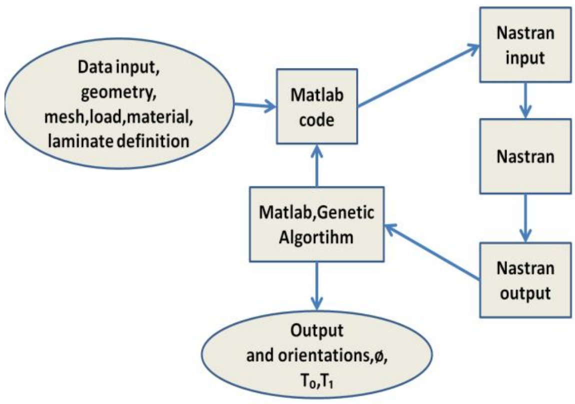

Figure 6 Optimization chart

5. MANUFACTURING CONSTRAINTS

Manufacturing constraints are dominant for optimization and analysis. Curvature constraint prevents local wrinkling of tow. Curvature is minimum turning radius of a central path to violate curvature constraint causes local fiber buckling as seen at Figure 7. A minimum turning radius of 635 mm is suggested by Nagendra et al.[8]. Decreasing the turning radius causes wrinkle out-of-plane, and this leads to imperfection and decreases load-carrying capacity.

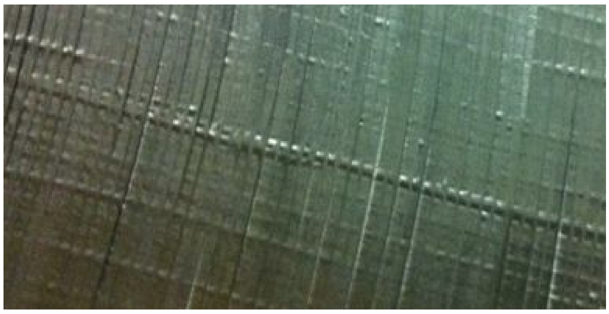

Figure 7 Local Fiber Buckling

Gaps and overlaps between tows must be simulated correctly by doing analysis. Figure 8 and 9 shows that gap and overlap of two courses. If overlap exists between two curved courses, the shell element takes the thickness of 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.

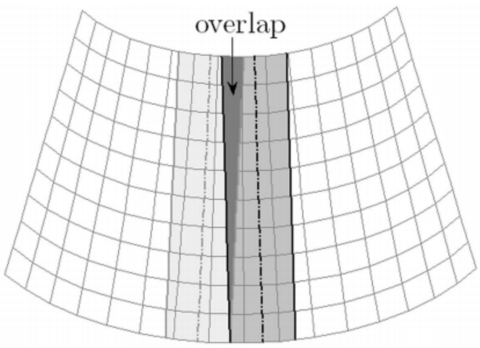

Figure 8 Overlapping courses on curved surface [1]

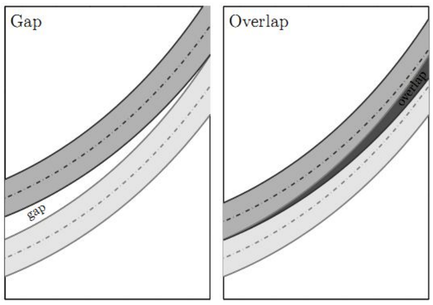

Figure 9 Gap and overlap between two courses [1]

If overlap or gap is not desired in the ply, the machine overlap/gap parameters can be used. If overlap ratio is 0%, the machine does not let overlap between two courses like Figure 9. White areas are the gaps, if the overlap ratio was 100%, there will be no gap between the courses and overlaps will exist.

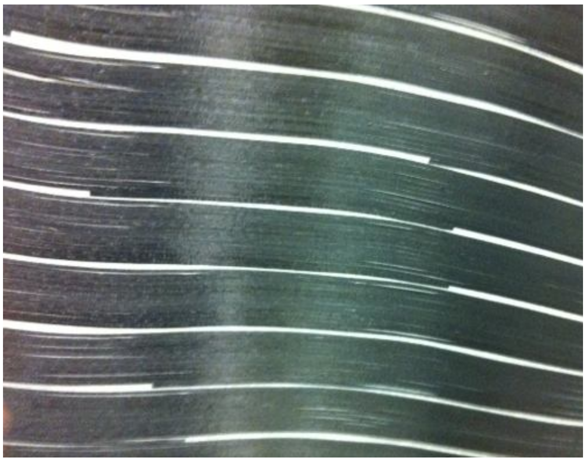

Figure 10 0% overlap ratio ply lay-up

Another design considerations for the manufacturing are the heat flux, head pressure and lay-up speed parameters. These parameters depend on the fiber placement machine. The effects of these parameters are not taken into account, but they can be investigated by different test and the effect of these parameters can be understood. The optimum combination of parameters can be defined for manufacturing.

