Abstract

Drive shafts find their extensive use in automotives, locomotives, air crafts and ships. In recent years, composite drive shafts are getting popular because of their reduced weight and extraordinary strength and stiffness. Torque carrying drive shafts experience torsion, shear stress, buckling and vibration loads, depending upon the input force and the load applied. While designing the drive shaft, it is considered that shaft must be strong enough to bear all types of loads, while its weight should be as low as possible so it has negligible inertial effects. A number of parameters dictate the mechanical properties of a composite drive shaft such as fiber orientation, stacking sequence and ply thickness. Non-linear buckling analysis, modal analysis and structural analysis were carried out simultaneously to find optimum thicknesses of plies. A Hybrid structure which is a combination of Aluminum lining and Carbon Fiber Reinforced Plastic (CFRP) is then analyzed on optimized ply thicknesses. drive shaft. Hybrid drive shaft provides benefit of better connection with other metallic engine parts. Hybrid structure also enhances the buckling behavior of drive shaft. Therefore overall safety of drive shaft is achieved.

Keywords: Hybridization, Optimization, Buckling, Natural Frequency.

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Originality Report

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1. Shafts

Mechanical devices which transmit the mechanical power, work and torque from one point to another point are called shaft (1). Different types of shaft are being used and major types of shafts are given as below:

1. Transmission shaft
2. Machine shaft
3. Axle
4. Spindle
5. Drive shaft

1.1.1 Transmission Shaft

Transmission shafts deliver the power between the source where the power is being generated to the place machine where that power has to be consumed (2). All factory shafts such as overhead shaft, line shaft and counter shafts are few examples of transmission shafts. As these shaft also carry the load, such as weight of load, pulleys and gears therefore along the twisting, bending moment is also produced in these shafts.

1.1.2 Machine Shaft

Machine shafts are basic entity of machines. For example, in internal combustion engines crank shaft is used for the crank slider mechanism for the combustion (3).

1.1.3 Axle

The axle is shaft that help in transmission of moments and to support for rotating components of machines (1).

Application: To support in lifting of drum in a car wheel

1.1.4 Spindle

Spindle is a type of shaft which is very short in size and usually use to impart the motion to either a work piece or a cutting tools (4), for example in drill press, spindle is used to impart motion to cutting tool which is known as drill bits. In lathe machines spindles are used to impart motion to the work piece.

1.2 Drive Shafts

A mechanical device that transfers mechanical work or rotation from an engine or electric motor to a drive train is called drive shaft. Other names for drive shaft are propeller shaft, prop shaft, driving shaft or Cardin shaft (5). Major reason for using drive shaft is to maintain the distance from the prime mover as the components cannot be directly coupled. Reciprocating I.C Engines or electric motors are most commonly used prime movers to obtain rotary motion. In reciprocating I.C engines, reciprocal motion of pistons is converted in to the rotary motion by using crank shaft and gear train. Torque obtained from the gear train is carried out to useful end by drive shaft. Torque carrying drive shafts experience torsion, shear stress, buckling and vibration loads, depending upon the input force and the load applied. While designing the drive shaft, it is considered that shaft must be strong enough to bear all types of loads, while its weight should be as low as possible so it has negligible inertial effect on the complete machinery.

Applications of drive shaft are numerous, including the automobiles, ships, submarines, cooling towers, pumps, aircrafts and helicopters. The design of a metallic drive shaft is an easier engineering problem as knowing the values of allowable shear stress and torque is enough to calculate the design parameter for any given system.

In modern era, weight is considered to be one of the most important design parameters. To overcome weight issues, composite materials are extensively used in all the structural components. Design of drive shafts can be greatly improved by the use of composite materials.

1.3 Material for Drive Shafts

There are number of materials used for drive shafts and can be categorized in the following categories.

- Metal Alloys
- Composite Materials
- Hybrid Materials

1.3.1 Metallic Drive Shafts

Conventionally, the drive shafts used in the automobiles are made of steel. As the steel has very high strength, it is in high demand of industry to be used in the manufacturing of drive shafts. On the other hand, steel is relatively heavy so aluminum has been adopted as an alternative for the steel. Aluminum is lighter and therefore a very convenient substitute to be used in light trucks, vans or high performance vehicles.

1.3.2 Composite Drive Shafts

Composite materials are the best materials to be used in drive shafts as they are extremely light and have high strength. By reducing the weight of drive shaft, overall weight of the vehicle can be reduced hence advantage of fuel economy can be achieved efficiently (5).

1.3.3 Hybrid Drive Shafts

Hybrid drive shafts are fabricated by the combination of metallic and composite materials. For the last several years composite drive shafts are being replaced by hybrid drive shafts to achieve the advantage of metallic properties. In hybrid drive shafts central section of shaft is made up of composite material, while outer core of shaft consists of metallic material. Drive shaft of a commercial helicopter of Boeing Vertrol Model 234 is a typical example of a hybrid drive shaft (6).

Carbon Fiber Reinforced Plastic (CFRP) used in composite material increase the fundamental natural frequency of the drive shaft, while torque/ power transmission of drive shaft is increased by metallic material. Using metallic material also provide the ease to connect drive shaft with other metallic parts such as bolting, welding etc. (7).

1.4 Composite Materials

The composite materials are synthetic materials engineered by using two or more than two fundamental material having variant properties and chemically stable with each other (8). The constituents of a composite material remain separate and withhold their physical and mechanical properties. Use of composite ranges from armed aircrafts to small domestic items (9) (10) (11)due to their tailored mechanical properties, lighter in weight and being cheaper in price. To achieve high specific strength and high specific modulus different types of composites like carbon, glass, graphite, Kevlar etc. are combined with suitable resin (12). Weight of vehicle can be reduced by manufacturing different automotive parts through composite materials such as elliptical spring, leap spring, drive shafts etc. (13).

Major usage of composite materials is following

- Used in buildings such as concrete
- Used as reinforcement in plastics such as carbon epoxy
- Metallic composites
- Ceramic Composites.
- Pressure Vessels

1.4.1 Components of a Composite Material

The constituent of composite materials are divided into two classes as given below:

1. Reinforcement
2. Matrix/binder

Both matrix and reinforcement mutually form composite material. Matrix binds reinforcement that is why it is also known as binder, and reinforcements strengthen the matrix. Control over amount of reinforcement and matrix gives us complete control over various physical properties of composites (14).

Most commonly used matrices are organic polymer matrix in commercial products. They are usually in the form of resin. Reinforcement are usually used in the form of fibers, they may as long or small even like whiskers Fibers may be used weaved, 3D braded, unweave unidirectional, randomly arrange short strands or may be in the form of fabric. Most commonly used reinforcements come from carbon fiber, glass fiber, Aramid and Kevlar. In most common layups volume fraction 60% fiber and 40% matrix or resin, adaptation of better manufacturing techniques can enhance the volume fraction ratio.

Composite materials are classified into two major classes depending upon their macro constituents as given below:

- Organic Composites
- Hybrid Composites

1.4.2 Organic Composite

Organic composite materials used for the drive shafts are mad carbon polymer fibers reinforce with polymer resins are used. The major advent of carbon composite shafts are light in weight and less torque is required for the rotation and due to being light weighted has minimal and even no inertial effects on overall system (15) (16).

1.4.3 Metal Hybrid Composite

Hybrid composite material is consisting of organic polymer with nanometer or molecular level metallic compounds reinforced with resin. Due to very small size of constituents hybrid composites have more homogenized and very better properties.

Hybrid composites are little heavier than organic composites but they are much better in stress bearing due to inorganic constituents (metals).

1.5 Properties of Composites

Composite materials are usually orthotropic in nature that’s why their physical properties vary in every direction of material. These orthotropic properties depend upon the direction of fiber and weave, type of fiber, type of resin, volume fraction and manufacturing methods.

1.6 Failure in Composites

Cycling loading and impacts can cause the elimination of plies or fiber pull out. The failure spectrum of composites can vary from a microscopic level to a macroscopic level. Compression failures or tensions failure can occur at both levels. Some of the composite materials are brittle and tend to rupture after an initial microscopic failure whereas some of the materials are ductile and undergo large deformations before the complete rupture.

1.7 Pros and Cons of Composite Drive shaft

Drive Shaft has its own advantages and disadvantages when used in any mechanical system which are given below:

Advantages

1. Composite drive shaft have high specific strength and high specific modulus and less weight.
2. Specific stiffness of composite drive shaft is approximately 4 times as compared to aluminum or steel, therefore natural frequency of composite drive shaft is almost twice as compared to aluminum or steel.
3. Due to high specific stiffness composite drive shaft can be manufactured in one piece, which eliminates assembly of connecting two pieces. Hence weight and cost can be reduced.
4. Composite drive shaft has high damping capacity, which reduces vibration and noise levels.
5. Composite drive shaft has higher torque transmitting capability as compared to metals.
6. Drive shaft based systems have lesser chance of being jammed as compared to chain driven system.
7. Drive shaft system required less maintenance as compared to chain/belt driven system
8. They are good corrosive resistance and have longer fatigue life.
   (1), (17), (18), (19)

Disadvantages

1. Composite drive shaft has more complex mechanical system than that of conventional metallic one.
2. Fabrication cost of composite drive shaft is high.
3. Repairing is difficult.
   (20)

Chapter 2

Literature Review

Fiber reinforced composites such as carbon fiber reinforced are taking over the conventional metals and alloys due their high specific strength and stiffness and tailor ability of their property. Carbon fiber reinforced polymers composites usage is being increased in aerospace, construction structures and automobile industries are few names. Drive shaft is one of most important part of automobiles. Beardmore, P., et al. (1986) discussed the application of composites in the vehicle with structural aspects and mass optimization. Beardmore, P. work shows that composites are lighter and stiffer than metals and metallic alloys conventionally used in the automobiles and vehicles (3) (2). Pollard, A. (1989) suggested the usage of the polymer matrix based composite in the drive shaft (21).

Driveshaft is mechanical device which transfer the power from the automobile engine or prime mover to another location where it is required (22) (13) (20). In automobile usually engine is placed at front and power and torque is transferred to the rare axle (23) (7). During power transmission drive shaft may experience constantly change of angle and position as it is connected to rear axle which is constantly in motion due to the torque delivered by driving shaft (6).Two piece metallic drive shaft is shown below in Figure 1.

Mallick, P. K. (1988), suggest drive shaft manufactured in two pieces using steel as material. Benefits of two shaft increase in bending natural frequencies which reduces other vibrational frequencies. Though two-piece drive shaft is very good due to natural bending frequencies but required other parts like universal joints and supporting bearings which are collectively making the system Havier (22) (24) (23). Parshuram D (2013), study shows that metallic drive shafts are

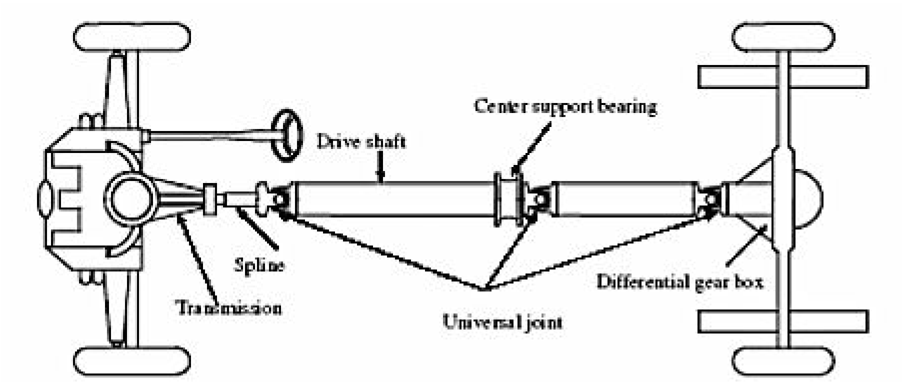

Figure 1: Two Piece Metallic Driveshaft

Prone to corrosion (7) and due to isotropic properties of metals they have bad in damping of vibrations (25). Steel having good physical properties are used such as Steel SM 45 (23).Physical properties of Steel SM45 (26)are discussed in Table 1 given below:

Table 1: Mechanical properties of Steel (SM45)

Mechanical properties Steel	Values
Young Modulus(E) GPa	207
Shear Modulus(G) GPa	80
Possion Ration(v)	0.3
Density (ρ) Kg/ m^3	7600
Yield strength (Sy) MPa	3700

Adaptations of composites as a material is very helpful in reduction of weight of drive shaft and improvement in life of journals and bearings (19) (4). One piece driveshaft (27) can be fabricated by using composite as shown in Figure 2 on next page. RANGASWAMY (2005), suggested E-glass/epoxy and High Modulus (HM) Carbon /epoxy composites due to their light weight properties and better material properties (24).High Strength (HS) Carbon and polymer matrix is also used as material of choice for the drive shaft (26). R. SrinivasaMoorthy, et al. (2013) used carbon epoxy and Kevlar epoxy as a material for the fabrication of drive shaft (28).

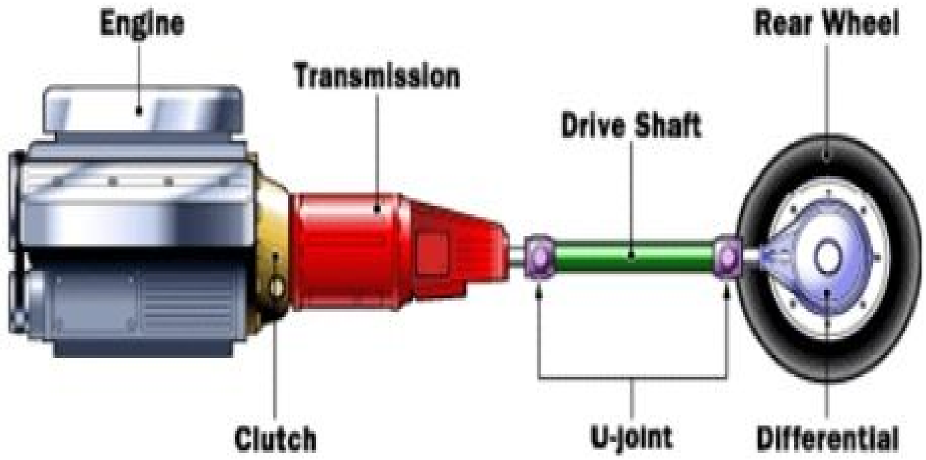

Figure 2: Single piece Composite Drive Shaft

Comparison of physical properties of various composite materials used for the fabrication of drive shaft is given below in Table 2:

Table 2: The materials and their properties used for driveshaft

Material	E_{XX} (Pa)	E_{yy} (Pa)	E_{zz} (Pa)	μ_{12}	μ_{23}	μ_{31}	G_{XY} (Pa)	G_{Yz} (Pa)	G_{XZ} (Pa)	ρ Kg/m^3	Allowable Stress (Pa)
E-Glass	5e10	1.2e10	1.2e10	0.3	0.3	0.3	5.6e9	5.6e9	5.6e9	2000	400e6
HM-Carbon	1.9e11	7.7e9	7.7e9	0.3	0.3	0.3	4.2e9	4.2e9	4.2e9	1600	440e6
HM Carbon Polyester Resin	3.4e10	6.53e9	6.53e9	0.2	0.3	0.2	2.433e9	1.698e9	2.433e9	2100	420e6
HS Carbon	1.34e11	7e9	7e9	0.3	0.3	0.3	5.8e9	5.8e9	5.8e9	1600	600e6

Various orientation of fibers in plies and ply orientation have different physical properties (3) (21) (14) (15) (20). Using the orientation of fiber and laminates one can engineered the composite material according to his own requirement (8).

Laminates of composites behave like a leaf spring; more over the orthotropic properties of composites make them material choice due to ability to damp the vibrations and shocks over the isotropic material such as metals and metal alloys (25).

Drive shaft experiences different kind of loadings during its operation which are primarily torsion, buckling, vibration and fatigue. Primary load in the drive shaft is torsion which can develop bending in the drive shaft (28). Herd. N.J(1996) studied torsion effects in automobile drive shaft (29) and found the relationship between torsion and length of the shaft.

