# Finite Element Modelling of Composite Rotor-Shaft-System

*A thesis submitted in partial requirements for the degree of*

**Bachelor of Technology**
**in**
**Mechanical Engineering**

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2012

**National Institute Of Technology**

**Rourkela**

**CERTIFICATE**

This is to certify that the thesis entitled, "**Finite Element Modelling of Composite Rotor-Shaft-System"** submitted by Mr. **Satyaranjan Sahoo (108ME036)**, Mr. **Ajay Shankar Suman (108ME045)** and Mr. **Manoj Kumar Beldar (108ME056)** in partial fulfilments for the requirement of the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by them under our guidance. To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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# ACKNOWLEDGEMENT

I wish to express my sincere thanks and gratitude to **Prof. Tarapada Roy** for suggesting me the topic and providing me the guidance, motivation and constructive criticism throughout the course of the project.

I am grateful to **Prof. (Dr.) K. P. Maity**, Head of the Department, Mechanical Engineering for providing me the necessary opportunities for the completion of my project. Our project supervisors were instrumental in the process of bringing this project to its present form. Without their key support, knowledge and experience, procurement of set-up, set-up of project equipment and analysis work would not have been possible.

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**Abstract**:

The objective while manufacturing various machinery or automobile parts is usually to make components of high strength and durability along with less weight or density. Generally composite materials are preferred as compared to single material for high performance. Composite consists of two or more material having same or different physical and chemical properties. One of the materials serves as matrix holding together the other material embedded in it which provides the reinforcement in the form of fibres. Glass epoxy materials are generally used for its sustainability under heavy electrical and mechanical stresses under high temperature operating conditions. In this project, various type of rotor-shaft system with bearings is used having unbalance in rotor to study and compare better performance between composite and single material under transient analysis. The material property was set to orthotropic and isotropic for composite and single material respectively. E-Glass/Epoxy and steel are used as composite and single material respectively for the analysis. The study uses ANSYS-13 software for developing finite element model of the rotor-shaft system. The element type for shaft, disk rotor and bearing were defined as beam188, mass21 and combin14 respectively. The shafts were defined as solid and hollow by calculating the mass moment of inertia and polar moment of inertia accordingly. Based on these models, analyses were carried out to obtain a more stable rotor-shaft system. Graphs for bending stress vs. time and displacement vs. time were studied for each case.

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# CHAPTER 1

# INTRODUCTION

## INTRODUCTION

Generally, a composite material is made up of two components acting together i.e., reinforcement (fibres, particles, flakes, and/or fillers) embedded in a matrix (polymers, metals, or ceramics). The matrix holds the reinforcement to form the desired shape and size while the reinforcement improves the mechanical properties of the matrix as per requirement. A common example of a composite is disc brake pads, which consist of hard ceramic particles embedded in soft metal matrix.

### 1.1 Common Categories of Composite Materials

Classification based on the form of reinforcement

a. Based on matrix material

i. Metal matrix composites: It composed of metal matrix like aluminium, copper, cobalt, iron and magnesium and dispersed ceramic like oxides and carbides or metallic phase like lead, tungsten and molybdenum

ii. Ceramic matrix composites: They are composed of a ceramic matrix and embedded fibres of other ceramic material

iii. Polymer matrix composites: they are composed of matrix from thermoset i.e. unsaturated polyester and epoxy or thermoplastic i.e. polycarbonate, polyvinylchloride, nylon and polysterene and embedded glass, carbon, steel or Kevlar fibres

b. Based on fibres as reinforcement:

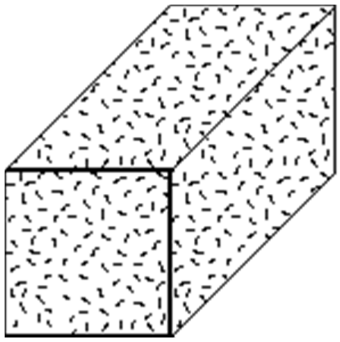

Fig 1 . Random fibre (short fibre) reinforced composites [1]

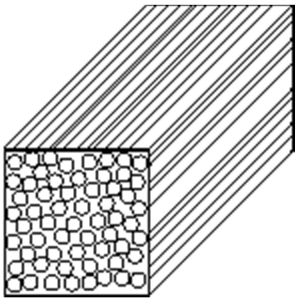

Fig 2. Continuous fibre (long fibre) reinforced composites [1]

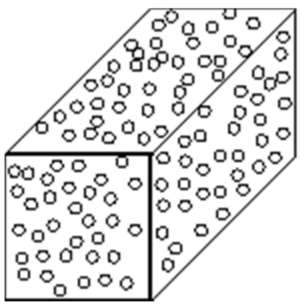

Fig 3. Particles as the reinforcement (Particulate composites) [1]

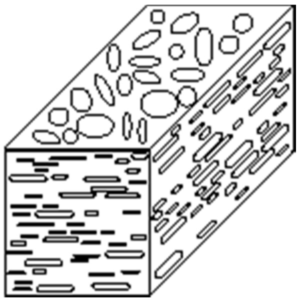

Fig 4. Flat flakes as the reinforcement (Flake composites) [1]

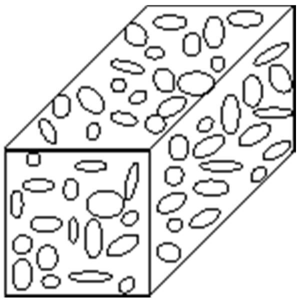

Fig 5. Reinforcement is filler (Filler composites) [1]

**1.2 Benefits of Composites**

a. Cost efficient for mass production, maintenance, fatigue life, durability and maturity of technology.

b. Light weight with proper weight distribution

c. High strength and stiffness as it has high strength to weight ratio and high directional strength and/or stiffness.

d. Highly useful in manufacture of large parts and special geometry

e. Better surface properties i.e. corrosion resistance, weather resistance and tailored surface finish

f. Thermal properties is good i.e. low thermal conductivity and low coefficient of thermal expansion

g. Useful electric properties were achieved i.e. high dielectric strength, non-magnetic and radar transparency.

### 1.3 About Fibre Reinforced Polymer (FRP)

FRPs are typically organized in a laminate structure, such that each lamina or flat layer contains an arrangement of unidirectional fibres fabrics embedded within a thin layer of polymer matrix material. The fibres consist of carbon or glass which provides the strength and stiffness. The matrix commonly made of polyester, Epoxy or Nylon which binds and protects the fibres from damage and transfers the stresses between fibres.

### 1.4 Applications of FRP Composites

a) **Uses in structural engineering:** When a FRP specimen is tested in axial tension, the applied stress is proportional to the ratio of strain. When the applied load is removed, it returns to its original shape or size. In other words, FRP follows linear-elastically to axial stress. FRP composite compression failure occurs when the fibres exhibit extreme lateral or sides-way deflection, often in sudden and dramatic condition, called fibre buckling. Usually, failure occurs within the matrix material parallel to the fibres. FRP's high strength properties also include excellent durability and corrosion resistance. Furthermore, their high strength-to-weight ratio is of significant benefit; a member composed of FRP can support larger live loads since its dead weight does not contribute significantly to the loads that it must carry out. Other advantages include its versatility, excellent fatigue life and fire resistant.

b) **Uses in construction:** Its applications for new construction repair and rehabilitation applications and architectural applications are common. FRP is used in building structures like bridges and columns. It demonstrated exceptional durability, and effective resistance to effects of environmental exposure. Several companies across the world are beginning to renovate damaged bridge piers to prevent collapse and steel-reinforced columns to improve the structural integrity and to prevent buckling of the reinforcement. Architects have discovered the applications of FRP in structures such as siding/cladding, roofing, flooring and partitions. Intelligent Sensing for Innovative Structures (ISIS), of Canadian Universities, is a program that consists of collaborative research and development efforts in various engineering disciplines. Its primary aim is in the development of innovative uses of FRPs in concrete structures. In Canada, engineers have integrated fibre optic sensors into numerous FRP systems to ensure that adequate supervision of the systems is provided

### 1.5 Rotor-shaft system

ROTARY machines are commonly used in turbine, generators, and electrical motors. Primary role of rotary shafts are in power transmission. Its applications are commonly seen in automobiles, induced draft fans in blast furnace. These shafts consist of different parts such as bearings, disks, gears and etc. on them. Common problem that occurs in this system is unbalance, due to which vibration occurs while operating. So bearings are used to diminish this vibration and prolong the tolerance of the system usage before it is balanced.

## 1.6 Classification of bearings and its application

a. Based on the direction of load

i. Radial bearings: It reduces support loads and rotational friction. As the bearing rotates the balls also rotate simultaneously. It lowers rolling resistance and coefficient of friction as compared to two flat surfaces was rotating. It’s used in of aircraft engines, wing flaps, fans, trains and automobiles joints, etc.

ii. Thrust bearings: It is designed to manage axial loads and provide high shock load resistance in a variety of operating conditions. It usually used in clutches, water pump, etc.

b. Based on nature of contact

i. Sliding contact bearings: It has excellent vibration and shock resistance. Damping capability is excellent normal to direction of motion due to squeeze film damping. It enables heat generated to conduct away. It is usually used in cam followers, insulators, liners, valve seats, etc.

ii. Rolling contact bearings: They are used widely in instruments and machines in order to support the shafts. It minimizes the friction and power loss associated with relative motion. It is used in gear pump, hydraulic pump, helicopter rotors and transmission, material handling equipment, etc.

iii. Journal bearings: There are no rolling elements in these bearings. Journal bearings operate in the boundary region (metal-to-metal contact) only during the start-up and shutdown of the equipment when the rotational speed of the shaft (journal) is insufficient to create an oil film. It is used in automobile and aircraft engine, marine steam engine, steam turbines, etc.

