ANALYSIS AND COMPARISON BETWEEN A CONVENTIONAL METAL AND A METAL-COMPOSITE MARINE PROPELLER SHAFT

by

KAUSHAL MAYANKKUMAR SHAH

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2018

ACKNOWLEDGEMENTS

I am grateful to Dr. Andrey Beyle for his valued advice and expert guidance throughout the course of my work. It is with his immense support that this work has been possible. It has been very rare in my student life where I have come across a person with such humbleness.

I am extremely thankful to Dr. Kent Lawrence and Dr. Abdolhossein Haji-Sheikh for taking time out of their schedules and being a part of my defense committee.

I would also like to extend my gratitude towards UTA and specially the MAE department for letting me be a part of this huge community.

Finally, I would like to thank my parents, fiancé and friends for their love and encouragement over the time.

April 23, 2018

Abstract

ANALYSIS AND COMPARISON BETWEEN A CONVENTIONAL METAL AND A METAL-COMPOSITE MARINE PROPELLER SHAFT

Kaushal Shah, MS

The University of Texas at Arlington, YYYY

Supervising Professor: Andrey Beyle

The basic principal of a ship propulsion is the reactive (thrust) force generated by the propellers against the stream of water which forces the ship to propel in the opposite direction. The Shafting system is thus required to transmit the necessary torque to the propeller at a certain speed. Studies have suggested that shafts are the most common reason of failures amongst the whole marine propulsion system comprising of the main engine and propeller apart from the shaft. Stress concentration and torsional vibrations are the two major causes of failure in the propulsion shafting systems based on the case study of existing data [1]. Other minor causes of shaft failures can be crack propagation in shaft line assembly, wear, corrosion, overload conditions, and material imperfections in the shaft [2]. In comparison to Metals or Alloys, Composite materials have a high strength to weight ratio along with a high impact strength. Also, composites show a better fatigue resistance than most of the metals. By arranging the fibers in multiple directions using different orientations, the effect of stress and vibrations can be dampened. The overall aim of this paper is to analyze a Metal-Composite shaft for marine propulsion system which shows better behavior under various stress conditions as compared to the conventional metal/alloy shaft. A combination of metal and composite material in shafting system results in lower stresses and reduced torsional vibrations as compared to the existing metal shafts whereas the deformation over a longer period is also reduced. Moreover, the presence of composites in the shaft also provides superior thermal stability. The comparisons were done between the Conventional Metal shaft and the Metal-composite shaft under similar loading conditions using ANSYS Workbench for the simulation and results whereas the modelling was done using solid works 2017.

Table of Contents

List of Illustrations

List of Tables

Chapter 1

Introduction to marine propulsion

Marine propulsion system in simple words can be explained as the mechanism required to propel a ship or boat through water. Up until the 18th century, oars or wind were the only means of marine propulsion. It was around the 19th century when the steam engines were introduced in marine propulsion becoming the first mechanical means of marine propulsion. In the modern times, most ships are propelled by mechanical systems like electric motor or diesel engine which replaces the coal fired steam engines. The most common mechanical system used is the diesel engine and in some cases like an ice breaker ship, nuclear propulsion is being implemented.

The operating principal of a ship is based on the concept of thrust or thrust force which is generated by the propellers against a steam of water which causes a column of water to displace in one direction and forces the ship to propel in the opposite direction [3]. The basic function of a propulsion shafting system is to transmit the torque generated in the engine to the propeller at a certain required speed. The propeller shaft serves as a connecting link between the main engine which is inside the ships hub and the propeller which is outside the hub.

Numerous experiments have been carried out in the past to increase the efficiency of marine propulsion system by preventing failures of various parts. The propeller shaft is identified as the most common point of failure in the propulsion system. The causes of failure for the propulsion shafting system have been studied and it is seen that stress concentration and torsional vibrations remain to be the most prominent of all [1] [4].

1.1 Failures of shafting system

Over the years, various analysis techniques have been implemented to figure out the causes of failures in the propulsion shafting system. Under static loading conditions, the loads are not taken as a function of time i.e. they are expected to vary slowly or stay constant during the analysis. Several case studies suggests fatigue failure on critical points of the propulsion shafts [1]. Torsional vibrations are a common system characteristic which leads to fatigue failure in most of the shafting systems. These torsional vibrations are related to vibration modes at natural frequencies of the shaft [5]. Stress concentrations in the shaft contribute as the second major cause of fatigue failure in the marine propulsion shafts [1, 2]. For static loads, the major stress is due to weight of the shaft and the mountings along the shaft line. The shaft has to satisfy the needs of torque transmission at certain speeds without failure. Crack propagation along the shaft material is another cause of failure which is generally seen in the metal/alloy shafts due to material imperfections or poor machinability of the shaft material.

For most of the conventional propulsion systems, the dominating load remains to be torque moment [6]. High strength and stiffness thus becomes a necessity along the axial direction of the shaft. The loads normal to the shaft are comparatively meagre and apart from the perpendicular bending loads, any major stress inducing loads do not occur in the direction perpendicular to the axis of the shaft. Corrosion of the propeller end of the shaft is another concern since that part is in direct contact of the sea water.

Chapter 2

Objective

One feasible way to reduce the effect of stress failures on the shaft is the use of composite materials in the manufacturing of shafts. Not only does composites have higher strength than most metals, it also offers reduction in the overall weight of the shaft. Composites have a higher strength to weight ratio than most metals. Reduction in weight of the shaft can also be helpful for energy reduction to be achieved. Metal shaft has a rigidity when subjected to deformation making it vulnerable against tension. If we consider composite materials, the plies oriented in a certain direction can nullify the effect of the tension coming along the ply direction.

There are several numbers of composite materials available to choose from, thereby making the selection of the right material a top priority. Moreover, it is quite essential to figure out the best suited stacking sequence of composite plies keeping in mind the direction of loads on the shaft. The propeller shaft is mainly under torsion along with a little bit of bending force.

The overall objective of this thesis is to compare and corelate the results obtained by analyzing a metal-composite shaft under the same static loading conditions as a conventional metal/alloy shaft and compare the behavior for stress and deformation of both the shafts. In addition to that, analyze both the shafts for natural frequency for multiple modes to achieve a better dynamic response towards excitation of elements. Solid works was used to model the geometry and the static structural and modal analysis were performed in ANSYS workbench for both the Metal and the composite shafts.

Chapter 3

What are Composites?

Composite material as the name suggests is a material which is formed by the combination of two or more constituent materials with significantly different properties. Two or more distinctly characterized materials when combined forms a material with a set of properties which varies from that of the individual constituent materials [7]. At a macroscopic level, the constituent materials still retain their distinct properties thereby differentiating composites from mixtures or alloys as such. From the two constituent materials, one is a polymer which serves as a matrix and it is reinforced by a high strength Fibre [8]. The resultant material is generally stronger and lighter than most of the conventional materials [9]. The matrix acts as a binder and keeps the fiber together providing resistance to external damage. The fibers in turn increases the strength and stiffness of the matrix preventing fractures or crack propagation in the material [8]. Fibers occupy majority volume of the composite and in this case, it is 60% of the composite. The fibers are the major load carrying components whereas the matrix is responsible for transferring the stresses between the fibers.

(a) Unidirectional (b) Bi–directional

(c) Discontinuous fiber (d) Woven

Figure 1 Fiber reinforced composite [10]

Following are the advantages of composites over metal:

- Low density
- High specific strength
- High strength to weight ratio
- High stiffness
- Corrosion resistance
- Fatigue resistant
- High impact strength
- Design flexibility.

Chapter 4

Modelling and geometry

This chapter includes the design parameters for a conventional marine propeller shaft as per the SAE shaft standards. A shaft with outer diameter of 100 mm and the corresponding set of values was used for the study. The design of shaft and taper specifications are used from the available SAE propeller shaft specifications.

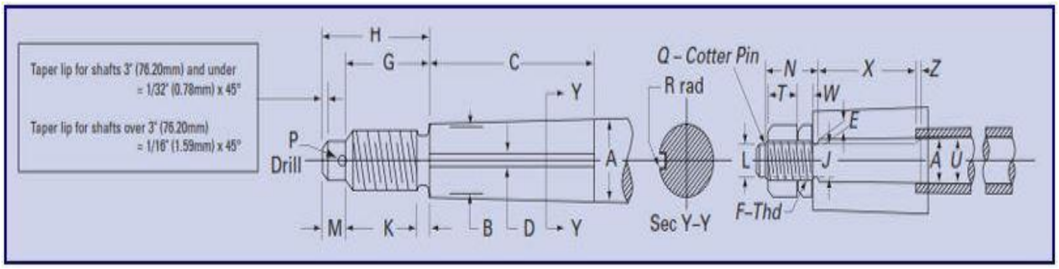
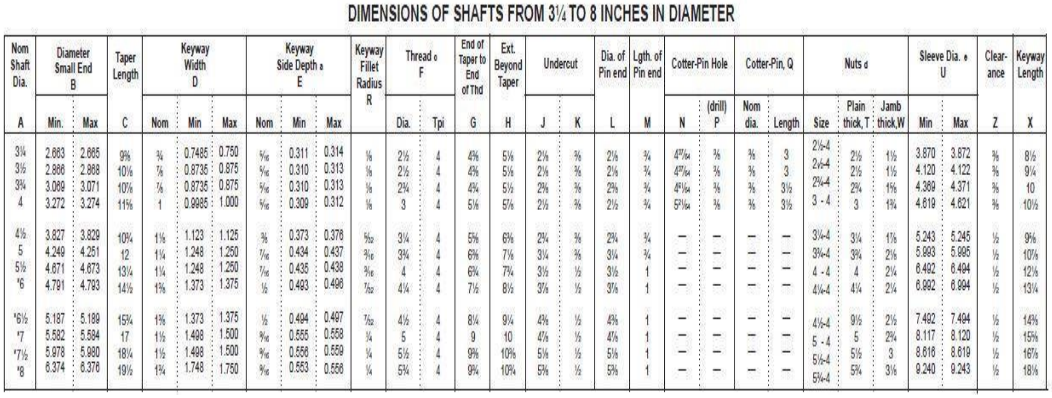


Figure 2 Shaft design



DIMENSIONS OF SHAFTS FROM 3¼ TO 8 INCHES IN DIAMETER

Nom Shaft Dia.	Diameter Small End B		Taper Length	Keyway Width D			Keyway Side Depth a E			Keyway Fillet Radius R	Thread c F		End of Taper to End of Thd	Ext. Beyond Taper	Undercut		Dia. of Pin end	Lgth. of Pin end	Cotter-Pin Hole		Cotter-Pin, Q		Nuts d			Sleeve Dia. e U		Clear-ance	Keyway Length
A	Min.	Max	C	Nom	Min	Max	Nom	Min	Max		Dia.	Tpi	G	H	J	K	L	M	N	(drill) P	Nom dia.	Length	Size	Plain thick, T	Jamb thick, W	Min	Max	Z	X
3¼	2.663	2.665	9⅝	¾	0.7485	0.750	5/16	0.311	0.314	⅛	2½	4	4⅜	5⅛	2⅛	⅜	2⅛	¾	4 27/64	⅜	⅜	3	2½-4	2½	1½	3.870	3.872	⅜	8½
3½	2.866	2.868	10⅛	⅞	0.8735	0.875	5/16	0.310	0.313	⅛	2½	4	4⅜	5⅛	2⅛	⅜	2⅛	¾	4 27/64	⅜	⅜	3	2½-4	2½	1½	4.120	4.122	⅜	9¼
3¾	3.069	3.071	10⅞	⅞	0.8735	0.875	5/16	0.310	0.313	⅛	2¾	4	4¾	5½	2⅜	⅜	2⅜	¾	4 51/64	⅜	⅜	3½	2¾-4	2¾	1⅝	4.369	4.371	⅜	10
4	3.272	3.274	11⅝	1	0.9985	1.000	5/16	0.309	0.312	⅛	3	4	5⅛	5⅞	2½	⅜	2½	¾	5 21/64	⅜	⅜	3½	3 - 4	3	1¾	4.619	4.621	⅜	10½
4½	3.827	3.829	10¾	1⅛	1.123	1.125	⅜	0.373	0.376	5/32	3¼	4	5⅝	6⅜	2¾	⅜	2¾	¾	—	—	—	—	3¼-4	3¼	1⅞	5.243	5.245	½	9⅝
5	4.249	4.251	12	1¼	1.248	1.250	7/16	0.434	0.437	3/16	3¾	4	6⅜	7⅛	3¼	⅜	3¼	¾	—	—	—	—	3¾-4	3¾	2⅛	5.993	5.995	½	10⅞
5½	4.671	4.673	13¼	1¼	1.248	1.250	7/16	0.435	0.438	3/16	4	4	6¾	7¾	3½	½	3½	1	—	—	—	—	4 - 4	4	2¼	6.492	6.494	½	12⅛
*6	4.791	4.793	14½	1⅜	1.373	1.375	½	0.493	0.496	7/32	4¼	4	7½	8½	3⅞	½	3⅞	1	—	—	—	—	4¼-4	4¼	2¼	6.992	6.994	½	13¼
*6½	5.187	5.189	15¾	1⅜	1.373	1.375	½	0.494	0.497	7/32	4½	4	8¼	9¼	4⅜	½	4⅜	1	—	—	—	—	4½-4	9½	2½	7.492	7.494	½	14⅜
*7	5.582	5.584	17	1½	1.498	1.500	9/16	0.555	0.558	¼	5	4	9	10	4⅞	½	4⅞	1	—	—	—	—	5 - 4	5	2¾	8.117	8.120	½	15⅝
*7½	5.978	5.980	18¼	1½	1.498	1.500	9/16	0.556	0.559	¼	5½	4	9⅝	10⅝	5⅛	½	5⅛	1	—	—	—	—	5½-4	5½	3	8.616	8.619	½	16⅞
*8	6.374	6.376	19½	1¾	1.748	1.750	9/16	0.553	0.556	¼	5¾	4	9¾	10¾	5⅝	½	5⅝	1	—	—	—	—	5¾-4	5¾	3⅛	9.240	9.243	½	18⅛

Figure 3 Shaft Dimensions

The shaft is basically divided into three sections when its operation is concerned. The engine side shaft is termed as the thrust shaft whereas the propeller end of the shaft is called propeller shaft and the longer middle portion of the shaft is called the intermediate shaft. The conventional metal shaft is one solid body made of Ck 45 steel material. The metal-composite shaft is designed in three parts. The outer most part is a hollow metal shaft and the inner most part is a solid metal shaft. Composite shaft is the one which is sandwiched between the outer and inner metal shafts. 250 F epoxy resin with intermediate modulus is used as the composite material for the analysis. For the analysis in ANSYS, four bolts are used to assemble the metal and composite portion of the shafts together. The design drawings and the parts are shown in the coming figures.

