Design and Evaluation of Composite Drive Shaft

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Declaration

I certify that this research work titled "*Design and Evaluation of Composite Drive Shaft*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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All Praise is for ALLAH Subhana-Watala. I wish that I may keep on thanking Almighty ALLAH in better and improved ways. I thank HIM for blessing me and seek HIS forgiveness, always.

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Dedicated to my wonderful family!

ABSTRACT

The Drive Shaft carries fundamental importance in power transmission. Nowadays focus is on to transmit power with losses being as low as possible. Design of a previous research thesis was revalidated. Two models were under consideration. One of CFRP Composite and the second of Hybrid nature in which Aluminium layer has been wound over the Carbon Composite layers. The plies' thickness and angles were varied. Three analyses namely Static Structural, Linear Buckling & Modal Analysis were carried out in ANSYS workbench 15. Effects on Frequency and IRF were studied to evaluate the designs. Aim was to achieve high strength with less mass. Hybrid drive shafts are becoming very useful in the industry as they are lightweight as compared to metals and provide ease of joining with other metals.

Key Words: Hybridization, Buckling, Static Structural Analysis

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CHAPTER 1

INTRODUCTION

1.1 History

The driveshaft was invented by Louis Renault in 1898. The term Driveshaft in automotives usually refers to refers to the particular *transverse* shaft which transfers power to wheels (esp. the front ones). The type of shaft that connects gearbox to the rear differential is referred to as Propeller Shaft. A shaft may sometimes be also called Cardan shaft [1].

1.2 Usage

Shaft is a mechanical device used for transferring power from an engine or a motor to the point of application of work [1]. A shaft is basically used for connecting the prime mover and ‘moving’ component(s).

1.3 Design Aim

While designing driveshaft, it is of prime importance that the shaft does not fail under the load it is subjected to. Moreover, the weight of the shaft should be as low as possible so that machinery inertia effects are minimized.

1.4 Applications

Drive shafts are employed in automobiles, aircrafts, helicopters, pumping and compression systems, etc.

1.5 Materials for Construction

Conventionally, metals were used for the fabrication of drive shafts. With the passing of time focus shifted to use shafts with low weights.

About 17-22 % of the power developed in an engine is lost to the rotating mass of the drivetrain. The power is lost because it takes more energy to rotate heavier parts. This loss can be decreased by using ‘decreased’ mass. Power transmission can be improved by the reduction of inertial mass and weight lightening. To achieve this, light weight flywheels and transmission gears, riffle-drilled axles and Aluminium hubs started replacing the conventional shafts [1].

With the advancement of research and technology, composite drive shafts started replacing the metallic ones. Replacing metallic with composite parts has many advantages due to their higher specific stiffness and specific strength [1].

Driveshaft must operate in high and low power transmission of fluctuating load. Fluctuating of loads may cause failure of the driveshaft [1].

The comparative light weight of composite drive shafts also addresses the power loss issues in drive train systems.

1.6 Types of Drive Shafts

Drive shafts can be categorized on the basis of the type of materials used. On material basis drive shafts can be of the following types:

- Metallic Drive shafts;
- Composite Drive shafts;
- Hybrid Drive shafts.

1.6.1 Metallic Drive Shafts

At first metallic shafts made up of Steel were employed in shaft applications, e.g. automobile industry, etc. Later, Aluminium replaced Steel because of it being lighter than Steel.

1.6.2 Composite Drive Shafts

Composite Drive shafts have high strength to weight ratio. By using Composite Drive shafts total weight of the machine can be decreased.

A composite material is formed by the combination of matrix and the reinforcement. Matrix and reinforcement dictate the overall properties of the composite [5].

1.6.3 Hybrid Drive Shafts

As the name suggests, Hybrid drive shaft use both composites and metals. The inner part is composite and the outer one is metallic [2]. Aluminium & Carbon-fibre drive shafts have been developed to address power loss issues by decreasing rotating mass [1]. Carbon Fibre Reinforced Plastic (CFRP) increases the natural fundamental frequency of the drive shaft while the metallic part increases the torque/power transmission of the drive shaft. Furthermore, the metallic layer helps to provide ease of connection with other metallic parts [3]. Another example of a hybrid drive shaft is that of Boeing Vertrol Model 234 helicopter [4].

CHAPTER 2

LITERATURE REVIEW

The use of composites is increasing day by day. They have the advantage of varying physical properties along with their high specific strength and stiffness. Due to this they have started replacing metals in many applications. Composites are being used in the aerospace, automobile and even in the bio-mechanics fields. The work of Beardmore, P., et al. 1986 emphasized on the use of composites in the automotive industry. It was concluded that mass optimization issues could be addressed by using composites [5]. In the late 1980s polymer matrix based composite was used in automotive drive shafts [6].

When power is transmitted, the drive shaft undergoes changes in angle and position. The torque is transmitted through the axle to the drive shaft [7].

At first drive shafts were manufactured in two pieces. Although two piece drive shafts have increased bending natural frequencies which in turn reduce other frequencies, however this arrangement makes the system heavier [8], [9], [10]. To address this issue, focus started shifting to one piece drive shafts. In metallic drive shafts Steel was used [9]. Overall metals due to their isotropic nature have poor damping effects and also subjected to corrosion [11]. Therefore the need arose for finding other materials.

Composites were started to be used because of them causing low weight of drive shaft which also helped in prolonging the life of journals & bearings [12]. E-glass/epoxy and HM Carbon/epoxy composites are used because of their light weight properties [10]. HS Carbon and polymer matrix are another choice for drive shaft [13]. Kevlar and Carbon epoxies are also used [14].

Fibre orientation in plies and ply orientation both play a role in the physical properties of the composite, so one can form composites with the desired properties by altering fibres and plies [16]. As composites are of orthotropic nature, they are the better choice when compared with metals as they dampen the vibrations better [17].

Main load on the drive shaft is ‘Torsion.’ It may lead to bending of the shaft [18].

Composites being orthotropic, different ply angles produce different shear and bending upon torque loading in the drive shaft.

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°irrespective of the type of the material of composite [19].

In thin walled cylinders critical torque causes buckling. This has direct relationship with flexural stiffness which can be dealt with by using layers at 90° also known as hoop layers [12].

Effects of longitudinal membrane stiffness of the composite material can be improved by addition of layers in composites in the longitudinal direction [10]**.**

The natural bending frequency during torque transmission can be increased if the shaft is made using Carbon fibre composite and Aluminium. Carbon increases natural bending frequency and Aluminium sustains the applied torque [20].

CHAPTER 3

METHODOLOGY

3.1 Problem Statement

To design two types of Drive Shafts, one of *'Composite'* & the other of 'Hybrid' type. The metallic layer of Hybrid type to be Aluminium 7075. Keeping the weight as minimum as possible, the shaft is to withstand torsional, buckling and vibration loads.

3.2 Design Requirements

3.2.1 Torsional Strength

The drive shaft should be able to withstand a torque of 4250 N-m without failing. For composite materials 'Tsai Hill Failure' Criteria will be considered while von-Mises criteria will be considered for metallic layer. 'First Ply Failure' will be considered as failure of the composite.

3.2.2 Buckling

The drive shaft is to be designed in such a way that it does not buckle under load.

3.2.3 Vibration

In order to avoid resonance, natural frequency of the composite drive shaft should be greater than 200 Hz [4].

3.3 Design Variables

Thickness of the plies;

Fibre orientation angle of the plies;

Stacking sequence of the plies.

3.4 State Variables

IRF (Inverse Reserve Factor) to be less than or equal to 1

For safety under buckling load, load multiplier to be greater than 1

3.5 Finite Element Model Development

The model has been developed in ANSYS 15. For composite analysis ACP 15 module was used. Drive shaft is considered as a thin walled tube. Design Methodology of [4] was followed.

L= 1400 mm ; D= 100 mm.

Shell 281 element was used for meshing. Element size= 10 mm. 13268 nodes and 4402 elements were generated.

Two remote points are formed at the ends of the shaft.

3.6 Materials

- Composite Fibre Reinforced Plastic (CFRP)
- Aluminium 7075

3.7 Mechanical Properties of CFRP [4]

- 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

3.8 Mechanical Properties of Aluminium

[4]

- Young’s Modulus (GPa): 73
- Poison ratio : 0.3
- Yield strength (MPa) : 550
- Ultimate strength (MPa): 600

CHAPTER 4

ANALYSIS

In this chapter the analysis undertaken for the problem statement have been presented. The snapshots to follow will provide an insight into the design methodology in the ANSYS Workbench environment.

4.1 Assumptions

The analysis was done assuming that the shaft rotates at constant speed with uniform cross section. Hooke's law is applied [4].