# CHAPTER 2

# LITERATURE SURVEY

## 2.1 Literature survey

In the study of numerical modelling and analysis of composite beam structures subjected to torsional loading by Kunlin Hsieh [2], his work deals with the effect of torsion of cylindrical composite shaft. To solve the problem, eigen function expansion method is used. Torsion response of laminated composite beam was studied in detail. Finite element model was prepared using ANSYS PLANE77 (2D 8-node Thermal Solid) element. PLANE77 element type has one degree of freedom, temperature at every node. The loading condition of the heat transfer problem is specified as heat generation rate equals to twice the angle of twist per unit length. After thermal analysis of the model, temperature at each node was obtained. Torsional rigidity is concluded by summation of temperature at each node. For the composite model, material properties were defined for graphite-polymer and glass-polymer. Finally, the results were compared between the values of present analytic method and ansys.

In genetic algorithm based optimal control of smart composite shell structures under mechanical loading and thermal gradient by Tarapada Roy and Debabrata Chakraborty, they used material properties as shown in the table below.

In the study of a simple spinning laminated composite shaft model by Min-Yung Chang, Jeng-Keag Chen, Chin-Yung Chang [3], a simple spinning composite shaft model was developed. Its material was defined isotropically. The model contains bearing at both ends of the shaft and a rigid disk at middle of the shaft. Using first order shear deformable beam theory, strain energy of the shaft was obtained by considering three dimensional constitutive relation of the material with the use of coordinate transformation. Kinetic energy of the shaft was also obtained. Critical speed for the developed model was compared with the result available in the literature.

In analysis of composite bars in torsion by Filiz ÇIVGIN [4], his objective was to develop a finite element model of a composite bar and analyse for transmission application. The material was defined as E-Glass/ Epoxy composites. The load condition was torque transmission, torsional buckling strength capabilities. The element type was defined for the model was Pipe Elast Straight i.e. Pipe16 with material property for anisotropic material. The bar was constrained at one end i.e. at first node by setting all degree of freedom to zero. At other end torsion was applied as -3e+06. The analysis was static and as result, displacements were noted.

## 2.2 Objective:

In this study, a simply supported shaft is modelled using finite element modelling method. The model is used for static analysis. The shaft is designed for both solid and hollow. One material is defined for the shaft. Stress, strain and deformation were obtained. Secondly, the shaft in rotor-shaft system is considered of composite material and single material and transient analysis is carried out. Bending stress with respect to time and displacement wrt time were calculated. From these results, the most stable system is concluded.

# CHAPTER 3

# MATERIALS AND METHODS

### 3.1 Composite material

The material properties were set to orthotropic medium for modelling of composite rotor shaft system. For simply supported shaft, graphite material was used. Secondly, for rotor shaft system, Glass-Epoxy material was used. The material properties used in the study are shown below.

Table 1. Material properties used in analyses [2,5]

| Material properties | GR/E laminae | Glass/Epoxy | Structural steel |
|---|---|---|---|
| $E_1$ (GPa) | 172.5 | 55.77 | 200 |
| $E_2=E_3$ (GPa) | 6.9 | 17.92 | -- |
| $G_{12}=G_{13}$ (GPa) | 3.45 | 8.96 | -- |
| $G_{23}$ (GPa) | 1.38 | 7.58 | -- |
| $\acute{\upsilon}_{12} = \acute{\upsilon}_{23} = \acute{\upsilon}_{13}$ | 0.25 | 0.25 | 0.30 |
| $\rho$ (Kg/m$^3$) | 1600 | 2550 | 7800 |

3.2 Finite element Modelling

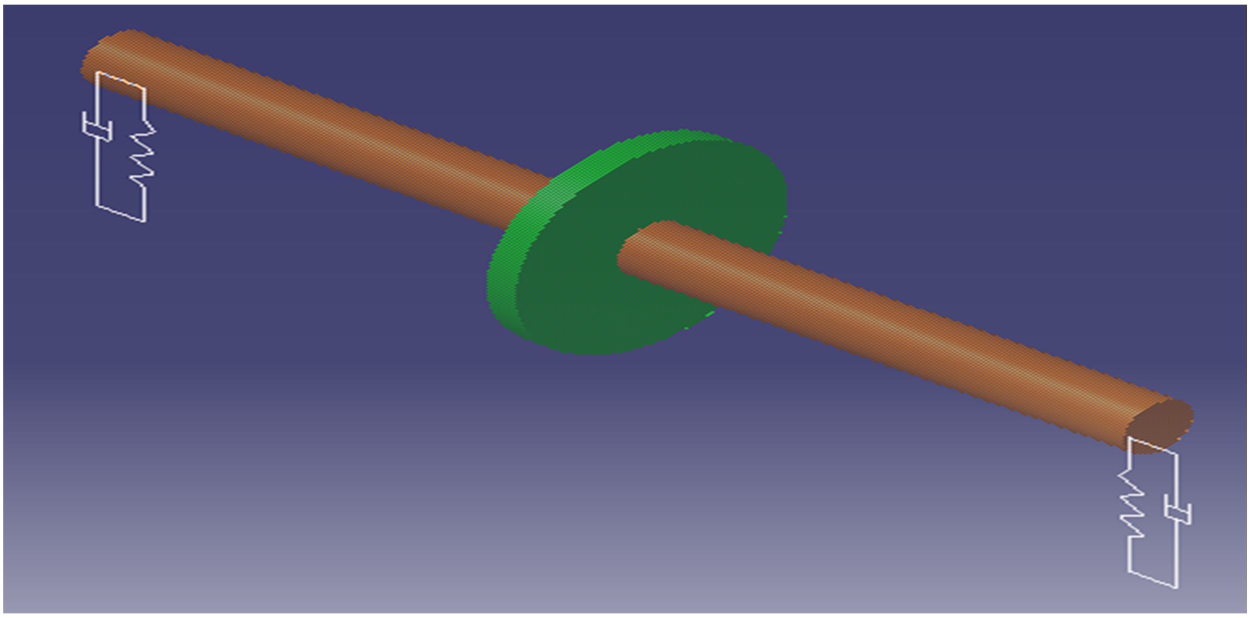

Fig 6. Isometric view of a model of rotor-shaft system with bearings

A rotor shaft system with bearings at both the ends of the shaft view was developed by CATIA V9 is shown above in fig. 6. Mesh view of the system of solid and hollow shaft are shown in the proceeding figure 7 and figure 8 respectively.