If M is material property, r is radius of the shaft, t thickness of the shaft and E is modulus of elasticity, l is length of the shaft and B_{cr} is critical buckling stress and $S_{cr}$is critical stress (30) than shaft will called long shaft if :

$$\frac{1}{\sqrt{1-}}\frac{}{2} \qquad 5.5$$

In other cases, shaft is considered to be either short or medium if critical stress S_{cr}:

$$_{cr} \quad \frac{}{3\sqrt{2}}\frac{1}{1-} \quad / \quad ^{/}$$

The relationship between maximum torsion buckling Bcr and critical stress S_{cr}isgiven below (30) (4) (20):

$$_{cr} \qquad _{cr}2$$

If the T_r is torque and S_x is shear strength and d_o and d_i are outer and inner dia of the shaft respectively the relationship between torque and shear strength is given below (31) (30) (7):

$$_{r} \qquad \frac{-}{16}$$

As composites are orthotropic in nature, different ply angels produce different response of shear and bending upon torque loading in the drive shaft.

Vinson, J.R. and Sierakowski, R.L (2002) found that shear stress developed in the wall of drive shaft under the applied torque produces very small when ply angle of composites was chosen as ±45°irrespect of the type of the material of composite.

AleksandrCherniaev and ValeriyKomarov (2014) used Timoshinko beam theory and found that in thin walled cylinders critical torque causes buckling has direct relationship with flexural stiffness which can be efficiently addressed by using orientation of layers at 90° also known as hoop layers (18) (27) (30) (4).

Effects of longitudinal membrane stiffness of the composite material can be improved by addition of layers in composites in the longitudinal direction but manufacturability can be possible with at least winding angle by ±15° (30) (24) (18).

Chapter 3

Development of Design Methodology

3.1. Problem Statement

To design a hybrid drive shaft of a helicopter made up of Carbon Fiber Reinforced Plastic (CFRP) and Aluminum 7075, in such a way that shaft can withstand torsional, buckling and vibration loads with minimum weight.

3.2. Design Requirements

Drive shaft needs to be designed in such a way that shaft can withstand following loading conditions.

a. Torsional Strength
b. Buckling
c. Vibration

3.2.1. Strength

The drive shaft should be strong enough to transmit a torque of 4250 N-m without failure. As the hybrid drive shaft is made up of metallic and composite materials therefore for metallic portion von-Mises criteria will be considered for failure, while Tsai Hill Failure criteria will be considered for composite materials. Moreover "First Ply Failure" will be considered as failure of composite. Inverse Reserve Factor (IRF) for Tsai Hill criteria can be theoretically calculated as

$$f_{Th} = (\sigma_1/X)^2 + (\sigma_2/Y)^2 - \sigma_1\sigma_2/X^2 + (\tau/S)$$

Where as:

X is ultimate normal stress along fiber direction

Y is the ultimate normal stress perpendicular to fiber direction

S is ultimate shear stress

σ_1 is the longitudinal strength

σ_2 is the transverse strength

τ is the in plane shear strength

3.2.2. Torsional Buckling

The drive shaft should have enough stability such that it should not buckle under torsional load. The torsional buckling capability of composite drive shaft can be expressed in term of critical buckling torque. T_{cr}. Where T_{cr} can be theoretically calculated by using the same equation as Venson (10)

$$T_{cr}= 14.57.(D_{yy})^{5/8}(\delta_{\sum}E_x)^{3/8}.R^{5/4}/L^{1/2}$$

Where as:

D_{yy} is a flexural stiffness in tangential direction

$\delta_{\sum}$ is the laminate thickness

E_x is the effective modulus in the longitudinal direction

R is the radius of drive shaft

L is the length of drive shaft

3.2.3. Lateral vibration

Natural frequency of a composite drive shaft should be higher than W_{max}= 200Hz to avoid any resonance phenomenon. Natural frequency as pinned condition was theoretically calculated by Timoshenko (11)

$$\omega = \frac{\pi}{2}\sqrt{\frac{E_x I_x}{m.L^3}} = \frac{}{\sqrt{}} . \frac{}{} = \sqrt{E_x}$$

Where as:

Ex is the longitudinal modulus

Ix is the moment of inertia

m is the mass of drive shaft

L is the length of drive shaft

3.3.Design Formulation

Design problem is formulated below.

3.3.1. Objective Function

The main objective of the design activity is to minimize the weight of drive shaft.

3.3.2. Design Variables

Following variables play an important role in the design activity of drive shaft

a) Thickness of the plies
b) Orientation angle of plies
c) Staking sequence of plies

3.3.3. State Variables

State variables are the constraints on the output results. Following state variables will be considered while designing.

a) IRF ≤ 1 (Strength)
b) $Fn \quad \frac{Wcr}{Wmax} \quad 1$ (Vibration)
c) $L \quad \frac{cr}{} \quad 1$ (Buckling)
d) □≥15 (Fabrication)

3.4.Development of Finite Element Model

Finite element model has been prepared in ANSYS Workbench 16. Development of FE model is carried out in the following stages.

3.4.1. Model and Meshing

Drive shaft of a helicopter is modeled as a thin walled tube, having length of 1400 mm and diameter of 100 mm as shown in **Error! Reference source not found.**. Solid model of the drive shaft has been meshed by using Shell 281 element. Element size of the mesh has been taken as 10 mm and face map option has been used for meshing. As a result of meshing 13268 nodes and 4402 elements were generated. Meshed model has been shown in figure 3.

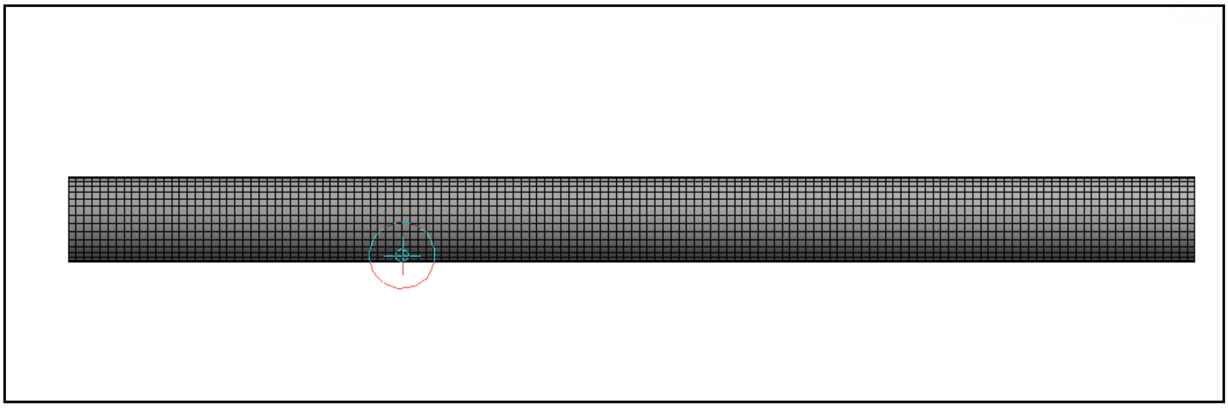

Figure 3: Model of Drive Shaft

3.4.2. Boundary Conditions

Two remote points are generated at the centers of each end of drive shaft. Then each remote point is linked to the corresponding edge of shaft. At one end of the shaft is fixed by applying remote displacement in all directions while torque of 4250 N-m is applied on the other end of drive shaft as shown in Figure 4.

3.4.3. Material Properties

Materials proposed in the design process of hybrid drive shaft are Composite Fiber Reinforced Plastic (CFRP) and Aluminum7075. CFRP is suggested due to its high strength and stiffness, while Aluminum 7075 is suggested due to its compatibility with other metallic parts of drive line. Mechanical properties of both materials are given in Table 3 and Table 4.

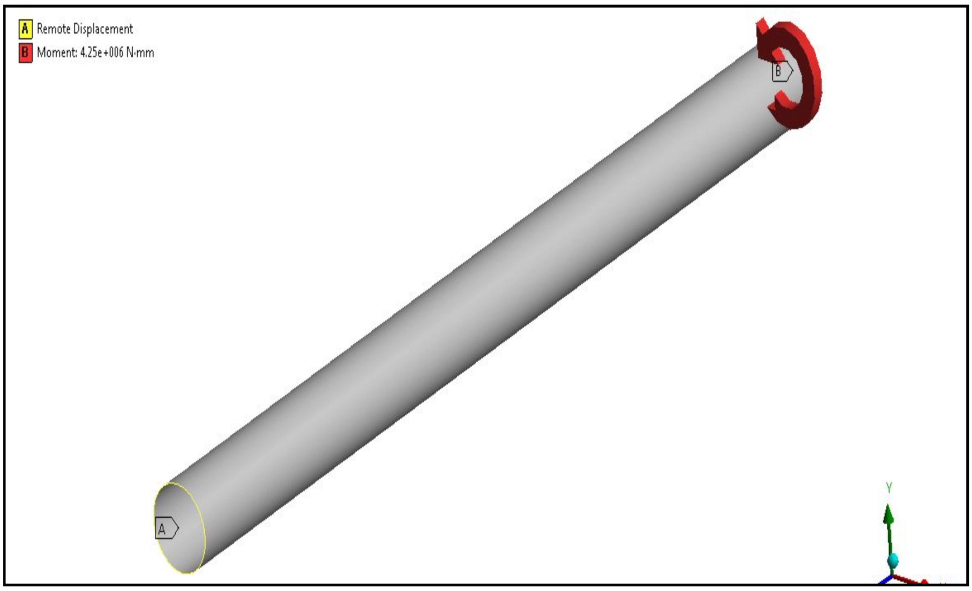

Figure 4: Boundary Conditions Applied on a Drive Shaft

Table 3: Mechanical Properties of CFRP

Longitudinal modulus (GPa)	121
Transverse modulus (GPa)	8.6
In-plain shear modulus (GPa)	4.7
Major Poison ratio	0.27
Longitudinal strength in tension (MPa)	2231
Longitudinal strength in compression (MPa)	1082
Transverse strength in tension (MPa)	29
Transverse strength in compression (MPa)	100
In-plain shear strength (MPa)	60

Table 4: Mechanical Properties of Aluminum

Youngs Modulus (GPa)	73
Poison ratio	0.3
Yield trength (MPa)	550
Ultimate strength (MPa)	600

3.4.4. Selection of plies orientation angle and stacking sequence of plies

Shear stresses are produced due to torque transmission and shear stresses can be minimized by inserting some layers of plies wound at ±45º.

(32)Showed that plies wound in hoop direction or 90º increase the buckling resistance capability of drive shaft.

Natural frequency of drive shaft can be increased by adding plies in longitudinal direction or 0º (33). However, due to manufacturing constraint minimum winding angle is restricted up to 15º.

According to the above considerations, the initial layup of plies of laminate is suggested as [90/±15/±45], which shows that hoop layer is the outer most layer and plies at 45 are at the bottom of laminate. Orientation of plies is shown in Figure 6 to 10.