4.2 Drive Shaft Geometry

The below snapshot taken from ANSYS DM (Design Modeler) shows the shaft geometry

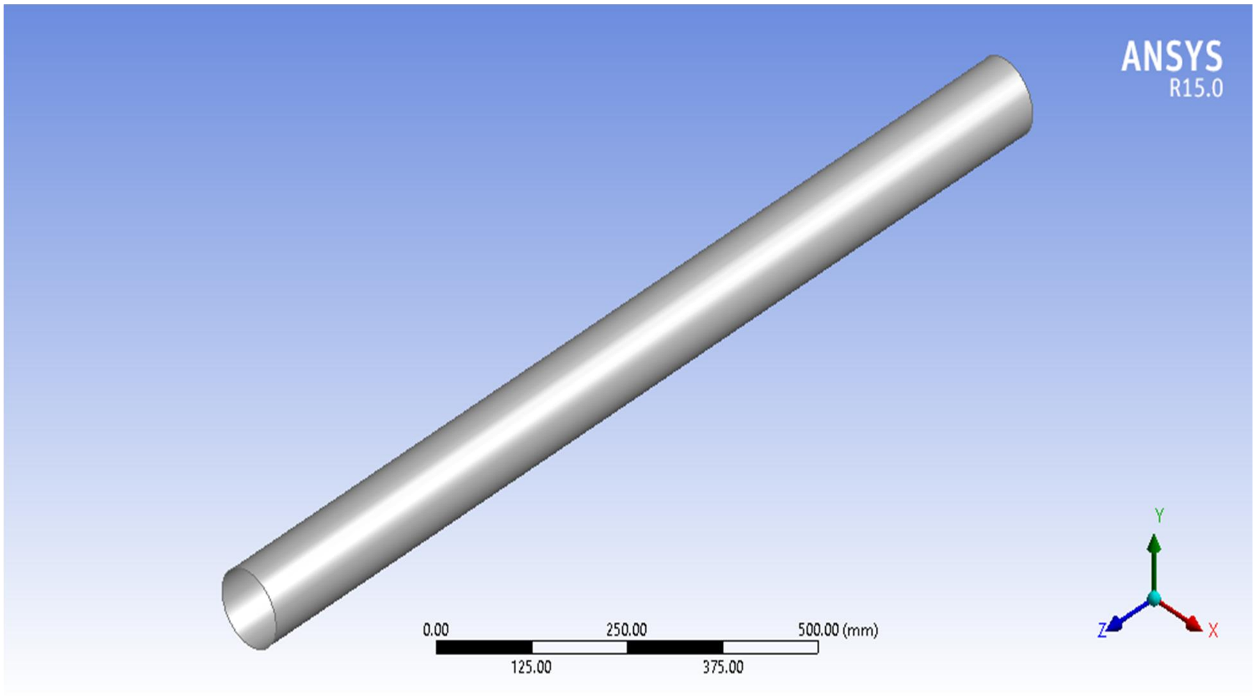


Figure 1: Drive Shaft Geometry

4.3 Mesh

For mesh shell element 281 was recommended [4].

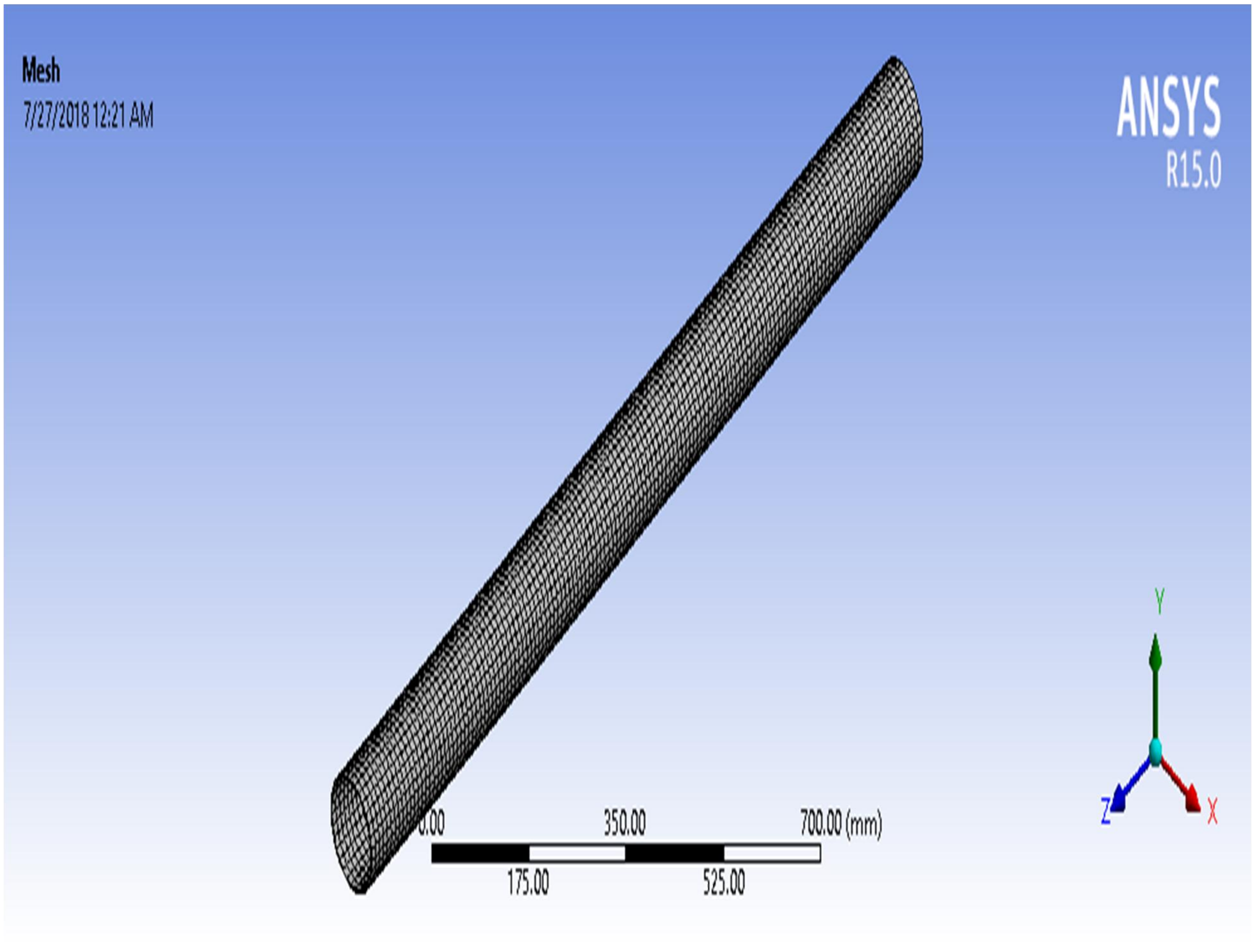


Figure 2: Drive Shaft Mesh

4.4 REMOTE POINTS

Two remote were generated at the ends of the shaft

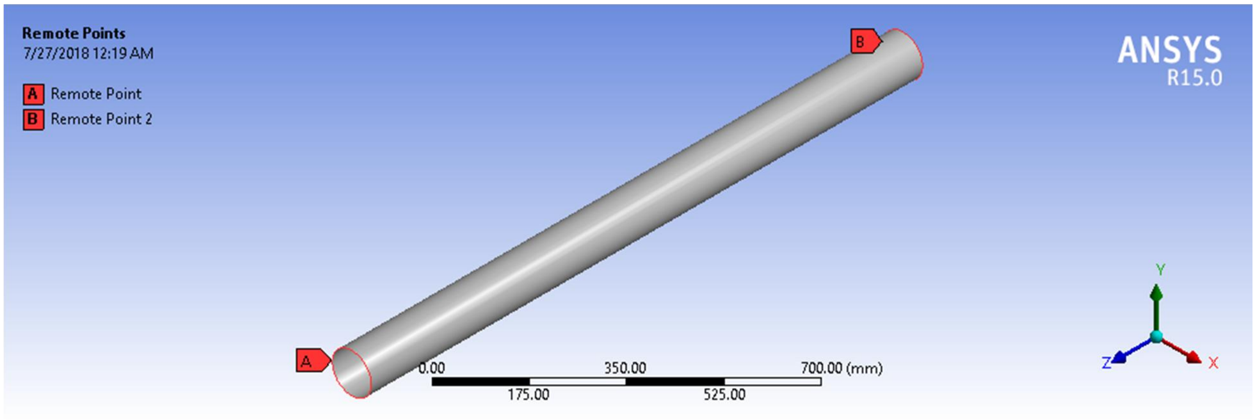


Figure 3: Remote Points

4.5 LOADING

At one remote point, remote displacement was applied while on the other side Torque was applied.