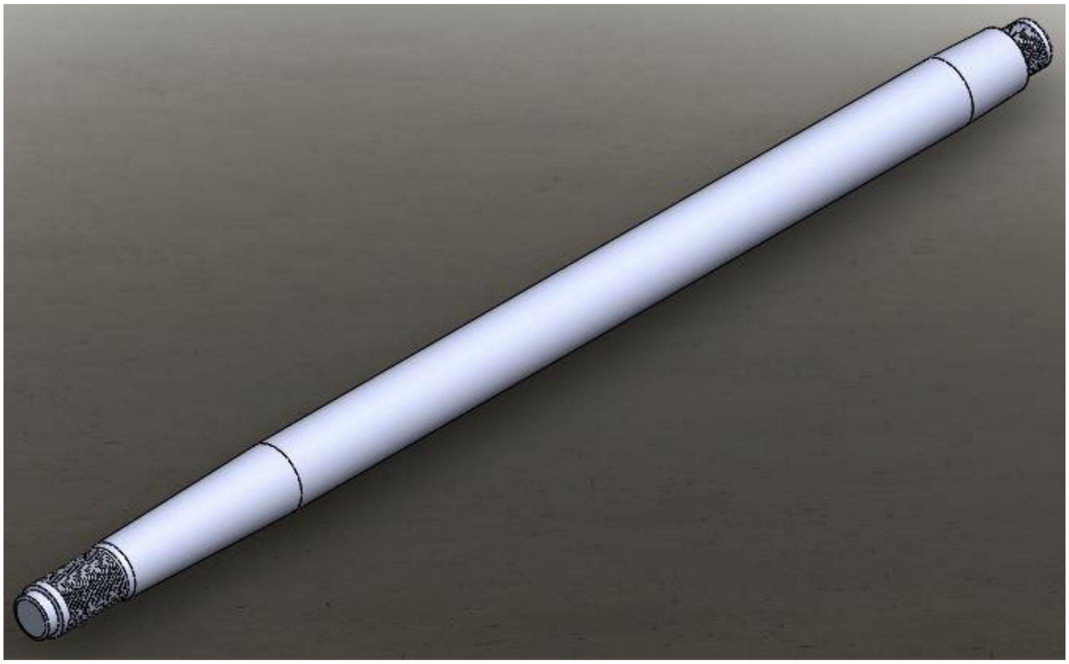


Figure 4 Metal shaft

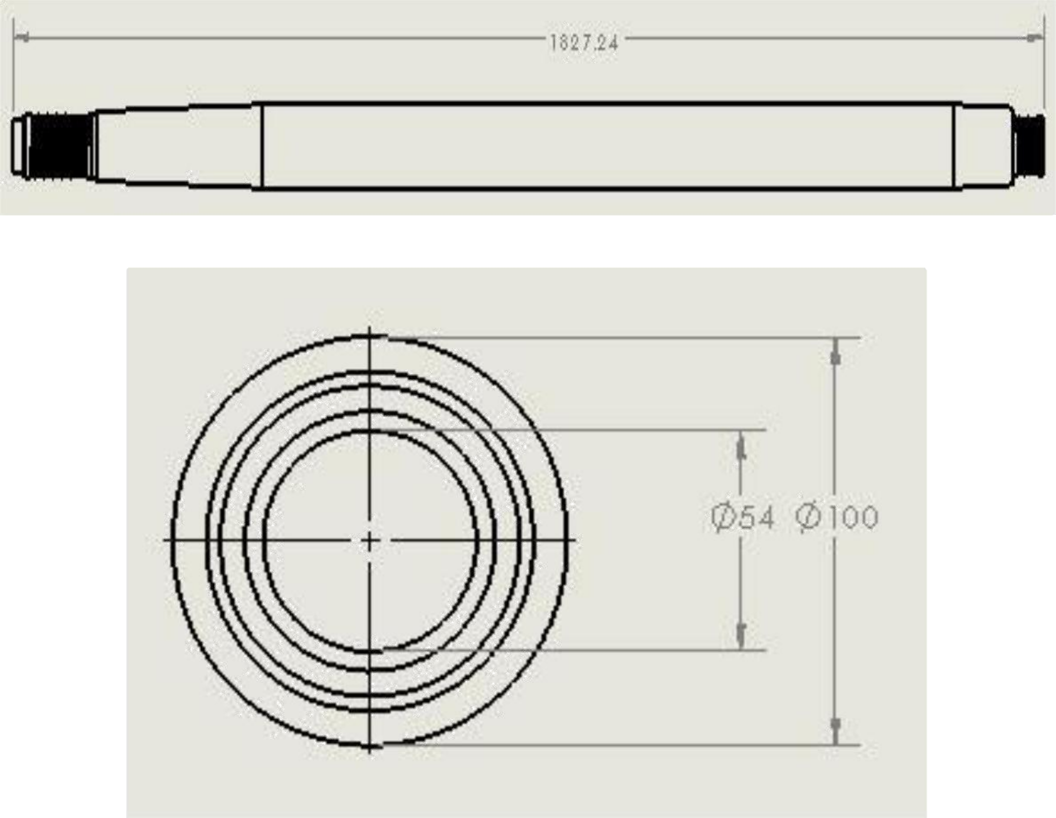


Figure 5 (a) (b) Shaft Drawings

These drawings are the right and front view of the conventional metal shaft. For the metal-composite shaft, the three bodies are modelled separately. The inner and outer metal shaft were modelled using Solid works where the inner shaft is solid, and the outer shaft is a hollow shaft. A surface was extruded just over the inner shaft and the geometry is exported to ANSYS, the surface extrusion becomes the base for the ply stackup. The following are the Outer, Inner and the composite shaft for the Metal-composite shaft assembly. In ANSYS workbench, ACP was used to create the laminate by using multiple 0, 90 and 45-degree plies. The stacking sequence used here consists of all these plies.

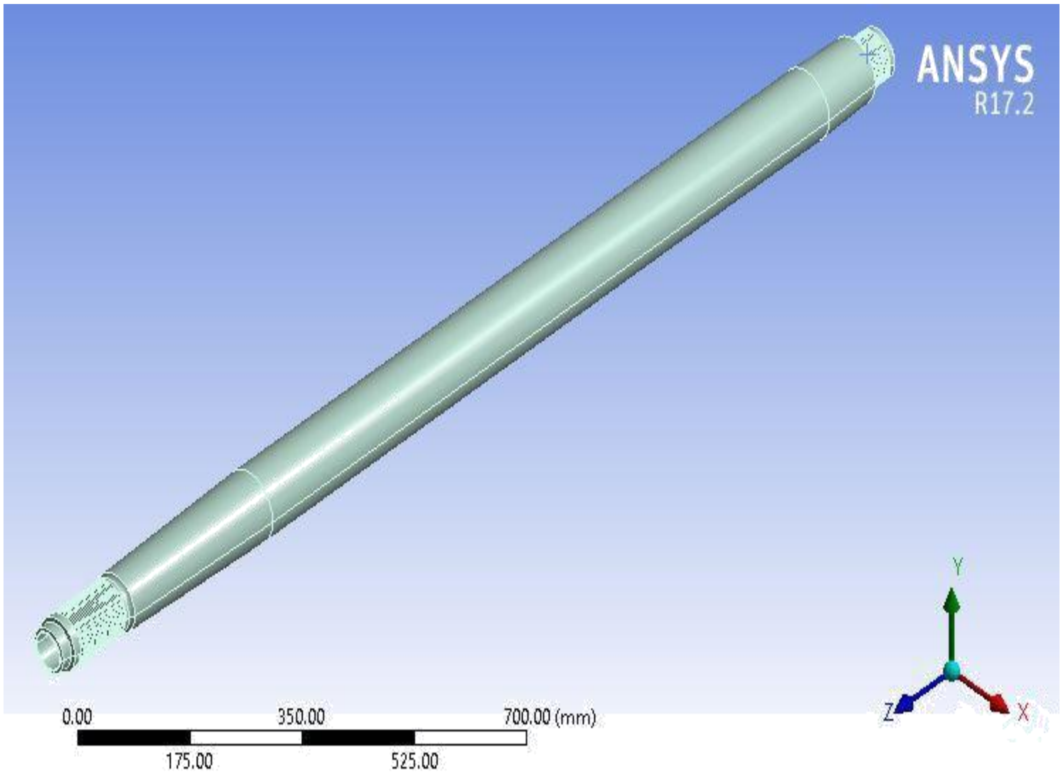
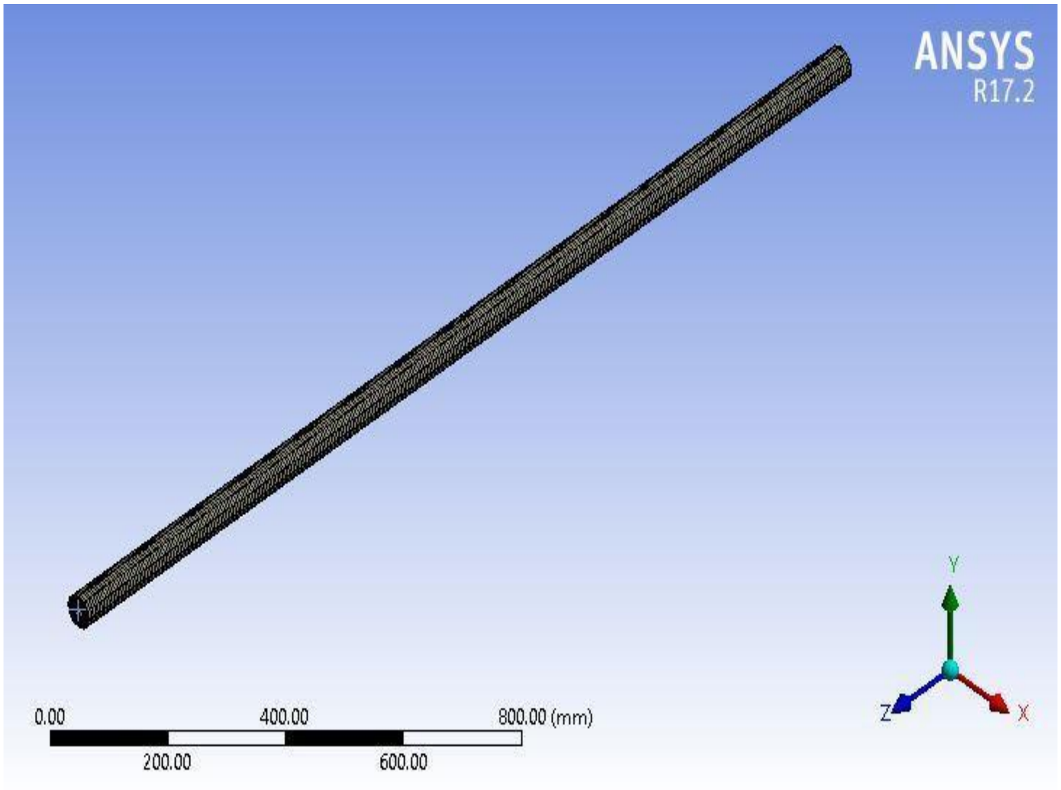
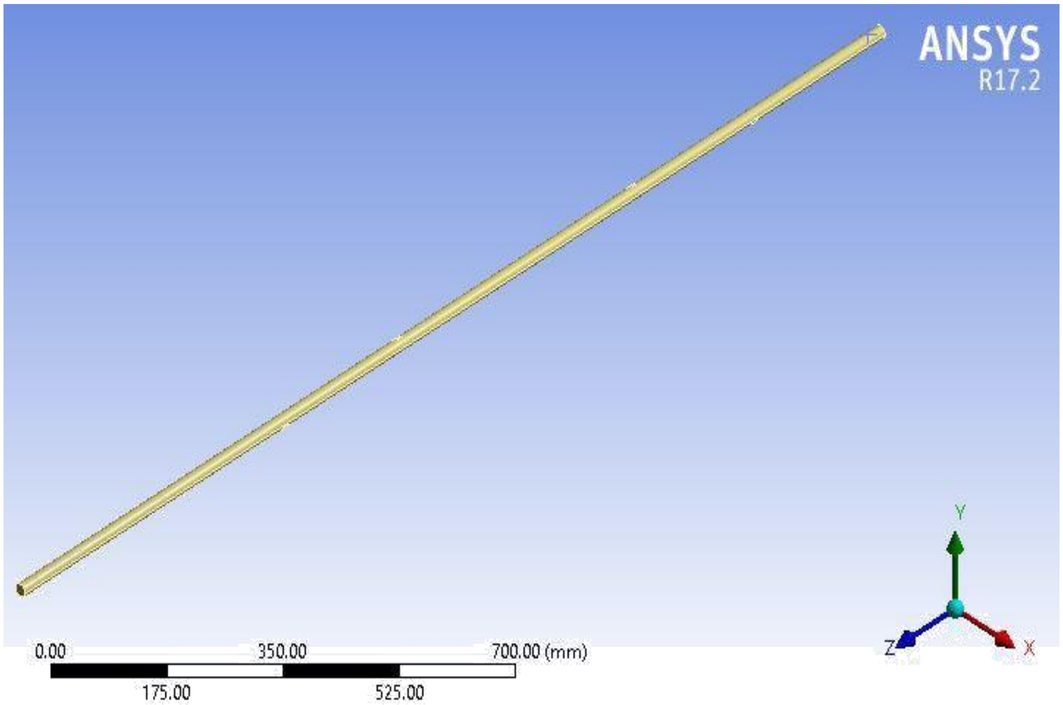


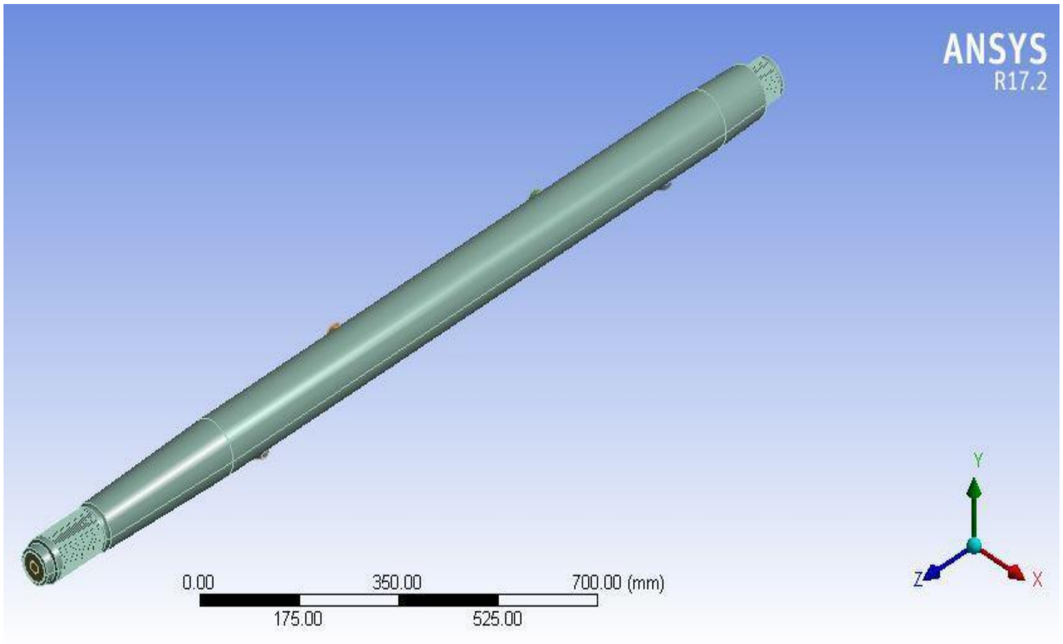
Figure 6 (a) Outer shaft



6 (b) Composite shaft



6 (c) inner shaft



6 (d) Composite assembly

The three entities shown above in figures 6 (a) (b) (c) are the outer, center composite and inner part of the hybrid metal-composite shaft assembly. The outer and inner parts are of the same material as conventional metal shaft. Composite part is made in the ACP pre-model of ANSYS workbench. The three bodies were considered as bounded during the time of analysis as shown in figure 6 (d). Four bolts in total are used to bound the assembly. Stress and deformation have been considered separately for all the three bodies in order to get an accurate solution.

The properties of the metal and composite materials used for the shaft are listed below.

Ck 45 Steel Properties

Density	8740 kg m^{-3}
Young' modulus	207 GPa
Ultimate tensile strength	600 MPa
Yield strength	450 MPa
Poisson ratio	0.29

Table 1 Ck 45 Properties

Composite (250 F Epoxy resin) Properties

Density	1800 kg m^{-3}
Young’ modulus	165 GPa
Ultimate tensile strength	3040 MPa
Compressive strength	1570 MPa
Poisson ratio	0.25

Table 2 Composite Properties

Ck 45 is a medium carbon steel which is used when greater strength and hardness is desired mainly in mechanical engineering and automotive components. The 250 F Epoxy resin composite material is normalized to 60% fiber volume with the tensile strength of the fiber being 6370 MPa. The composite material used here has very low density as compared to Ck45 steel. A weight reduction of around 25% is achieved in the hybrid metal-composite shaft. At the same time, the tensile strength of the shaft does not take a dip in its value. The high strength to weight ratio of the composite materials is a key property that is taken into consideration.