Mandrel for manufacturing is another important point, because it must have enough rigidity for head pressure and there must be no sag at mandrel. Considering these points, the mandrel is designed like in Figure 11.

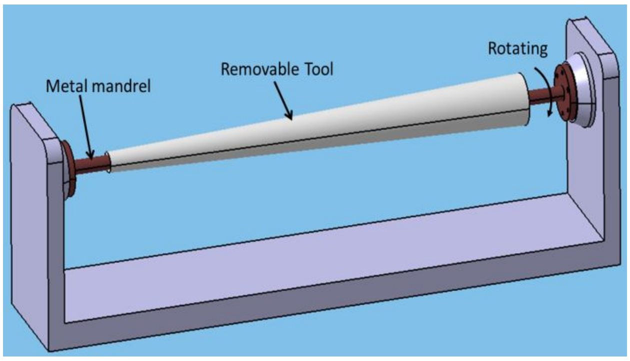

Figure 11 Mandrel for manufacturing of tail boom

After the lay-up and curing, the conical laminate must be removed from mandrel. For this purpose, removable tools can be used. This tool can be bladder with inside removable foam, aquapour or paraplast. The cone can be removed from the mandrel easily, one piece, seamless the tail boom cone can be obtained.

The tool surface is contoured so that the rigid compaction roller leads to non-uniform pressure distribution to tows. The centers tows are exposed higher pressure than sides due to the roller clearance as seen in Figure 12.

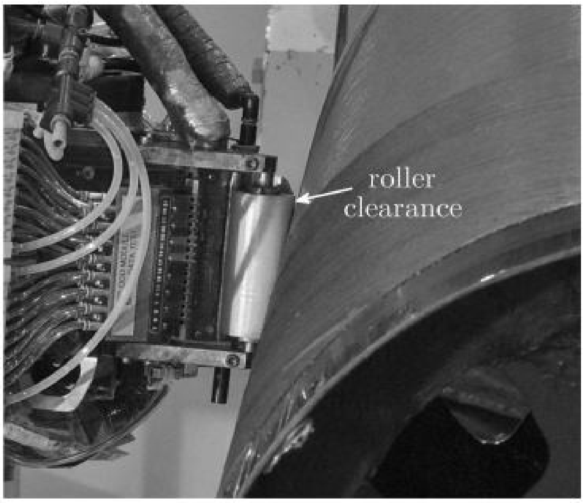

Figure 12 Roller clearance on cylinder surface [1]

For the contoured surface, tow number for the lay-up must be taken into account for design consideration. In our case, it is taken 12 tows with 3.175mm width.

6. RESULTS AND DISCUSSION

An analysis and optimization tool for fiber placed conic tail boom is developed. The analysis can be done by using the tool for different combination of lay-up. The analysis tool is calculating mean thickness of laminate, maximum failure index by using Tsai-Hill, maximum deflection, buckling load factor and natural frequency. The tool will be used for preliminary design for tail boom for potential helicopter project in TAI.

In order to better understand the results, a simple hand layup case is analyzed. Firstly, the stacking sequence [±45/0/0/0/±45] is given for all elements and analysis is done. The results are seen at Table 1.

Table 1 Analysis results of [±45/0/0/0/±45]

Mean Thickness(mm)	0,91
Max(FI)	0,2358
Max(Deflection)(mm)	94
Buckling load factor	0,6
Natural Frequency	6,38x10^6

The description of second model, the tail boom stacking sequence and thickness distribution design for 3 different sections are given at Figure 13. The aim of this design is to show structural performance can be increased with approximately same weight of first case. More 0 degree layers at side of tail boom and less 0 degree layers at upper and lower are better for design.