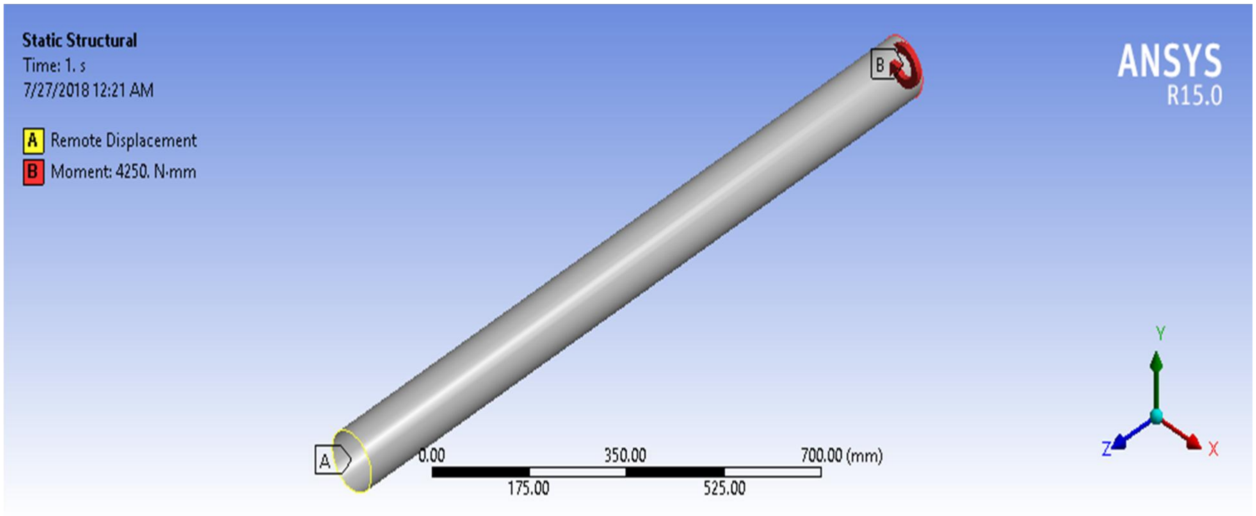


Figure 4: Loading

4.6 Flowchart

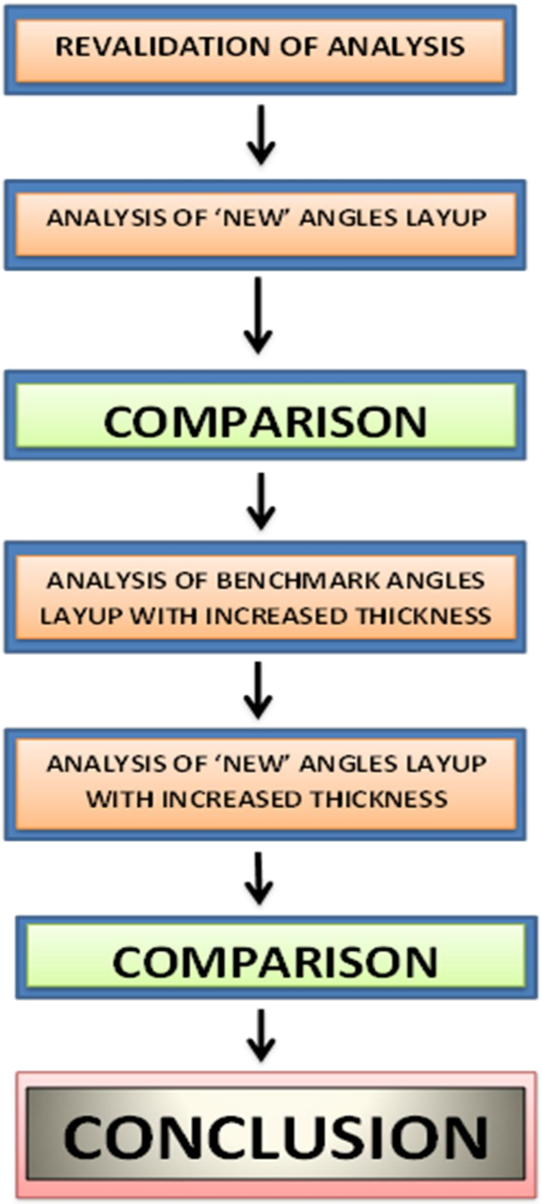


Figure 5: Flowchart

4.6.1 Flowchart Explanation

The flowchart explains the analyses process by using the terms ‘benchmark’ and ‘new’ angles.

Benchmark angles refer to the ply angles used by Kashif 2016 in [4].

New angles refer to ply angles taken from [23].

The ply angles are mentioned below:

The right-most angle is the inner-most layer while the left-most is the outer-most layer. The subscript refers to thickness of plies in mm.

Revalidation (Benchmark angles)

- $[90^\circ_{0.28}/\pm15^\circ_{0.56}/\pm45^\circ_{0.42}]$
- $[\mathrm{Al}^{90^\circ}_{0.28}/\pm45^\circ_{0.42}/\pm15^\circ_{0.56}]$

New Angles

- $[\pm85^\circ_{0.28}/0^\circ_{0.56}/\pm34^\circ_{0.42}]$
- $[\mathrm{Al}^{0^\circ}_{0.56}/\pm85^\circ_{0.28}/\pm34^\circ_{0.42}]$

Two more layers added to bench mark angles

- $[90^\circ_{0.56}/\pm15^\circ_{1.12}/\pm45^\circ_{0.84}]$

One more layer added to Hybrid case of bench mark angles

- $[\mathrm{Al}^{90^\circ}_{0.56}/\pm45^\circ_{0.42}/\pm15^\circ_{0.56}]$

Two more layers added to new angles

- $[\pm85^\circ_{0.56}/0^\circ_{1.12}/\pm34^\circ_{0.84}]$

One more layer added to Hybrid case of new angles

- $[\mathrm{Al}^{90^\circ}_{1.12}/\pm85^\circ_{0.56}/\pm34^\circ_{0.84}]$

4.7 Fiber Orientations

The following snapshots will depict the fiber orientations, i.e. the angles of the plies.