Chapter 5

Boundary Conditions and simulation

In this chapter we will have a look at the pre-analysis setup for static structural as well as modal analysis. In static analysis, the loads and the boundary conditions are not a function of time [11]. For static analysis, the shaft has to satisfy the requirements for static torque transmission capability. Generally, for a static analysis the Load matrix is the product of the stiffness matrix and the displacement vector [11] [12]. A static analysis is used to find the displacements and stresses caused by the loads that do not induce significant inertia. For the analysis, both ends of the finite element model of the shaft were defined as fixed supports and load is applied on the thrust, intermediate and inner shafts. For the hybrid metal-composite shaft, static structural analysis has been used for shaft and deformation calculations. ANSYS composite prepost is used for the composite laminate set up layer by layer. The layers can be oriented at various angles depending on the loading conditions. Different stackup sequences were tried for the composite part and the optimum one is taken for the comparison of all results further. Apart from Static structural analysis, Modal analysis is performed for both the shafts in order to find the natural frequencies of the shaft. Six modes were taken into consideration for the modal analysis and also the deformations are calculated for each different frequency. The whole analysis procedure can be divided into three major parts: Preprocess, Solution and Postprocess. First process involves mesh generation for the part and setup for the solver. Solution is where the analysis takes place and postprocessing includes the review and evaluation of the results. The setup and results from the analysis are shown in the following images.

5.1 Meshing

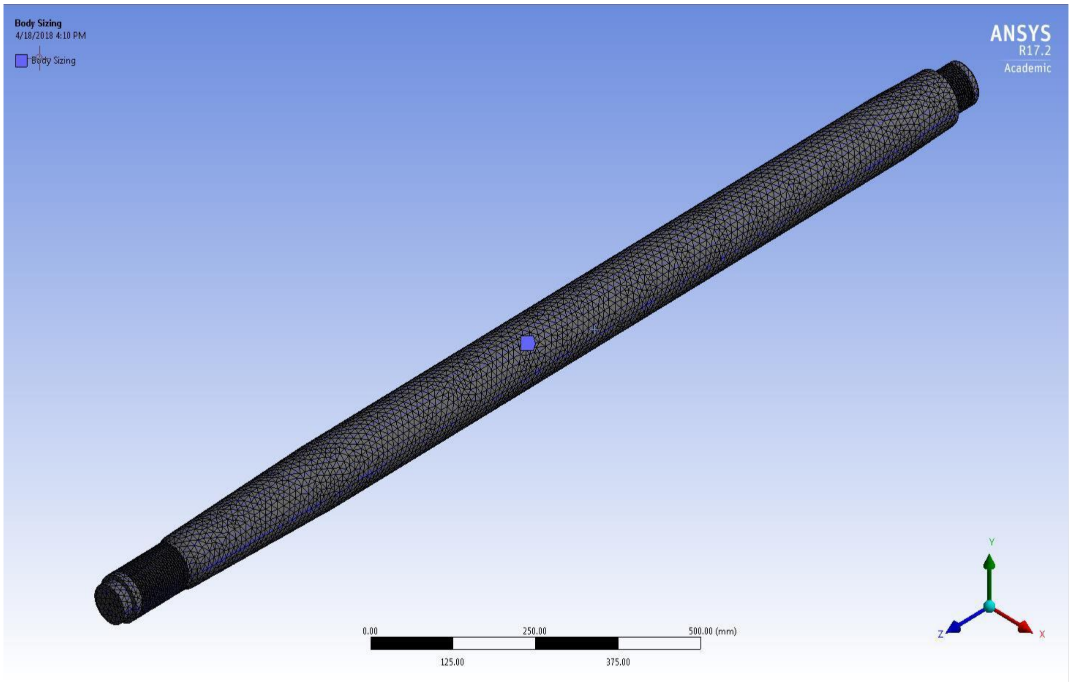


Figure 7 Mesh generation.

The meshing is done by using tetrahedron element method and it was generated by body sizing method. Refinement has been applied at edges to get a finely meshed component for better analysis results. The element size was kept to 10 mm and large deflections were kept ON in order to take non linearities into account. The total number of elements are 120407 and the number of nodes is 176932. 5 mm mesh is determined to provide better results, but solution generation time increases considerably making it hard to obtain all the results due to the limitations of the system.

5.2 Stacking sequence.

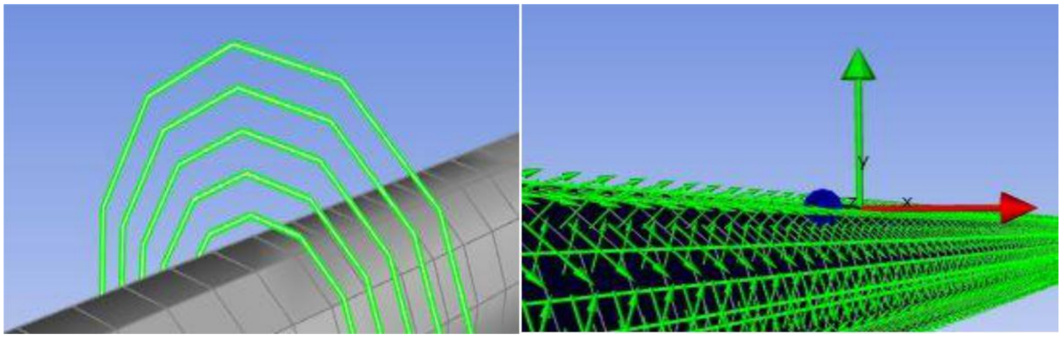


Figure 8 (a) (b)

Figures 8 (a) (b) show the stackup direction and the fiber direction as well. The fiber direction is along the X-axis and the plies are stackup normal to the fiber direction.

Stacking sequence of [0/0/0/0/90/0/0/0/0], [0/0/45/-45/90/-45/45/0/0], and [0/0/0/45/-45/90/-45/45/0/0/0] were initially considered in order to identify an ideal one and the third sequence was found to be the best for the given loading conditions.

All the results discussed here have the stacking sequence of [0/0/0/45/-45/90/-45/45/0/0/0]. Major loads are applied across the axial direction and thus there are more 0-degree plies. For quick turning of ship and overhauling, there is torsion at 45 and -45 degrees which justifies the inclusion of angular plies. The 90-degree ply is used to bond the layers together providing it a support and sustains any perpendicular forces to the fiber direction.

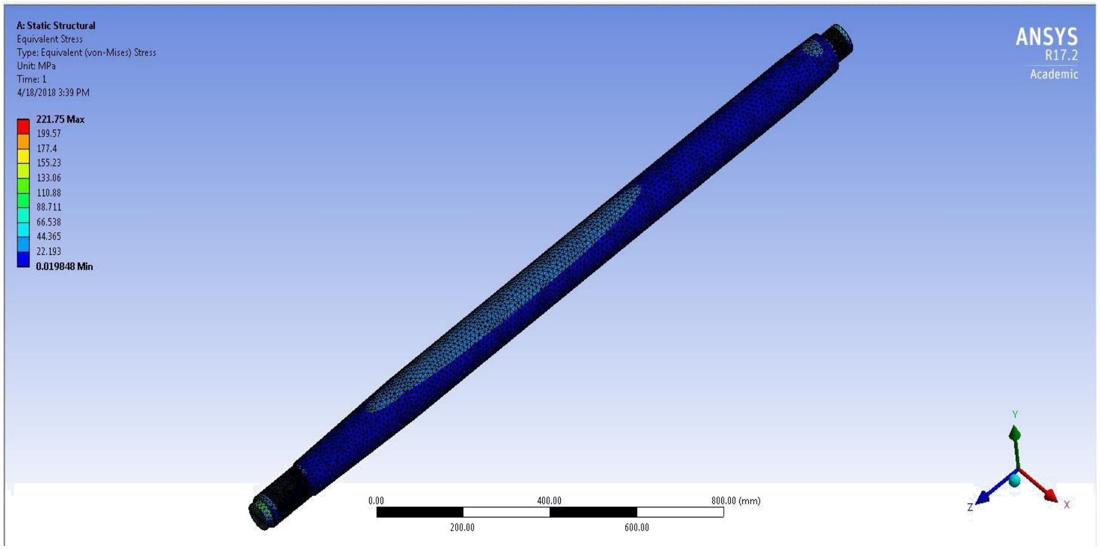


Figure 9 Stress on metal shaft

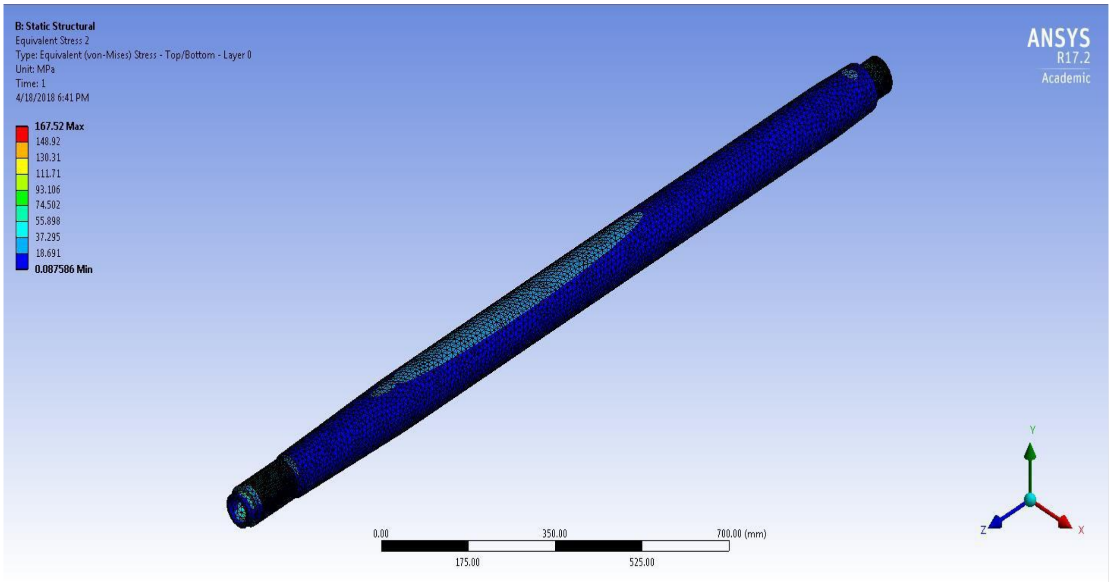


Figure 10 Stress on outer shaft

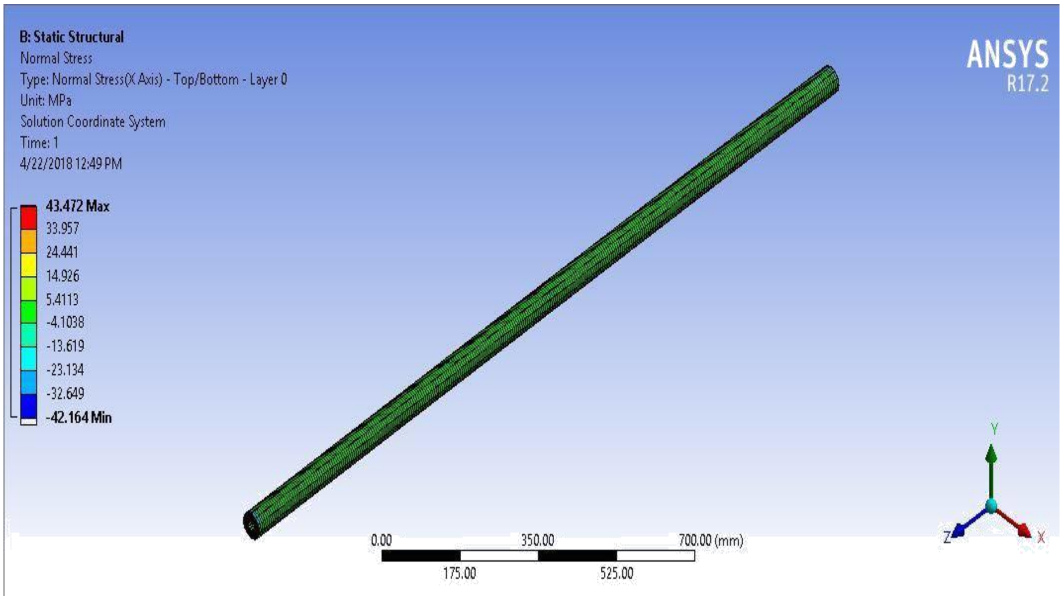


Figure 11 Axial Stress on Composite Shaft

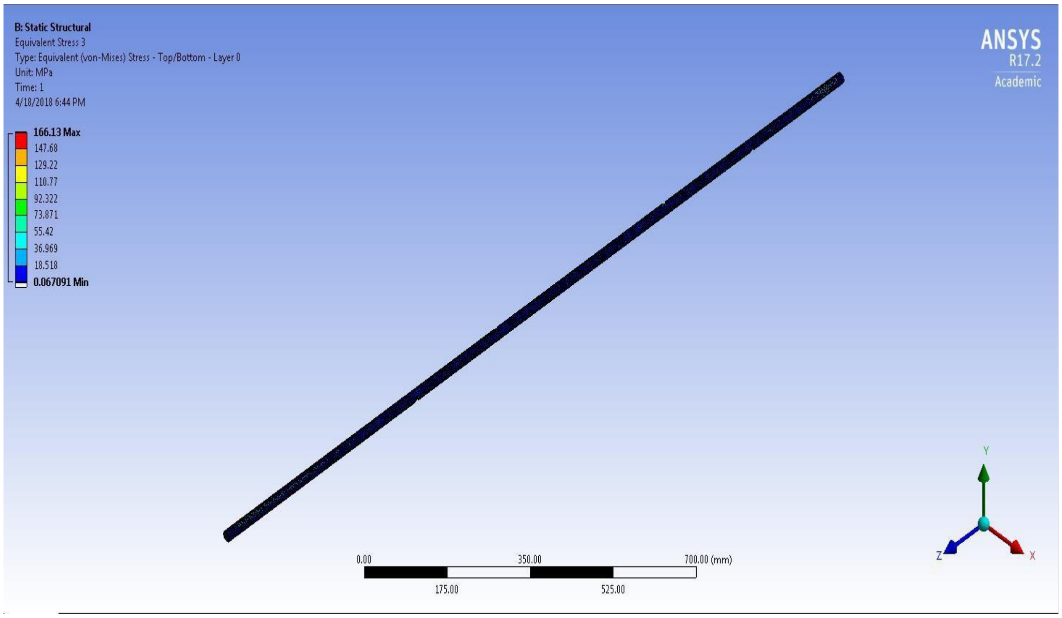


Figure 12 Stress on inner shaft

Figures 9 – 12 shows the stresses on the conventional metal shaft and all three layers of the composite shaft assembly. For the composite shaft, the normal stress is obtained along the X-axis. The following table sums up the results for stresses on each shaft for normal conditions.