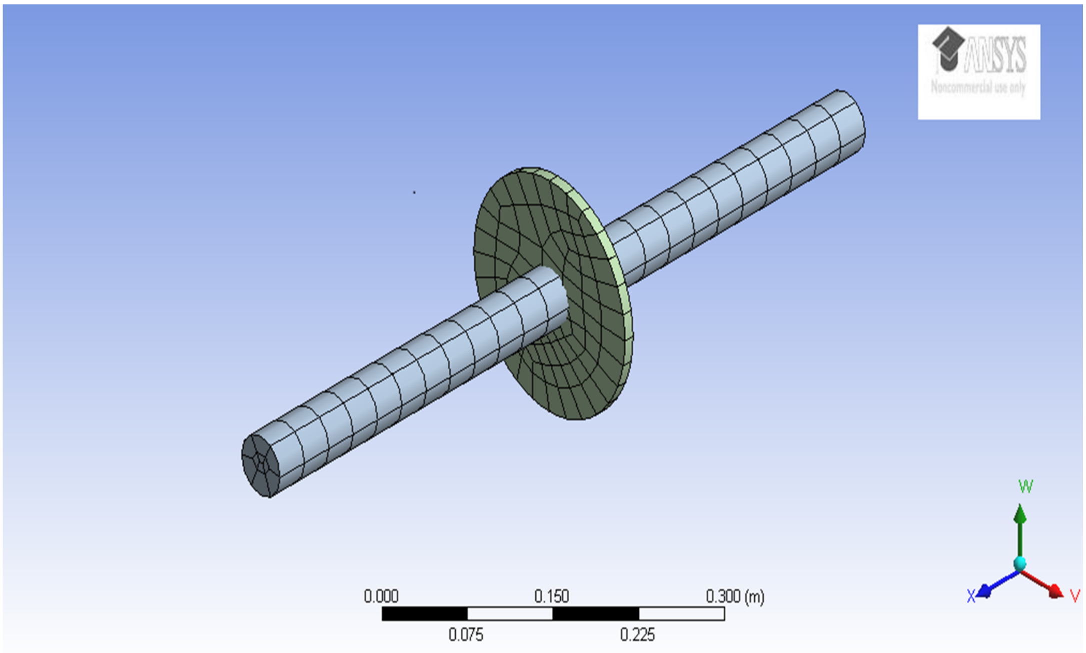


Fig 7. Mesh view of solid rotor-shaft system

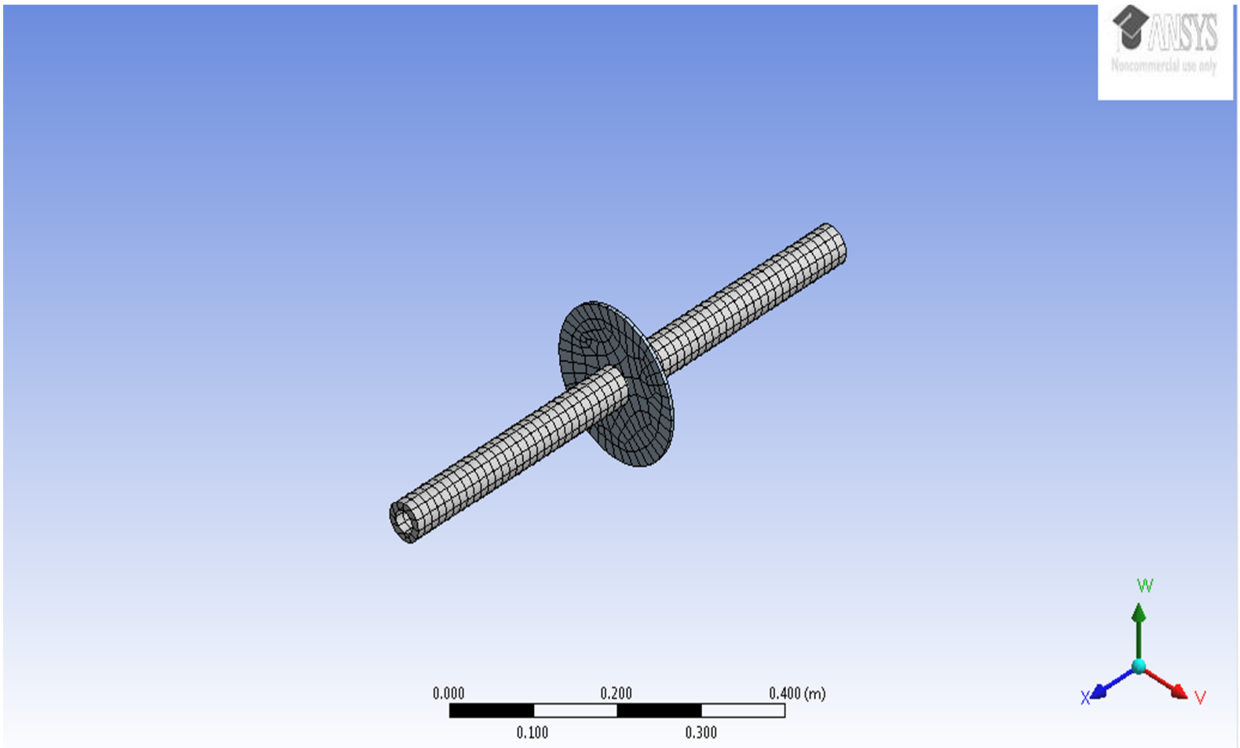


Fig 8. Mesh view of hollow rotor-shaft system

The above finite element models were set to spin at 8000 rpm for 5 seconds. The element type for shaft, disk rotor and bearing were defined as beam188, mass21 and combin14 respectively.

**Beam 188:** It has six or seven degrees of freedom at each node. These include translations in the x, y, and z directions and rotations about the x, y, and z directions. A seventh degree of freedom (warping magnitude) is optional. This element is well-suited for linear, large rotation, and/or large strain nonlinear applications [6].

**Mass 21:** It is a point element having up to six degrees of freedom: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes [6].

**Combin 14:** It has longitudinal or torsional capability in 1-D, 2-D or 3-D applications. The longitudinal spring-damper option is a uniaxial tension-compression element with up to three degrees of freedom at each node: translations in the nodal x, y, and z directions. No bending or torsion is considered. The torsional spring-damper option is a purely rotational element with three degrees of freedom at each node: rotations about the nodal x, y, and z axes. No bending or axial loads are considered [6].

Dimensions of the shaft and disk are mentioned in table 3 as shown below.

Table 2. Dimension of shaft and disk, and properties of bearing [3]

| | Shaft | Disk | Bearing |
|---|---|---|---|
| Length(m) | 0.72 | -- | -- |
| Inner diameter(m) | 0.028 | -- | -- |
| Outer diameter(m) | 0.048 | -- | -- |
| Mass(Kg) | -- | 2.4364 | -- |
| Polar moment of inertia($Kgm^2$) | -- | 0.3778 | -- |
| Diameter moment of inertia($Kgm^2$) | -- | 0.1901 | -- |
| $K_{yy}=K_{zz}(10^7\ Nm^{-1})$ | -- | -- | 1.75 |

Mesh view of simply supported shaft of graphite material is shown below for solid and hollow shaft respectively in figure 9 and figure 10.

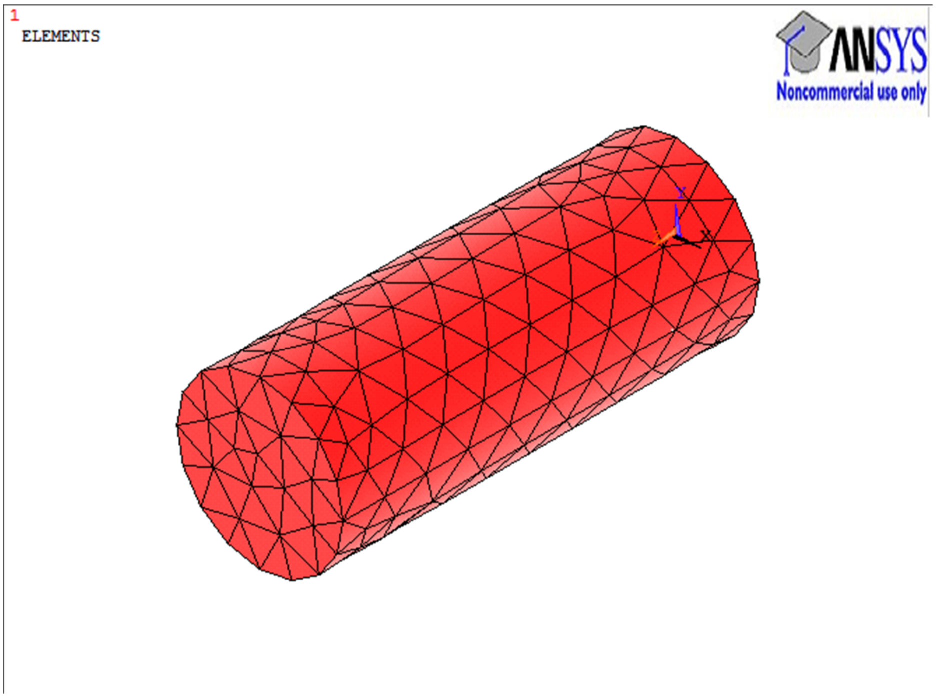


Fig 9. Mesh view of solid shaft

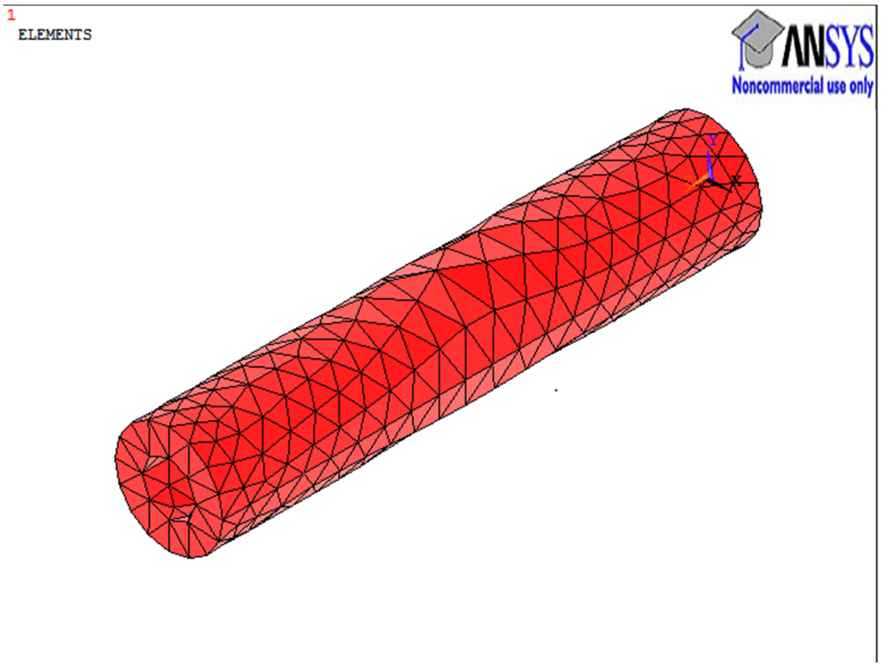


Fig. 10 Mesh view of hollow shaft

The above finite element models element type for shaft was defined as SOLID 272 and SOLID 45 for solid and hollow shaft respectively.

**SOLID 272:** It is used to model axisymmetric solid structures. It is defined by four nodes on the master plane, and nodes created automatically in the circumferential direction based on the four master plane nodes. Each node has three degrees of freedom: translations in the nodal x, y and z directions [6].

**SOLID 45:** It is used for the 3-D modelling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions [6].

# CHAPTER 4

# RESULTS AND DISCUSSIONS

### 4.1 Static analysis of a shaft

A finite element model of simply supported solid and hollow shaft was designed. The material properties were set for GR/E. Static analysis was carried out for bending load and torsion, as loading conditions for each model. Also for the same models, both bending load and torsion were applied together at one end.

#### 4.1.1 Application of torsion on solid and hollow shaft:

1) Boundary conditions for torsion are: UX and UY is free

   UZ = constant

2) Loading conditions for torsion are: Moment (at both ends in opposite direction) = 100Nm

**Results for solid shaft:**

a)

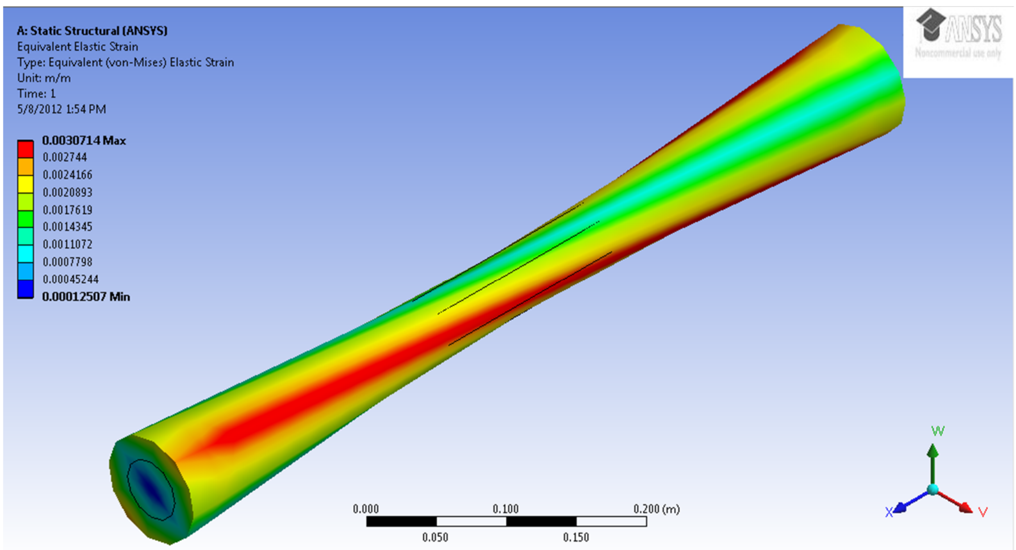


Fig. 11 Smooth contours view for equivalent elastic strain

The maximum limit of equivalent elastic strain is noted as 3.0714e-3 m/m b)