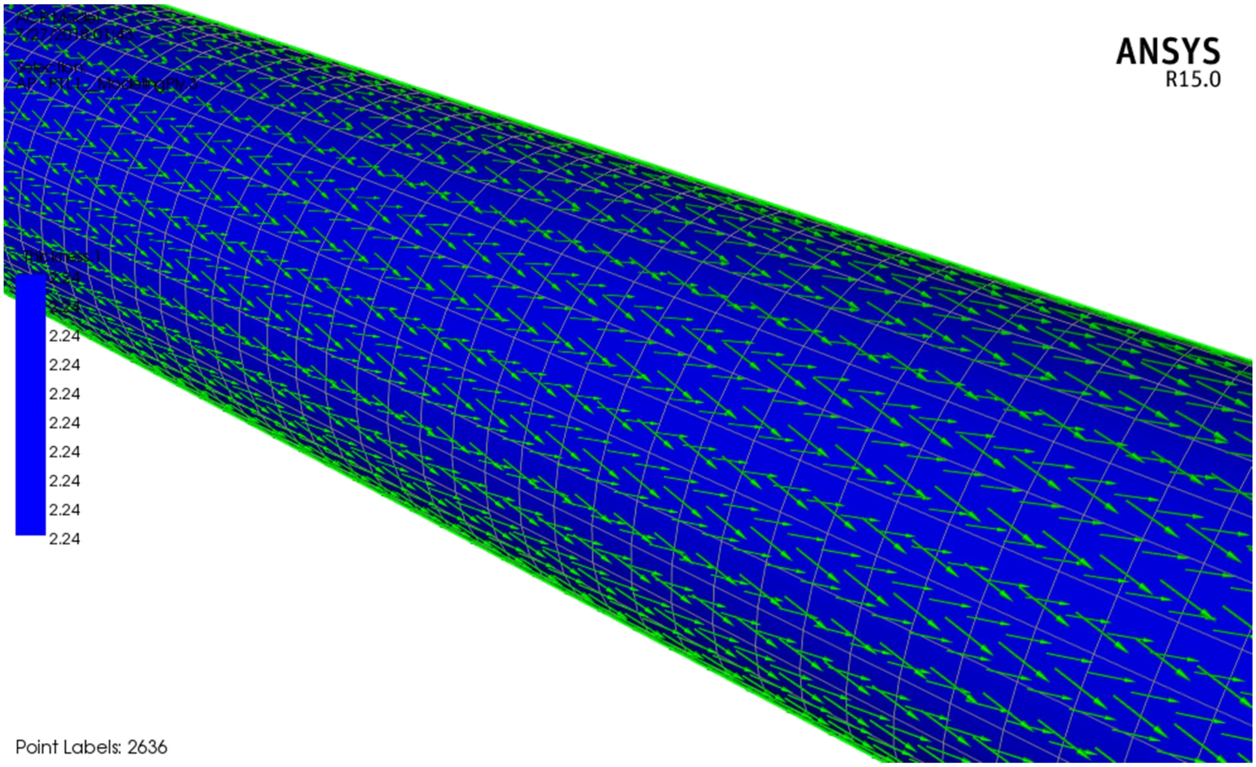


Figure 6: Fiber Orientation@ -15°

Fibre Orientation: 15°

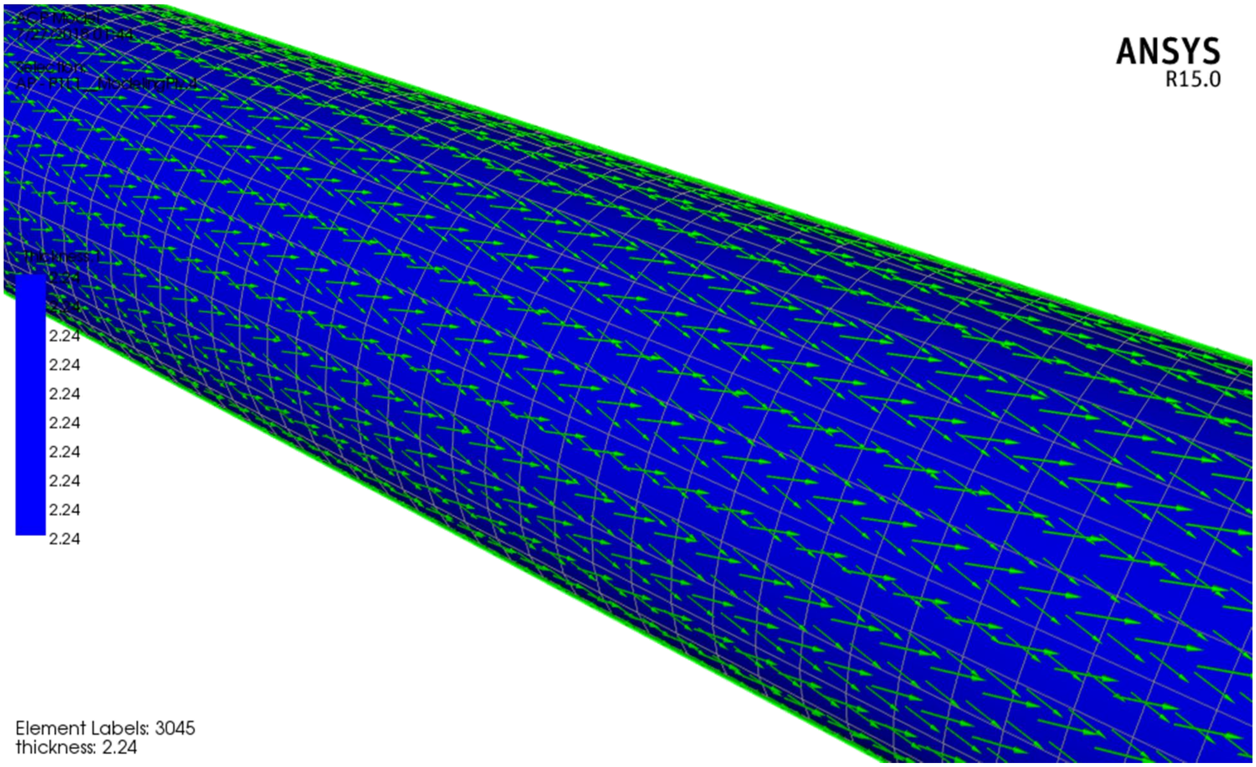


Figure 7: Fiber Orientation@ +15°

Fibre Orientation:-45°

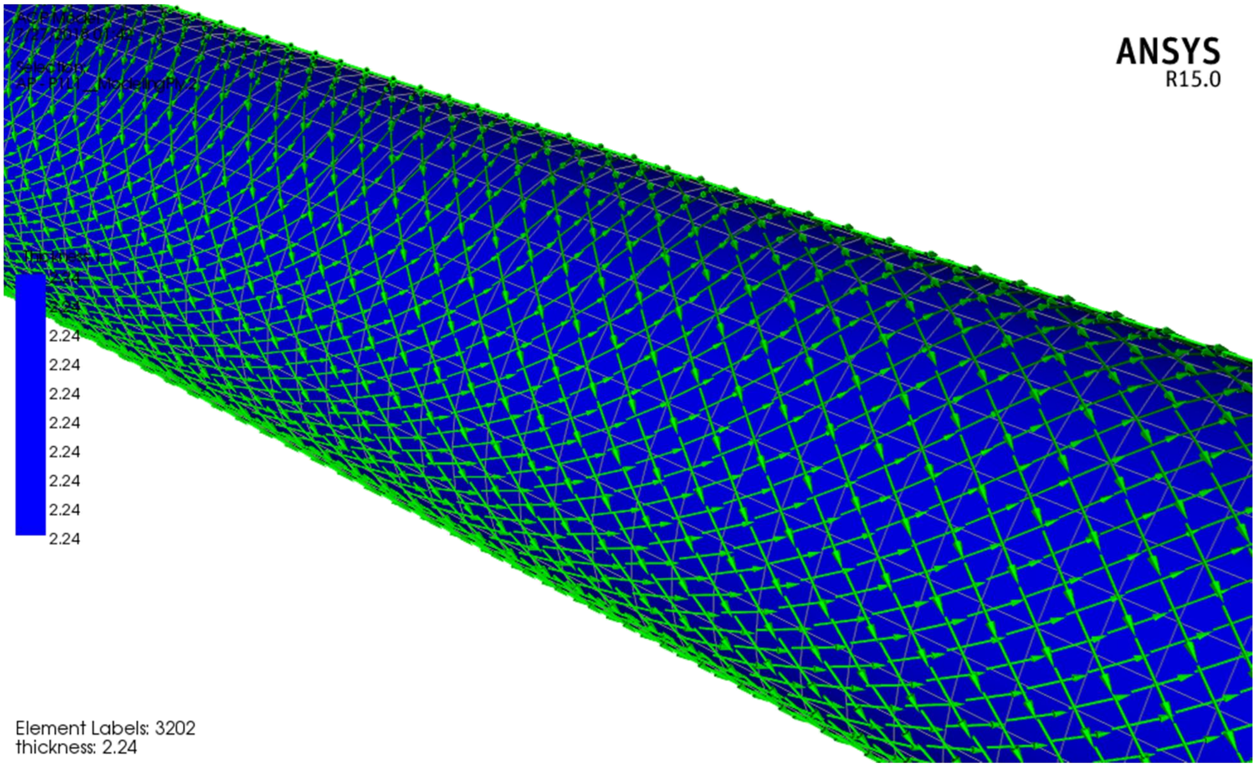


Figure 8: Fiber Orientation@ -45°

Fibre Orientation: 45°

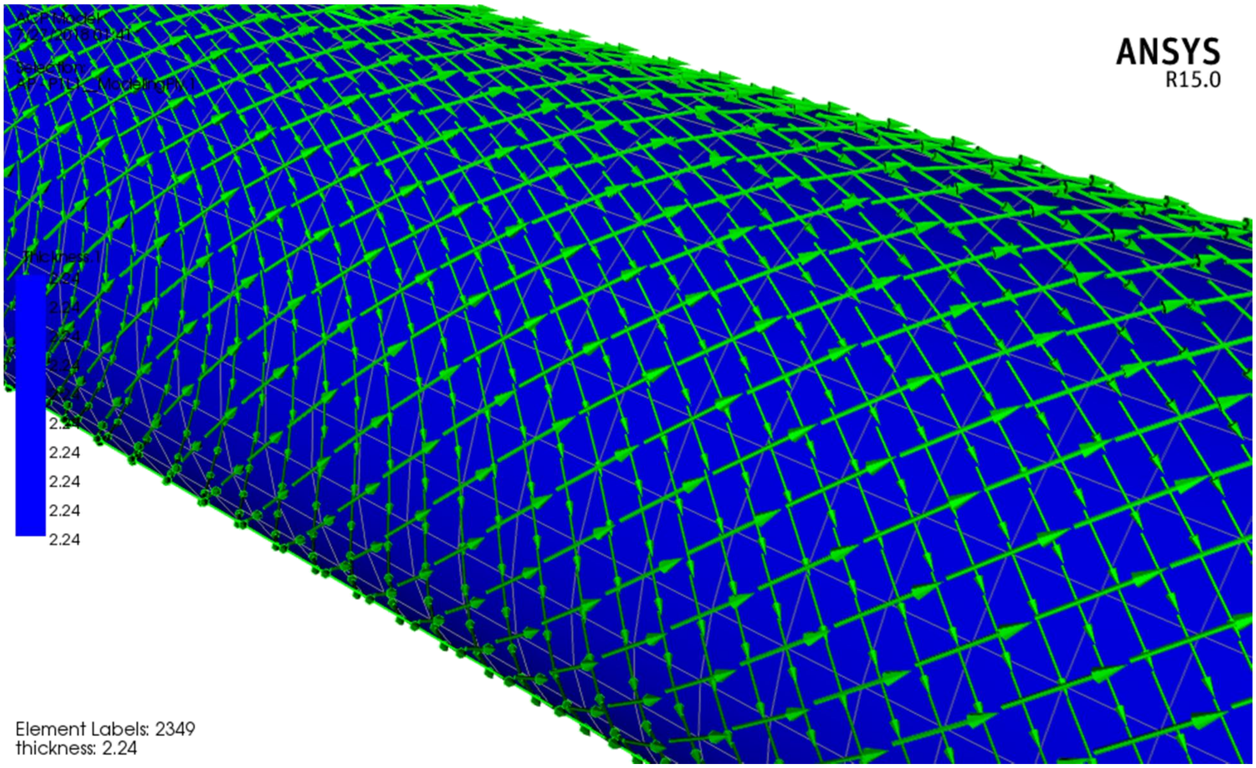


Figure 9: Fiber Orientation@ +45°

Fiber Orientation:90°

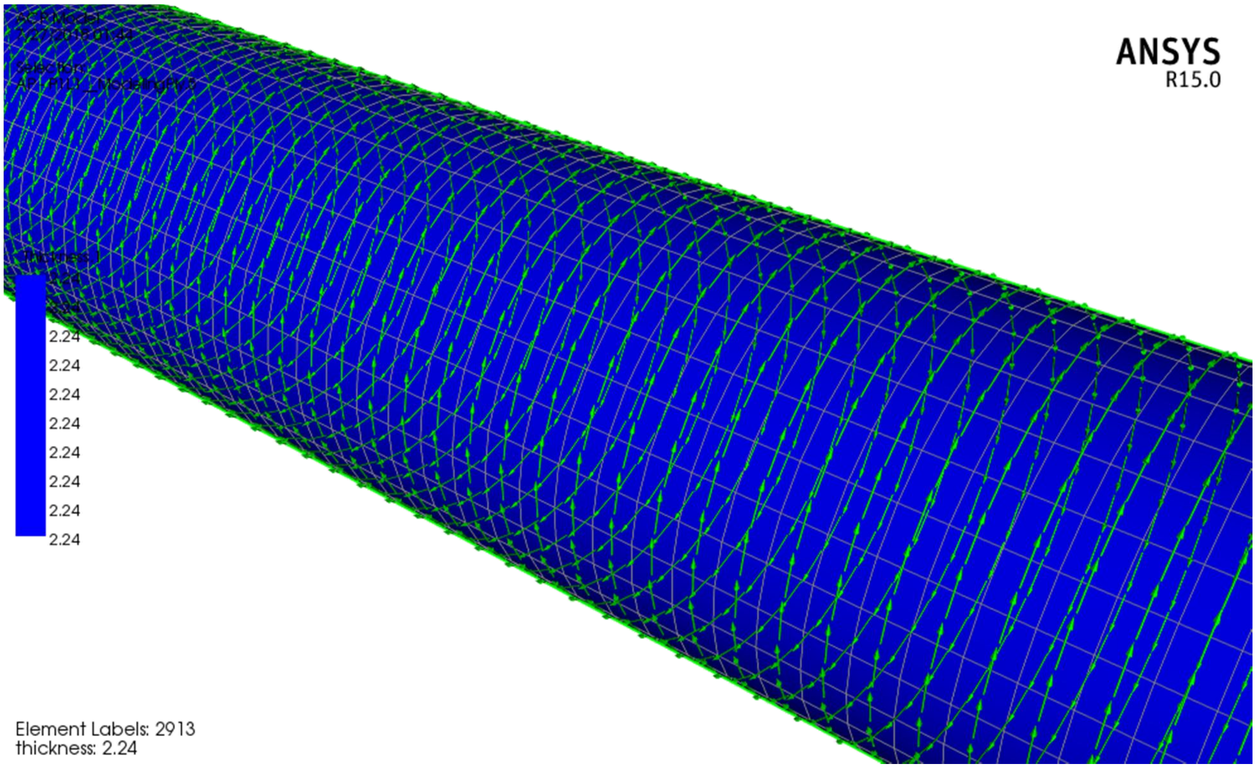


Figure 10: Fiber Orientation@ 90°