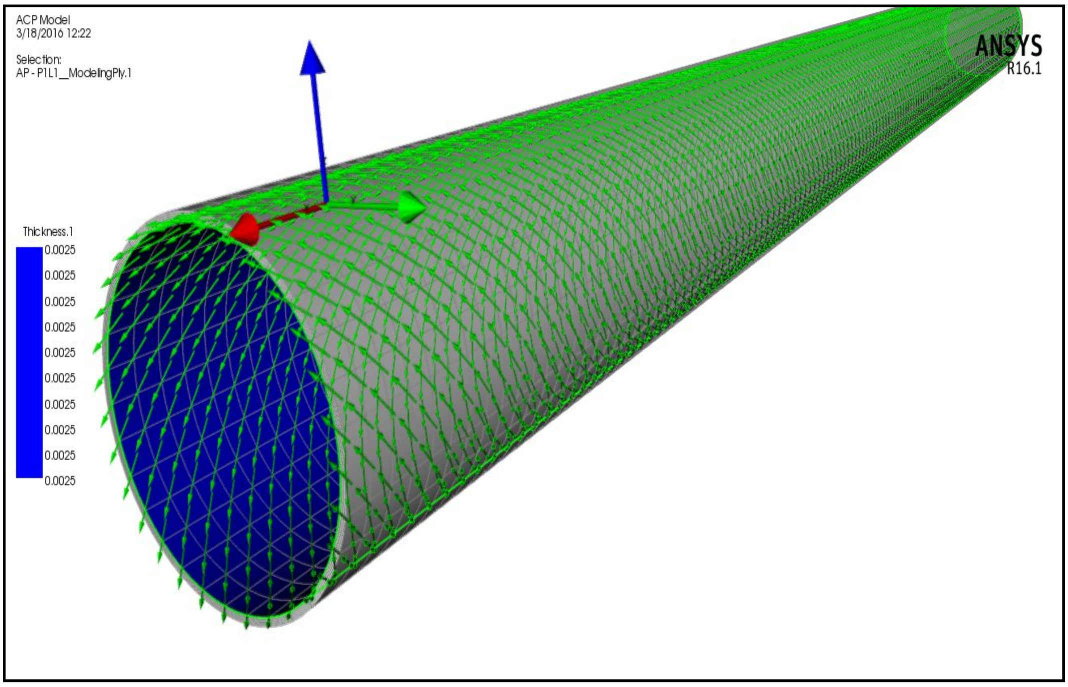

Figure 5 Ply orientation at -45º

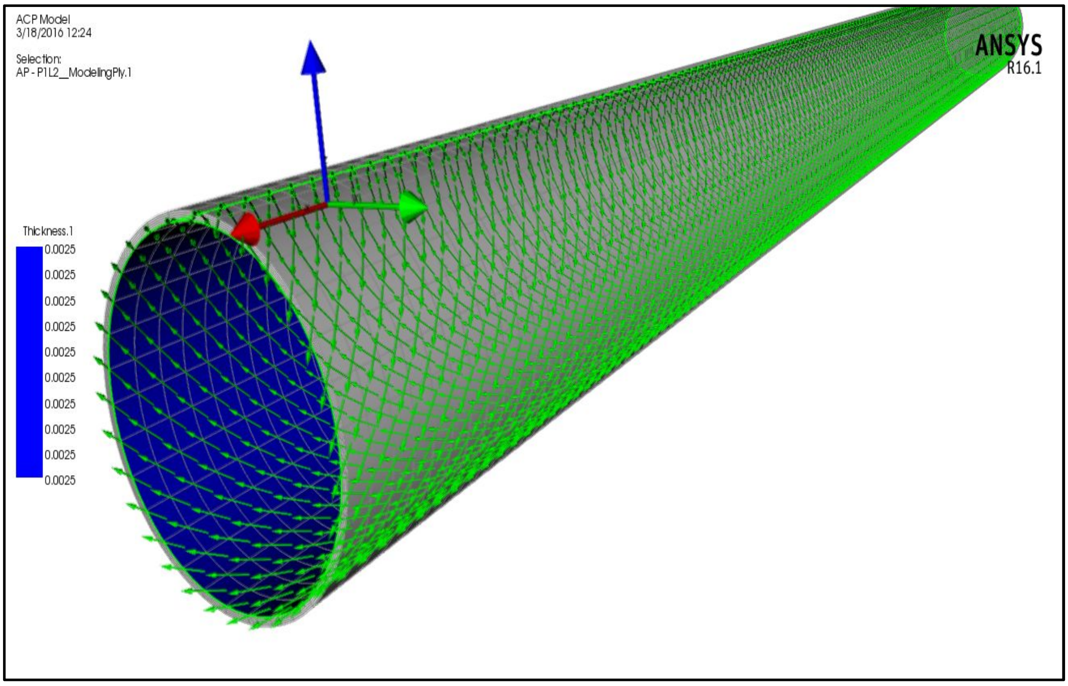

Figure 6: Ply Orientation at 45º

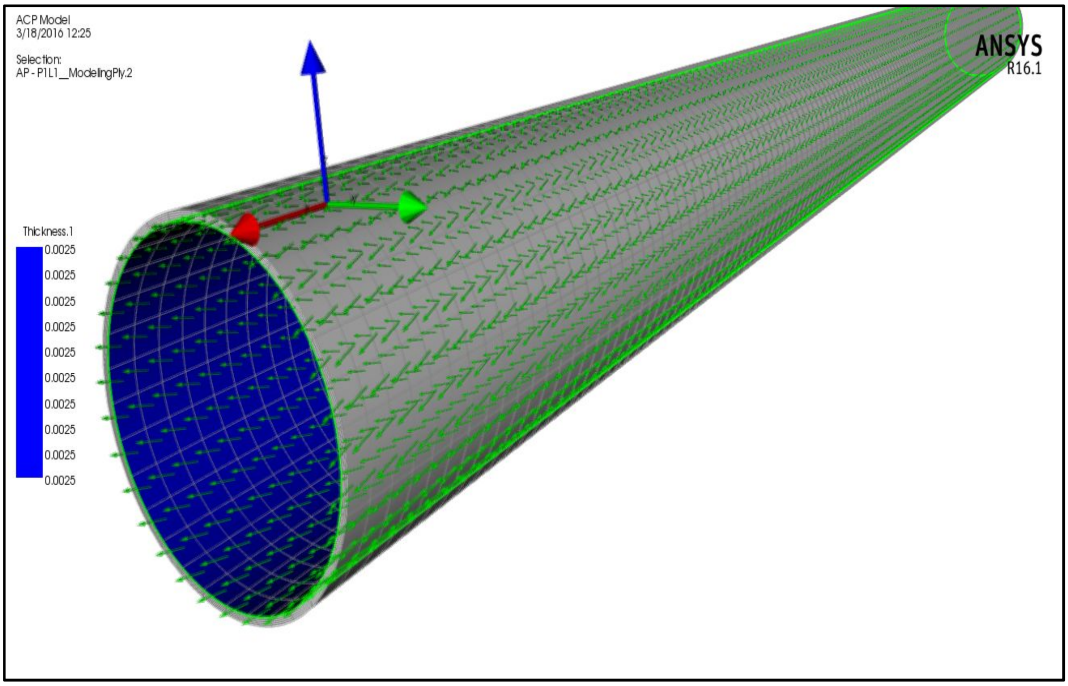

Figure 7: Ply Orientation at 15º

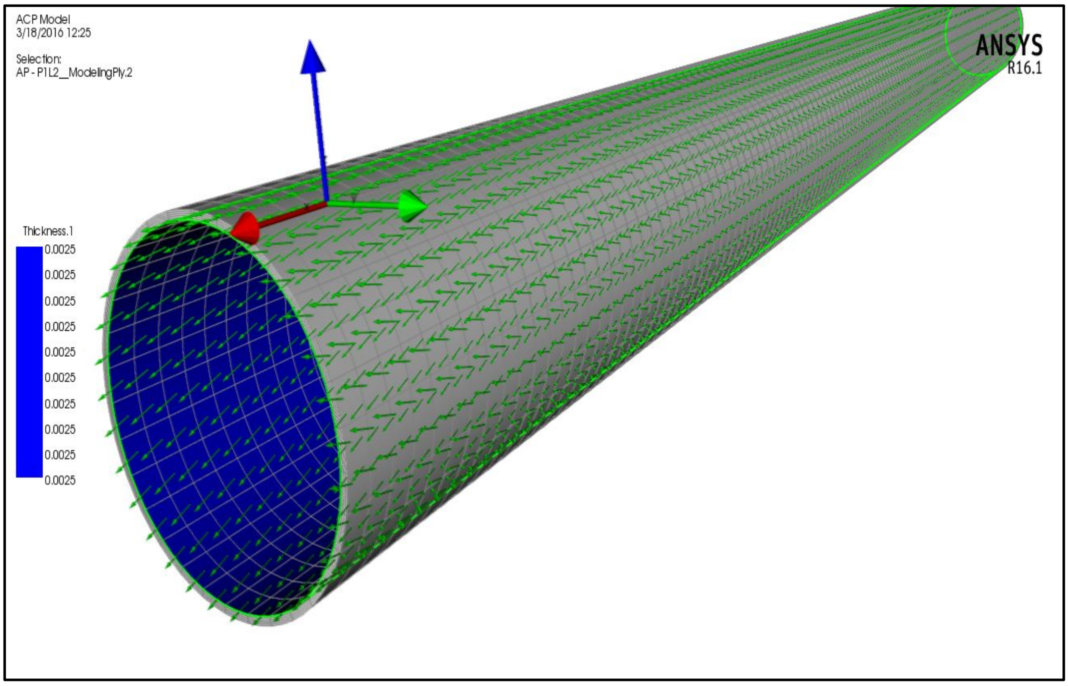

Figure 8: Ply orientation at -15º

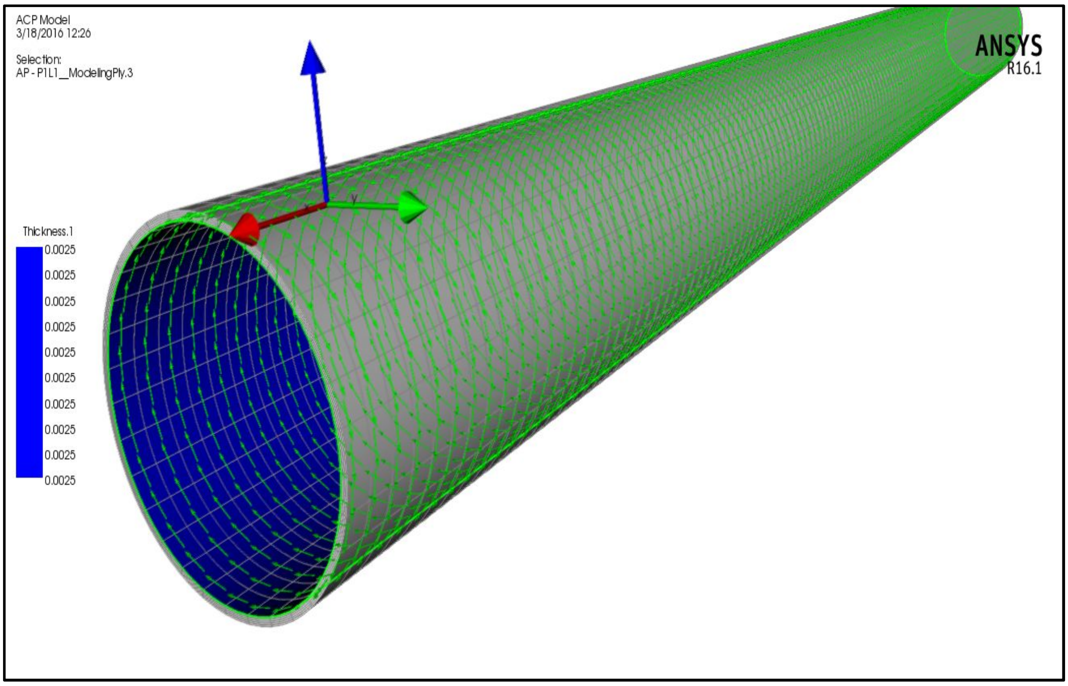

Figure 9:Ply orientation at 90º

3.4.5. Analysis required

For the initial analysis laminate consisting of 3 stake ups is considered. First stake up consist of two plies which are oriented at ±45º. Second stake up also consist of two plies oriented at ±15º and the third stake up consist of a single ply oriented at 90º. Thickness of each ply is taken as 0.5 mm. The laminate can be expressed as $[90^{o}_{0.5}/\pm15^{o}_{0.5}/\pm45^{o}_{0.5}]$. Stacking sequence shows that hoop layer is the outer most layer wound on mandrel.

Structural integrity of the drive shaft will be checked by following analysis.

a) Static Structural Analysis
b) Linear Buckling Analysis
c) Modal Analysis

After performing above analyses optimal thicknesses of the stake ups will be found by Design Xplorer Module of Ansys Workbench. On the basis of results of optimized thicknesses of plies and orientation, hybrid structure will be decided.

Chapter 4

Results and Conclusion

4.1.Analysis Assumptions

1. Drive shaft rotates at constant speed about longitudinal axis.
2. Drive shaft has uniform cross section.
3. Shaft is perfectly balanced.
4. All damping and non linear effects are excluded.
5. Stress strain relationship for composite material is linear, hence hook’s law is applicable.

4.2. Initial Analyses

The laminate considered for initial analysis was assumed as [90°/±15°/±45°]. Which shows that hoop layer is the outer most ply layer, while stake up of ±45° is the inner most layer. Thickness of each ply is taken as 0.5 mm. Three types of analysis were performed to check the behavior of composite drive. Which are

- Static Structural Analysis
- Eigen Buckling Analysis
- Modal Analysis

Results of these analyses are shown as follows

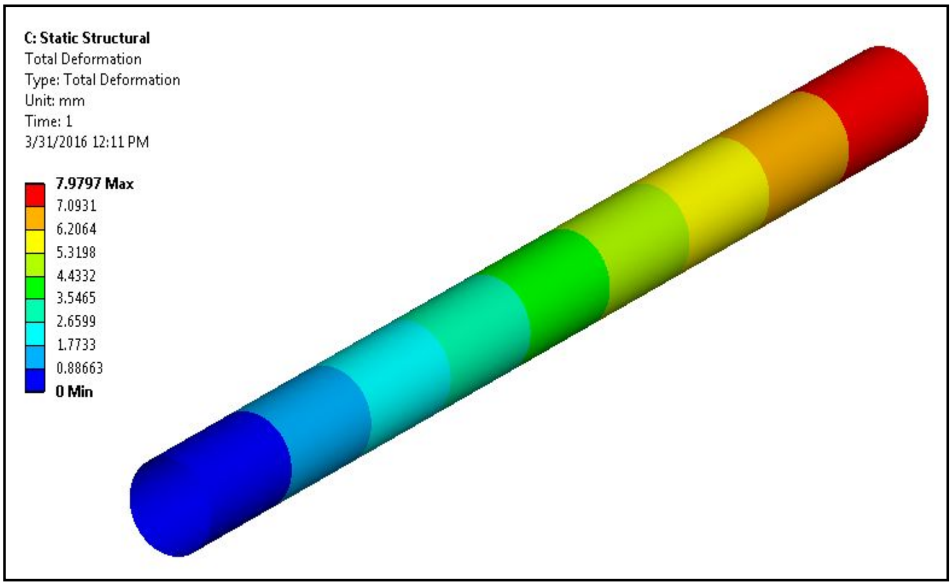

Figure 10: Base Case -Total Deformation

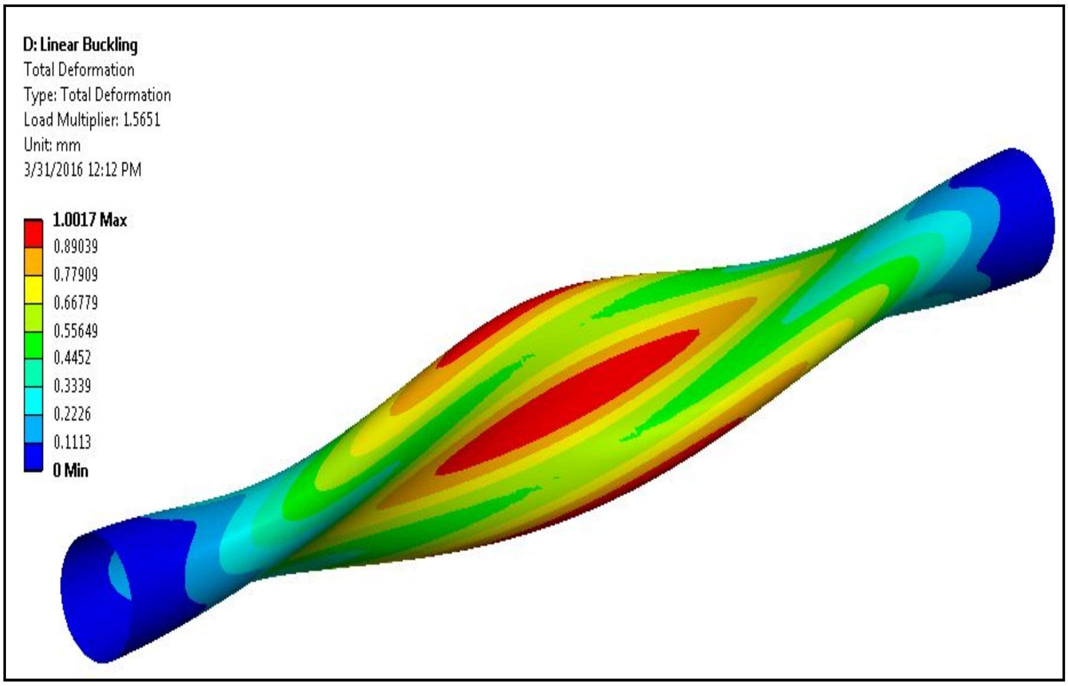

Figure 11: Base Case -Eigen Buckling Analysis

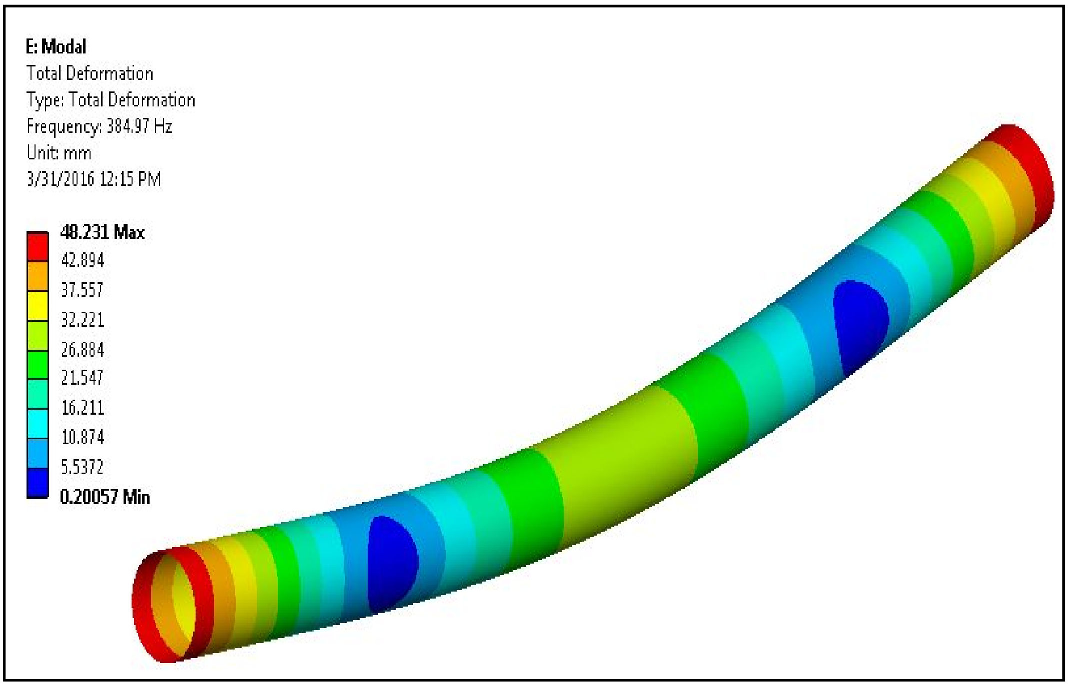

Figure 12: Base Case-Modal Analysis

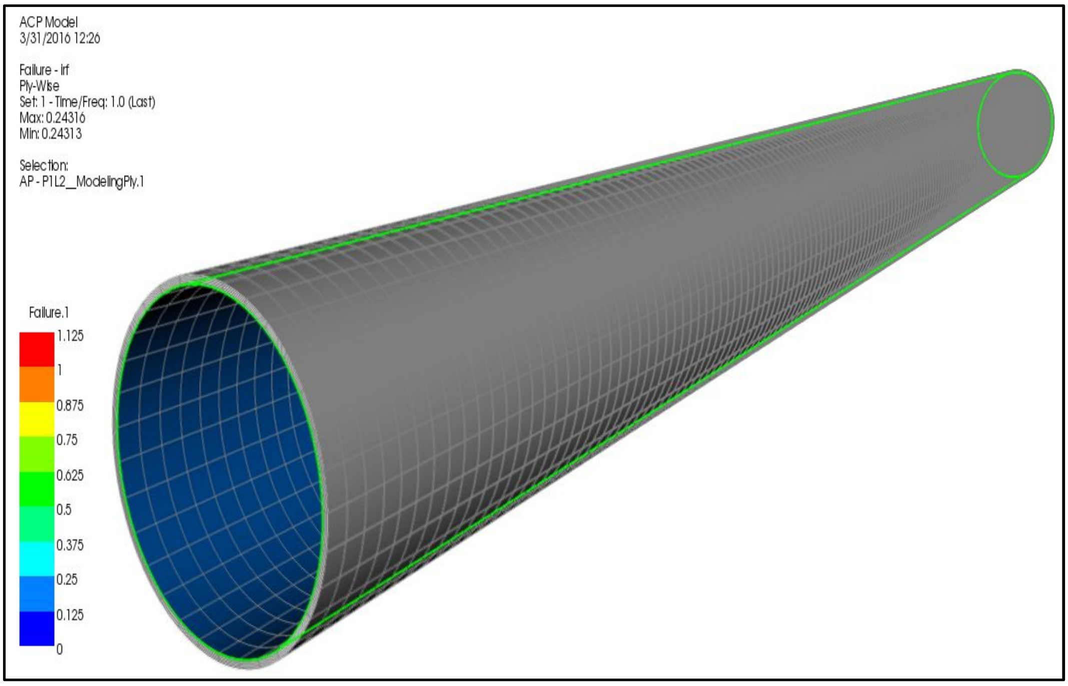

Figure 13: Base Case-IRF for 45° Ply (Bottom most)