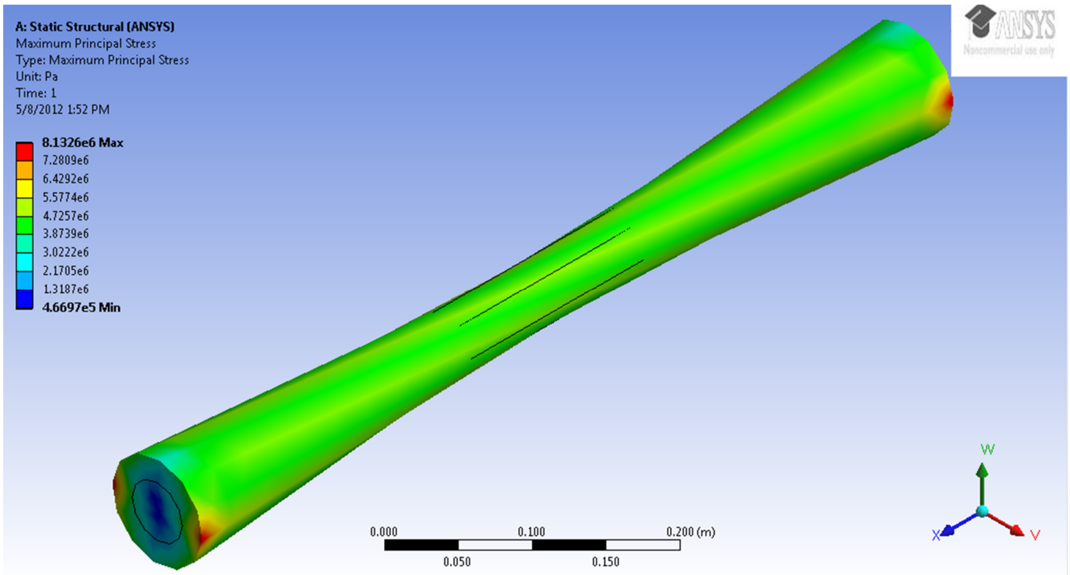


Fig. 12 Smooth contours view for maximum principal stress

Maximum principal stress it is notes as 8.1326e6 Pa

c)

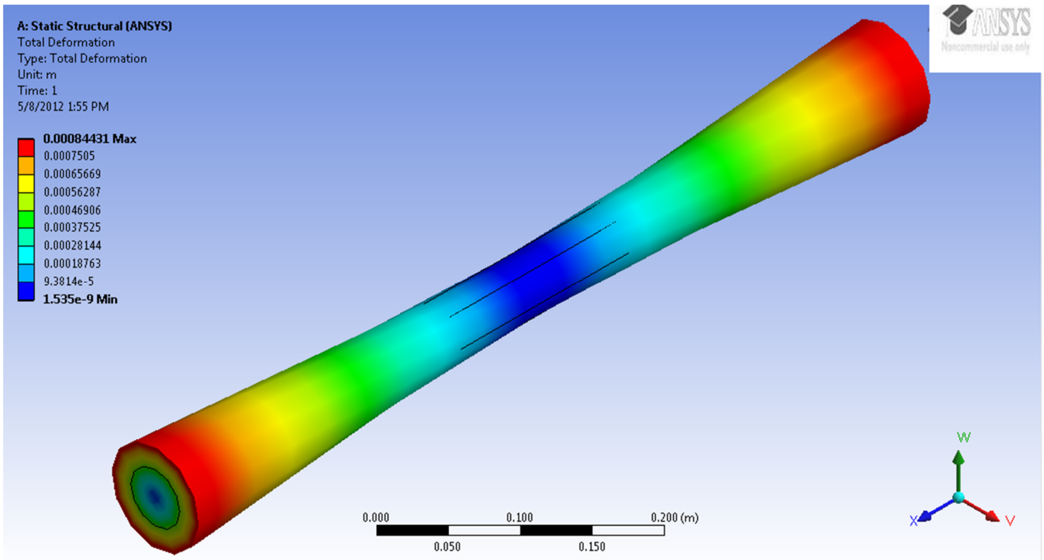


Fig. 13 Smooth contours view for total deformation

Maximum total deformation is 8.4431e-4 m

**Results for hollow shaft:**

a)

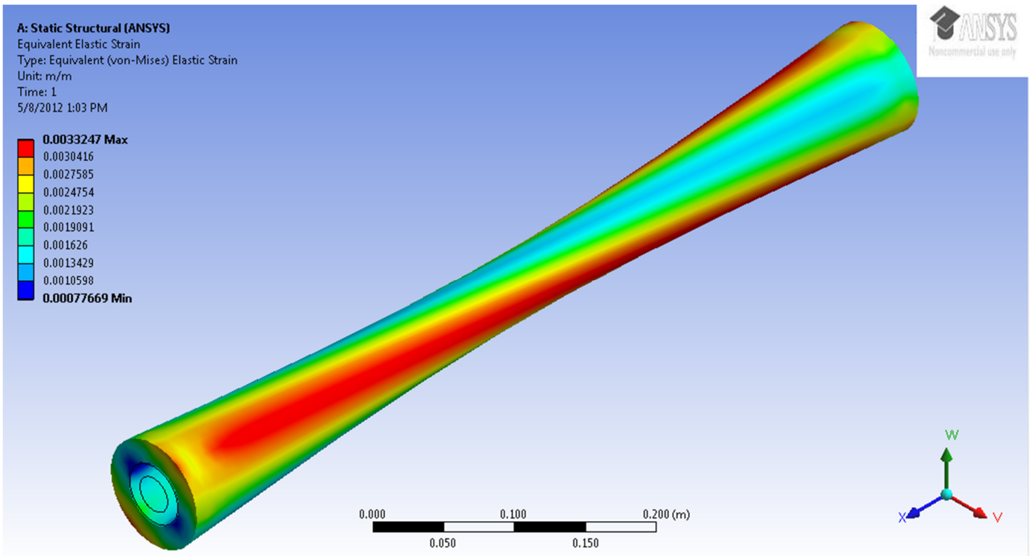


Fig. 14 Smooth contours view for equivalent elastic strain

The maximum limit of equivalent elastic strain is 3.3247e-3 m/m

b)

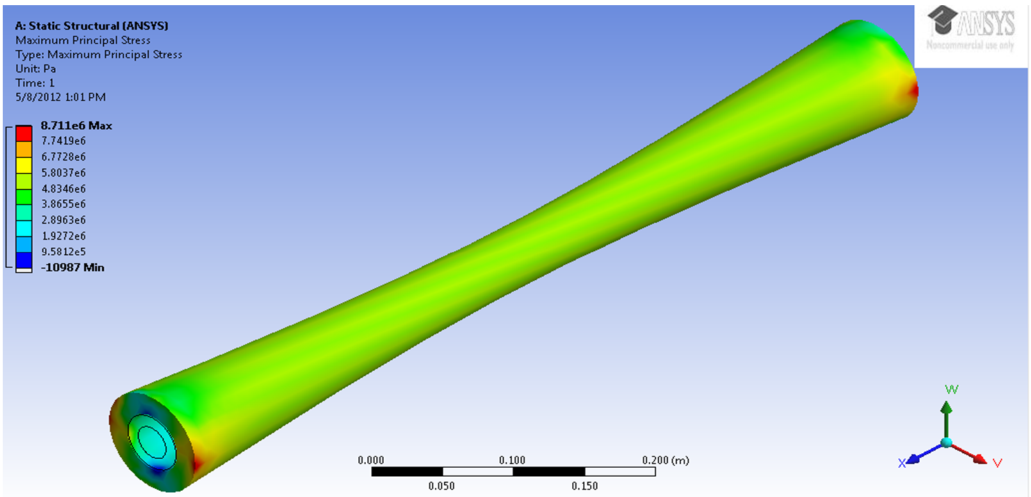


Fig. 15 Smooth contours view for maximum principal stress

The maximum principal stress is 8.711e6 Pa

c)

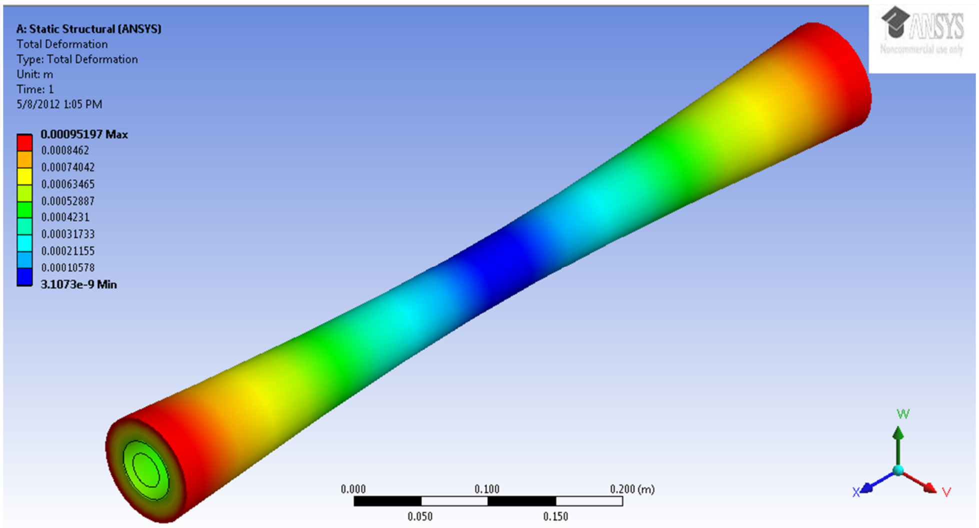


Fig. 16 Smooth contours view for total deformation

The maximum limit of total deformation is 9.5197e-4 m

### 4.1.2 Application of bending load on solid and hollow shaft:

Boundary conditions are: UX =UY =UZ = constant

Loading conditions = 10 N along negative Y axis direction(at mid-span)