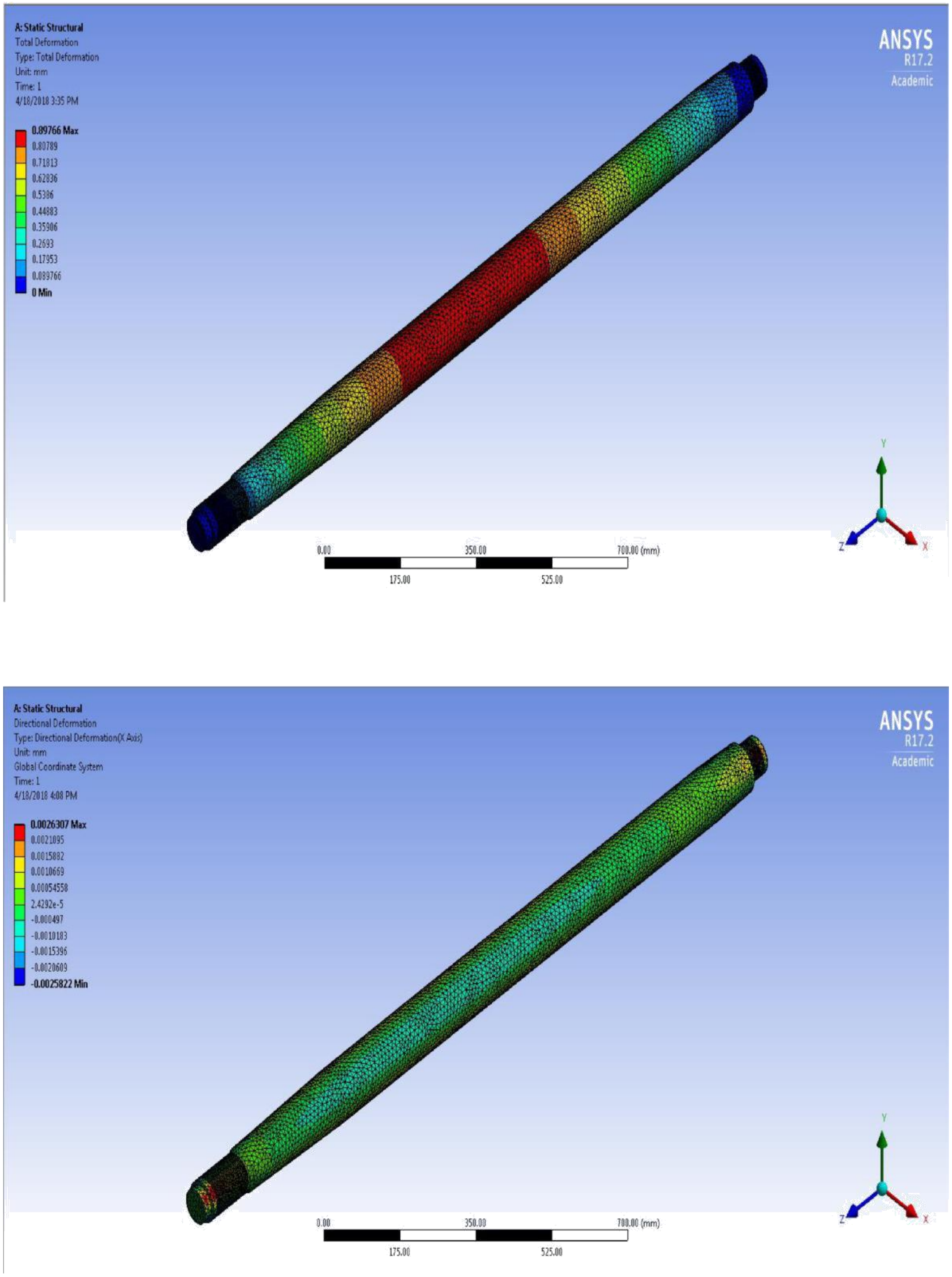
Stress in Metal shaft	221.75 MPa

Table 3 Stress in metal shaft

Stress in Outer shaft	167.52 MPa
Stress in inner shaft	156.13 MPa
Normal stress in composite shaft	43.47 MPa

Table 4 Summary of stress in composite shaft

As we can see from the above tables, the stress on the conventional metal shaft is higher as compared to all three layers of the metal-composite shaft assembly. Keeping the same boundary and loading conditions, the results for deformations are obtained for all the shafts. The following are the results for deformation in the shaft.



A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
4/18/2018 3:35 PM

A: Static Structural
Directional Deformation
Type: Directional Deformation(X Axis)
Unit: mm
Global Coordinate System
Time: 1
4/18/2018 4:08 PM

Figure 12 (a) (b) Deformation in metal shaft

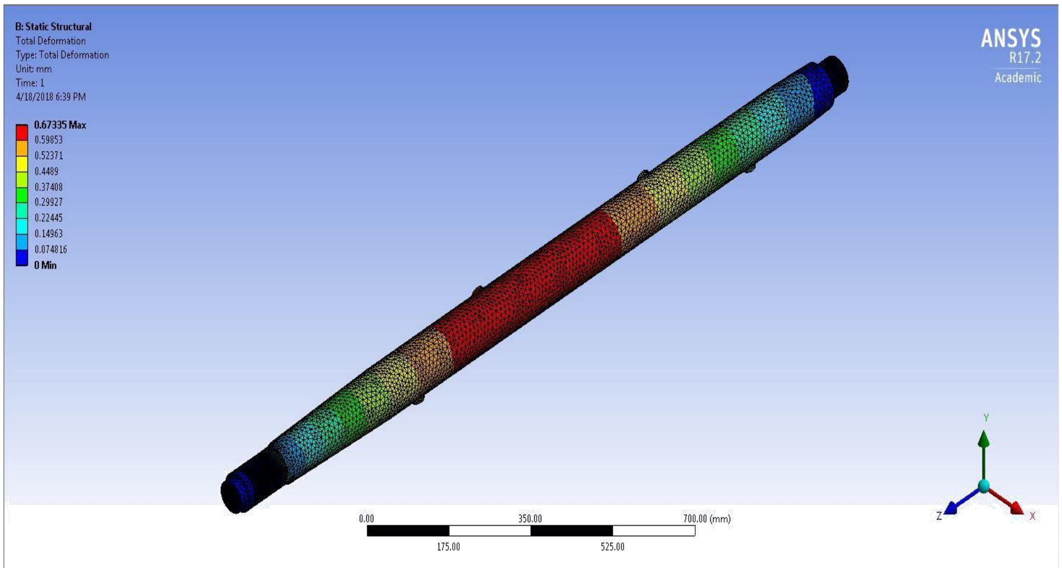
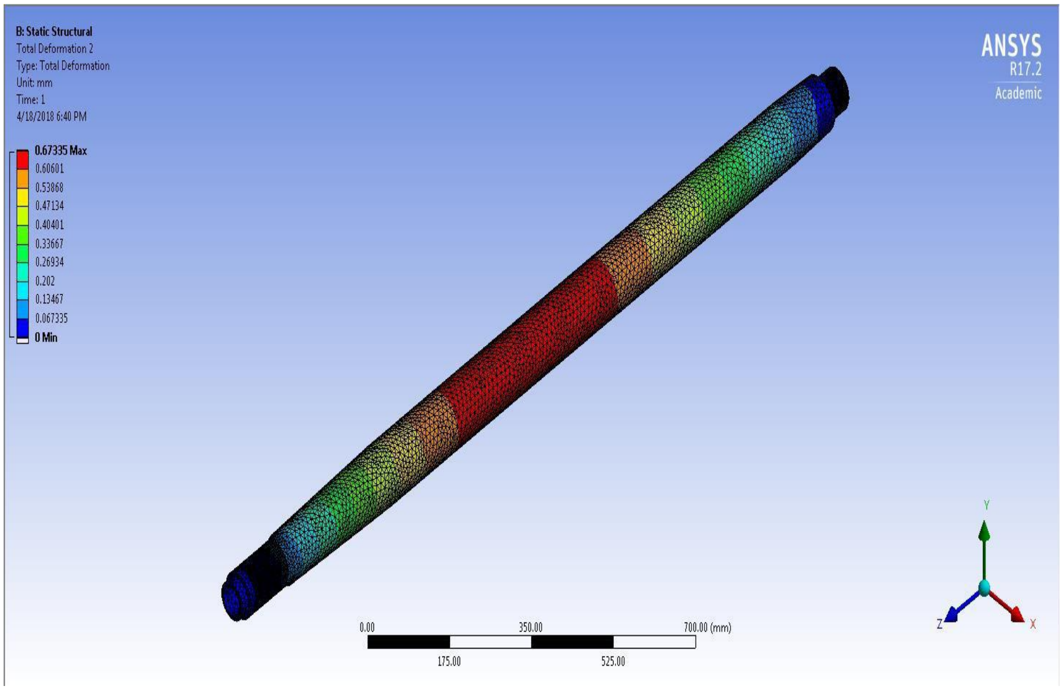


Figure 13 Overall deformation of composite shaft



(a)

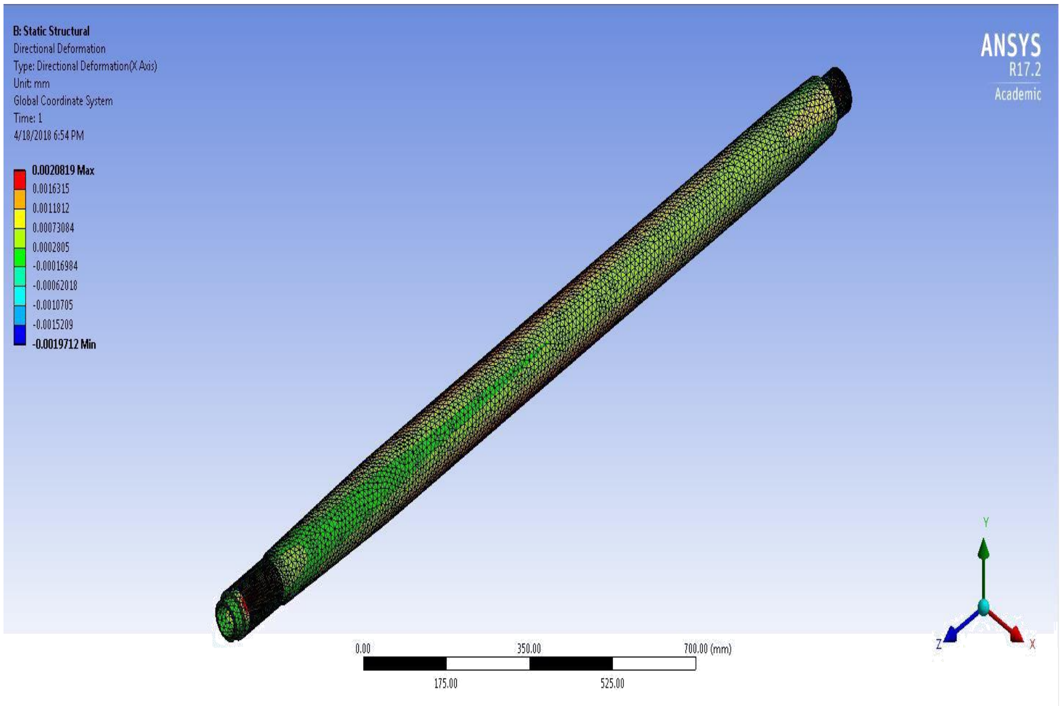
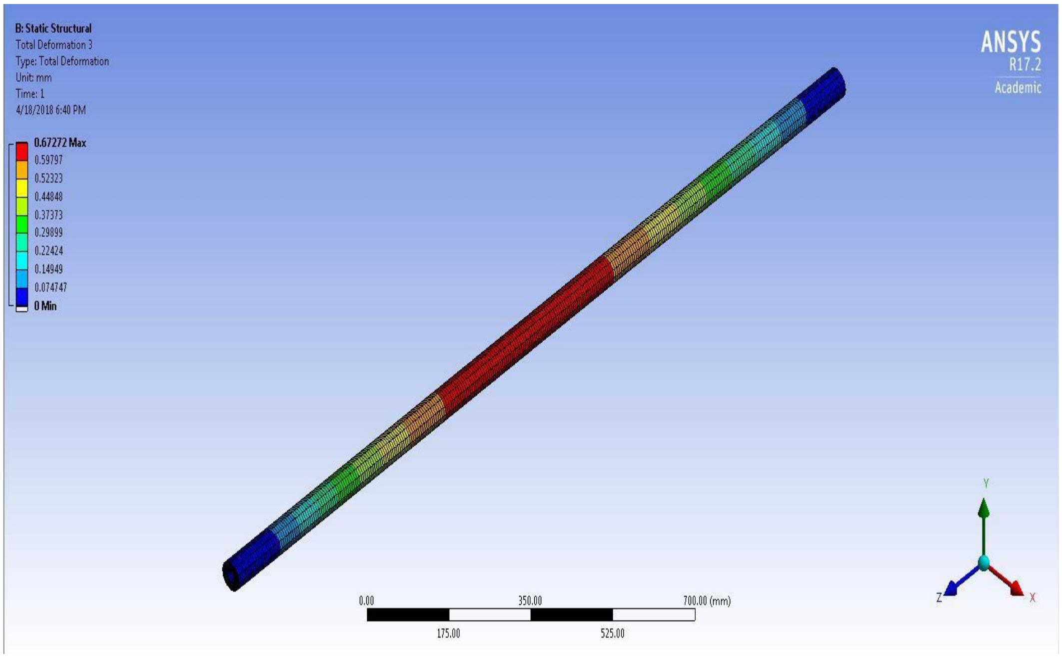


Figure 14 (a) (b) Deformation of outer part



(a)

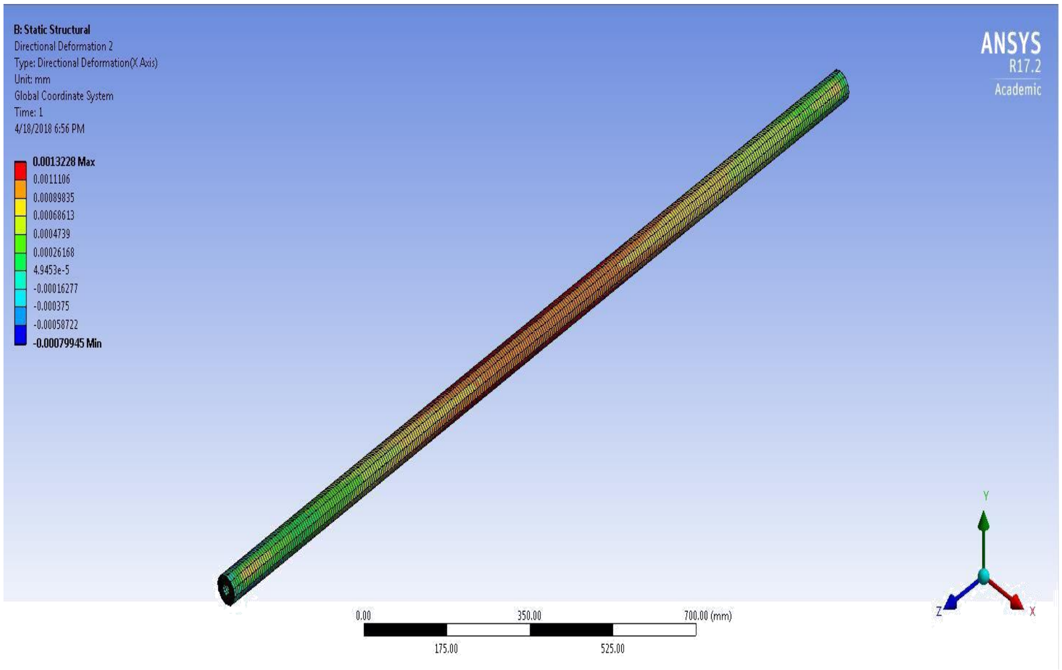
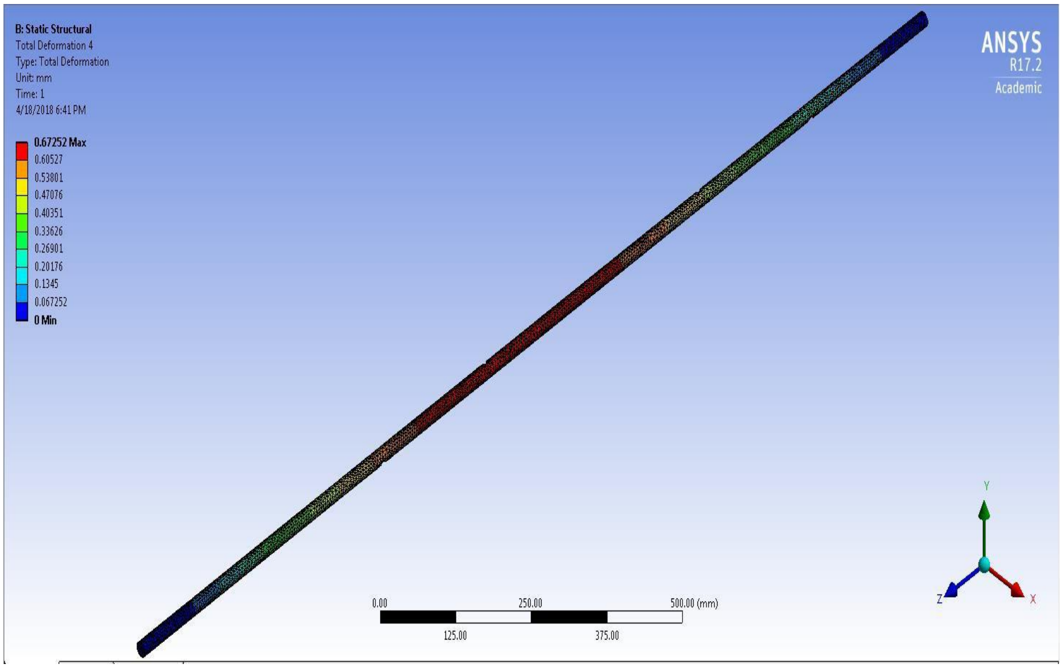