Fiber Orientation:-34°

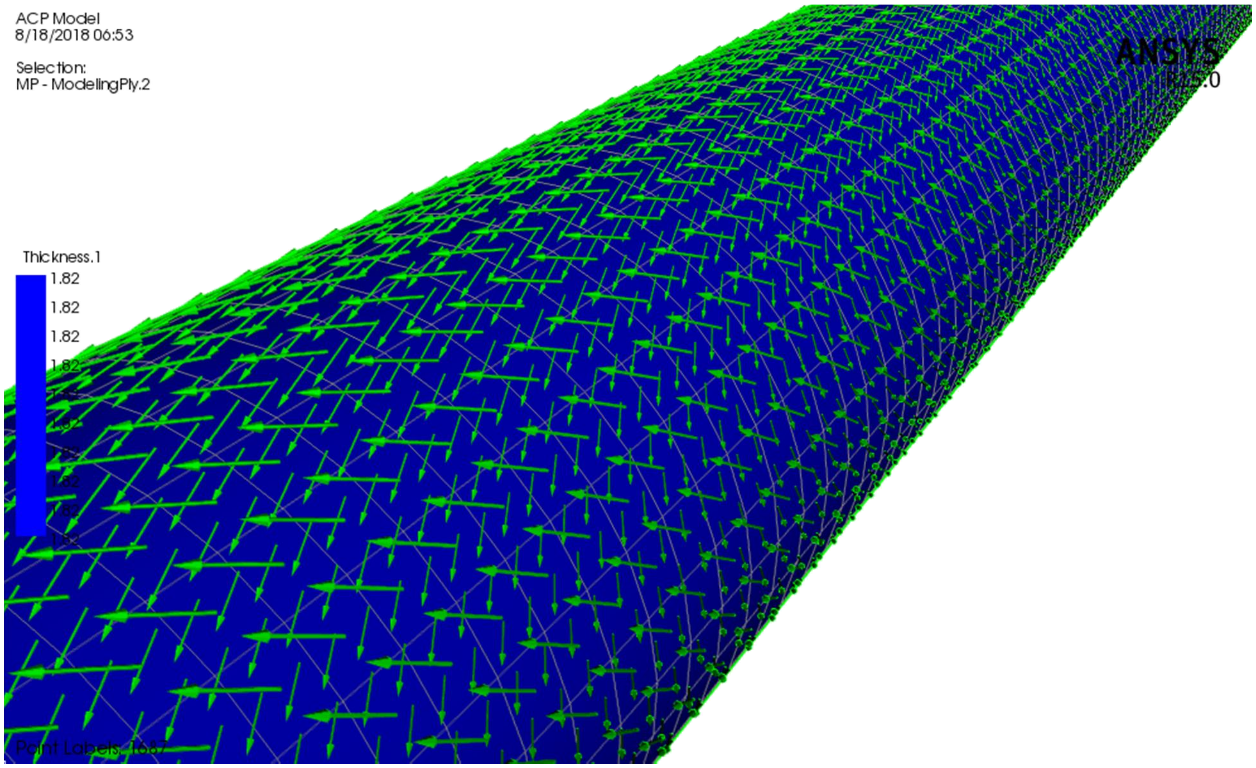


Figure 11: Fiber Orientation@ -34°

Fiber Orientation: +34°

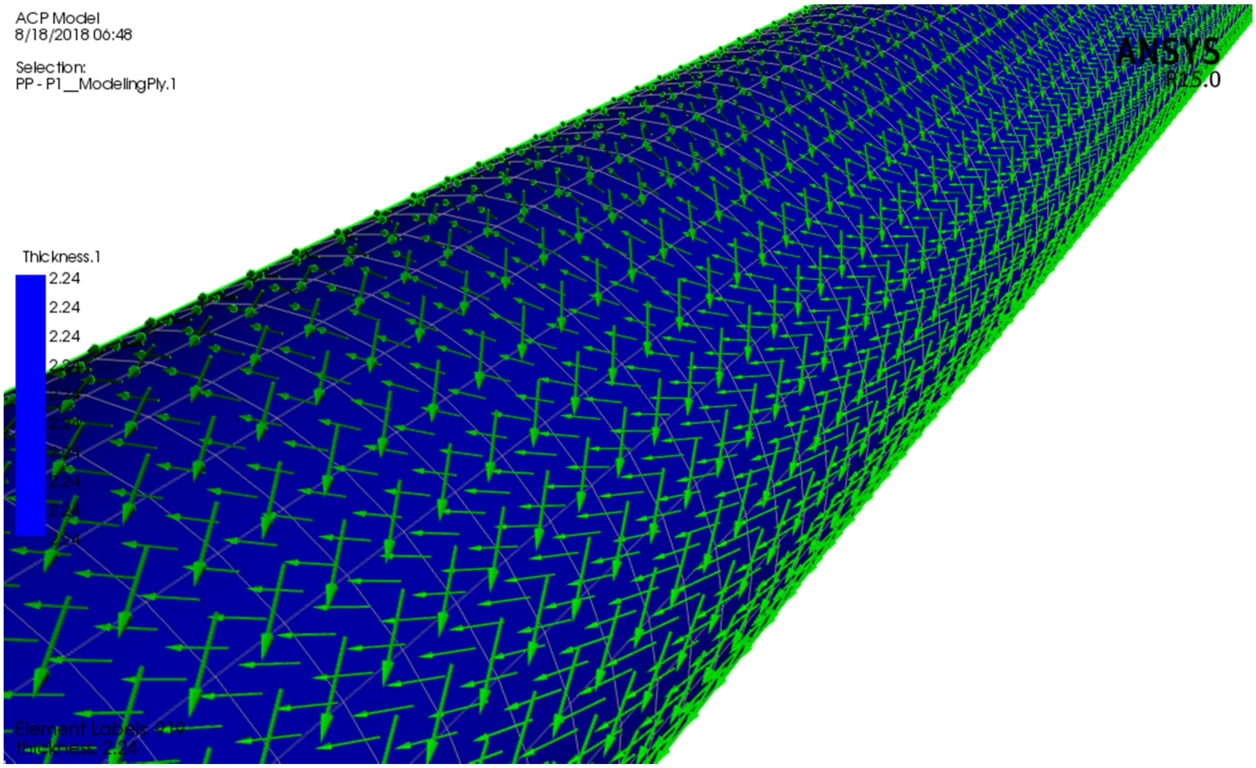


Figure 12: Fiber Orientation@ +34°

Fiber Orientation: +85°

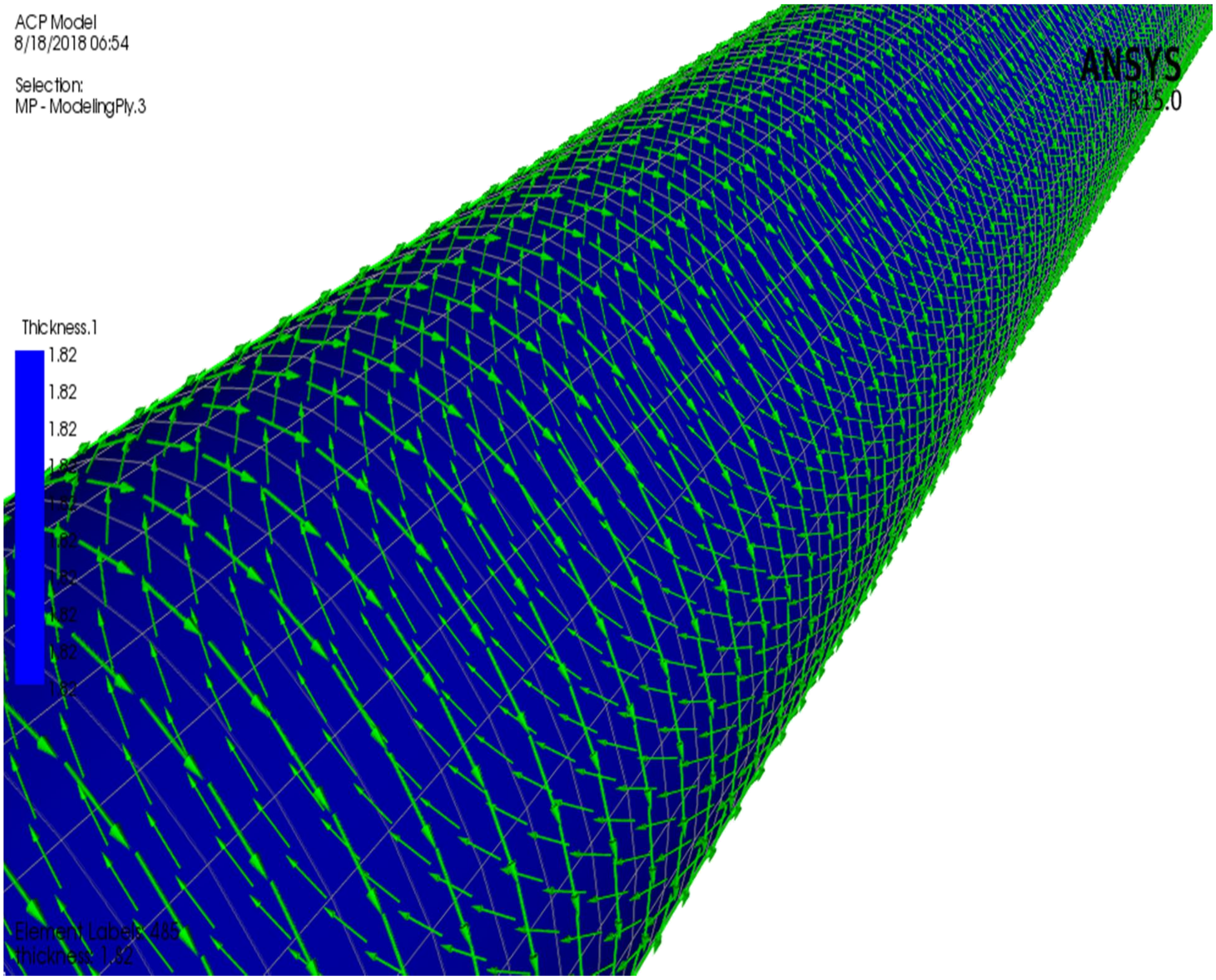


Figure 13: Fiber Orientation@ +85°

Fiber Orientation: -85°

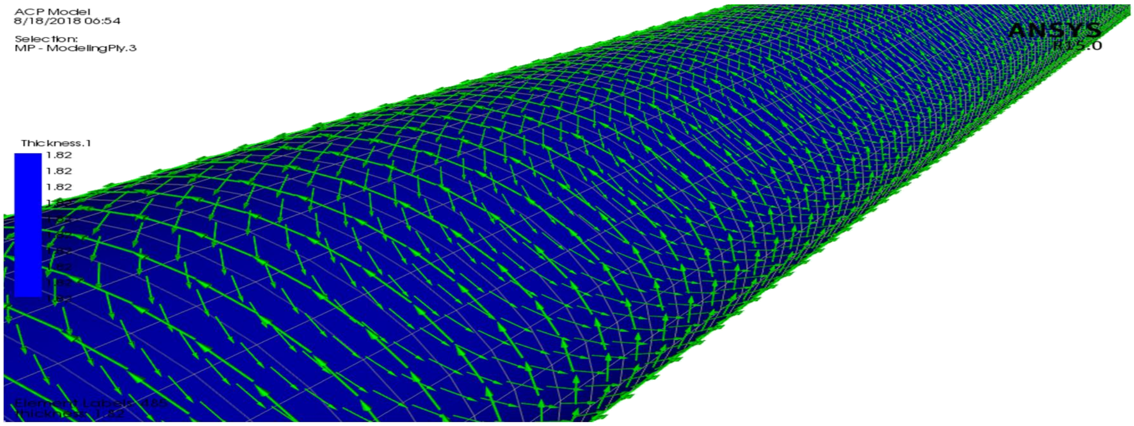


Figure 14: Fiber Orientation@ -85°

Fiber Orientation: 0°

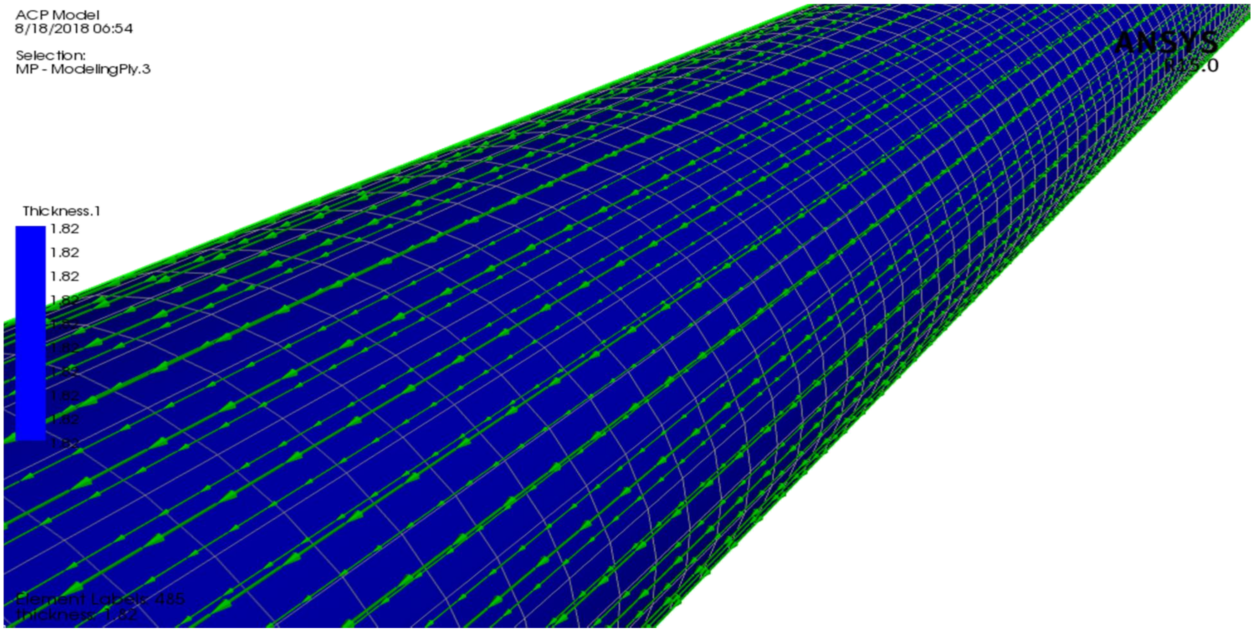


Figure 15: Fiber Orientation@ 0°