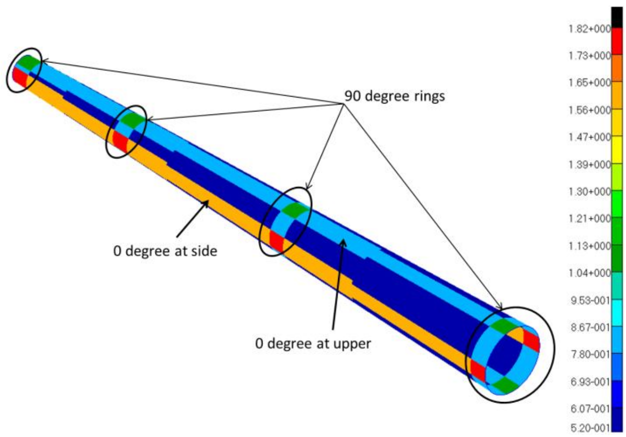

Figure 13 Thickness distribution

There are front, middle and rear sections in the model. The 4 rings between transitions are similar to frames of traditional semi-monocoque structures. The sequence is changing, at 90^0 ring areas which are represented by different colors:

green sequence is $[\pm45/0/90]_S$

for blue, it is $[\pm45/90]_S$,

for red, it is $[\pm45/0_4/90]_S$

for orange, 0 degree at side,

the sequence is $[\pm45/0_4]_S$, again blue for 0^0 upper,

the sequence is $[\pm45/0_2]_S$,

the last dark blue is $[\pm45]_S$.

The design is inner and outer ±45 degree, between the +-45 degree, there are eight 0^0 at left and right sides (orange), and two 0^0 at left and right sides (blue) and 90^0 rings. The analysis is carried out and the results are seen at Table 2.

Table 2 Analysis results of second case

Mean Thickness(mm)	0,92
Max(FI)	0,2224
Max(Deflection)(mm)	85,8
Buckling load factor	0,745
Natural Frequency	4,65x10^6

In the third case, the same model as second case, [±45] in the laminate of second case is changed for maximum buckling load factor. It is seen that buckling load factor is critical for tail boom. The optimum angle is found 39^0 and the results are given at Table 3.

Table 3 Analysis results of third case

Mean Thickness(mm)	0,92
Max(FI)	0,1819
Max(Deflection)(mm)	80,55
Buckling load factor	0,7457
Natural Frequency	4,65x10^6

There is a very small increase in buckling load factor, but deflection and failure index get better than second case.

The fourth and last model is the variable stiffness laminates model, the inner and outer [±45] ply is changed to variable stiffness plies. The weight optimization is performed by means of overlaps, the laminate which has minimum overlap without gap is tried to obtain. The variable stiffness laminates parameter T_0 and T_1 are optimized. For optimization constraint, the buckling load factor is more than 1, maximum deflection is less than 80 mm and maximum failure index is less than 1. The radius of curvature for the reference path can be calculated analytically, it can be checked to turning radius constraint, also curvature constraint is also added to optimization.

The optimum T_0 and T_1 were found, and applied the structure, they are -51^0 and -30^0. The results are demonstrated in Table 4 and thickness distribution is shown in Figure 14.

Table 4 Analysis results of last case

Mean Thickness(mm)	1,13
Max(FI)	0,19
Max(Deflection)(mm)	67,29
Buckling load factor	1,053
Natural Frequency	5,47x10^6

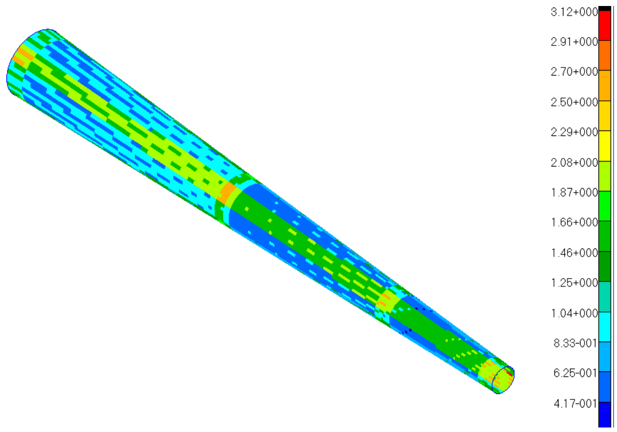

Figure 14 Thickness distribution of tail boom

Evaluation of four cases results, it is seen that the structural performance is increasing generally. Comparing to third case and last case, variable stiffness laminates lead to increase in mean thickness as 22%, but for buckling load factor increase is 41%, and also maximum deflection decrease is 28%.

The increase in buckling load factor is a result of local thickness distribution. Local thickness increase is superior to buckling capacity of structure.