Figure 15 (a) (b) Deformation of composite shaft



(a)

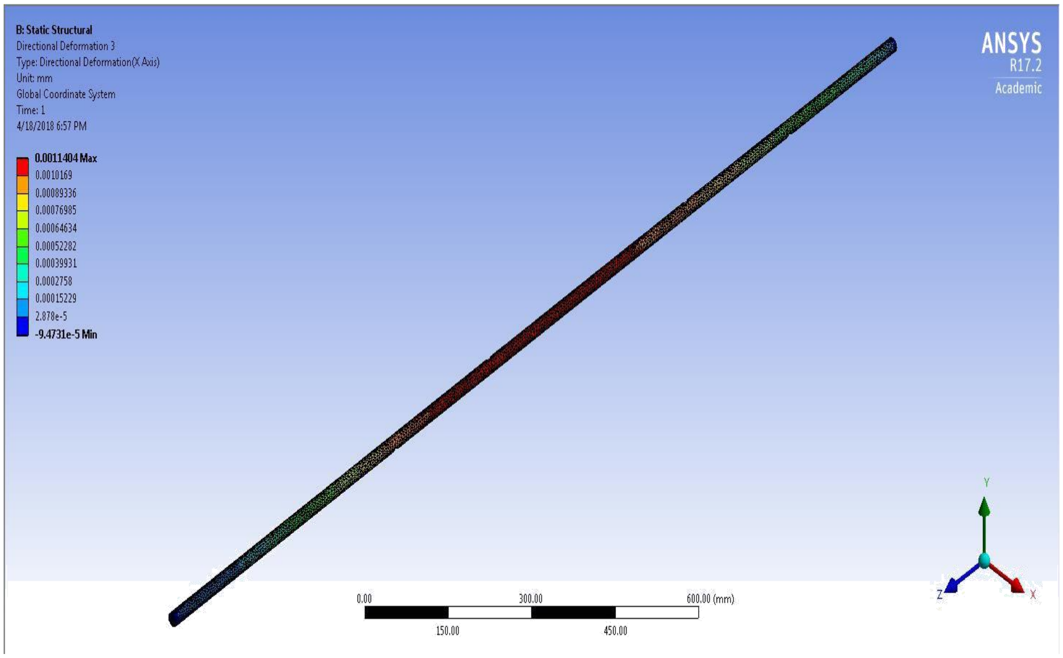


Figure 16 (a) (b) Deformation of inner shaft

The above images show the overall and directional (X-axis) deformation for both metal and composite shafts. As it is seen in both the case, the composite shaft shows lesser deformation when compared to the conventional metal shaft.

Metal Shaft	In mm
Total Deformation	0.89
Axial Deformation (X-axis)	$2.6 * 10^{-3}$

Table 5 Metal shaft Deformation

	Overall (in mm)	Axial (X-axis) (in mm)
Outer Shaft	0.6733	$2.08*10^{-3}$
Composite Shaft	0.6727	$1.32*10^{-3}$
Inner Shaft	0.6725	$1.14*10^{-3}$

Table 6 Deformation in metal-composite shaft

The results for overall deformation as well as axial deformation are better in the hybrid metal-composite shaft as compared to the conventional metal shaft.

The same results for stress and deformation were taken again but this time, thermal conditions were included. The temperature was taken up to 86 F for both the shafts and then the solutions were generated in order the check the behavior of the shaft when subjected to a higher temperature compared to the normal temperature conditions. The following images show the results obtained through static structural analysis for both the shaft under thermal conditions.

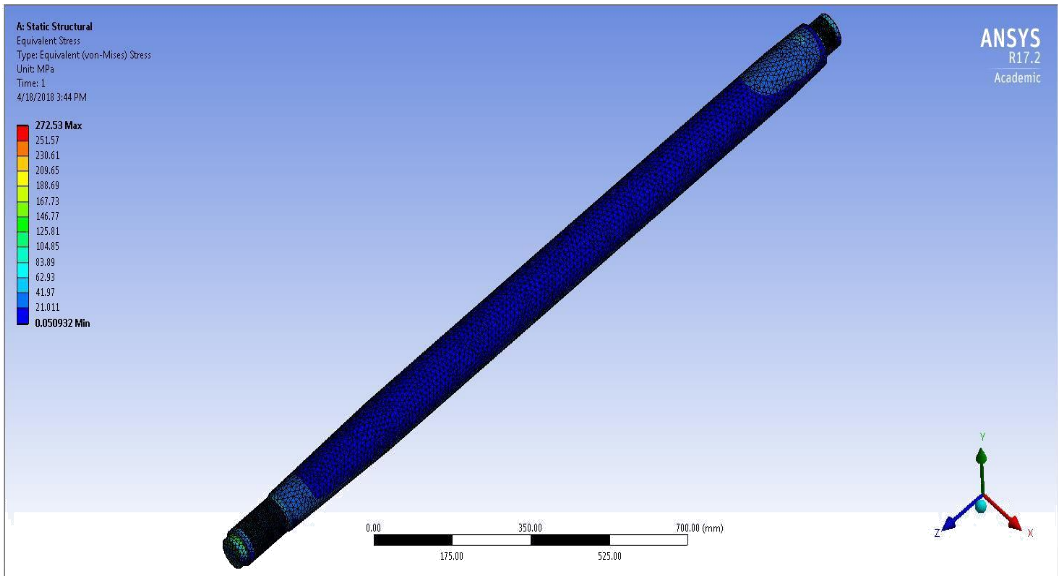


Figure 17 Stress on metal shaft

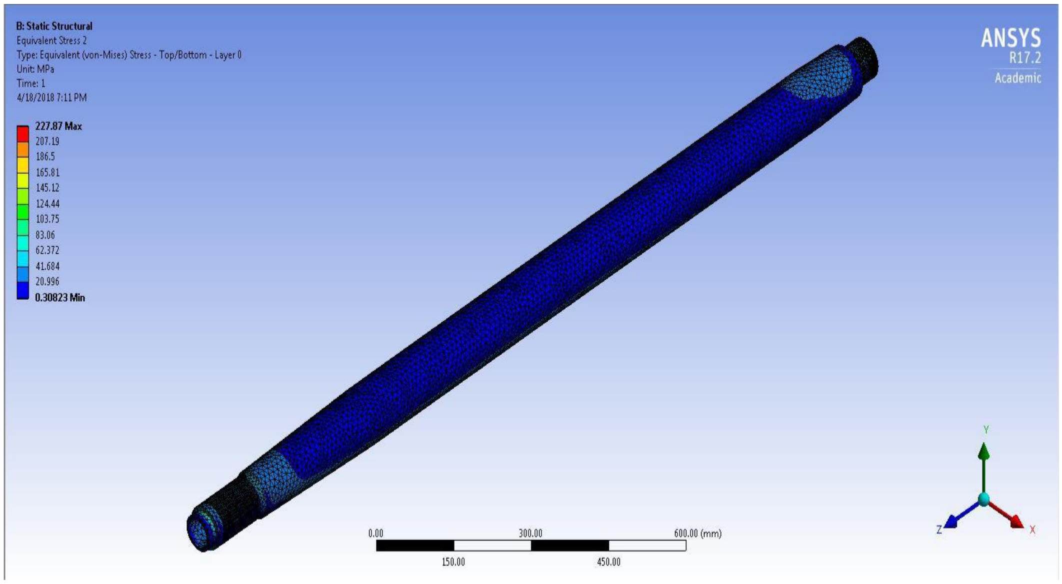


Figure 18 Stress on outer shaft

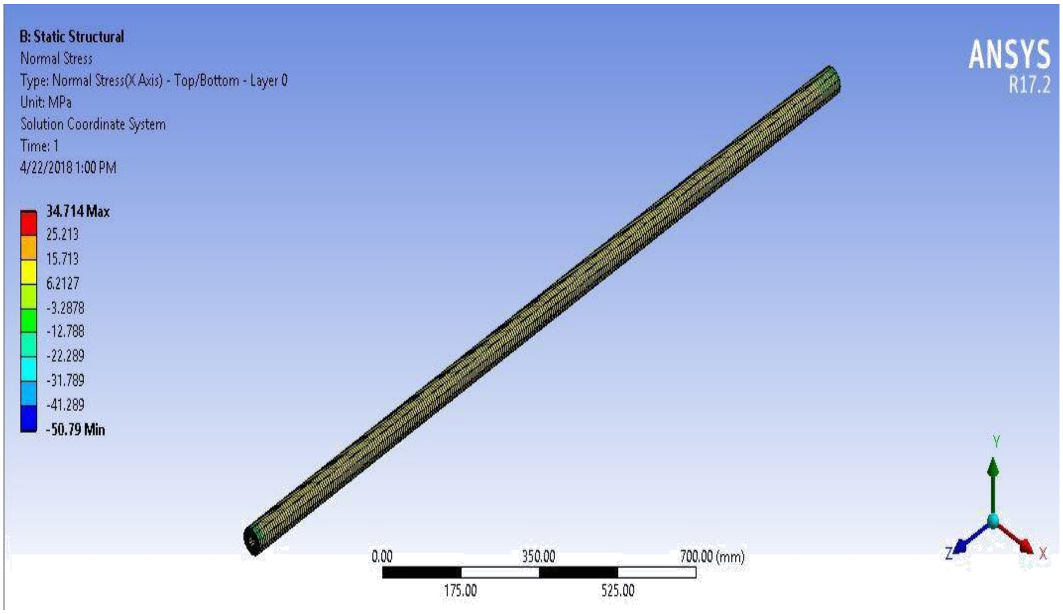


Figure 19 Normal Stress on composite shaft

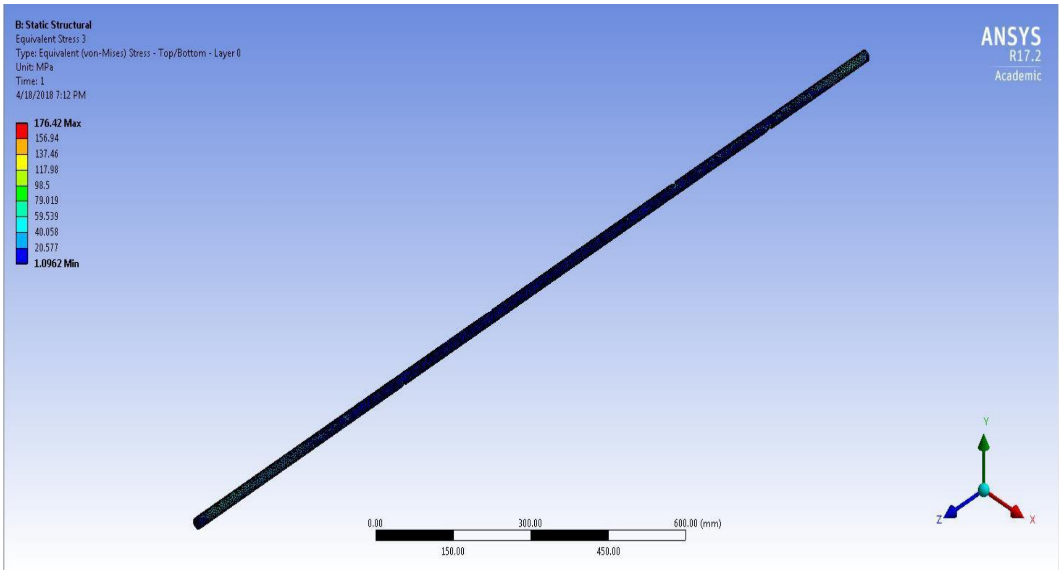


Figure 20 Stress on inner shaft

Stress at 86 F	272.53 MPa

Table 7 Stress in Metal Shaft

	Stress (In MPa)
Outer Shaft	227.87
Inner Shaft	176.42

Normal Stress in Composite shaft	24.89 MPa

Table 8 Stress in Metal-composite shaft

Keeping the same boundary and loading conditions, the deformation in the shafts were taken. Following images show the results obtained.

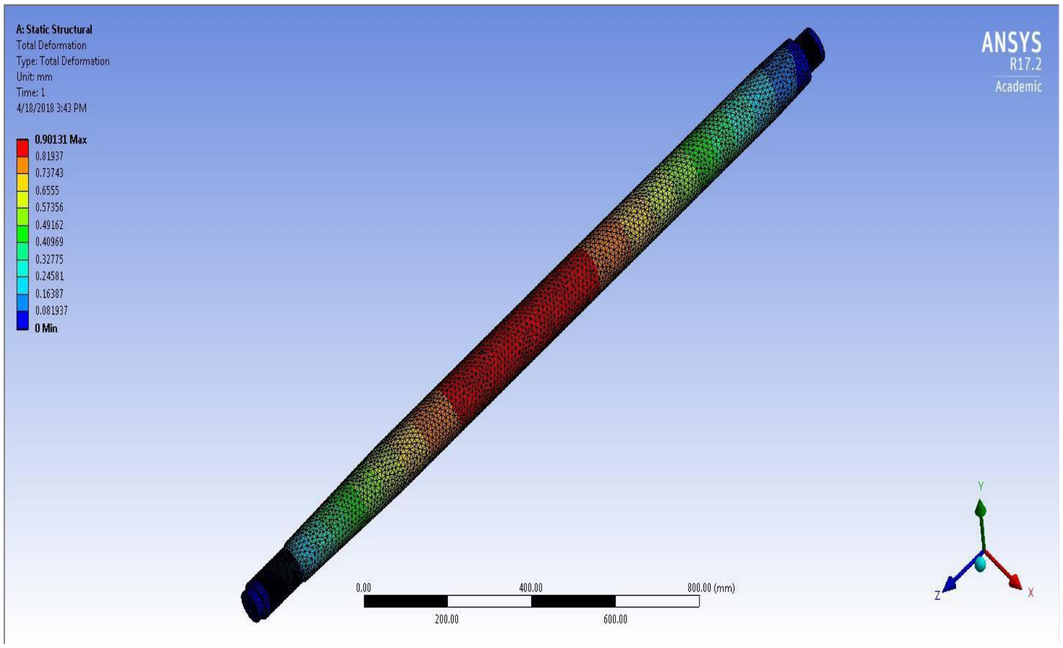


Figure 21 (a)