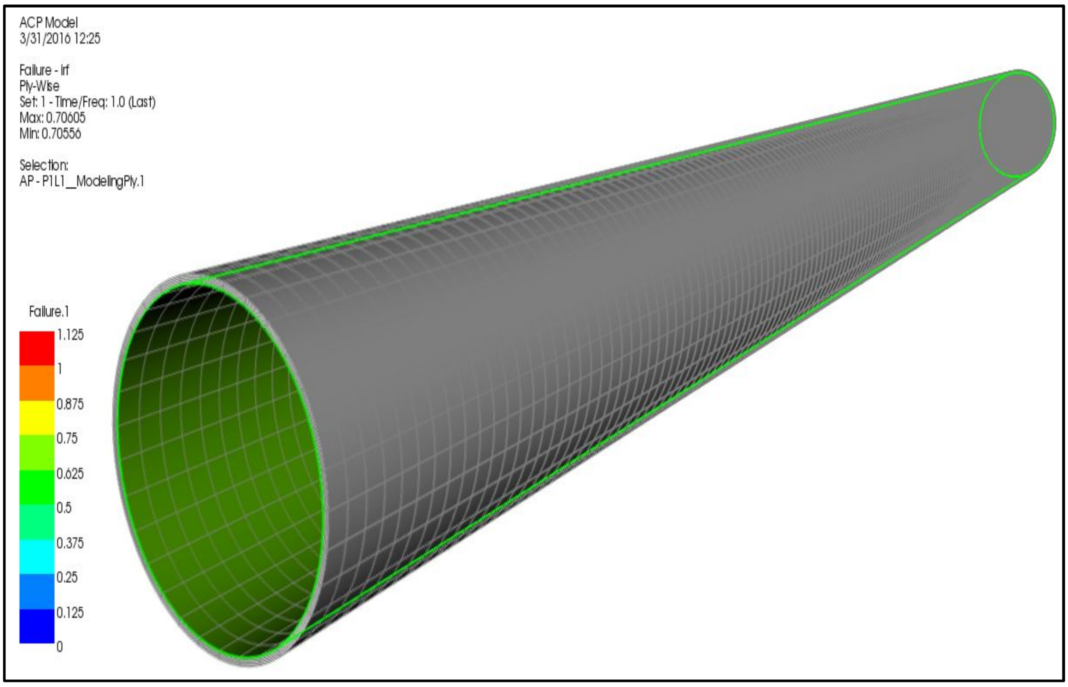

Figure 14: Base Case-IRF for -45° Ply

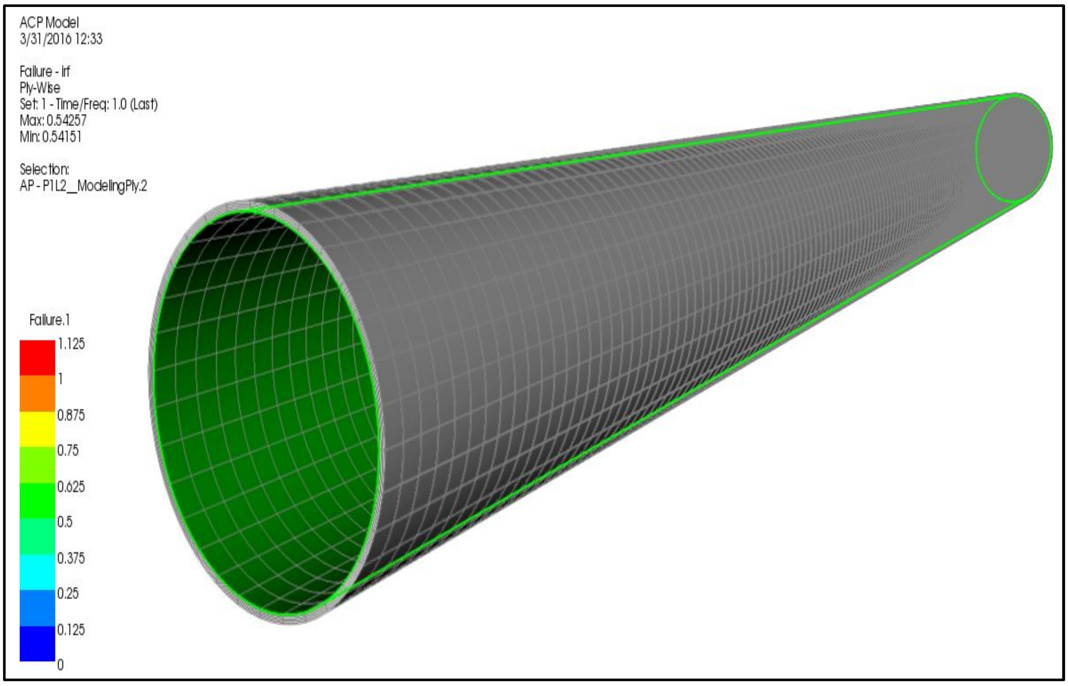

Figure 15: Base Case-IRF for -15° Ply

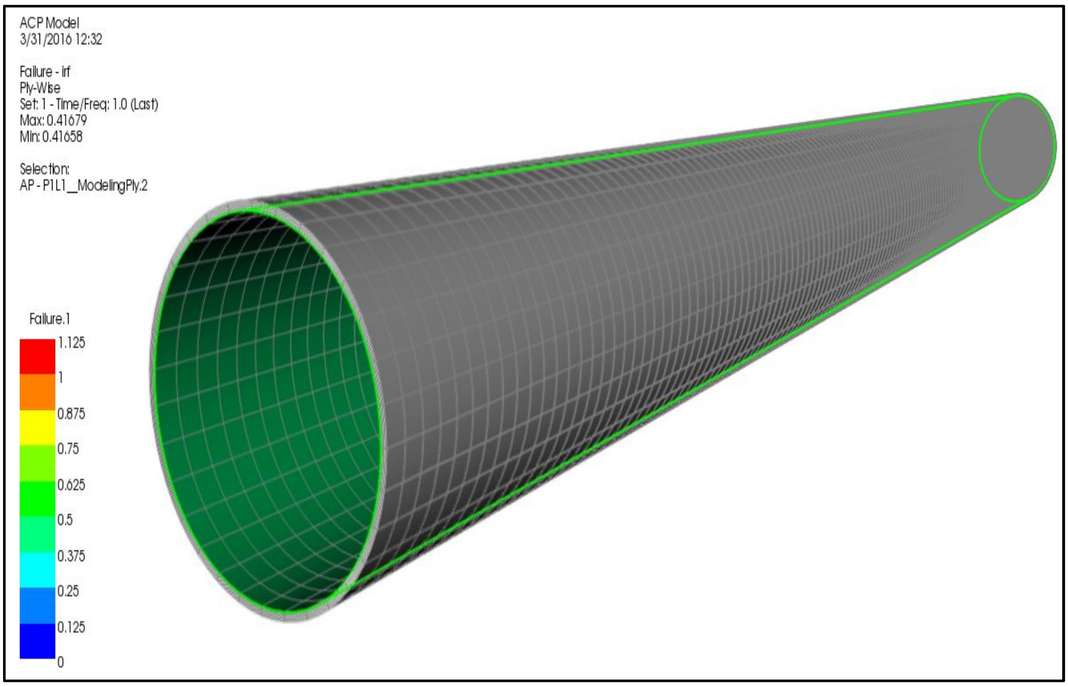

Figure 16: Base Case-IRF for 15° Ply

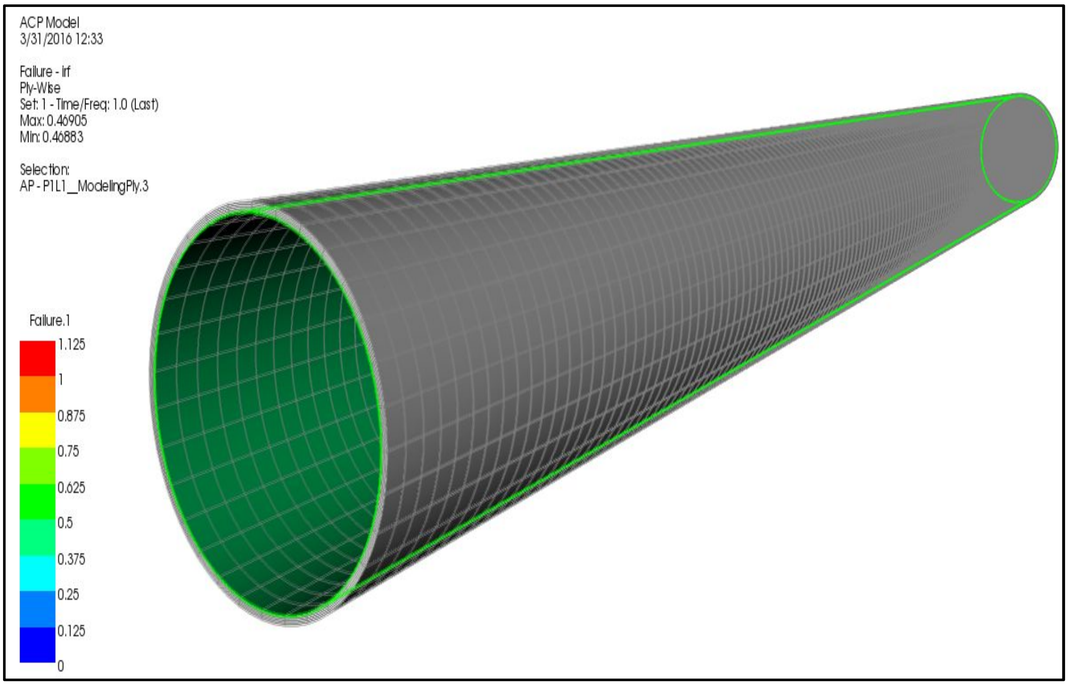

Figure 17: Base Case-IRF for 90° Ply (Top most)

Results of the above Analysis can be summarized as :

Table 5: Summary of results of Base case Analysis

$[90^\circ_{0.5}/\pm15^\circ_{0.5}/\pm45^\circ_{0.5}]$	
Load Multiplier	1.565
Minimum Natural Frequency (Hz)	384.97
IRF in 45° Ply	0.243
IRF in -45° Ply	0.706
IRF in -15° Ply	0.542
IRF in 15° Ply	0.416
IRF in 90° Ply	0.469
Total mass of Drive Shaft (Kg)	1.68

4.2. Optimization

Optimization process is carried out to find the minimum thicknesses of plies in order to fulfill the requirements of design constraints. Design variables and state variables are linked together in Design Xplores of Ansys 16 as shown in Figure

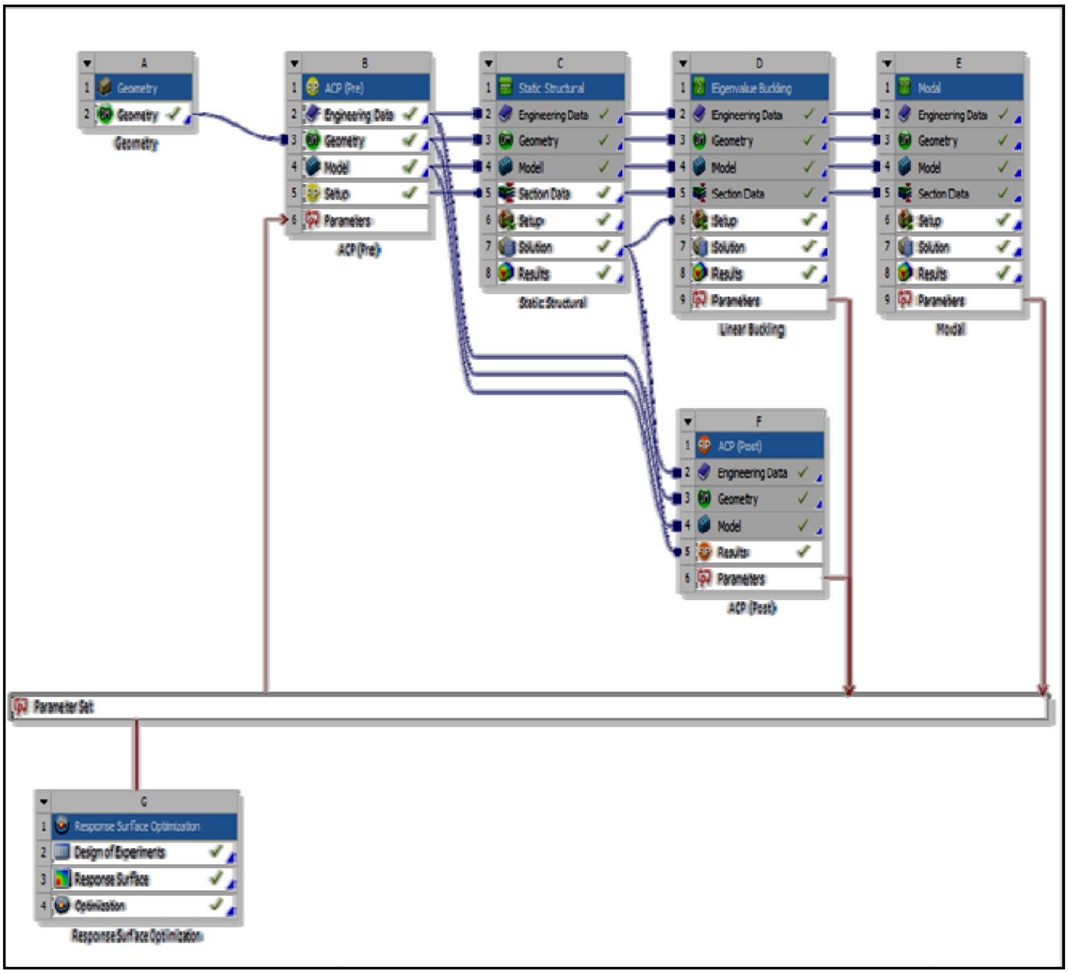

Figure 18: Optimization process

4.4. Design of experiment

Following data is generated:

Table 6: Experimental Data

Name	Fabric 45 thickness (m)	Fabric 15 thickness (m)	Fabric hoop thickness (m)	Total Deformation Load Multiplier	Total Deformation Reported Frequency (Hz)	Max IRF
1	0.000375	0.000475	0.000275	0.888407921	403.9215257	0.900507631
2	0.00035	0.000475	0.000275	0.841831225	406.6063295	0.942760992
3	0.0003625	0.000475	0.000275	0.865026633	405.2537068	0.921162422
4	0.0004	0.000475	0.000275	0.935748332	401.3175819	0.861792121
5	0.0003875	0.000475	0.000275	0.911980205	402.6095646	0.880736051
6	0.000375	0.00045	0.000275	0.834019335	400.4340201	0.915955512
7	0.000375	0.0004625	0.000275	0.86103812	402.204011	0.908171318
8	0.000375	0.0005	0.000275	0.944197854	407.2086593	0.885530845
9	0.000375	0.0004875	0.000275	0.916128055	405.5889842	0.892961698
10	0.000375	0.000475	0.00025	0.863437393	405.3294213	0.903707665

11	0.000375	0.000475	0.0002625	0.876047064	404.6306067	0.902105681
12	0.000375	0.000475	0.0003	0.912480039	402.4774634	0.897323625
13	0.000375	0.000475	0.0002875	0.900544801	403.2034326	0.898913651
14	0.00035	0.00045	0.00025	0.767334971	404.6832193	0.96328965
15	0.0003625	0.0004625	0.0002625	0.826513939	404.2832557	0.930872648
16	0.0004	0.00045	0.00025	0.85410774	399.11987	0.878985497
17	0.0003875	0.0004625	0.0002625	0.871670036	401.5716484	0.889626932
18	0.00035	0.0005	0.00025	0.870655377	411.3470147	0.929777496
19	0.0003625	0.0004875	0.0002625	0.879884734	407.6419623	0.91491928
20	0.0004	0.0005	0.00025	0.965901738	405.9388195	0.85089017
21	0.0003875	0.0004875	0.0002625	0.927192342	404.9671397	0.87501666
22	0.00035	0.00045	0.0003	0.811144735	401.5925443	0.956074598
23	0.0003625	0.0004625	0.0002875	0.849683541	402.7980831	0.927482422
24	0.0004	0.00045	0.0003	0.903400047	396.4368237	0.872944625
25	0.0003875	0.0004625	0.0002875	0.896241544	400.1863166	0.886522405
26	0.00035	0.0005	0.0003	0.919268086	408.3319547	0.923021432
27	0.0003625	0.0004875	0.0002875	0.904286178	406.1736715	0.911636159
28	0.0004	0.0005	0.0003	1.020513208	403.3001768	0.845200823
29	0.0003875	0.0004875	0.0002875	0.953060197	403.5947945	0.872005786