STATIC STRUCTURAL: Total Deformation

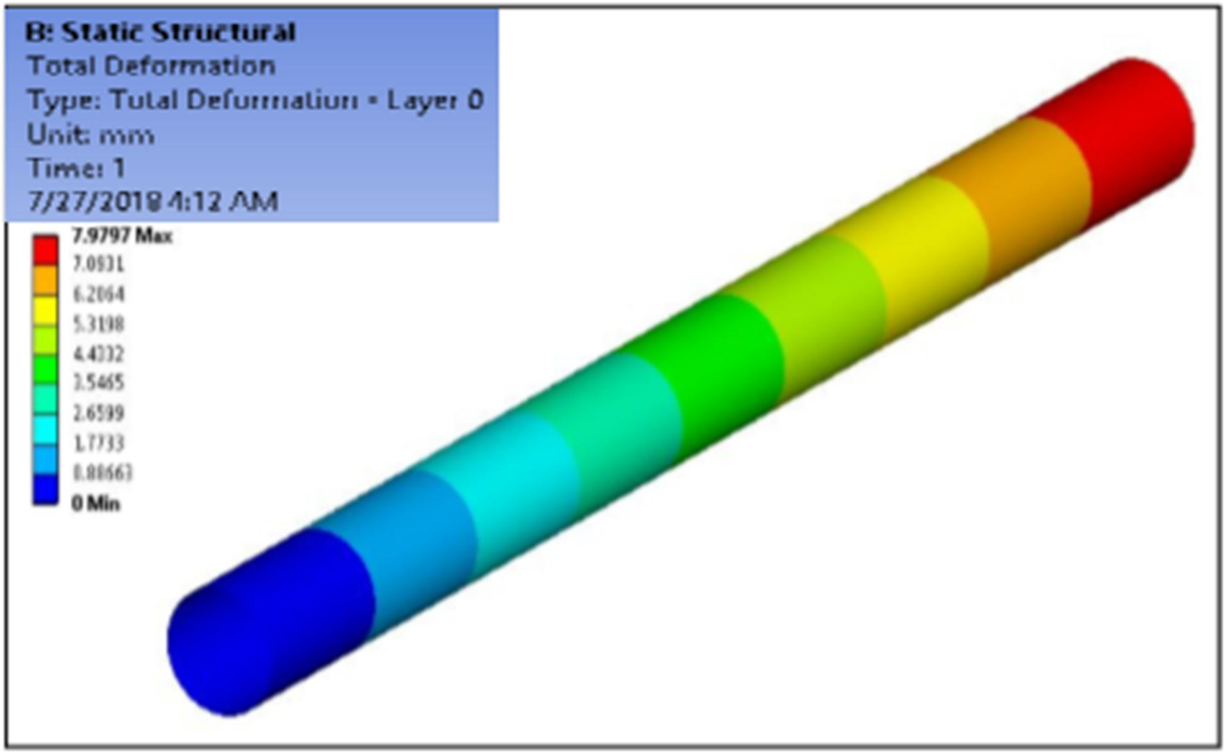


Figure 16: Total deformation

The above screenshot shows the derformation plot in [4] which is to be validated.

LINEAR BUCKLING

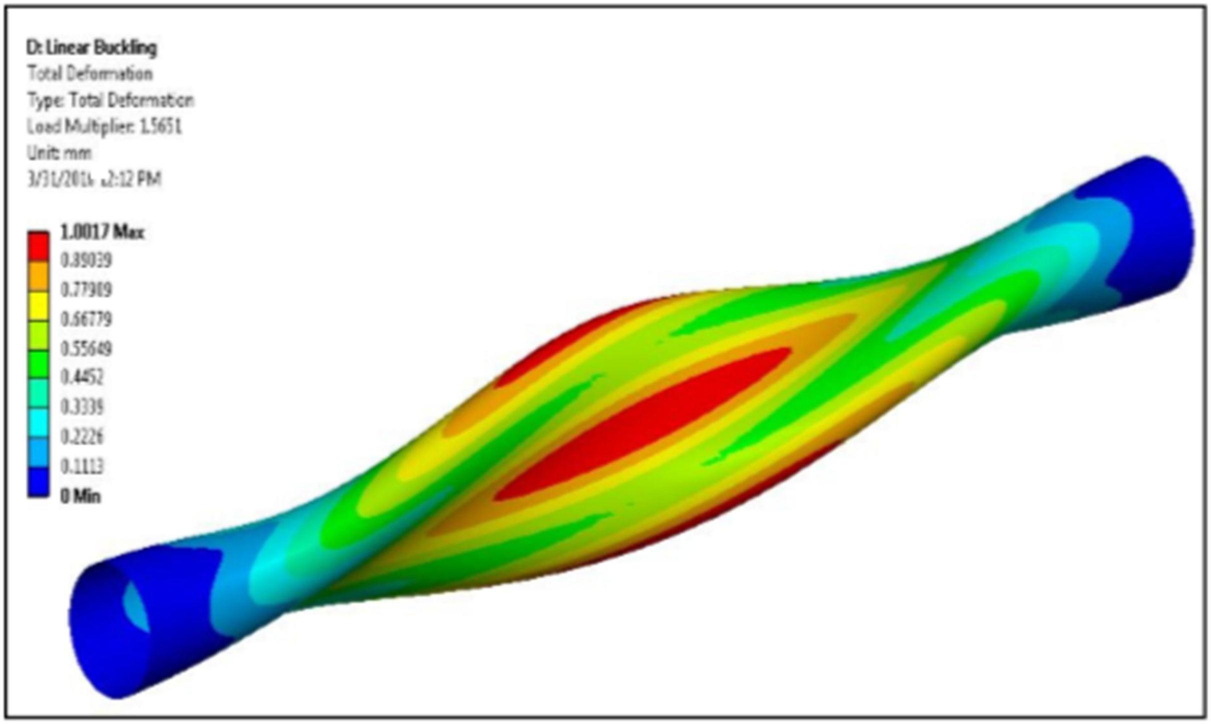


Figure 17: Buckling

Figure showing buckling analysis in [4]

Modal Analysis

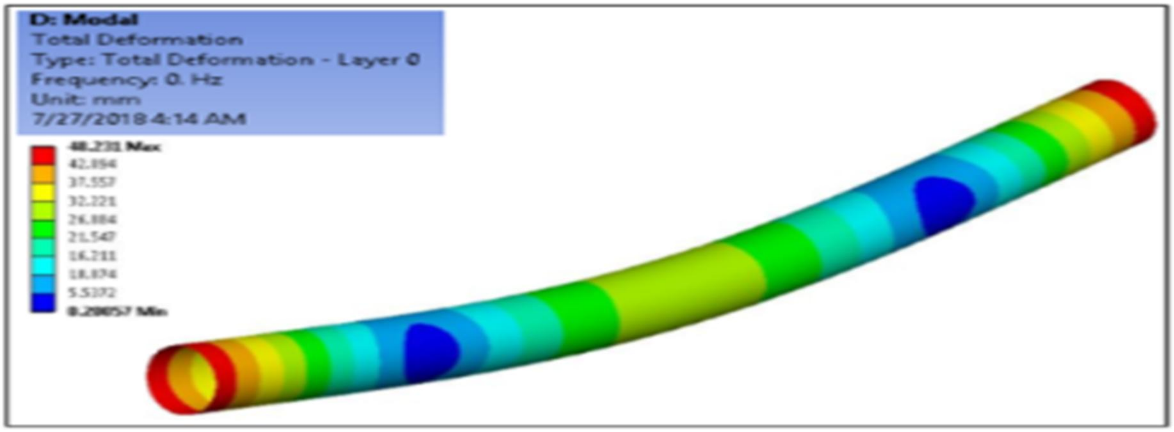


Figure 18: Modal Analysis [4]

Failure Analysis (ACP Post)

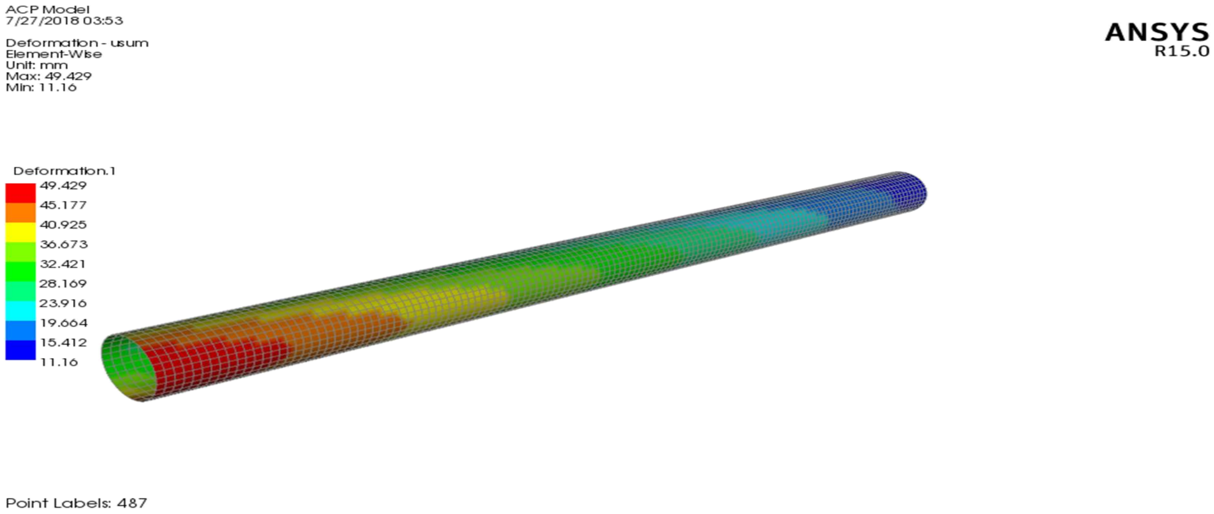


Figure 19: Failure Analysis

CHAPTER 5

RESULTS

5.1 Tables

The results of the analyses are presented below in tables

1: COMPARISON: REVALIDATION

	$[90^\circ_{0.28}/\pm15^\circ_{0.56}/\pm45^\circ_{0.42}]$	$[Al^{90}{}^\circ_{0.28}/\pm45^\circ_{0.42}/\pm15^\circ_{0.56}]$
Load Multiplier	1.18	1.209
Natural Frequency	409.7	407.78
IRF in 45° Ply	0.271	0.83
IRF in -45° Ply	0.790	0.70
IRF in -15° Ply	0.607	0.586
IRF in 15° Ply	0.465	0.442
IRF in 90° Ply	0.522	542.9 MPa
Mass (kg)	1.50	1.66