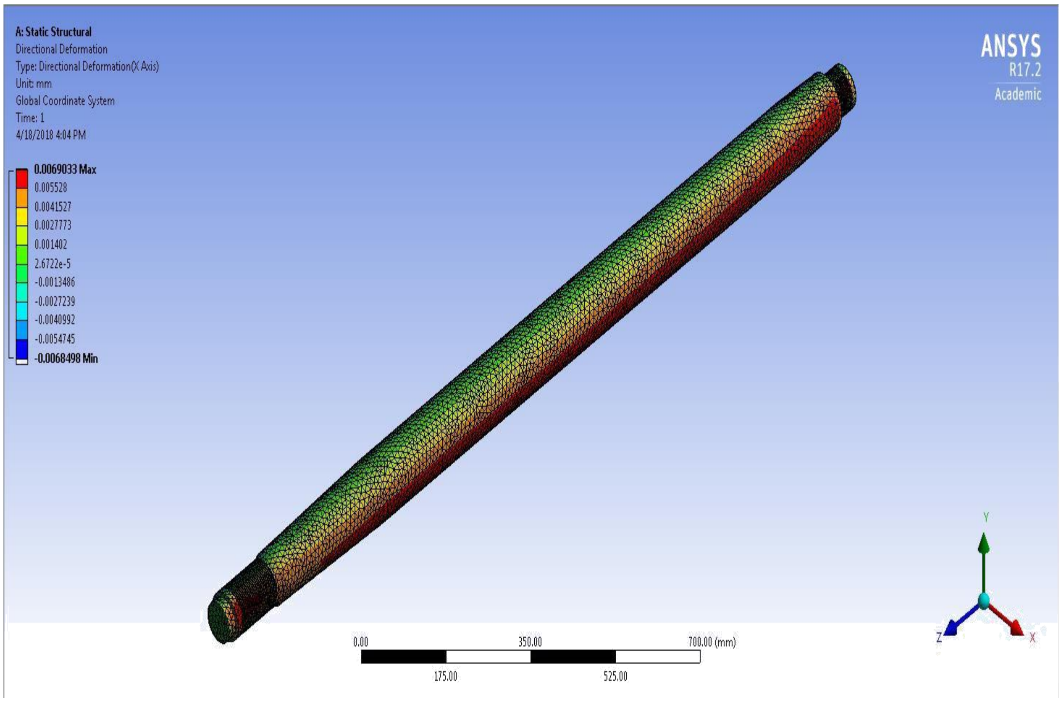


Figure 21 (b) Deformations of metal shaft

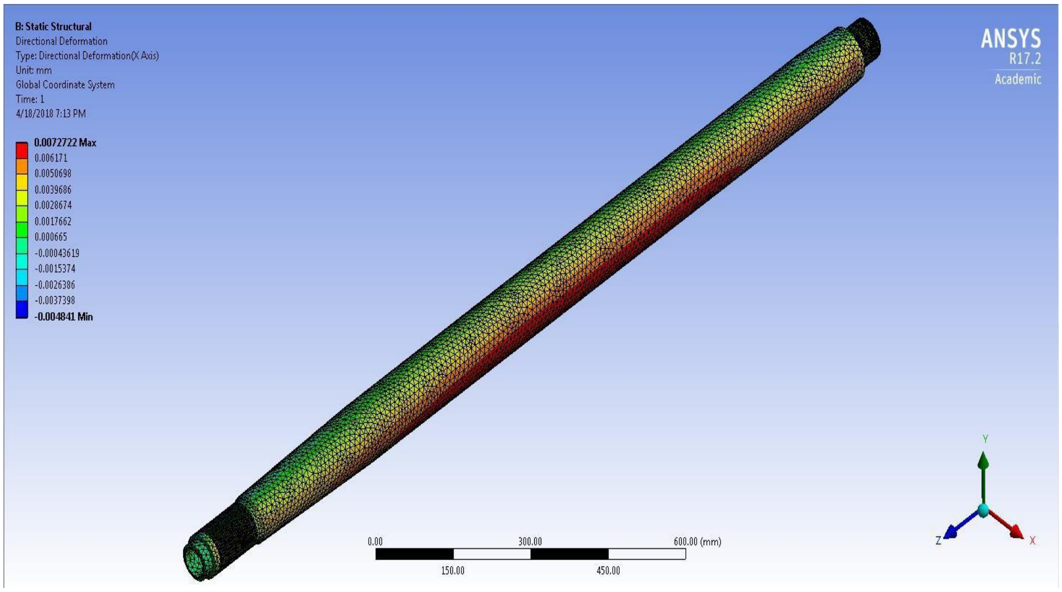
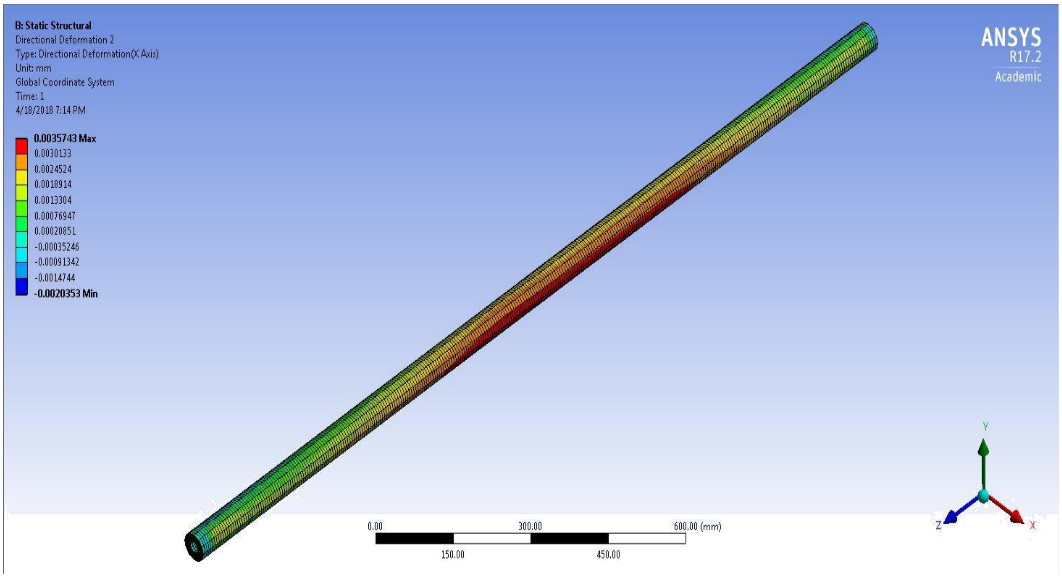
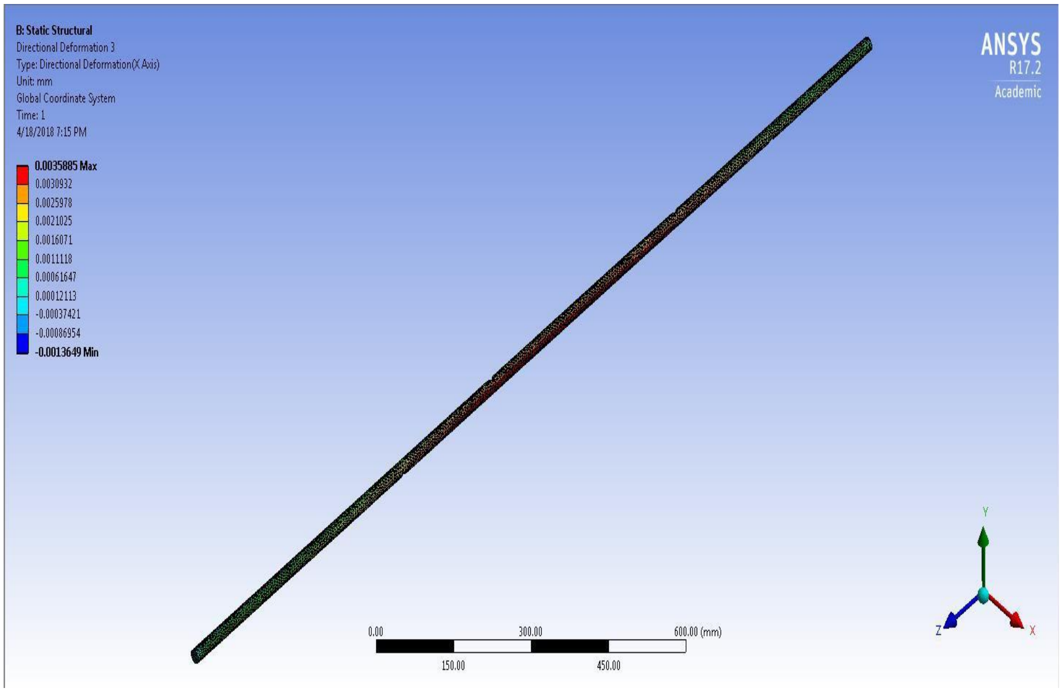


Figure 22 Deformation of outer shaft



B: Static Structural
Directional Deformation 2
Type: Directional Deformation(X Axis)
Unit: mm
Global Coordinate System
Time: 1
4/18/2018 7:14 PM

Figure 23 Deformation of composite shaft



B: Static Structural
Directional Deformation 3
Type: Directional Deformation(X Axis)
Unit: mm
Global Coordinate System
Time: 1
4/18/2018 7:15 PM

Figure 24 Deformation of inner shaft

Here the axial deformation along the X-axis for thermal conditions is noted. The results indicate that composite shaft is better to handle the rise in temperature in comparison to the metal shaft. Also, we can see that the deformation of inner shaft is pretty less than the outer part which shows that the composite plies take most of the effects of deformation and thereby keeping the shaft shape intact. The following table shows the summary of deformation for the shafts under thermal loading conditions.

Axial Deformation (X-axis)	$6.9*10^{-3}$ mm

Table 9 Metal shaft deformation @ 86 F

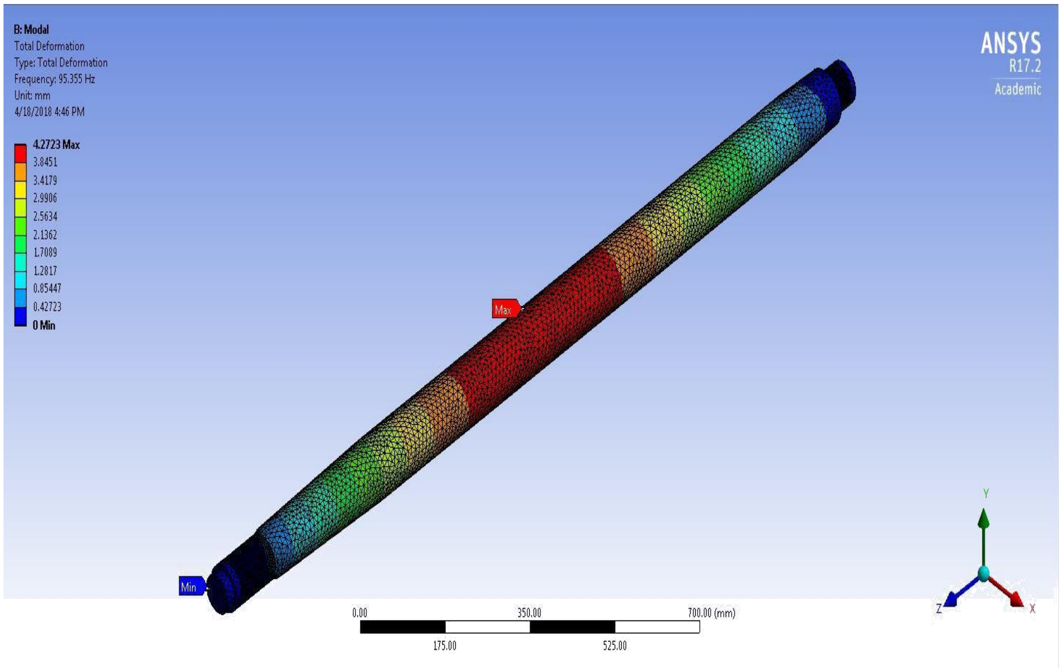
	Axial Deformation (X-axis) (in mm)
Outer shaft	$7.2*10^{-3}$
Inner shaft	$3.5*10^{-3}$
Composite shaft	$3.5*10^{-3}$

Table 10 Composite shaft deform. @ 86 F

5.3 Modal analysis

Modal analysis in the ANSYS are done for finding out the natural frequency of the shaft. In general, it is used to determine the dynamic properties of a system for frequency response. It can be defined as the procedure of finding a structures dynamic properties such as resonant frequencies and the associated pattern of structural deformation called mode shapes [11]. For this analysis, six modes of frequency were taken into consideration for both the shafts. Fixed supports were applied at both the ends of the shaft and the deformation for each mode were taken separately. Here we will see the results from the modal analysis and then compare the frequency between both the shafts to see the dynamic response of composite shaft in conjunction with the metal shaft. The frequency of the system indicates the dynamic response against excitations. These results can be further used to predict the harmonic response of the shafts.

The deformations for each modes of frequency for both metal and composite shaft are shown in the following figures. These results can also be used as the starting point for more detailed dynamic analysis like harmonic response of the system [11]. The frequencies and deformation mode shapes serve as a crucial element for the design of a part under dynamic loading conditions.



25 (a) Mode 1 for metal shaft

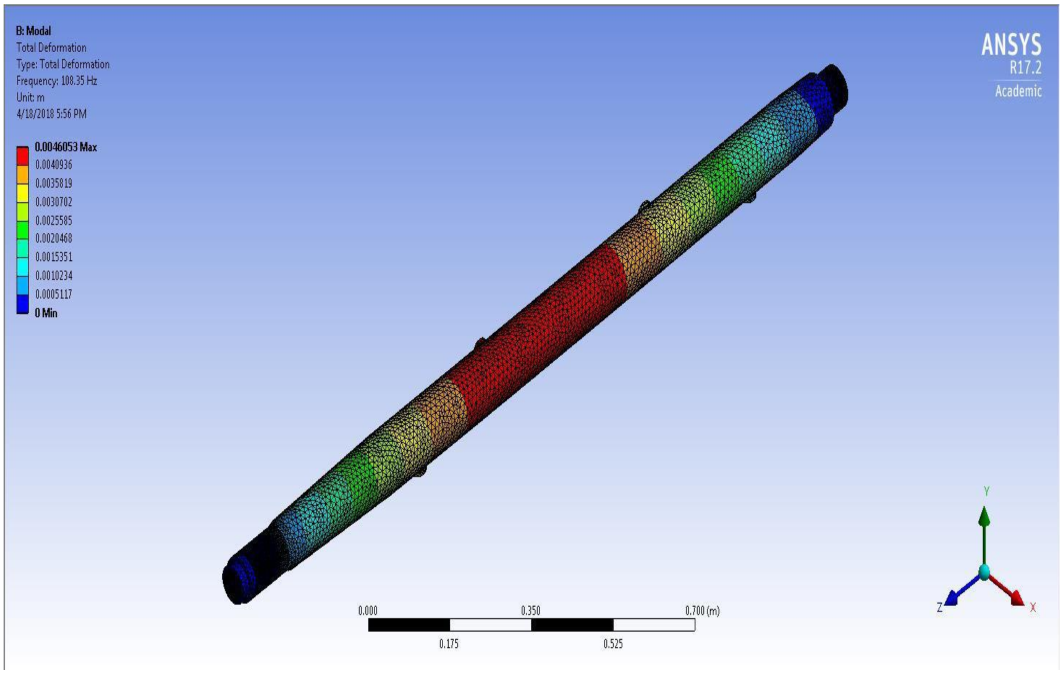
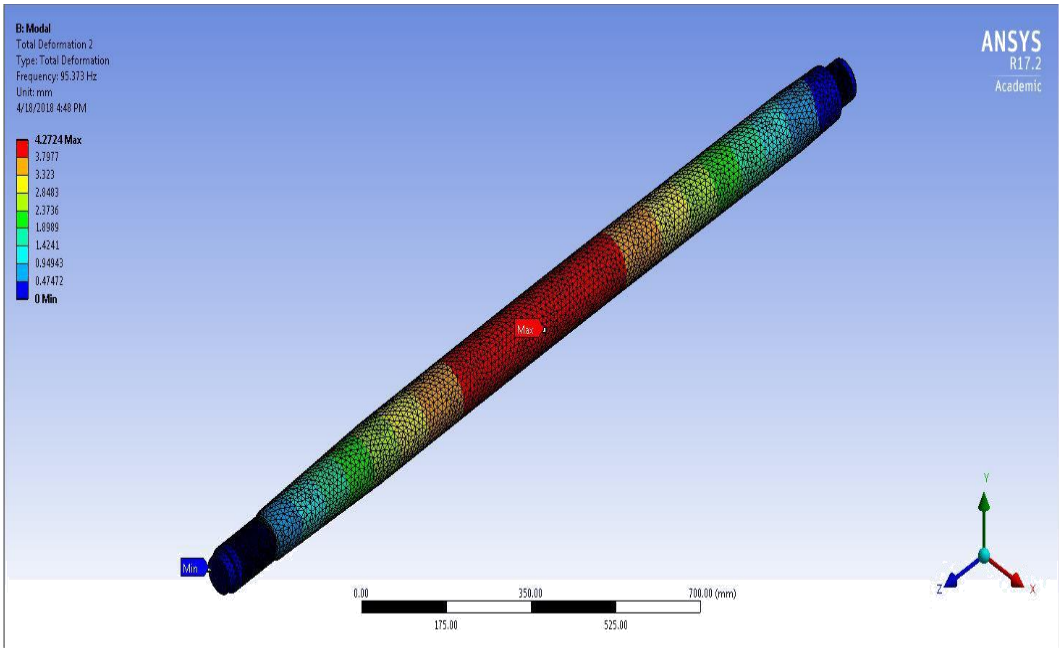