4.4.1. Response surface generation

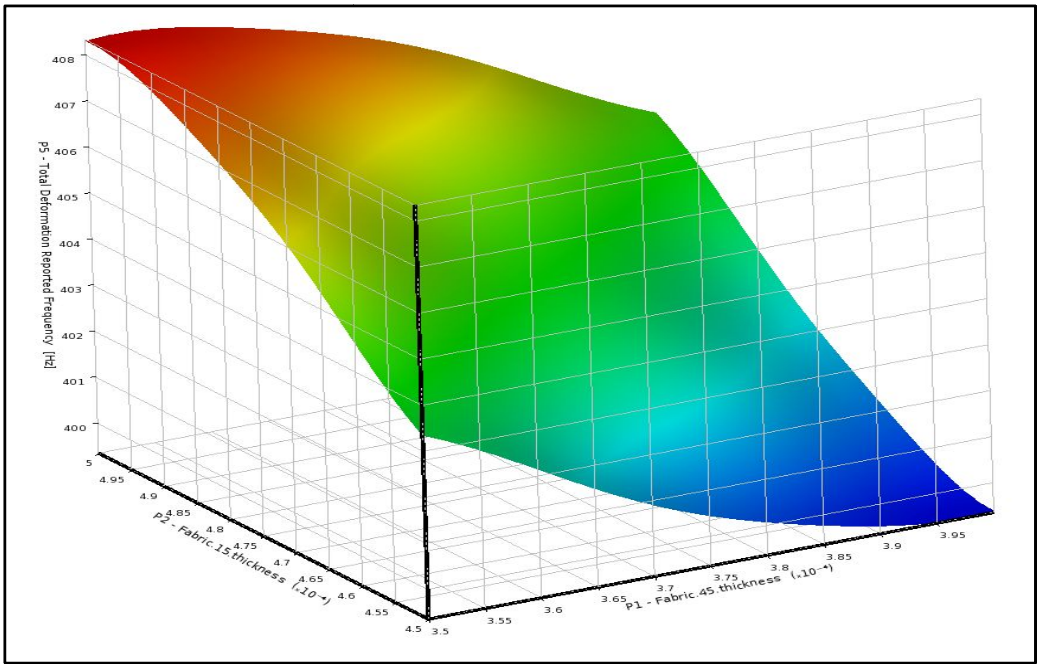

Figure 19:Response Surface-45 vs 15 vs Natural Frequency

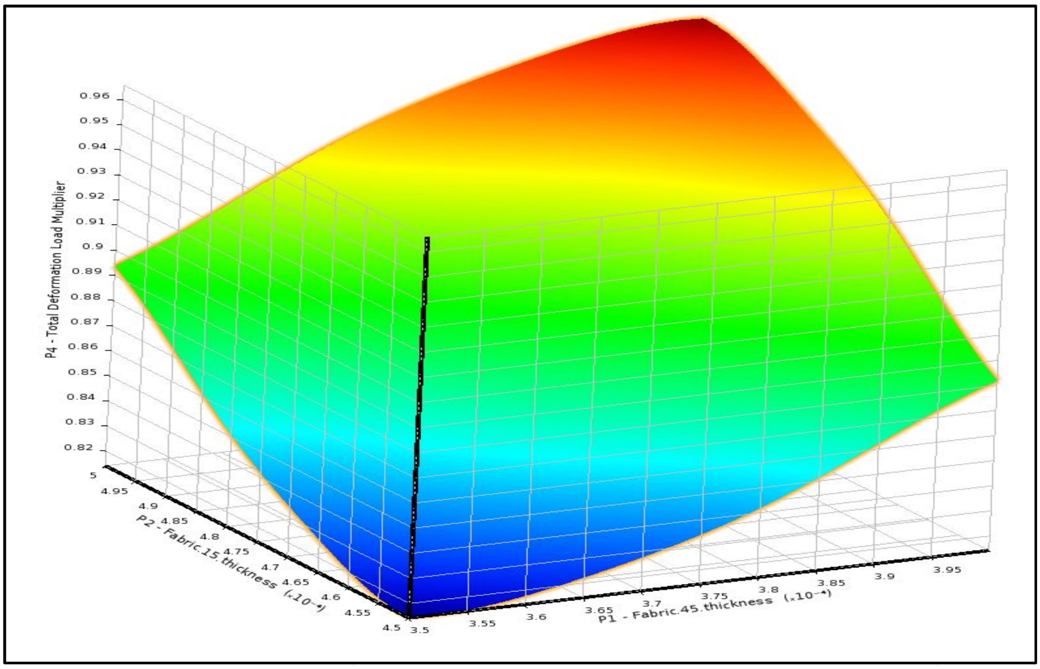

Figure 20: Response Surface-45 vs 15 vs Load Multiplier

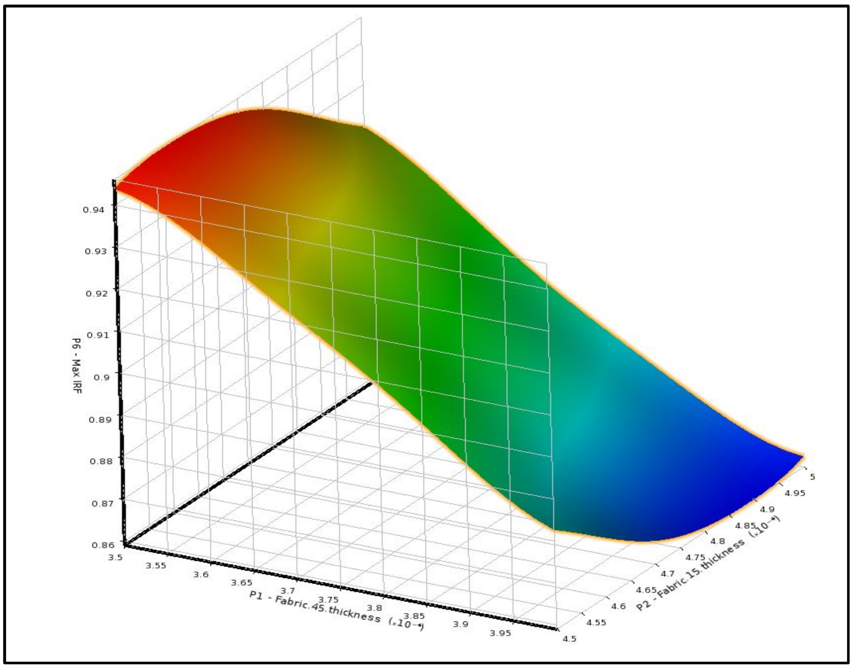

Figure 21: Response Surface- 45 vs 15 vs Max IRF

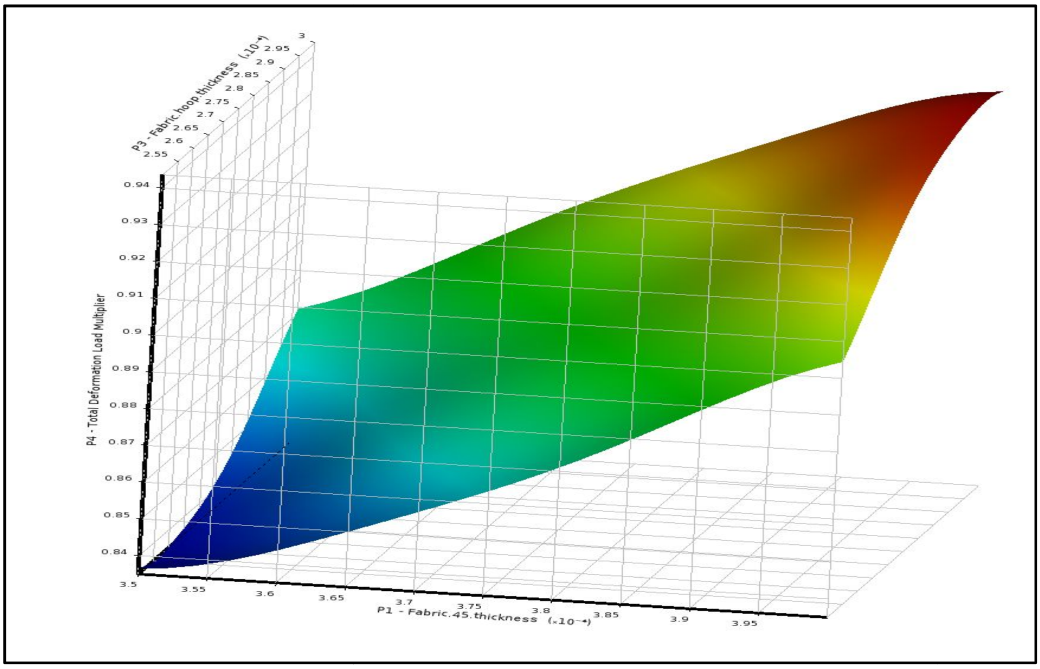

Figure 22: Response Surface-45 vs hoop vs Load Multiplier

4.5. Optimization

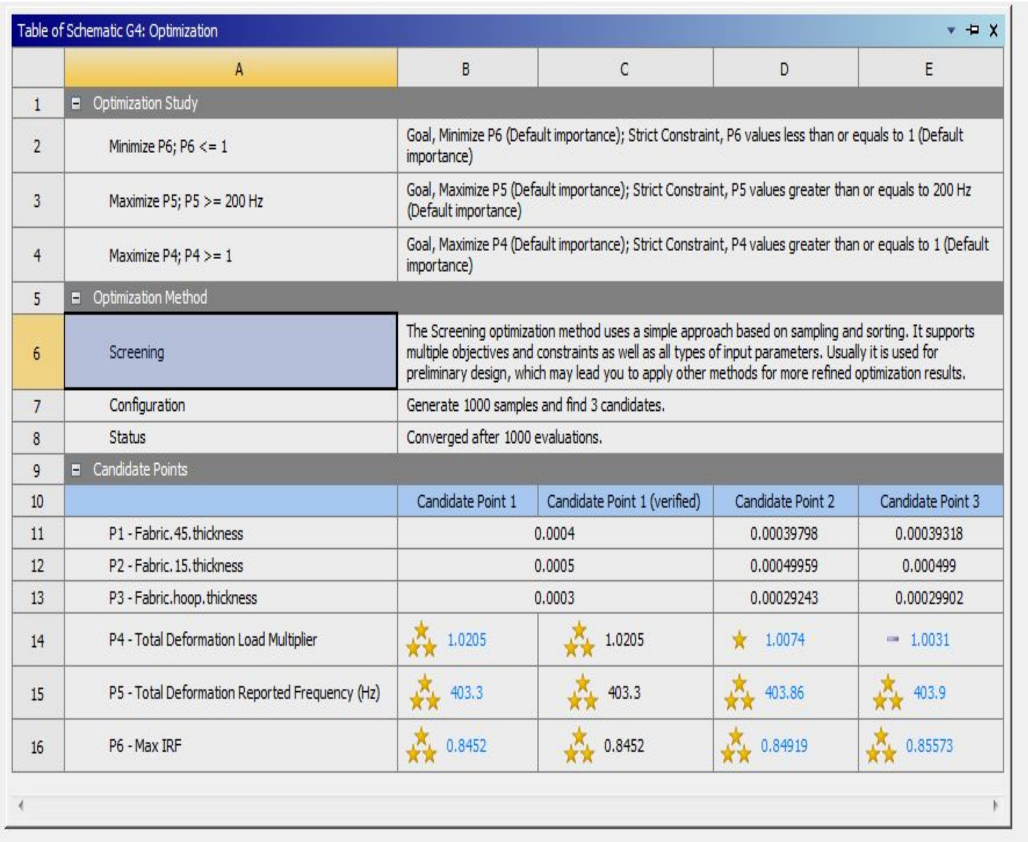

Table of Schematic G4: Optimization

	A	B	C	D	E
1	⊟ Optimization Study				
2	Minimize P6; P6 <= 1	Goal, Minimize P6 (Default importance); Strict Constraint, P6 values less than or equals to 1 (Default importance)			
3	Maximize P5; P5 >= 200 Hz	Goal, Maximize P5 (Default importance); Strict Constraint, P5 values greater than or equals to 200 Hz (Default importance)			
4	Maximize P4; P4 >= 1	Goal, Maximize P4 (Default importance); Strict Constraint, P4 values greater than or equals to 1 (Default importance)			
5	⊟ Optimization Method				
6	Screening	The Screening optimization method uses a simple approach based on sampling and sorting. It supports multiple objectives and constraints as well as all types of input parameters. Usually it is used for preliminary design, which may lead you to apply other methods for more refined optimization results.			
7	Configuration	Generate 1000 samples and find 3 candidates.			
8	Status	Converged after 1000 evaluations.			
9	⊟ Candidate Points				
10		Candidate Point 1	Candidate Point 1 (verified)	Candidate Point 2	Candidate Point 3
11	P1 - Fabric.45.thickness	0.0004		0.00039798	0.00039318
12	P2 - Fabric.15.thickness	0.0005		0.00049959	0.000499
13	P3 - Fabric.hoop.thickness	0.0003		0.00029243	0.00029902
14	P4 - Total Deformation Load Multiplier	★★★ 1.0205	★★★ 1.0205	★ 1.0074	− 1.0031
15	P5 - Total Deformation Reported Frequency (Hz)	★★★ 403.3	★★★ 403.3	★★★ 403.86	★★★ 403.9
16	P6 - Max IRF	★★★ 0.8452	★★★ 0.8452	★★★ 0.84919	★★★ 0.85573

Figure 23:

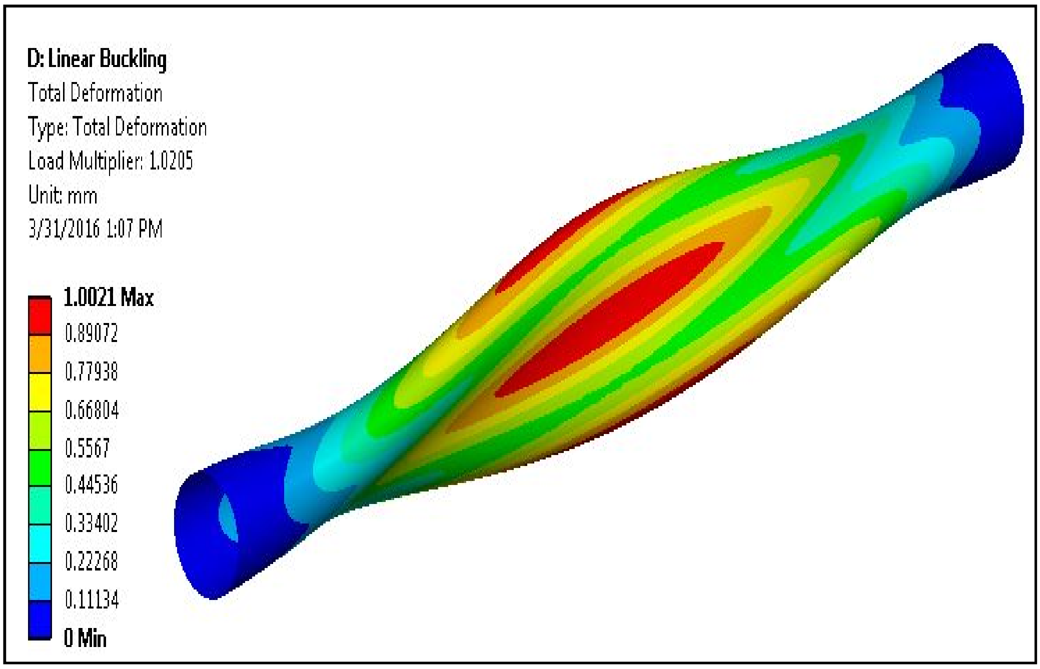

Figure 24: Optimized case- Eigen Buckling

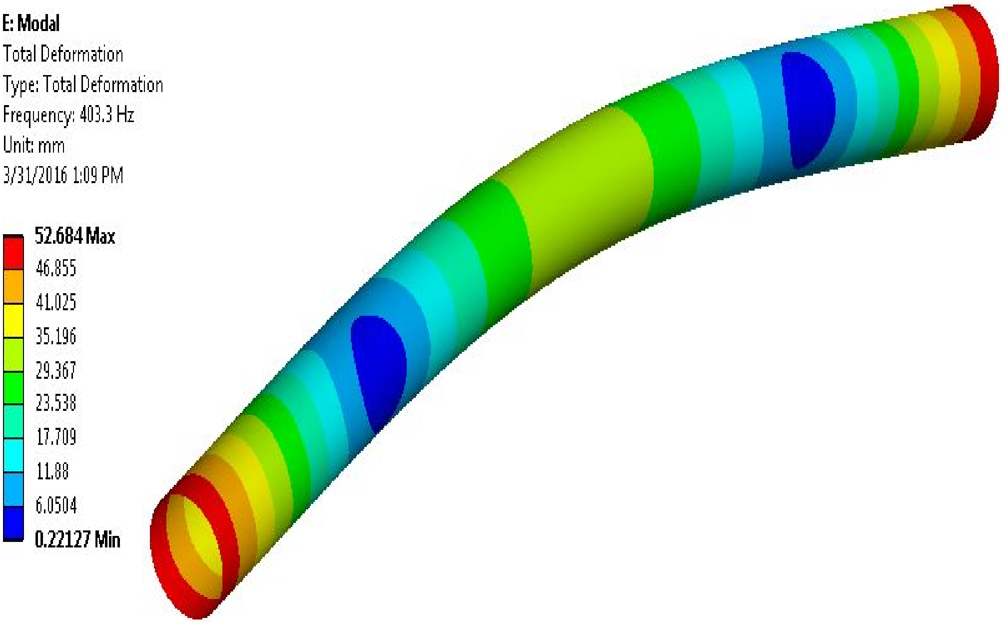

Figure 25: Optimized case-Modal Analysis

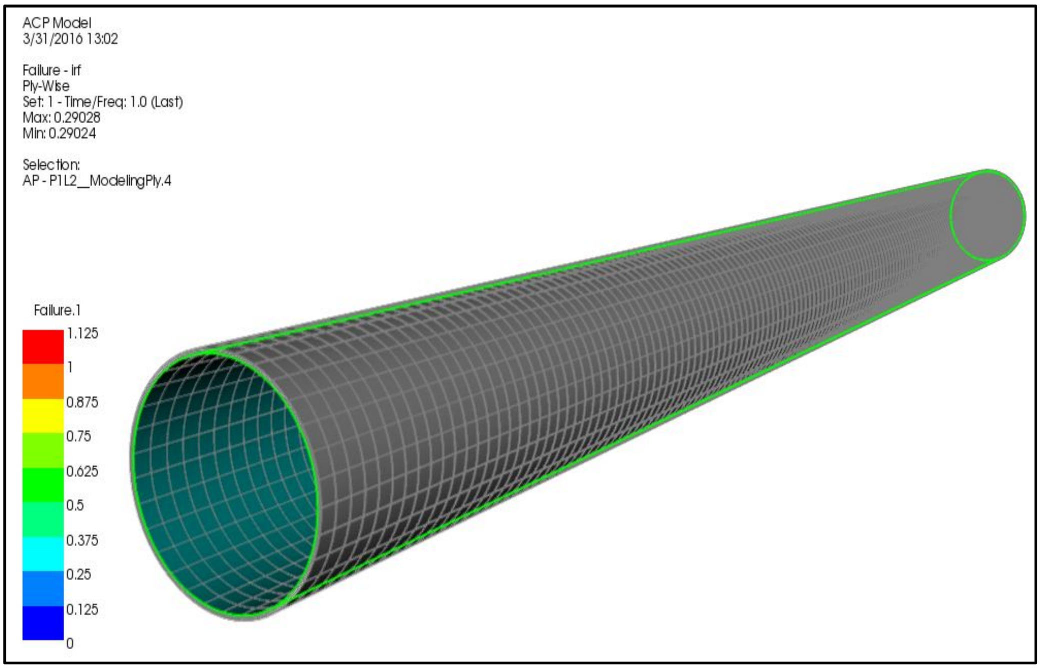

Figure 26: Optimized case -IRF for ply 45° (Bottom most)

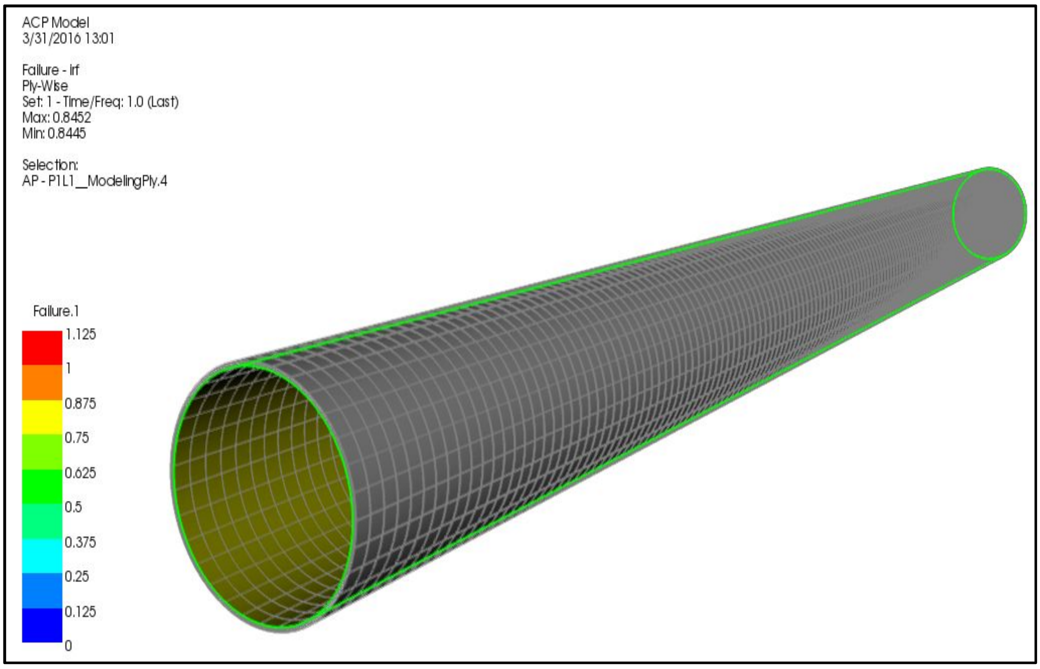

Figure 27: Optimized case- IRF for ply -45°

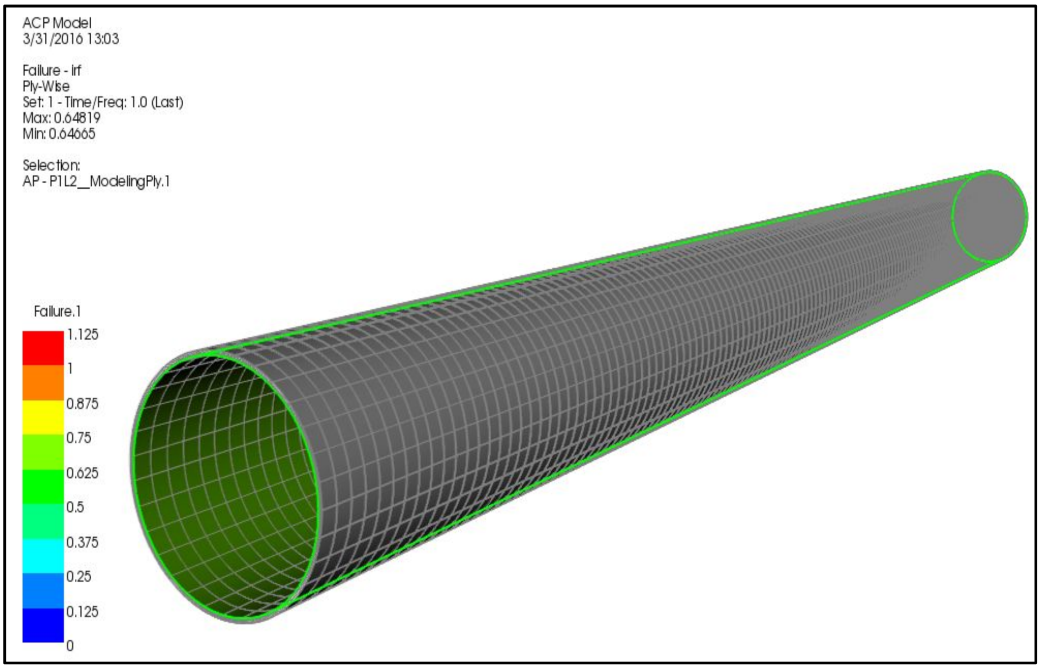

Figure 28: Optimized case- IRF for ply-15°

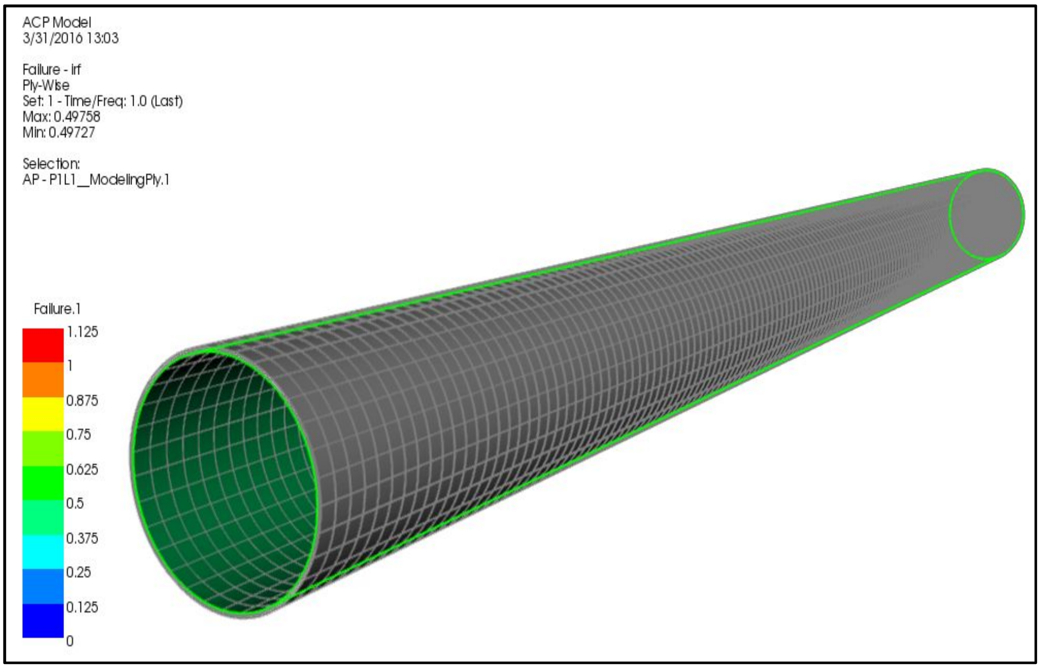

Figure 29: Optimized case-IRF for ply 15°

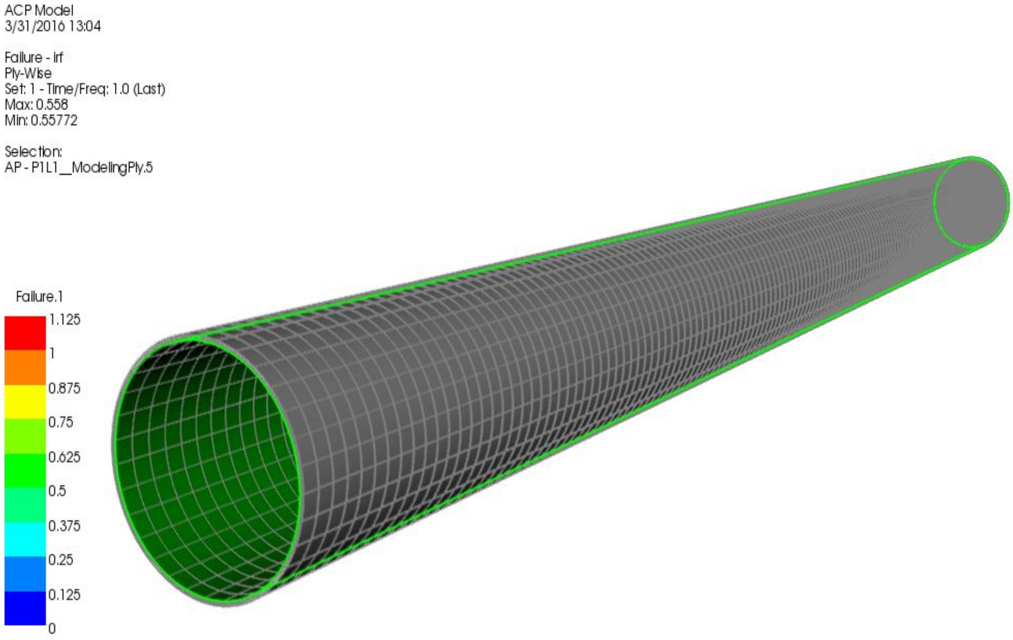

Figure 30: Optimized case-IRF for ply 90° (Top most)

Results of optimized thicknesses can be summarized as follows

Table 7: Summary of results of Optimized case Analysis

Thickness of 45° Ply (mm)	0.4
Thickness of 15° Ply (mm)	0.5
Thickness of 90° Ply (mm)	0.3
$[90^\circ_{0.3}/\pm 15^\circ_{0.5}/\pm 45_{0.4}{}^\circ]$	
Load Multiplier	1.02
Minimum Natural Frequency (Hz)	403.3
IRF in 45° Ply	0.290
IRF in -45° Ply	0.845
IRF in -15° Ply	0.648
IRF in 15° Ply	0.497
IRF in 90° Ply	0.557
Total mass of Drive Shaft (Kg)	1.4

4.6.Analysis on rationalized thicknesses

In actual thickness of a ply is a multiple of a filament band. The filament band used in simulation is 0.14 mm thick. Therefore thickness of plies is selected in such a way that it is a multiple of 0.14.