2: COMPARISON: NEW ANGLES

	$[\pm 85^\circ_{0.28}/0^\circ_{0.56}/\pm 34^\circ_{0.42}]$	$[\mathrm{Al}^{0}\,{}^\circ_{0.56}/\pm 45^\circ_{0.28}/\pm 15^\circ_{0.42}]$
Load Multiplier	1.15	1.29
Natural Frequency	407.8	403.6
IRF in 85° Ply	0.239	
IRF in -85° Ply	0.760	
IRF in 0° Ply	0.30	601.9 MPa
IRF in 34° Ply	0.402	
IRF in -34° Ply	0.518	
IRF in 45° Ply		0.78
IRF in -45° Ply		0.81
IRF in 15° Ply		0.483
IRF in -15° Ply		0.591
Mass (kg)	1.96	2.29

3: COMPARISON: BENCHMARK ANGLES LAYUP WITH INCREASED THICKNESS

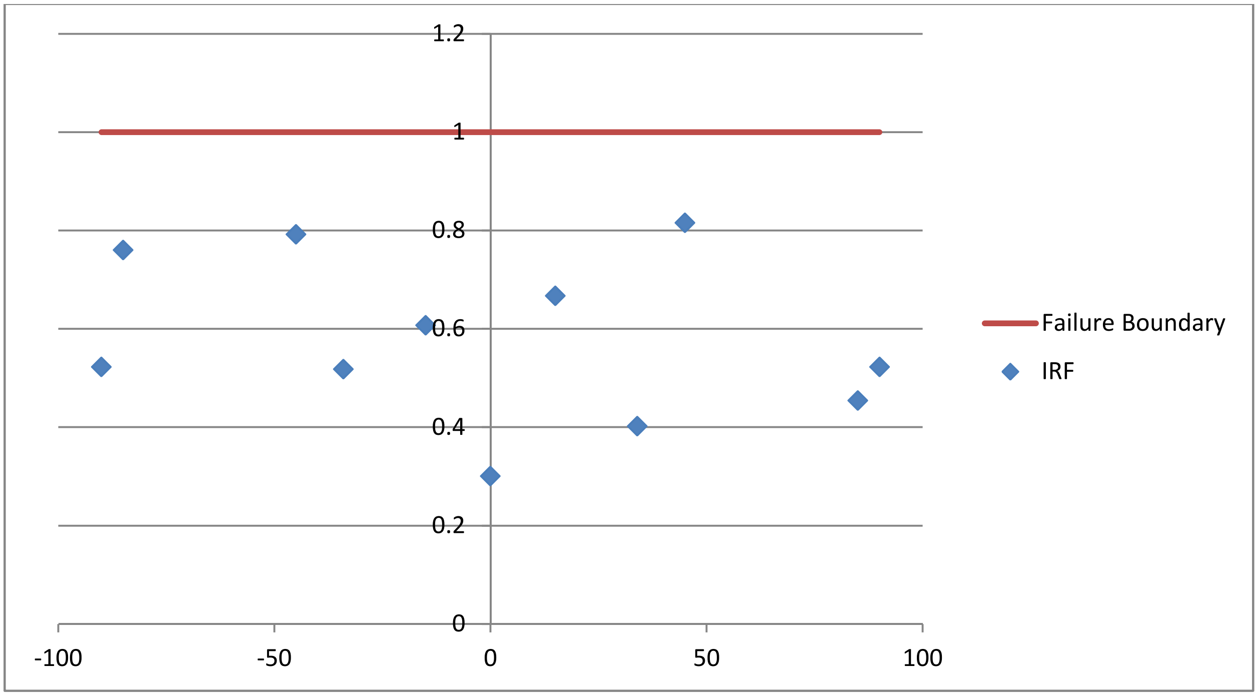
	$[90^\circ_{0.56}/\pm15^\circ_{1.12}/\pm45^\circ_{0.84}]$	$[\mathrm{Al}^{90^\circ}_{0.56}/\pm45^\circ_{0.42}/\pm15^\circ_{0.56}]$
Load Multiplier	1.609	1.403
Natural Frequency	381.19	417.78
IRF in 90° Ply	0.428	693.12 MPa
IRF in 45° Ply	0.253	0.815
IRF in -45° Ply	0.792	0.732
IRF in 15° Ply	0.667	0.622
IRF in -15° Ply	0.484	0.439
Mass (kg)	3.07	3.65

4: COMPARISON: NEW ANGLES LAYUP WITH INCREASED THICKNESS

	$[\pm 85°_{0.56}/0°_{1.12}/\pm 34°_{0.84}]$	$[Al^{90°}_{1.12}/\pm 85°_{0.56}/\pm 34°_{0.84}]$
Load Multiplier	1.498	1.184
Natural Frequency	397.4	401.19
IRF in 90° Ply		707.51 MPa
IRF in 0° Ply	0.423	
IRF in 85° Ply	0.454	0.401
IRF in -85° Ply	0.559	0.479
IRF in 34° Ply	0.227	0.219
IRF in -34° Ply	0.339	0.287
Mass (kg)	2.67	3.27

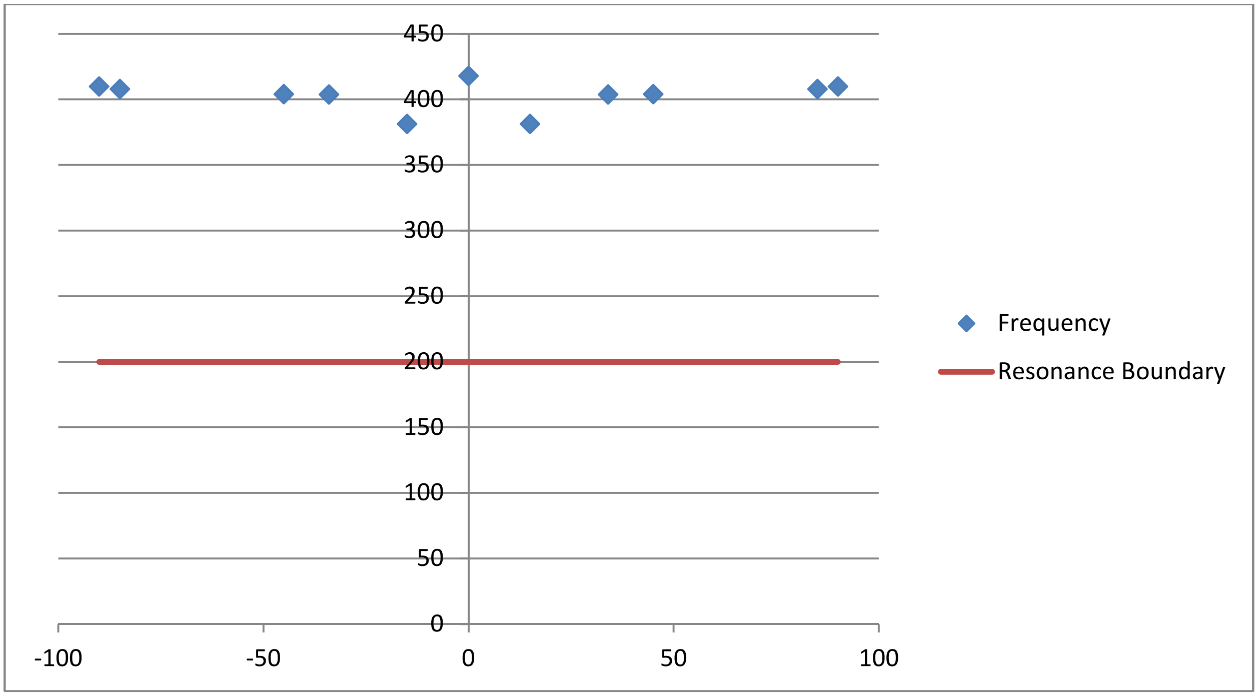
5.2 CONSOLIDATED RESULTS

Graph 1



Graph 1 above is a plot of IRF of all cases plotted against Failure Boundary. As failure occurs at IRF>1, the graph shows that respective shafts do not fail under current load settings.

Graph 2



Graph 2 is a plot of Frequency against Resonance Boundary. In [4] to avoid resonance, frequency had to be greater than 200 Hz, therefore graph shows that for current conditions resonance phenomenon will be avoided.

CONCLUSION

- Both types i.e. Composite & Hybrid have been found to withstand the conditions they were subjected to.
- 10-20 % mass increase was observed in Hybrid Shafts when compared with their composite counterparts
- Case 1, i.e Revalidation case was found to be better than other designs on basis of ‘mass.’ The hybrid drive shaft mass is 11% greater than that of the corresponding composite drive shaft.
- Hybrid shafts provide the advantage of getting joined to other metallic parts
- The analysis’ results need to be verified physically.

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