**Results for solid shaft:**

a)

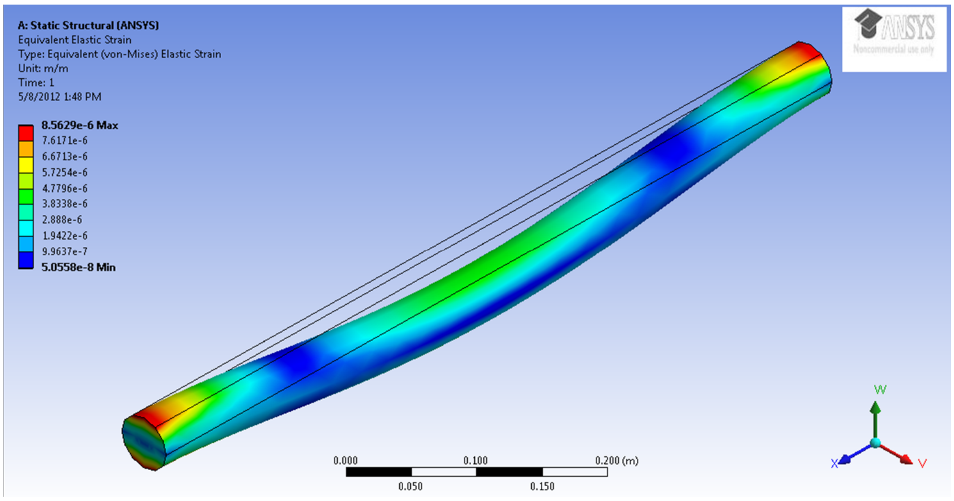

Fig. 17 Smooth contours view for equivalent elastic strain

The maximum limit of equivalent elastic strain is noted as 8.5629e-6 m/m.

b)

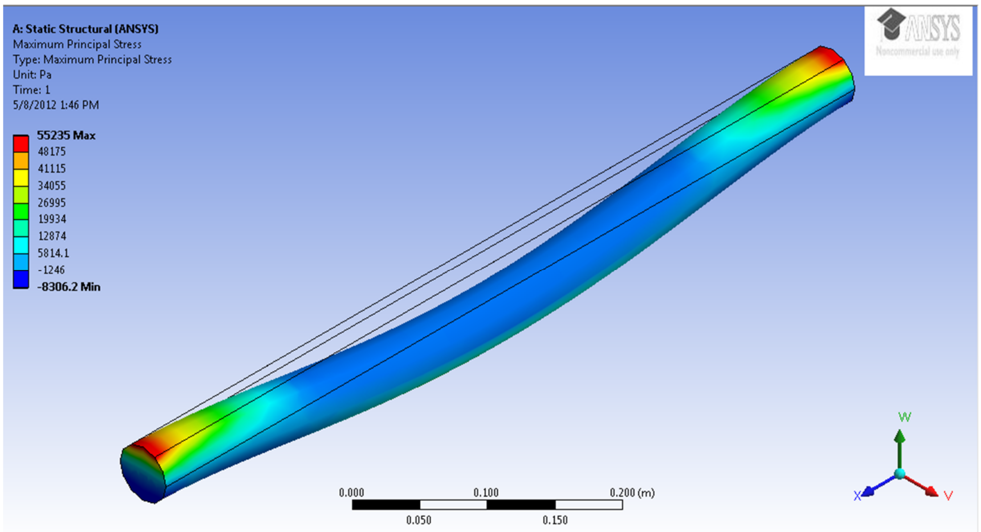


Fig. 18 Smooth contours view for maximum principal stress

The maximum principal stress limit is notes as 55235 Pa.

c)

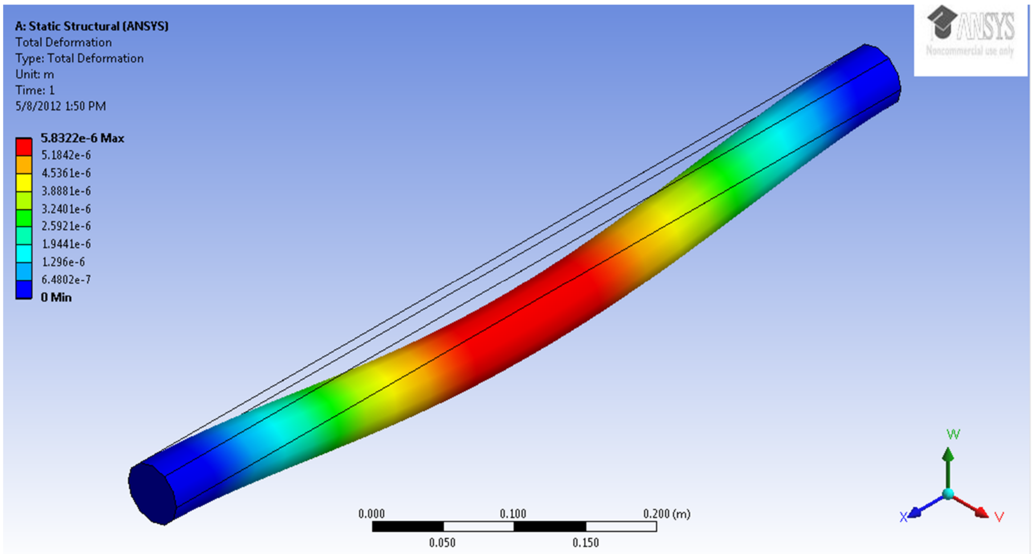


Fig. 19 Smooth contours view for total deformation

The maximum limit for total deformation is noted as 5.8322e-6 m.

**Results for hollow shaft:**

a)

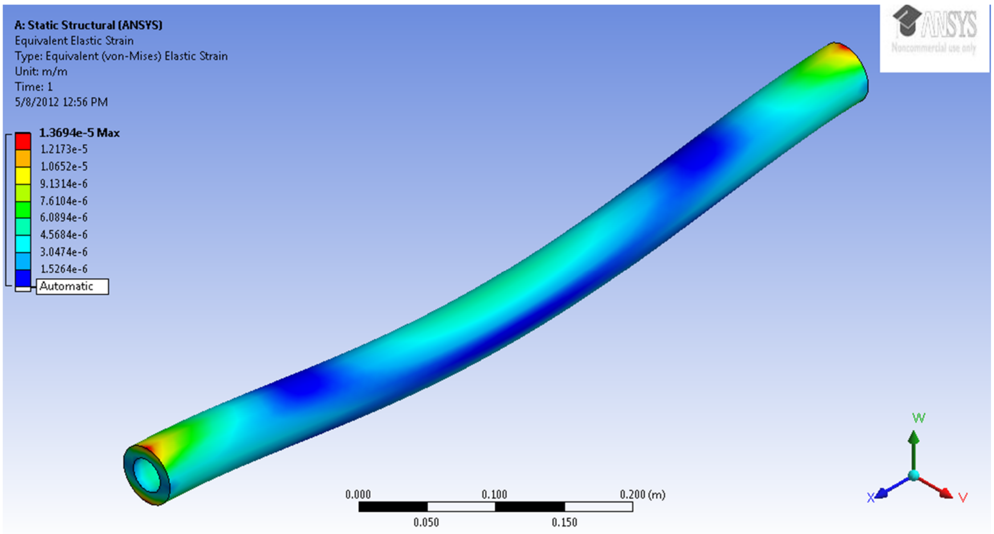


Fig. 20 Smooth contours view for equivalent elastic strain

The maximum limit of equivalent elastic strain is 1.3694e-5 m/m.

b)

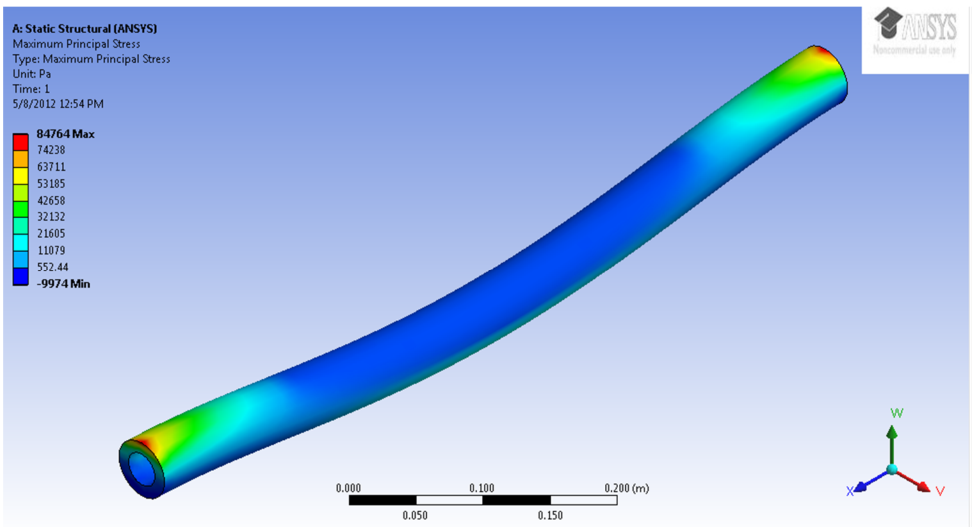

Fig. 21 Smooth contours view for maximum principal stress

The maximum limit of maximum principal stress is 84764 Pa

c)