Figure 25 (b) Mode 1 for composite shaft



26 (a) Mode 2 for metal shaft

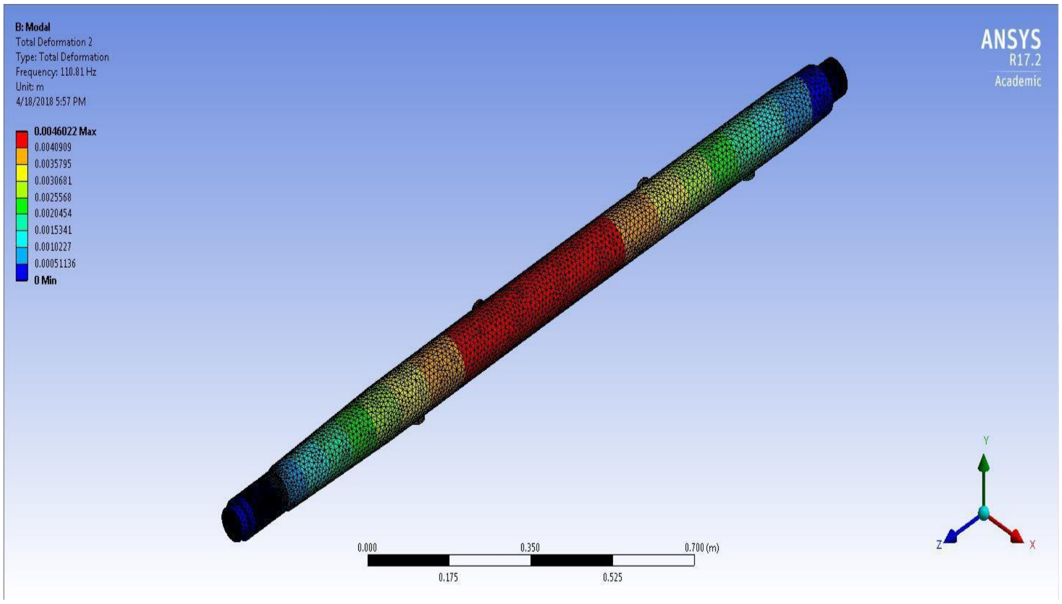
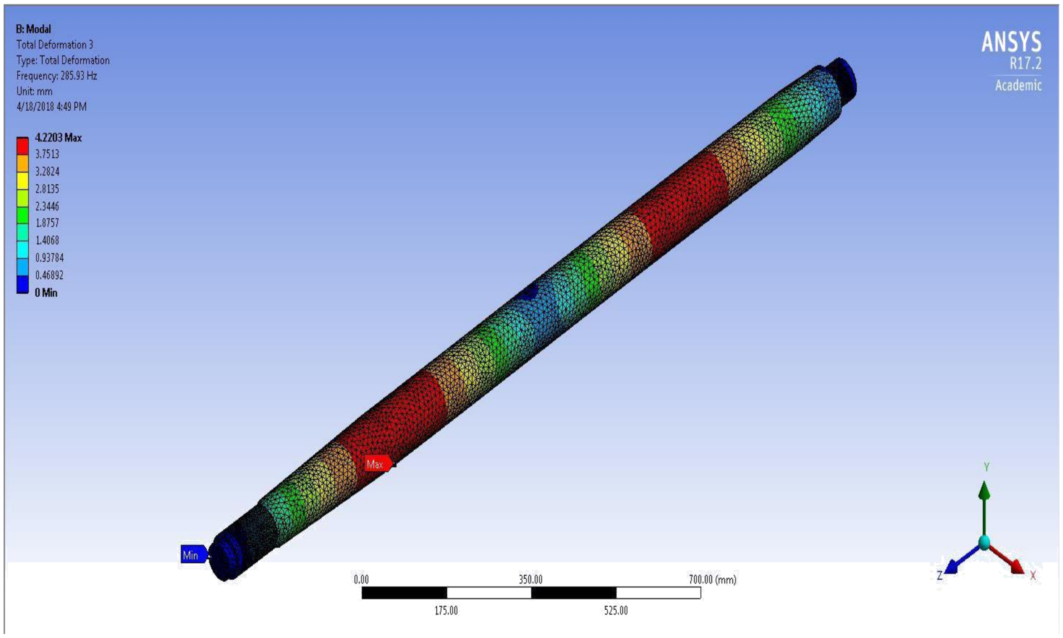


Figure 26 (b) Mode 2 for composite shaft



27 (a) Mode 3 for metal shaft

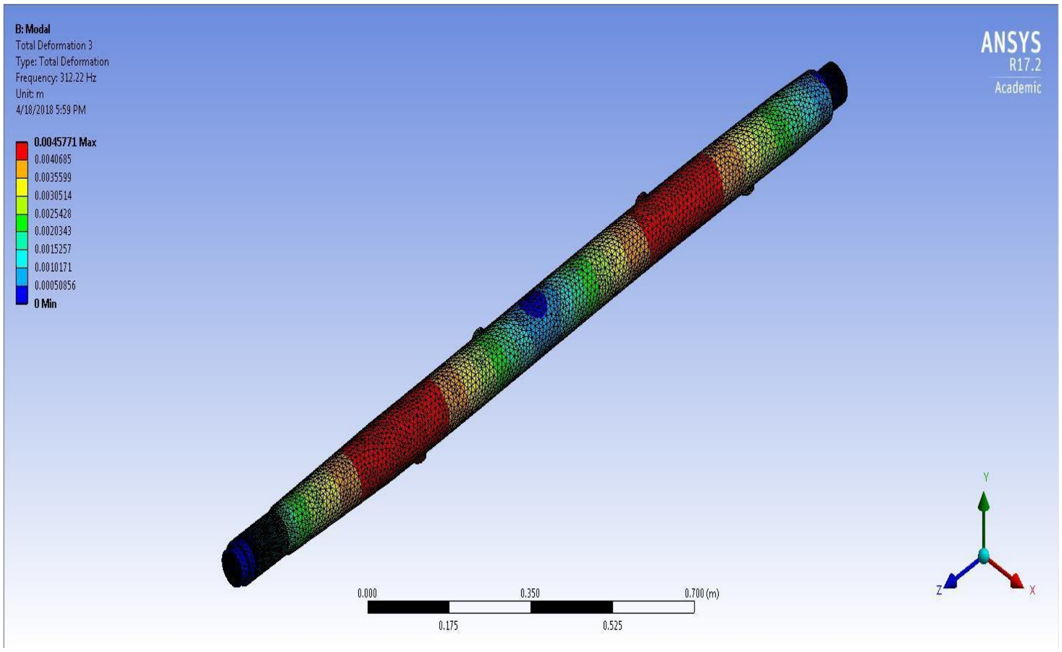
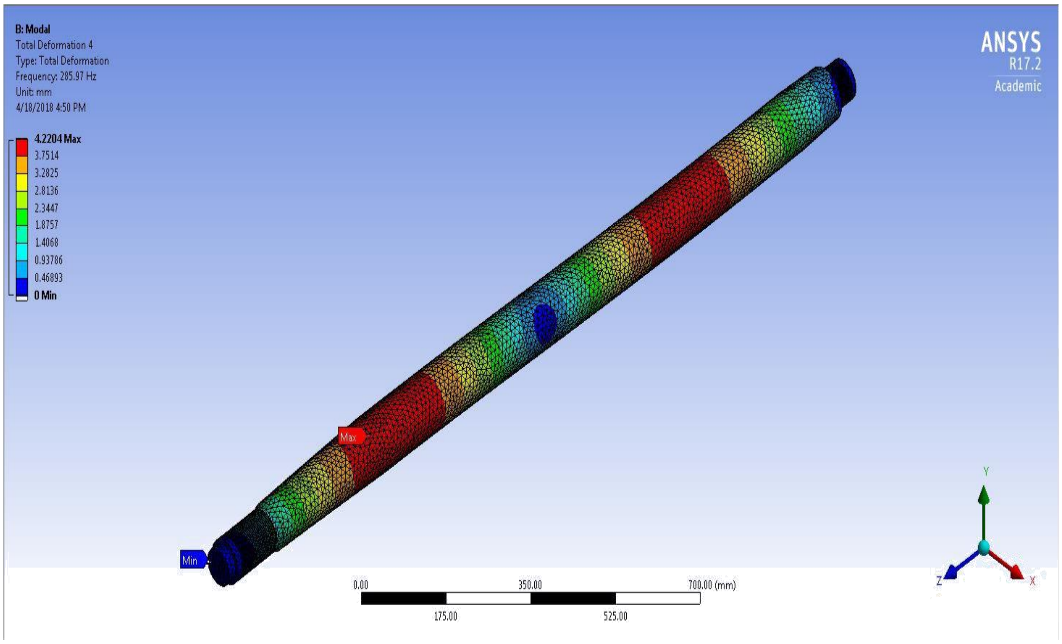


Figure 27 (b) Mode 3 for composite shaft



28 (a) Mode 4 for metal shaft

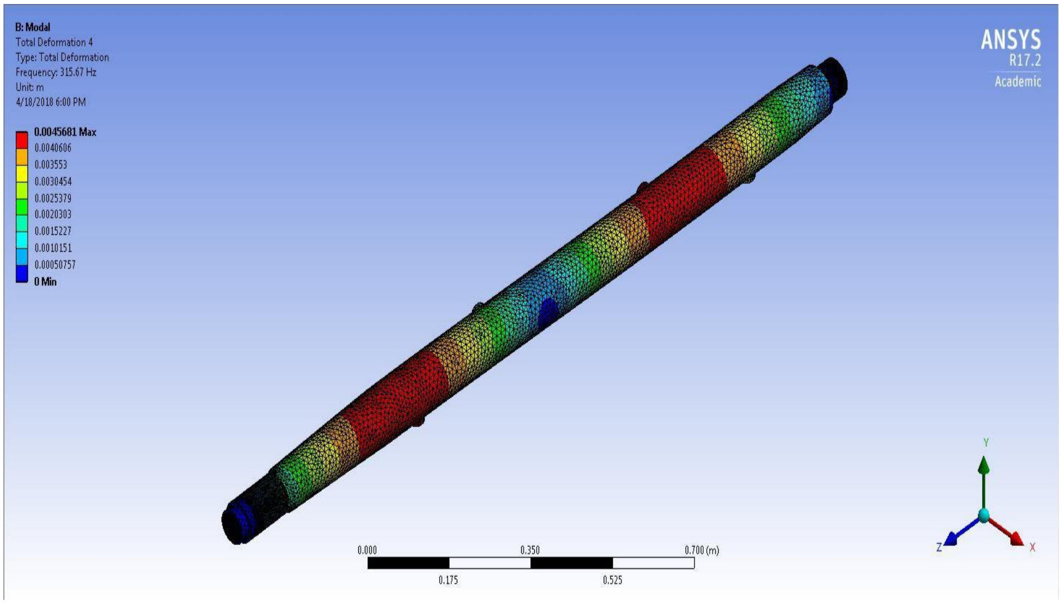
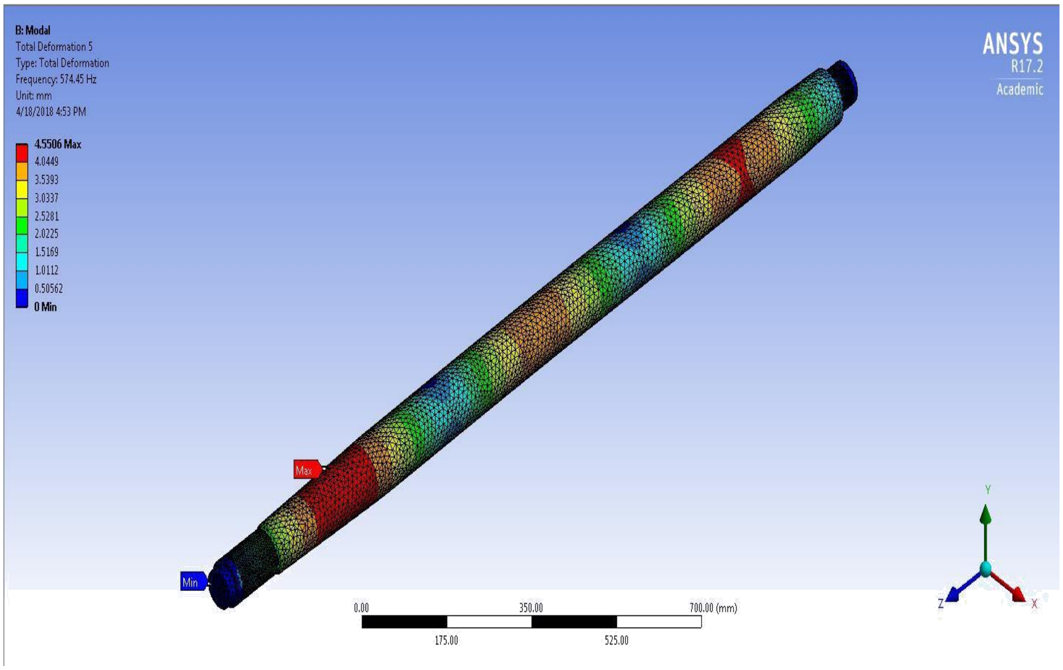


Figure 28 (b) Mode 4 for composite shaft



29 (a) Mode 5 for metal shaft

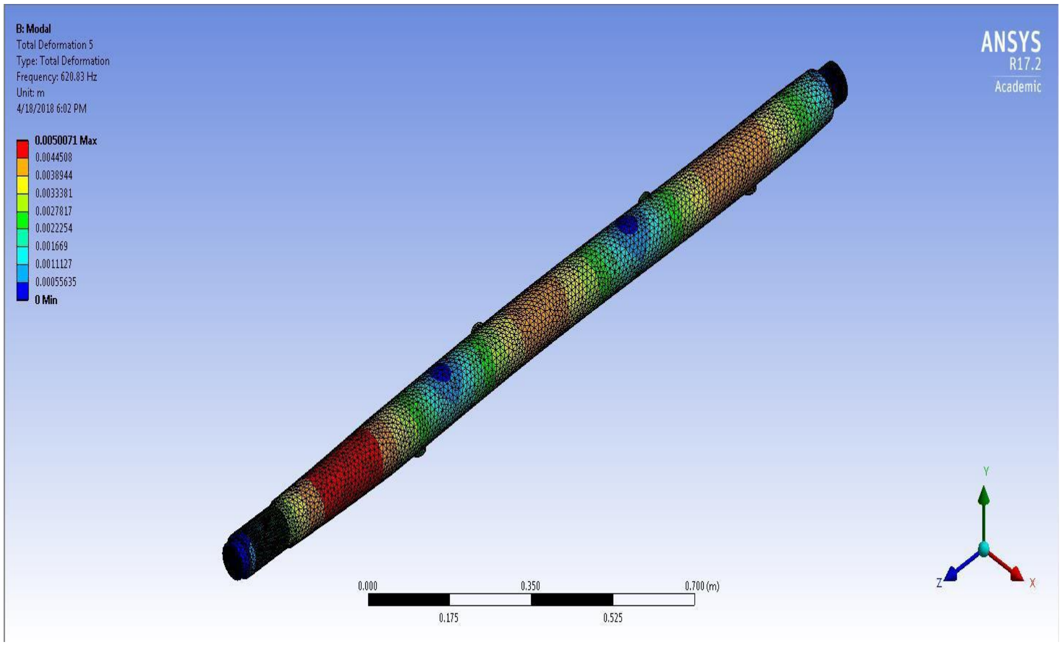
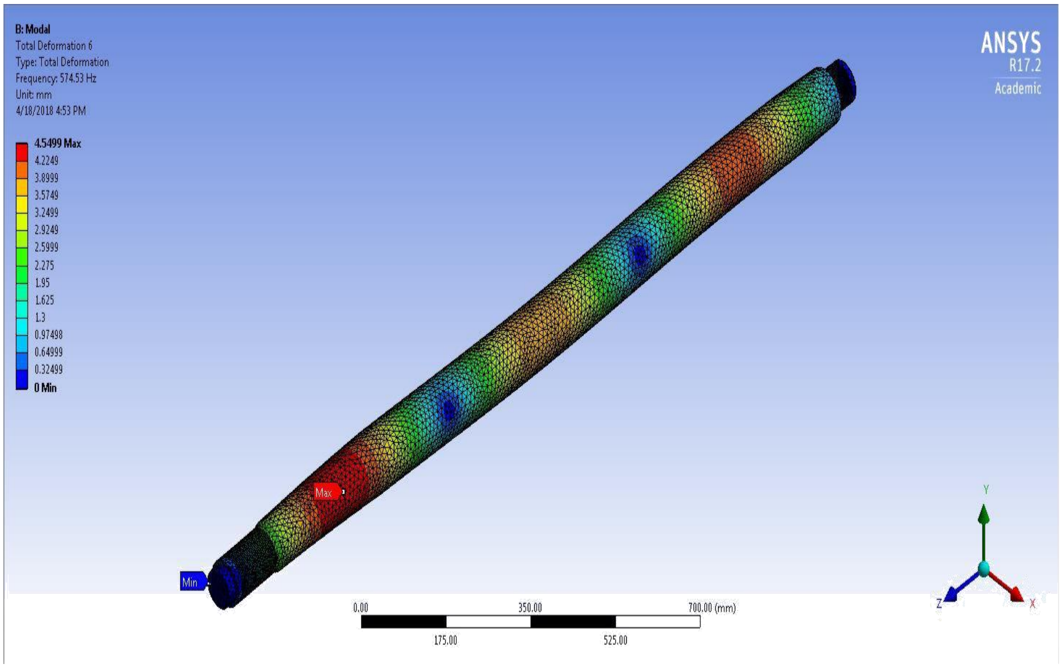
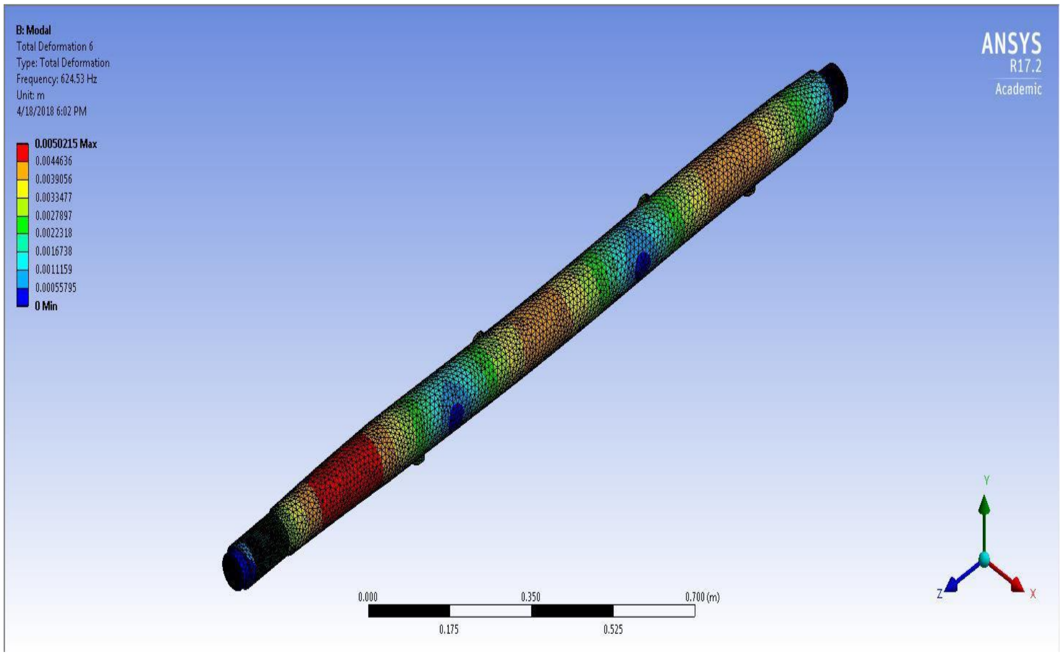