After finding optimized thicknesses of plies, an analysis based upon rationalized thicknesses of plies is carried out. Results based upon rational thicknesses are shown as follows

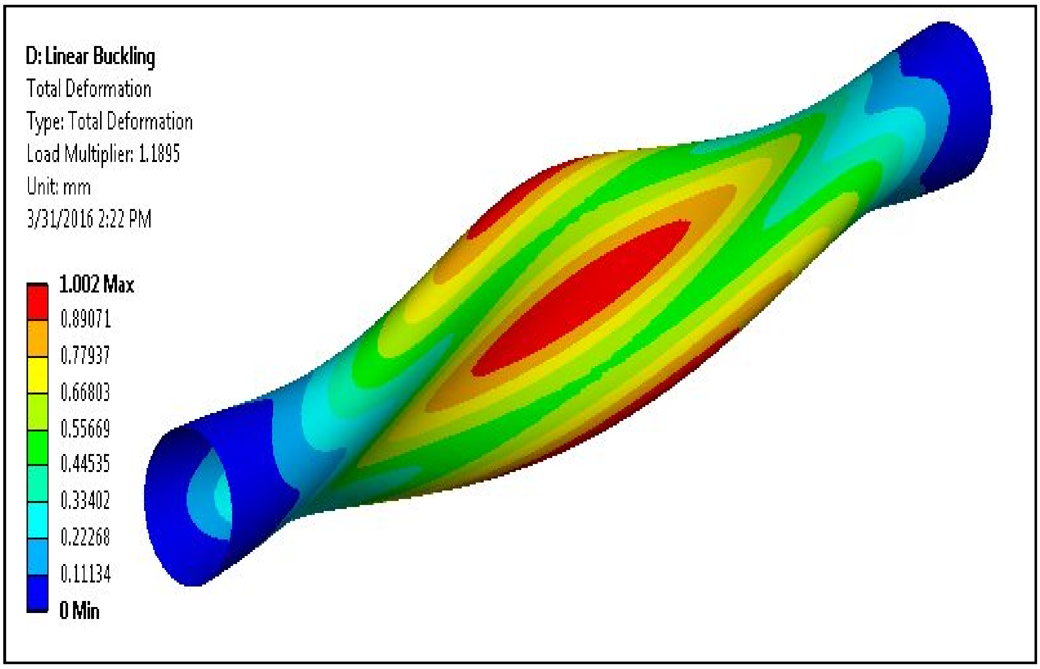

Figure 31: Rationalized Thicknesses-Eigen Buckling

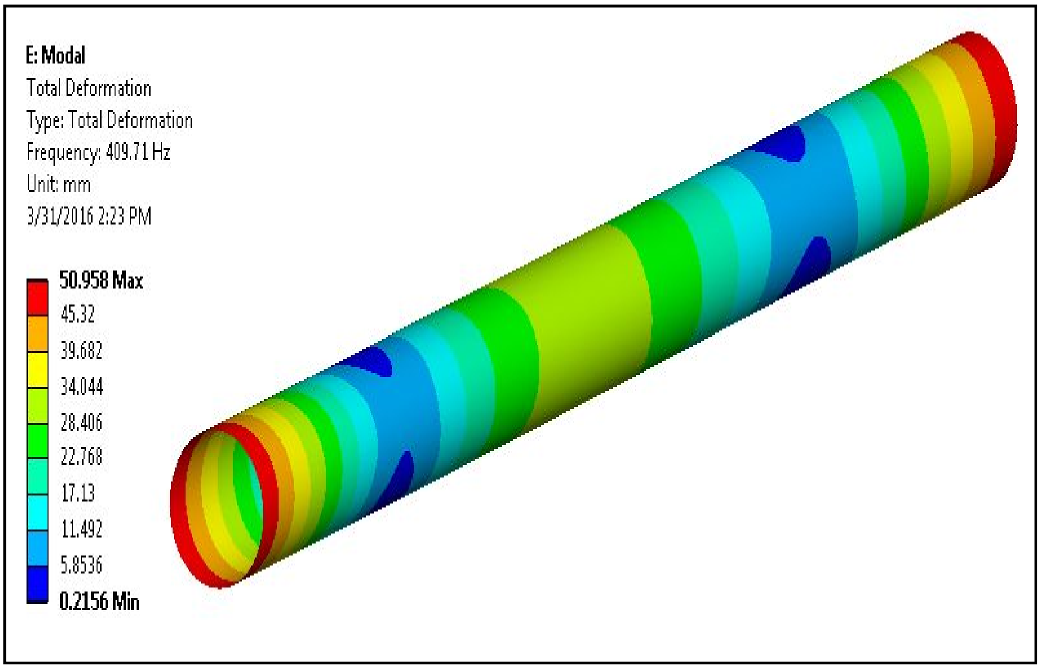

Figure 32:Rationalized Thicknesses-Modal Analysis

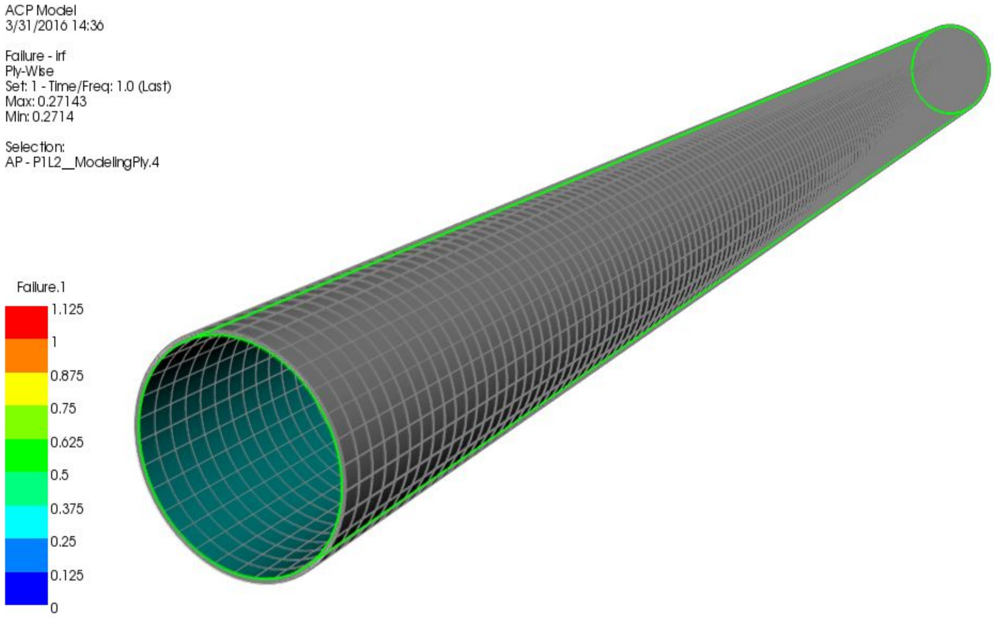

Figure 33: Rationalized Thicknesses-IRF for ply 45° (Bottom most)

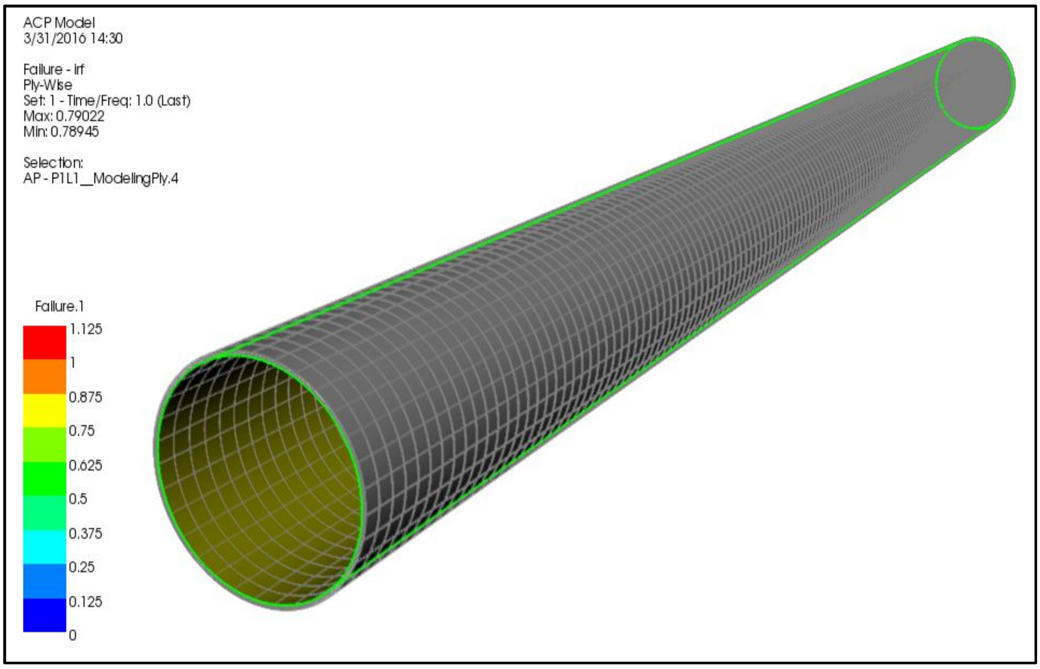

Figure 34: **Rationalized Thicknesses-IRF for ply -45°**

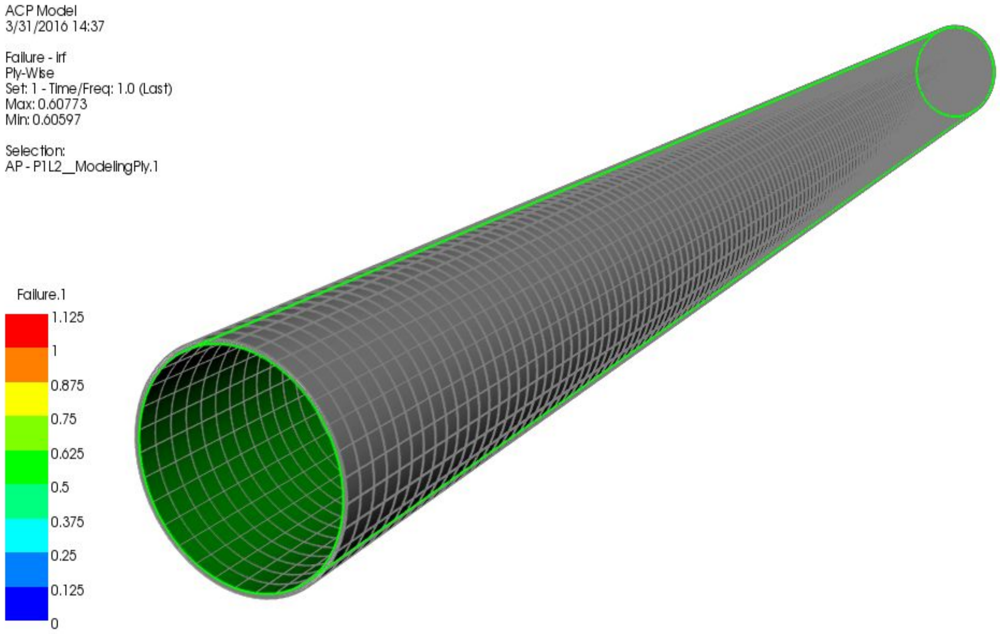

Figure 35: **Rationalized Thicknesses-IRF for ply-15°**

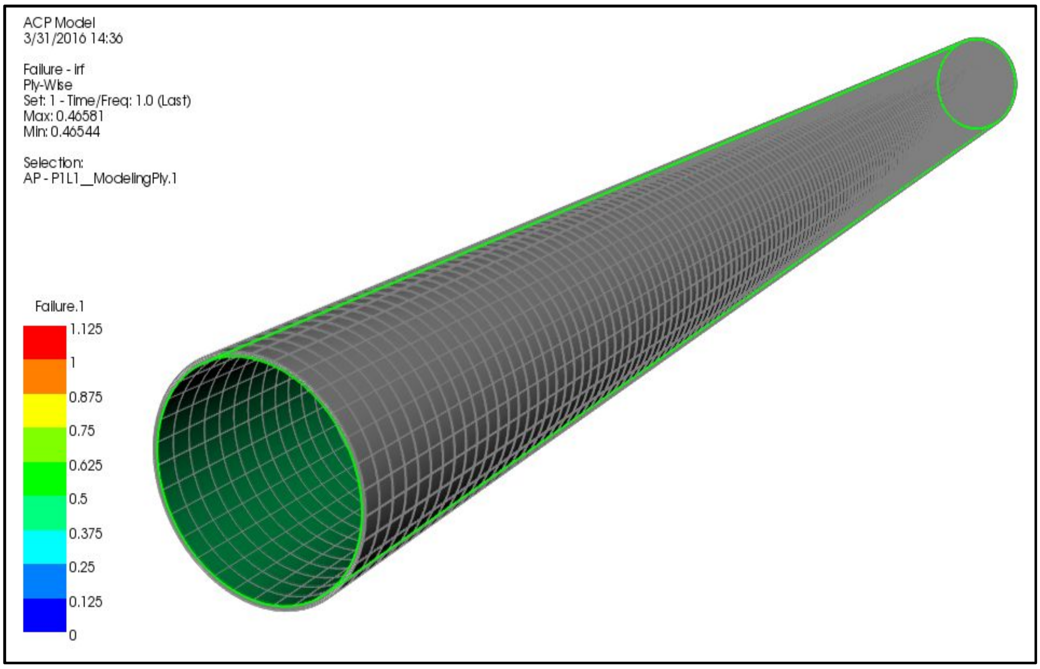

Figure 36: Rationalized Thicknesses-IRF for ply 15°

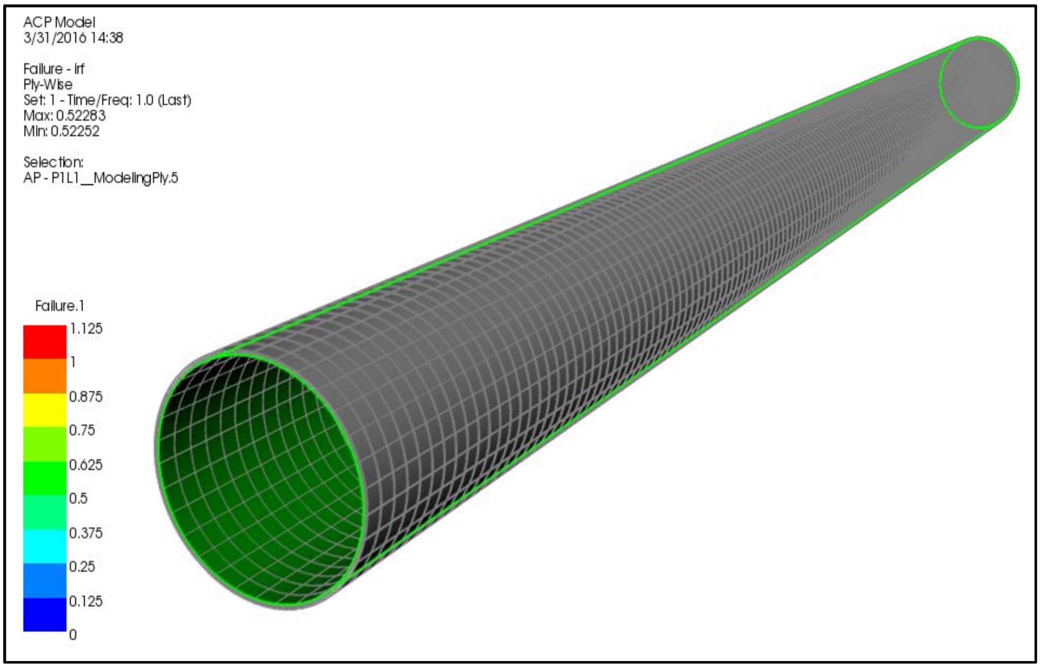

Figure 37: Rationalized Thicknesses-IRF for ply 90° (Top most)

Table 8: Summary of results of Rationalized case Analysis

Thickness of 45° Ply (mm)	0.42
Thickness of 15° Ply (mm)	0.56
Thickness of 90° Ply (mm)	0.28
$[90^\circ_{0.28}/\pm15^\circ_{0.56}/\pm45_{0.42}{}^\circ]$	
Load Multiplier	1.18
Minimum Natural Frequency (Hz)	409.7
IRF in 45° Ply	0.271
IRF in -45° Ply	0.790
IRF in -15° Ply	0.607
IRF in 15° Ply	0.465
IRF in 90° Ply	0.522
Total mass of Drive Shaft (Kg)	1.5

4.7.Analysis of Hybrid Composite Drive Shaft

The outer most layer hoop layer is replaced with Aluminum 7075-T6. Results are shown as follows:

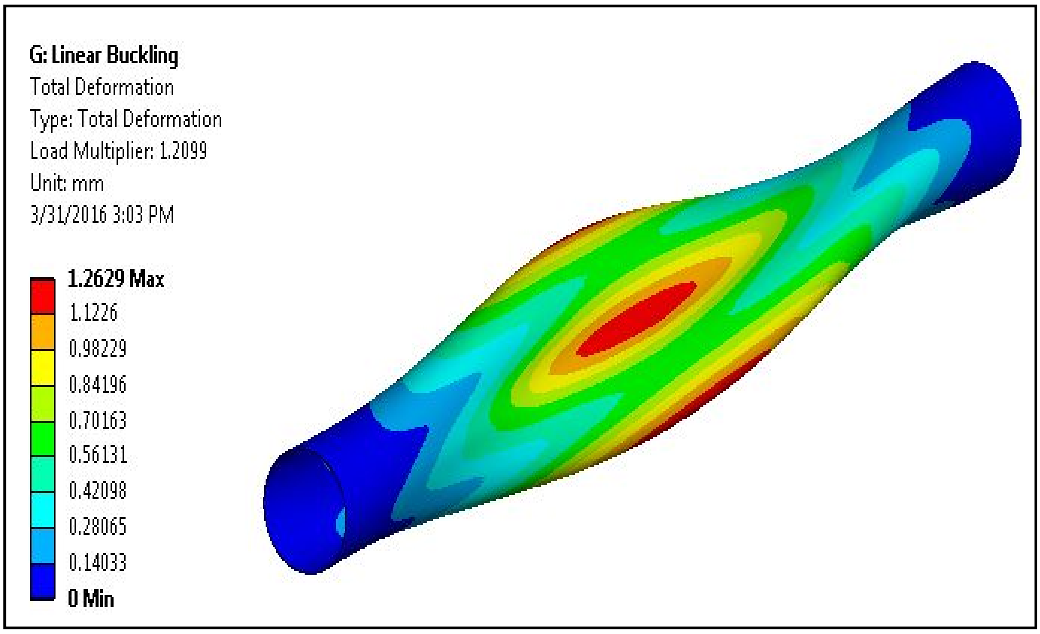

Figure 38:Hybrid Composite Drive Shaft Eigen Buckling

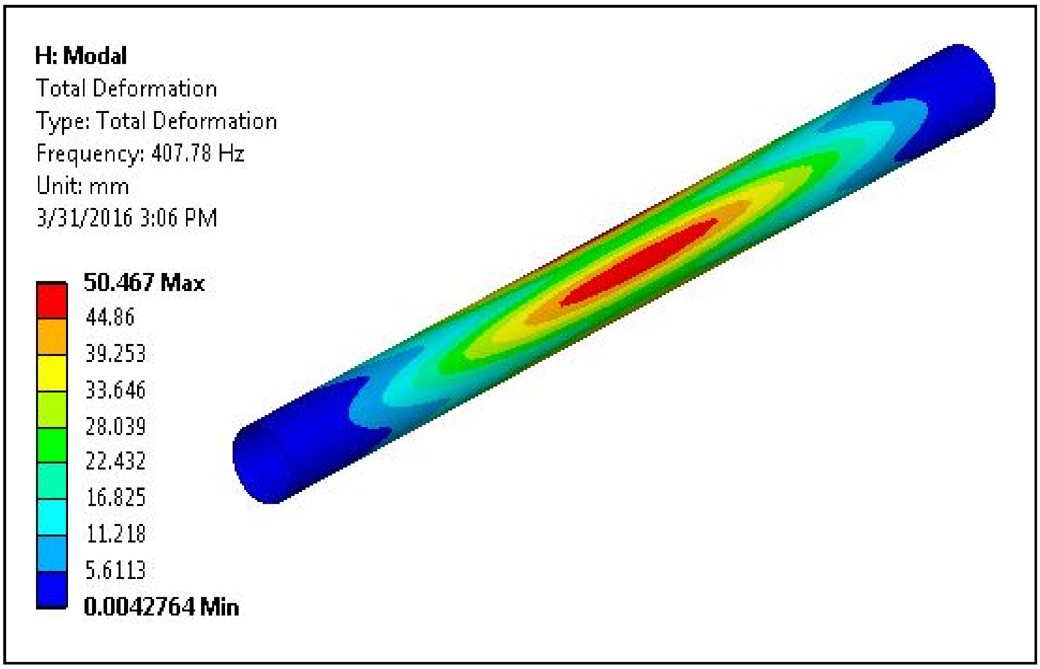

Figure 39: Hybrid Composite Drive Shaft Modal analysis

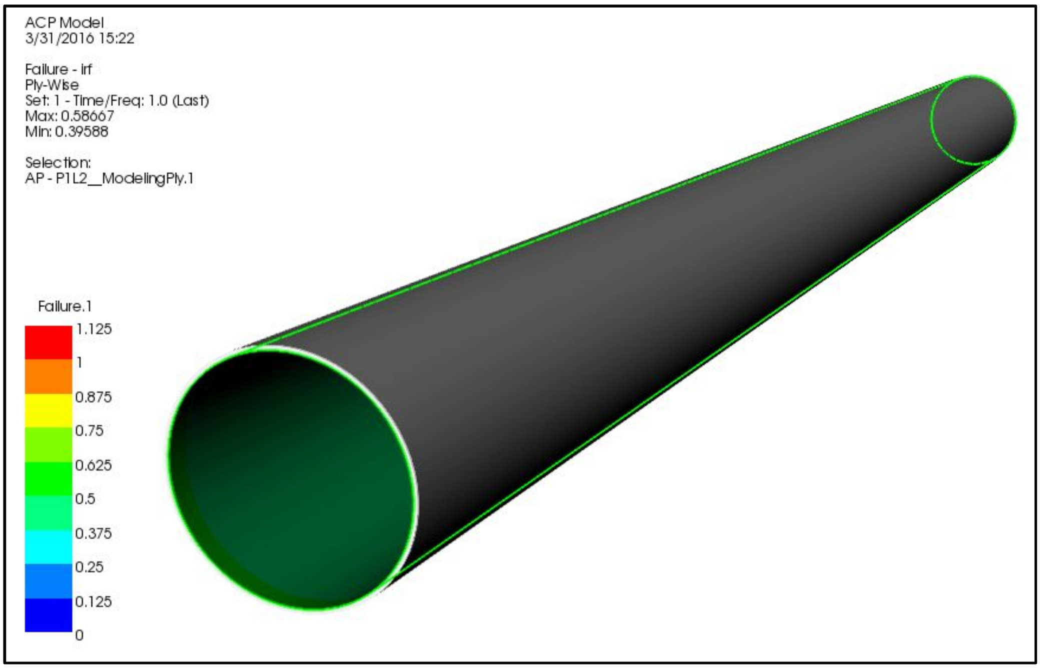

Figure 40: Hybrid Composite Drive Shaft IRF for ply -15° (Bottom most)

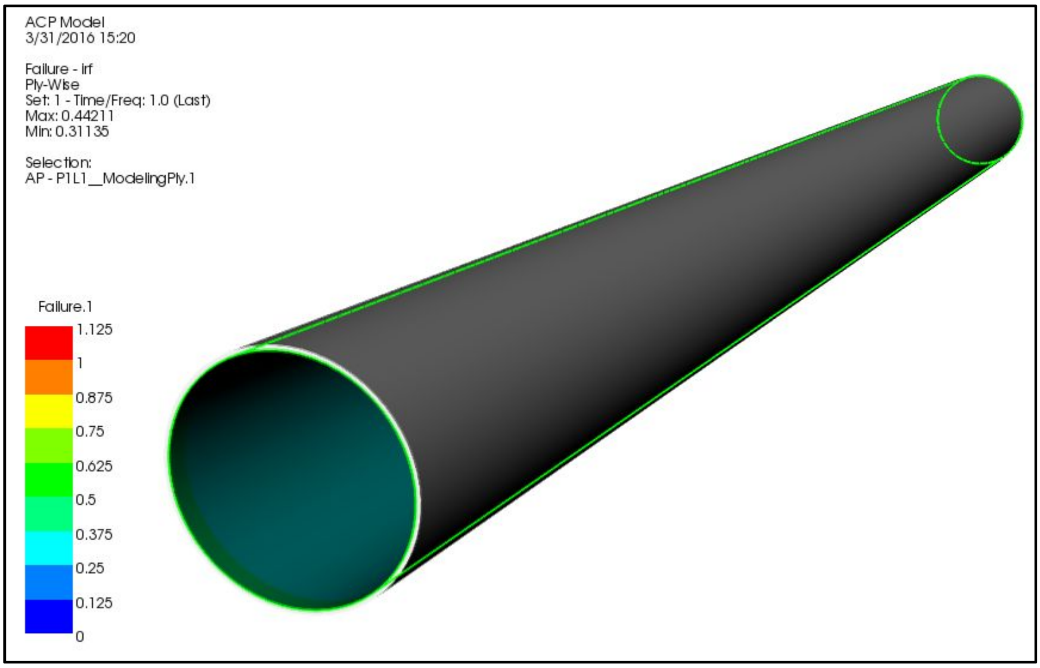

Figure 41: Hybrid Composite Drive Shaft, IRF for ply 15°

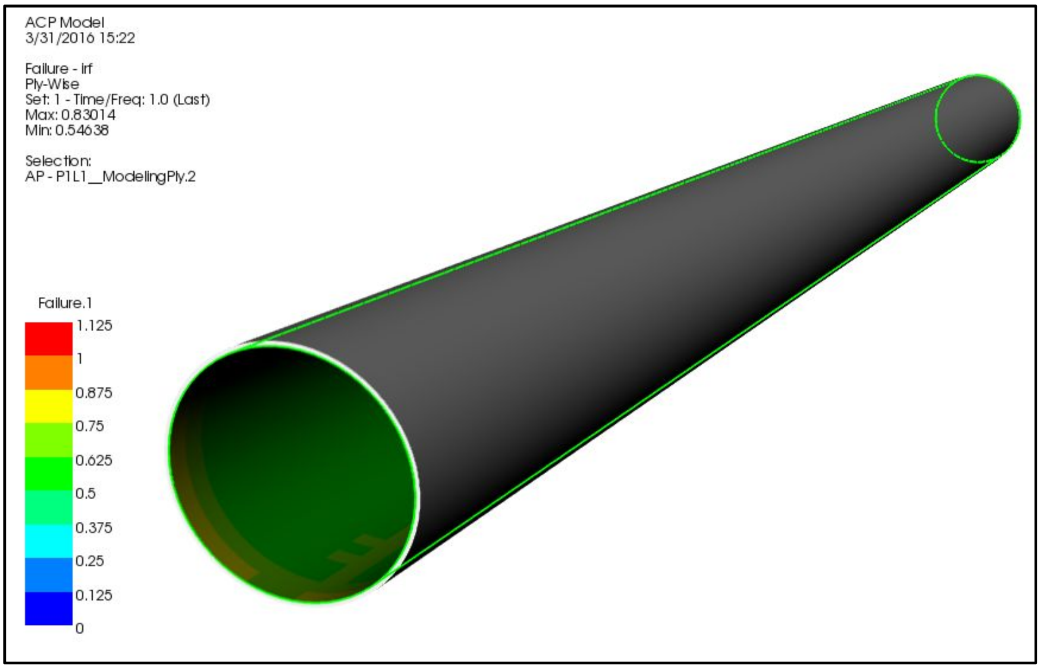

Figure 42: Hybrid Composite Drive Shaft IRF for ply 45°

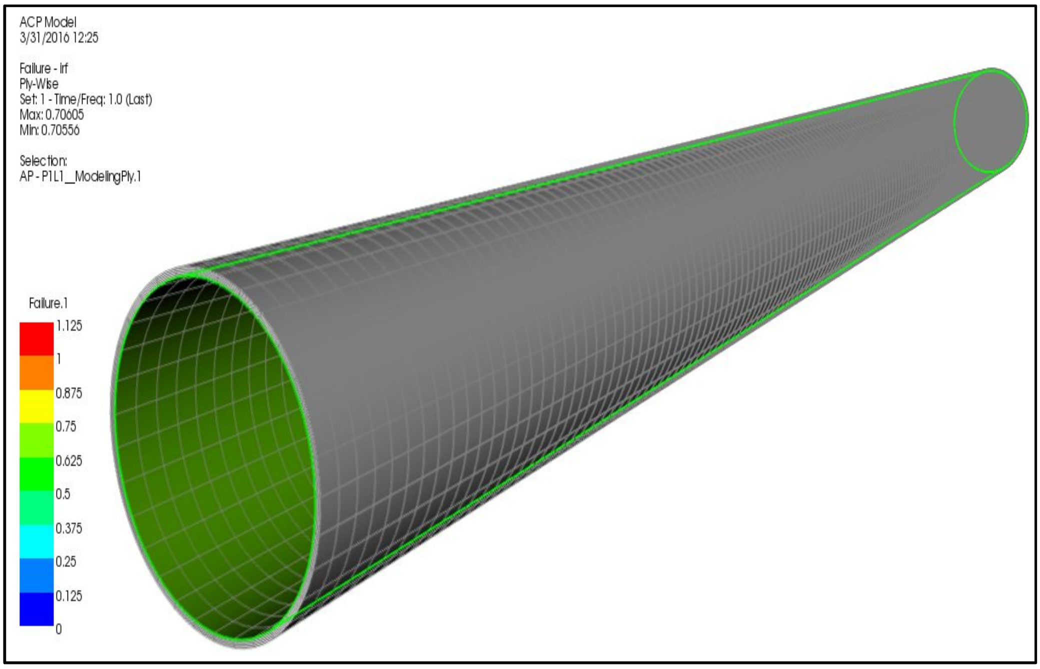

Figure 43: Hybrid Composite Drive Shaft IRF for ply -45° (Next to top)

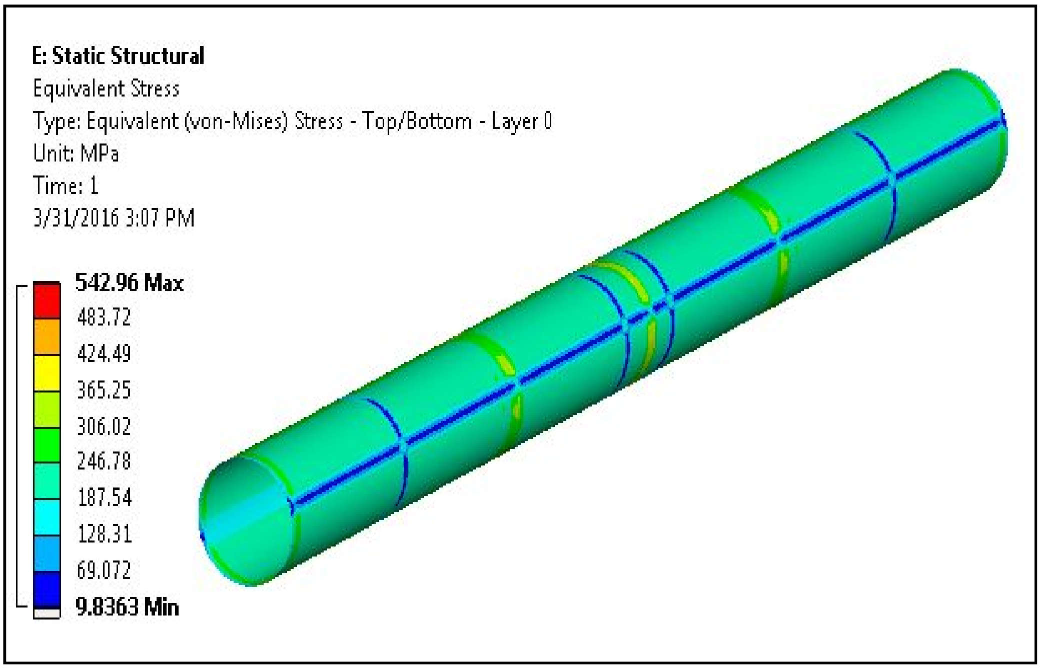

Figure 44: Hybrid Composite Drive Shaft von mises in Aluminum (Top most)

Table 9: Summary of results of Hybrid case Analysis

Thickness of 45° Ply (mm)	0.42
Thickness of 15° Ply (mm)	0.56
Thickness of Aluminum 7075-T6	0.28
$[45^\circ_{0.42}/\pm 15_{0.56}{}^\circ]$	
Load Multiplier	1.209
Minimum Natural Frequency (Hz)	407.78
IRF in -15° Ply	0.586
IRF in 15° Ply	0.442
IRF in 45° Ply	0.83
IRF in -45° Ply	0.70
Von Mises Aluminum 7075-T6	542.9 MPa
Total mass of Drive Shaft (Kg)	1.66

Chapter 5

Conclusion and Future recommendations

5.1.Conclusion

The overall summary of all the analysis cases is tabulated in Table 10, which shows that by switching to hybrid structure mass increases from 1.5 Kg to 1.66 Kg, which means that there is 10% penalty in mass. But at this cost we get benefit of ease of connecting drive shaft with other metallic engine parts such as welding, bolting etc.

Table 10 Overall Summery

	Base Case $[90^\circ_{0.5}/\pm15^\circ_{0.5}/\pm45_{0.5}{}^\circ]$	Optimized Case $[90^\circ_{0.3}/\pm15^\circ_{0.5}/\pm45_{0.4}{}^\circ]$	Rationalized Case $[90^\circ_{0.28}/\pm15^\circ_{0.56}/\pm45_{0.42}{}^\circ]$	Hybrid Case $[\pm45^\circ_{0.42}/\pm15_{0.56}{}^\circ]$
Load Multiplier	1.565	1.02	1.18	1.209
Natural Frequency	384.97	403.3	409.7	407.78
IRF in 45° Ply	0.243	0.290	0.271	0.83
IRF in -45° Ply	0.706	0.845	0.790	0.70
IRF in -15° Ply	0.542	0.648	0.607	0.586
IRF in 15° Ply	0.416	0.497	0.465	0.442
IRF in 90° Ply	0.469	0.557	0.522	542.9 MPa
Total mass (Kg)	1.68	1.4	1.5	1.66

5.2. Future recommendations

Analysis of hybrid drive shaft shows that it can withstand torsional, buckling and vibration loads without being failed. But it is recommended that these results should be verified by experimental testing.

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