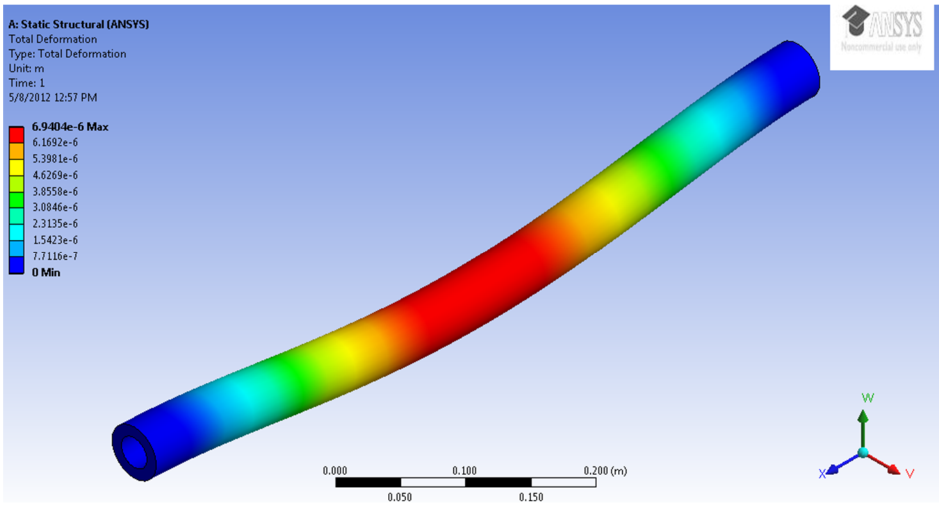


Fig. 22 Smooth contours view for total deformation

The maximum limit of total deformation is 6.9404e-6 m

**4.1.3 Application of combination of torsion and bending load on solid and hollow shaft:**

1) At one end boundary conditions are: UX =UY =UZ = constant

2) At other end loading conditions = 10N along -ve Y axis direction and moment = 100Nm

**Results for solid shaft:**

a)

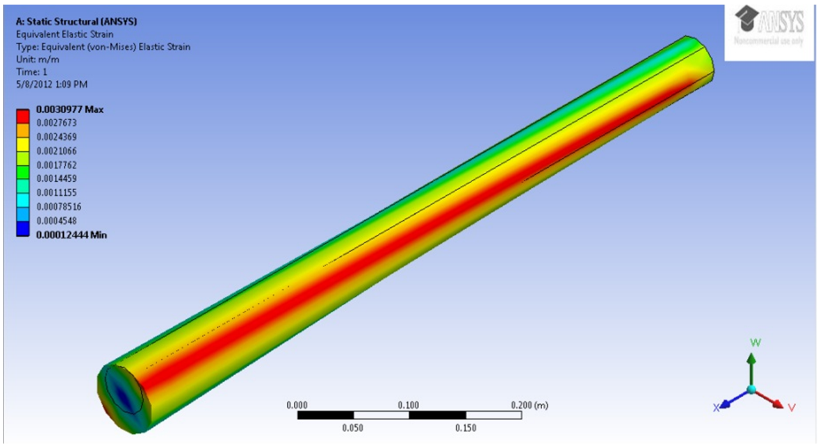


Fig. 23 Smooth contours view for equivalent elastic strain

The maximum limit of equivalent elastic strain is noted as 3.0977e-3 m/m

b)

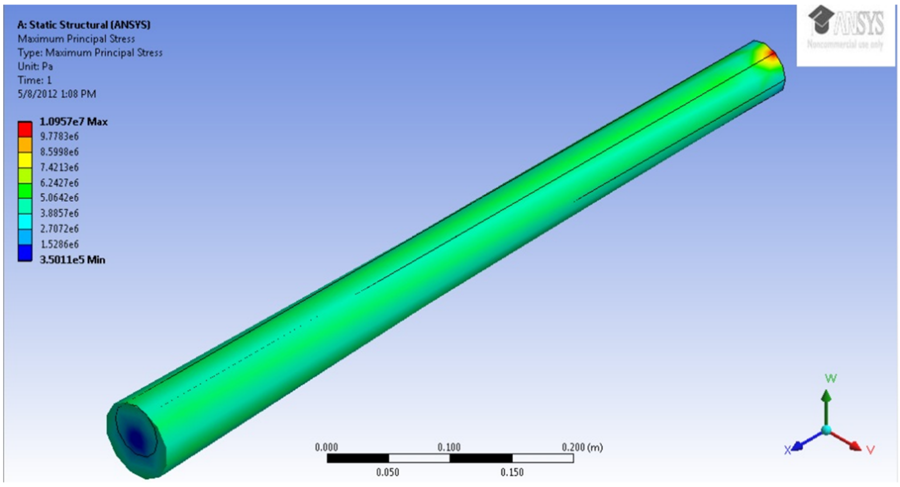


Fig. 24 Smooth contours view for maximum principal stress

The maximum limit of maximum principal stress is notes as 1.0957e7 Pa.

c)

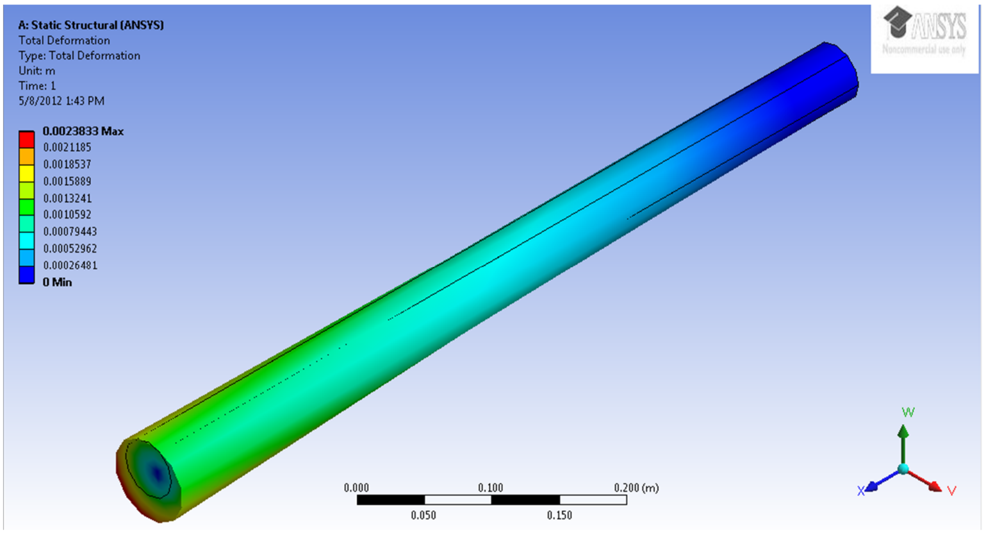


Fig. 25 Smooth contours view for total deformation

The maximum limit of total deformation is 2.3833e-3 m

**Results for hollow shaft:**

a)

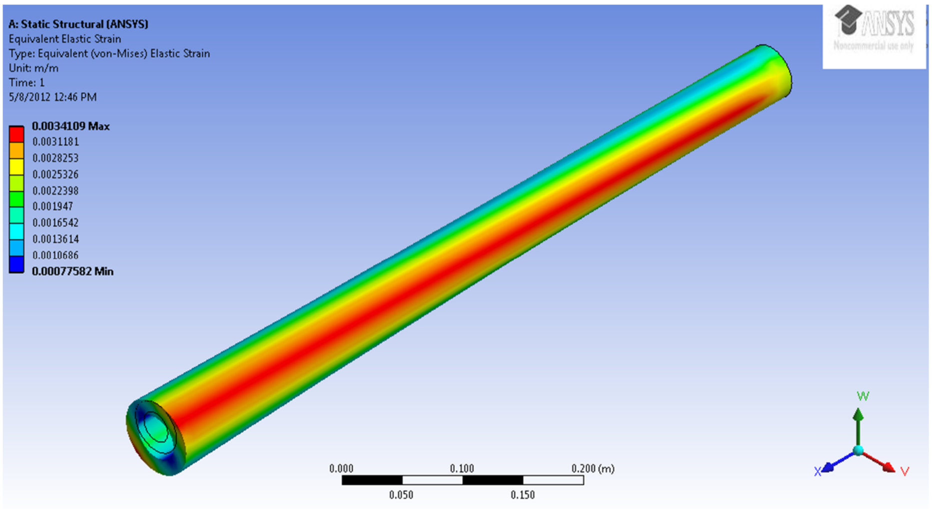


Fig. 26 Smooth contours view for total deformation

The maximum limit of equivalent elastic strain is 3.4109e-3 m/m.

b)

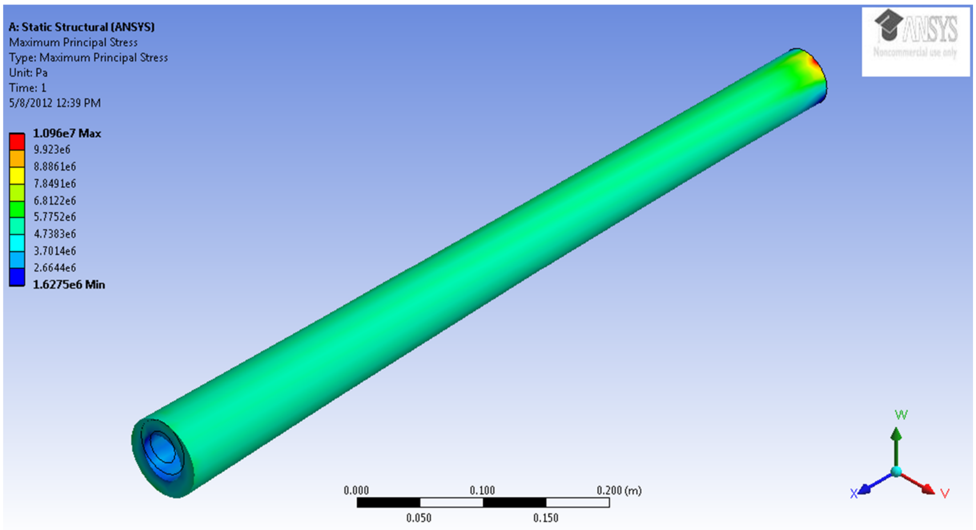


Fig. 27 Smooth contours view for total deformation

The maximum limit of maximum principal stress is 1.096e7 Pa.

c)

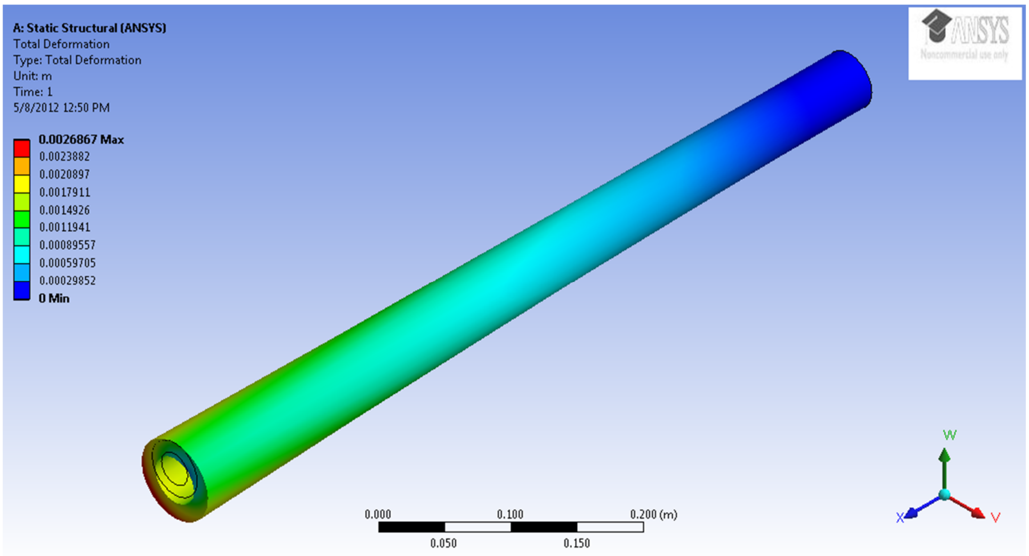


Fig. 28 Smooth contours view for total deformation

The maximum limit of total deformation is 2.6867e-3 m.