7. CONCLUSION AND FUTURE WORKS

Automated fiber placement is an innovative technique for manufacturing of composite structure. The analysis of composite structure manufactured by AFP needs a different approach so that analysis and optimization code for AFP is generated. Manufacturing constraints of AFP are included in finite element model.

Some of parameters like, overlap ratio and curvature constraint are added to model but head flux, head pressure and lay-up speed effects are not known yet and the tests should be made for better understanding the effect of these parameters.

In order to clearly demonstrate the mechanisms of the way how the response of structure of the fiber placed conical shell laminate changes, the stiffness and the buckling capacity of structure and natural frequency were studied in this paper. This study aims to generate an output for the design and the manufacturing of the composite tail boom manufactured with AFP. With the curvilinear fiber paths more favorable stress distributions and improved laminate performances were obtained. The buckling is the critical case for tail boom. The variable stiffness laminates shows great improvement over the structure because using the curvilinear fiber creates overlaps at some area of the structure and this increases the buckling capacity of the structure. The thickness changes over the surface of the cylinder because of the overlaps.

At this point, there appears enough potential benefits in the variable-stiffness design. The stiffness values are generally improved at the first case to last case. It shows that this concept can be applied to improve such structures like a tail boom. 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 going on to determine how the tow-placement machines perform on such complex parts. An experimental research is continuing to gain more insight into the effects of potentially changes on thickness. Similarly, the investigation of the failure behavior of the tow-placed variable- stiffness composite laminates will be done and comparison with theoretical results should be more beneficial.

8. REFERENCES

[1] A.W. Blom, "Structural Performance of Fiber-Placed Variable-Stiffness Composite Conical and Cylindrical Shells", Delft University of Technology, 09, 2010.

[2] Gürdal, Z., and Olmedo, R. A., "Composite Laminates with Spatially Varying Fiber Orientations: Variable Stiffness Panel Concept." AIAA Journal, Vol. 31, 4 April 1993 , pp 601-608

[3] Adriana W. Blom, Mostafa M. Abdalla , Zafer Gürdal "Optimization of Tow-Placed, Tailored Composite Laminates" 16th. International Conference on Composite Materials

[4] Waldhart, C. Analysis of Tow-Placed, Variable-Stiness Laminates, Virginia Polytechnic Institute and State University, 6, 1996

[5] Brian F. Tatting, Gürdal Z., "Automated Finite Element Analysis of Elastically-Tailored Plates" NASA/CR-2003-212679

[6] Hyer et L. H. Lee. The use of curvilinear fiber format to improve buckling resistance of compositeplates with central circular holes, Composite Structures, 1991,vol. 18, pp. 239-261.

[7] Kennedy J, Eberhart R. (1995). Particle Swarm Optimization.Proc of IEEE International Conference on Neural Network,Perth,Australia,IEEE Service Center Piscataway NJ,1995:1942-1948.

[8] Nagendra S., Kodiyalam A., Davis J.E. and Parthasarathy V.N. "Optimization of tow fiber paths for composite design". Proceedings of the 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials (SDM) Conference, New Orleans, LA, paper no. 1275, 1995.

[9] Design for Manufacturing- One piece, Fibre-Placed Composite Tail Boom C. Marsden, R. Fews, P. Oldyord, A. Yousefpour Trends in Aerospace Manufacturing 2009 International Conference 2012.

[10] Variable Stiffness Composite Panels: Effects of Stiffness Variation on the In-Plane and Buckling Response. Gürdal, Z., Tatting, B. F. and Wu, C. K. sl: Composites Journal, 2008, Vol. 39.

[11] Variable Stiffness Composite Panels: Buckling and First-Ply Failure İmprovements over Straight-Fiber Laminates. Lopes, C. S., Gürdal, Z. and Camanho, P. P. s.l.: Computers & Structures, 2008, Vol. 86.

[12] Design of variable-stiffness composite panels for maximum buckling load, Shahriar Setoodeh, Mostafa M. Abdalla, Samuel T. IJsselmuiden, Zafer Gurdal , Composite Structures 87 (2009) 109–117

[13] Determination of Process Parameters for the Manufacturing of Thermoplastic Composite Cones Using Automated Fiber Placement, Xiao Cai, Master Thesis, Concordia University, June 2012.

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ERF2013 proceedings or as individual offprints from the proceedings and for inclusion in a freely accessible web-based repository.