Figure 29 (b) Mode 5 for composite shaft



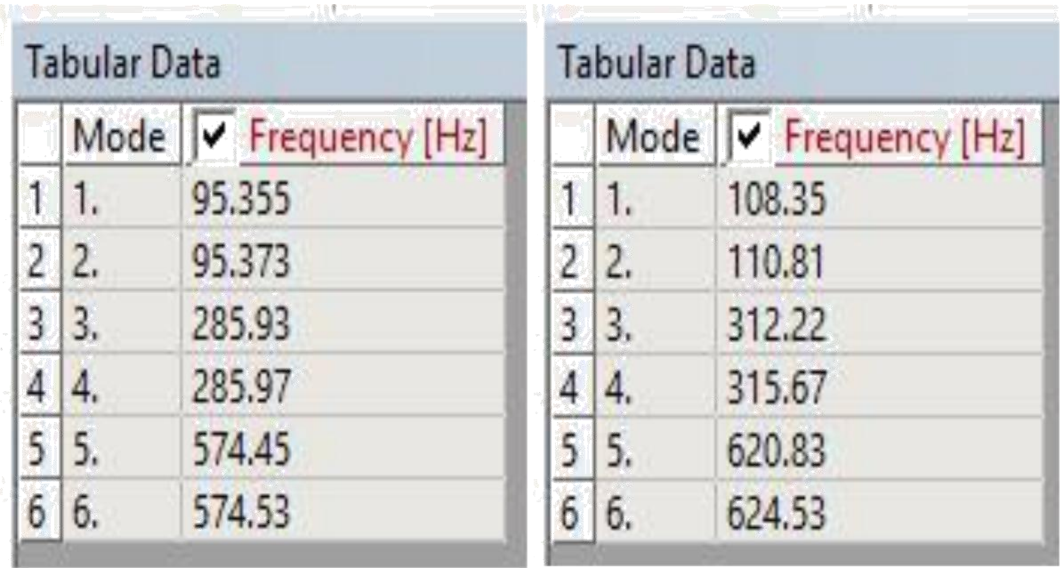
B: Modal
Total Deformation 6
Type: Total Deformation
Frequency: 574.53 Hz
Unit: mm
4/18/2018 4:53 PM

30 (a) Mode 6 for metal shaft



B: Modal
Total Deformation 6
Type: Total Deformation
Frequency: 624.53 Hz
Unit: m
4/18/2018 6:02 PM

Figure 30 (b) Mode 6 for composite shaft



Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	95.355
2	2.	95.373
3	3.	285.93
4	4.	285.97
5	5.	574.45
6	6.	574.53

Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	108.35
2	2.	110.81
3	3.	312.22
4	4.	315.67
5	5.	620.83
6	6.	624.53

Figure 31 Metal Frequency & Composite frequency

Figure 31 (a) shows the natural frequencies for the metal shaft for six modes. Figure 31 (b) shows the results for the frequencies of hybrid metal-composite shaft for the same number of modes. On an average the difference between frequency for any given mode is 15 Hz or higher. This adds to the fact that composite shaft has a better behavior when it comes to the dampening of vibrations. One of the prominent causes of failures for the ship shaft is torsional vibrations and further analysis can be done based on these results to obtain resistance against torsional vibrations [4] [1].

For each mode of frequency, mode shapes result for deformation were also obtained. The following table has the results for deformation corresponding to every frequency for both the shafts. Since the frequency of composites is higher than the metal shaft, the deformation follows the same pattern as well. The deformations are observed to be a little higher for the composite shaft as compared to the metal shaft.

Metal shaft		Composite shaft	
Frequency(Hz)	Deformation(mm)	Frequency(Hz)	Deformation(mm)
95.355	4.27	108.35	4.60
95.373	4.27	110.81	4.61
285.93	4.22	312.22	4.57
285.97	4.22	315.67	4.56
574.45	4.55	620.83	5.00
574.53	4.54	624.53	5.02

Table 11 Frequency and deformation comparison.

Composite shaft possesses about 10-15 % higher frequency than the metal shaft, providing a better dynamic response towards excitations. The deformations are slightly higher for the composite part which can be worked on a little bit. Ply orientation can be modified in order to achieve a control over the deformation for modal analysis. These results for modal analysis can be further used to find the harmonic response of both the shafts.

Chapter 6

Results and conclusion

Comparison for stress and deformation for both the shaft under normal conditions is shown in the following table.

Stress in Metal shaft (MPa)	Stress in Outer/Composite/Inner shafts (MPa)
221.75	167.52/ 43.47/ 156.13

Table 12 Stress comparison

Deformation in Metal shaft (* 10^{-3} mm)	Deformation in Outer/Composite/Inner shaft (* 10^{-3} mm)
2.1	2.0/ 1.3/ 1.1

Table 13 Deformation comparison

As seen from the above two tables, results indicate that the shaft with composite has better response to stress and deformation as compared to the conventional metal shaft. Based on the stress results, factor of safety has been calculated for the shafts and are shown in the coming table.

		Factor of Safety
Conventional Metal Shaft		2.70
Metal/Composite Shaft :	Outer part	3.58
	Composite part	27.97
	Inner part	3.84

Table 14 Factor of safety comparison

As seen in the table above, the factor of safety for the metal shaft is 2.70 and the for the composite shaft, the least of all three parts is for the outer shaft i.e. 3.58 which is almost 0.9 more than that of the conventional shaft. For the composite and inner part of the shaft, the FOS is higher than the outer part of the shaft. Factor of safety for the thermal conditions was also calculated and the following comparisons were drawn. Both the factor of safety for normal and thermal condition comes out to be higher for the composite shaft than the metal shaft.

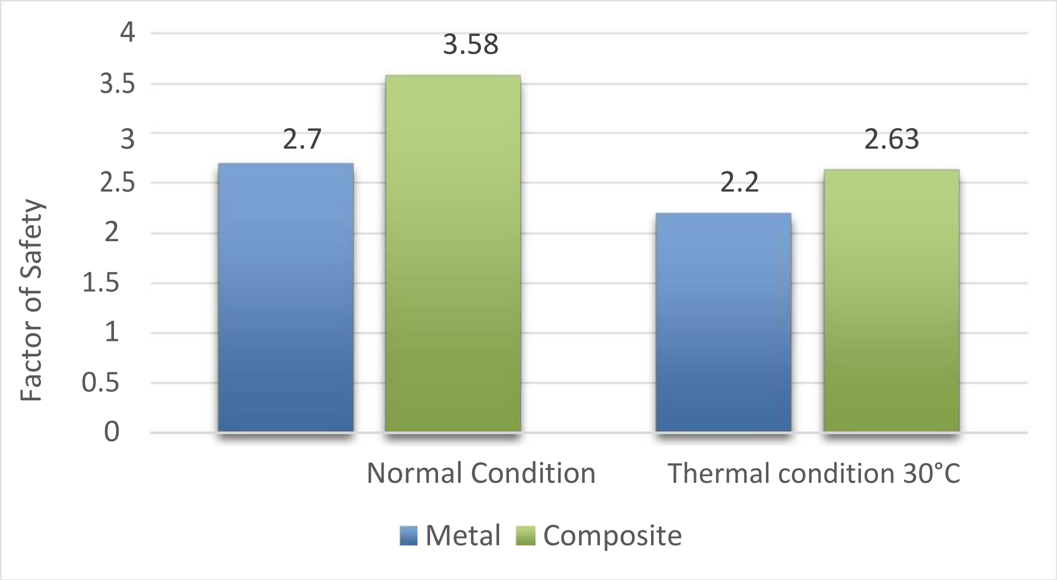


Chart 1 FOS comparison.

The above chart has the factor of safety for both the shafts under normal conditions and thermal conditions as well. Factor of safety in basic words can be written as the amount of overload the system can sustain before failing. As compared to 2.7 for the conventional metal shaft, the hybrid metal-composite shaft has a factor of safety of 3.6, lower stress concentration occurs due to the presence of composite layers.

Chapter 7

Conclusions and future work

The following conclusions can be made out of the results that have been obtained throughout the course of this work.

- Hybrid Metal-Composite shaft has a higher factor of safety than the conventional metal shaft indicating longer shaft life and good resistance to overloads.
- Stress and deformation are brought down by the introduction of composites.
- The density of composite material is less than the metal material thereby resulting into weight reduction of the shaft by about 12-16 % as compared to the metal shaft. This also results in the overall weight reduction of the engine room on the ship which is a major area of interest these days.
- Composite shaft has around 10-15 % higher frequencies than the metal shaft indicating a better dynamic response towards excitations.
- Due to the increased fatigue failure resistance of the composite materials, the shaft failure to fatigue has a lesser possibility when compared to the conventional shaft. Fatigue is a prime cause of failure marine structures which respond dynamically to random wave and wind loading [13].

- Composite materials are corrosion resistant and since some part of the shaft comes in direct contact with water, the inner portion of the shaft is prevented from corrosion due to the presence of a composite layer.
- Better natural frequency for the composite shaft indicates a better harmonic response which is crucial for a smooth operation specially in case of passenger boats where ride comfort is a necessity.
- Composite parts can easily be molded with very little waste. The overall material cost is thereby reduced as compared to the metal parts.
- The plies stacked up in the +45 and -45 directions prevent the propagation of cracks through the shaft which is another dominant cause of failure in the shafts.

7.1 Future work

In the future, this concept can be worked upon to achieve a firm solution. The following are the areas that can be worked on:

- Dynamic analysis could be done for cyclic loads and by varying the influencing parameters, shaft behavior can be predicted for extreme operating conditions.
- Various composite lay ups can be tried in order to obtain an even higher factor of safety for the shaft.
- Try different diameters of the propeller shaft and find an ideal metal-composite combination ratio for the manufacturing of the shaft.
- Fiber – matrix volume concentration has been taken as 60% fiber volume for the material. Different volume concentrations can be tried, and the results can be compared.

References

1. Vizentin, G., G. Vukelić, and M. Srok, *Common failures of ship propulsion shafts.* Pomorstvo, 2017. **31**(2): p. 85-90.
2. Van Ta, T., D.M. Thien, and V.T. Cang, *Marine Propulsion System Reliability Assesment by Fault Tree Analysis.*
3. Boddapati, V., et al., *DESIGN OF MARINE PROPULSION SHAFTING SYSTEM FOR 53000 DWT BULK CARRIER.* International Journal of Mechanical Engineering and Robotics Research, 2015. **4**(2): p. 171.
4. Xu, X., R. Zhou, and M. Wang, *Research on the Marine Shafting Torsional Vibration with Gears Transmission.*
5. Han, H.S., K.H. Lee, and S.H. Park, Parametric study to identify the cause of high torsional vibration of the propulsion shaft in the ship. Engineering Failure Analysis, 2016. **59**: p. 334-346.
6. Dymarski, C. and M. Narewski, *Analysis of ship shaft line coupling bolts failure.* Journal of Polish CIMAC, 2009. **4**(2): p. 33-40.
7. Roylance, D., *Introduction to composite materials.* Department of material science and engineering, Massachusetts Institute of Technology, Cambridge, 2000.
8. Erhard, G. and M. Thompson, *Designing with plastics*. 2006: Hanser Munich, Germany.
9. Smallman, R.E. and R.J. Bishop, *Modern physical metallurgy and materials engineering*. 1999: Elsevier.

10. Tawfik, B.E., et al., *Weight reduction and strengthening of marine hatch covers by using composite materials.* International Journal of Naval Architecture and Ocean Engineering, 2017. **9**(2): p. 185-198.
11. Srikanth, S., J. Bodapalli, and A. Gudimetla, *Design, Static and Modal Analysis of A Propeller Shaft for Reducing Vibrations Using Composite Damping.* International Journal of Emerging Technology And Advanced Engineering (IJETAE), Volume3, 2013(10).
12. Kaw, A.K., *Mechanics of composite materials*. 2005: CRC press.
13. Wirsching, P.H. and Y.-N. Chen, *Considerations of probability-based fatigue design for marine structures.* Marine Structures, 1988. **1**(1): p. 23-45.

Biographical Information

Kaushal Shah received his bachelor’s degree in Mechanical Engineering from Ahmedabad Institute of Technology Gujarat, India in May 2016. In the final year of his bachelor’s degree, he designed a mechanical motion machine operated by pedal power and integrated the system with a grinding/flour mill. This earned him a recognition from the GIC Gujarat, India for the innovative project. He also has certifications in AutoCAD and Creo parametric. He joined Creative Transpower, one of the prominent makers of transformers in India as a workshop trainee and design assistant during June 2016. He decided to enroll into Master of Science in Mechanical Engineering program at the University of Texas at Arlington in Fall 2016. He has worked on various projects during the course of his degree and also served as a research student under Dr. Andrey Beyle in Fall 2017. He continued with Dr. Beyle as a thesis student working on the applications of composite materials in the marine propulsion system in the Spring 2018 semester. He has one year’s experience in FEA and is prominent in Solid Works and ANSYS software’s. He graduated with a Master of Science degree in Mechanical Engineering in May 2018.