## 4.2 Transient analysis of rotor-shaft system

Transient analysis of a rotor-shaft system with bearing was studied. ANSYS 13.0 (Mechanical APDL) platform was used for the above analysis. The analysis was performed on both composite and single material system of solid and hollow shaft. For composite system, material properties of Glass/Epoxy material were used. Secondly, for single material system, material properties of steel were used. The material properties of Glass/Epoxy and steel are defined in table 2. Dimensions of shaft and disk, and properties of bearing are defined in table 3.

**Results for Epoxy/Glass composite:**

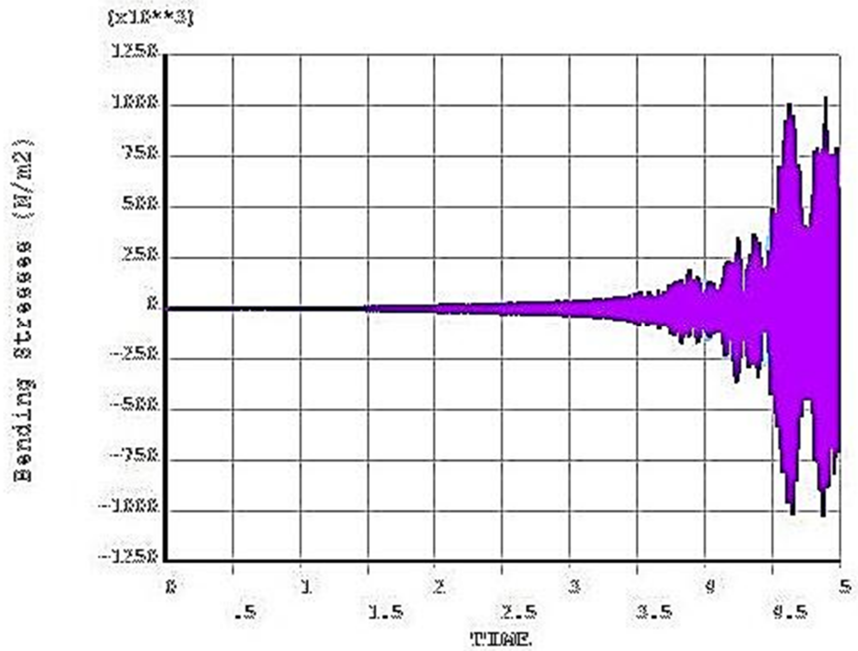


Fig. 29 Bending stress vs time diagram for solid rotor-shaft system

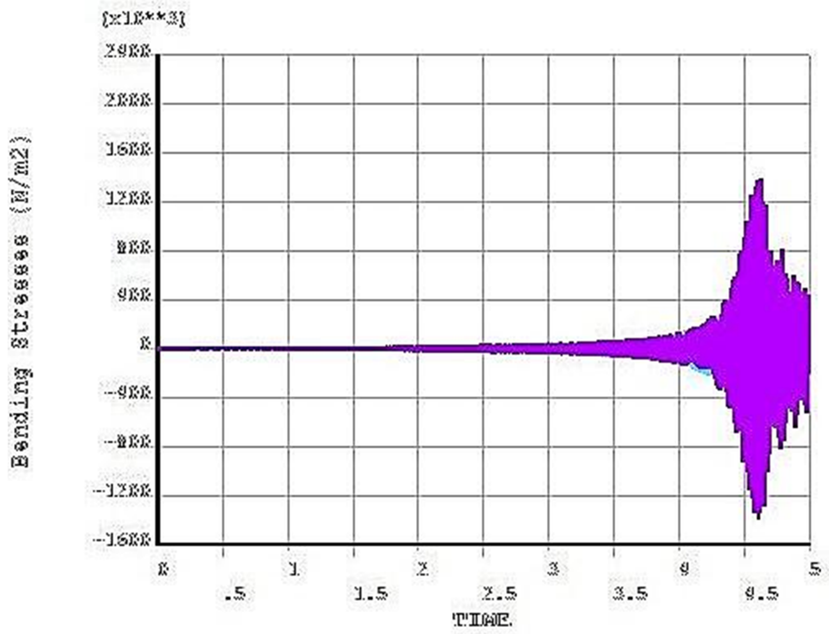


Fig. 30 Bending stress vs time diagram for hollow rotor-shaft system

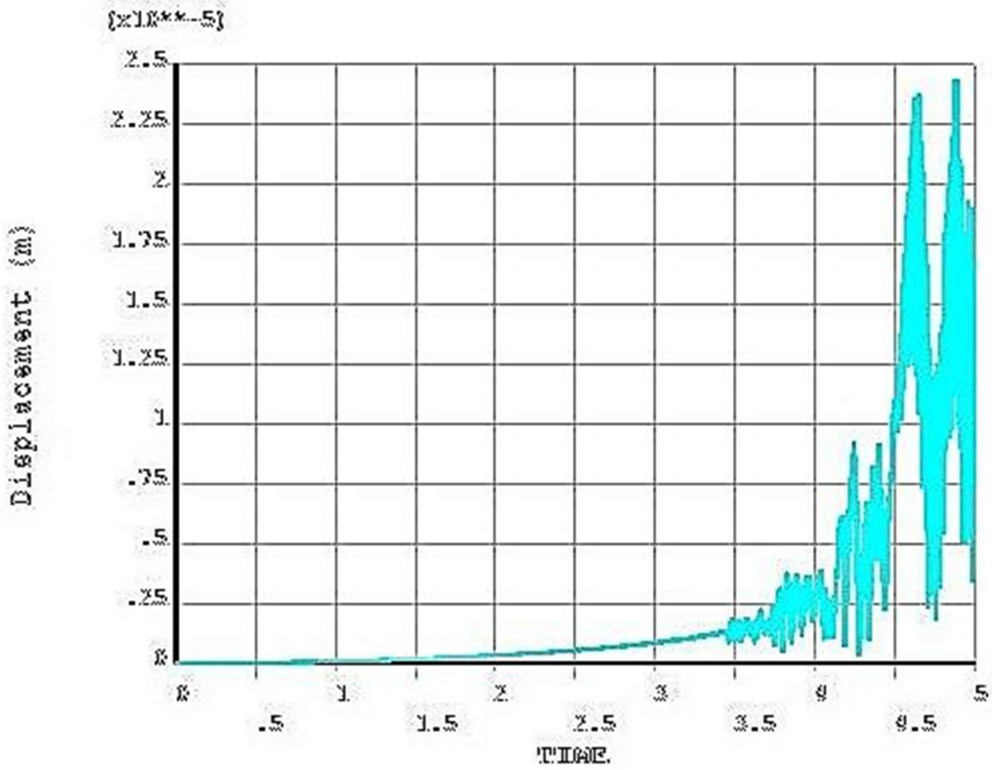


Fig. 31 Displacement vs time diagram for solid rotor-shaft system

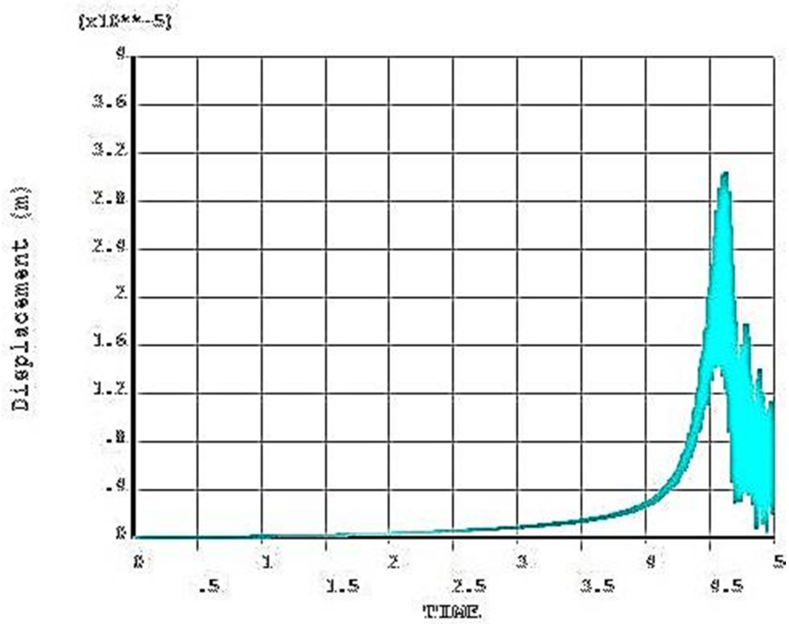


Fig. 32 Displacement vs time diagram for hollow rotor-shaft system

**Results for steel material:**

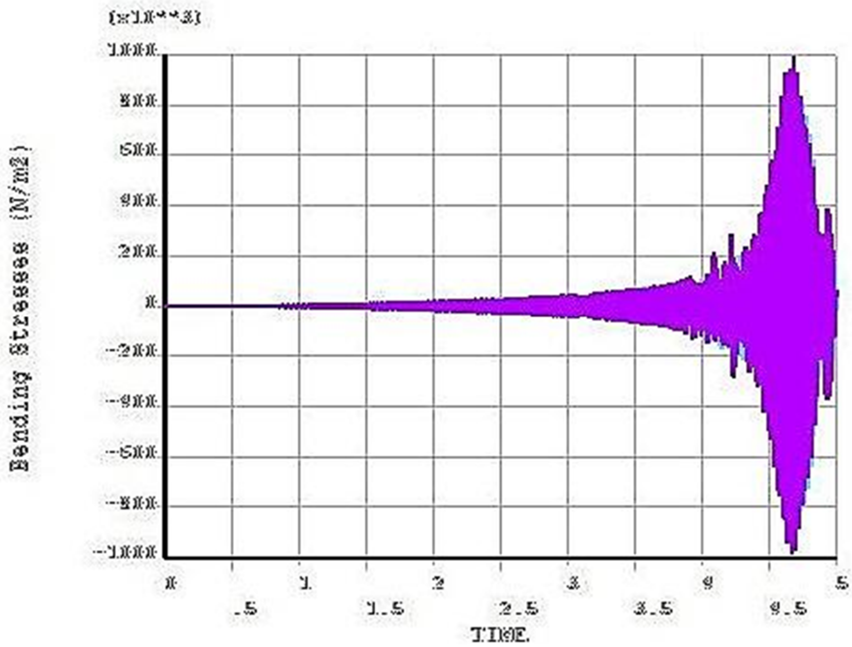


Fig. 33 Bending stress vs time diagram for solid rotor-shaft system

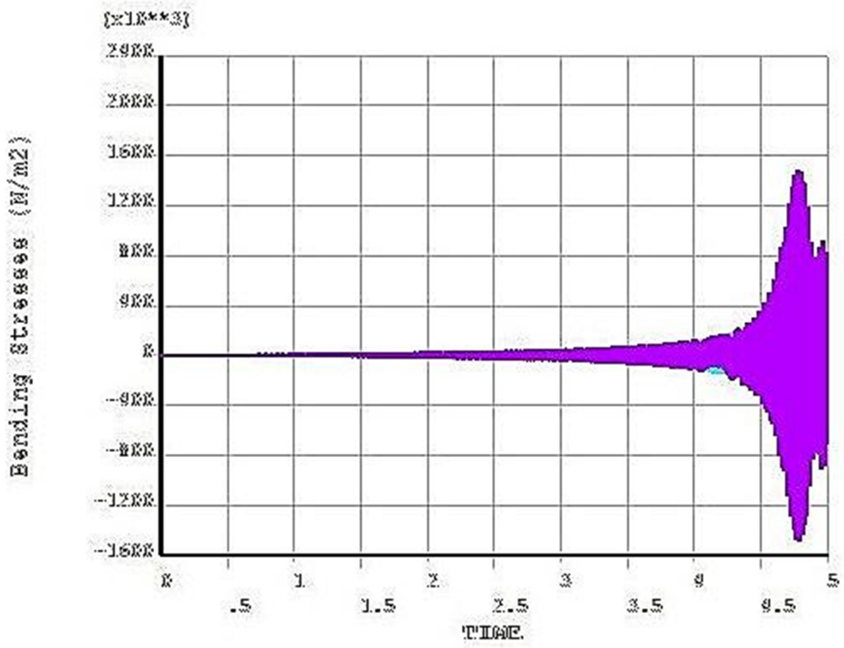


Fig. 34 Bending stress vs time diagram for hollow rotor-shaft system

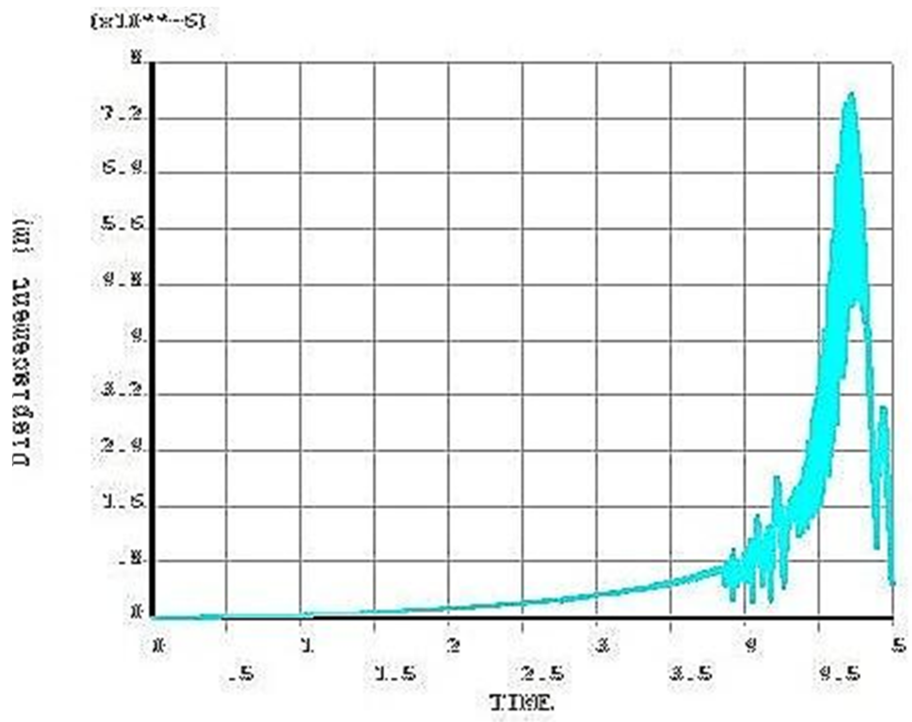


Fig. 35 Displacement vs time diagram for solid rotor-shaft system

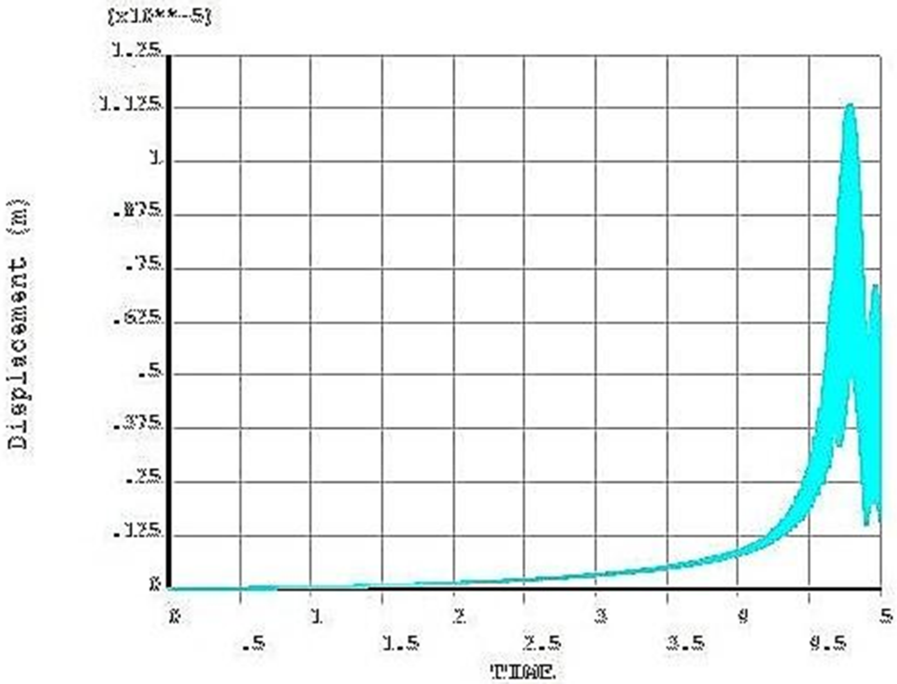


Fig. 34 Displacement vs time diagram for hollow rotor-shaft system

# CHAPTER 5

# CONCLUSIONS
# &
# SCOPE OF FUTURE WORK

## 5.1 Conclusion

### 5.1.1 Based on the static analysis

i) For the application of torsion on solid shaft, the maximum limit of equivalent elastic strain, maximum principal stress and total deformation are less as compared to the maximum limit of equivalent elastic strain, maximum principal stress and total deformation of hollow shaft respectively.

ii) For the application of bending load on solid shaft, the maximum limit of equivalent elastic strain, maximum principal stress and total deformation are less as compared to the maximum limit of equivalent elastic strain, maximum principal stress and total deformation of hollow shaft respectively.

iii) For the application of both torsion and bending load at a time on solid shaft, the maximum limit of equivalent elastic strain, maximum principal stress and total deformation are less as compared to the maximum limit of equivalent elastic strain, maximum principal stress and total deformation of hollow shaft respectively.

iv) From above readings, it shows that for an applied torsion, bending load or both, hollow shaft is more susceptible than solid shaft. Solid shaft has a more stiffness and brittleness as compared to hollow shaft.

### 5.1.2 Based on transient analysis

The Glass/Epoxy material system is having more strength and light weight as compared to steel material system. Due to unbalance in rotor, the vibration in hollow rotor-shaft of Glass/Epoxy material is low as compared to solid Glass/Epoxy rotor-shaft system. In other words, hollow rotor-shaft system of Glass/Epoxy material is the most stable system.

## 5.2 Scope of future work

1. Fatigue life could be determined for the above rotor-shaft systems of each component.

2. Better performance could be optimized through using different types of bearings having good stiffness coefficient and damping coefficient.

3. The study could be performed on various composite materials available of better strength, cheaper and less weight as compared to Glass/Epoxy composite material.

4. Various analyses could be carried out to obtain more results and study various effects on the rotor-shaft system. For an example, harmonic analysis could be performed to study about critical speeds of the rotor-shaft system under various operating conditions.

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