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ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

Weight Optimization of Front Coil Spring Suspension Using Composite Material for Bajaj by FEM

A Thesis Submitted to the Graduate School of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Masters of Science in

Mechanical Engineering (Mechanical Design)

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This is to certify that the thesis prepared by MedhanyeBerhane, entitled: Weight Optimization of FrontCoil Spring Suspension Using Composite Material for Bajaj by FEM, do here by declare this thesis is my original work and that it has not been submitted in full for a degree in any university/institution, which compiles with the regulations of the university and meets the accepted standards with respect to originality and quality.

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ABSTRACT

The main objective of this research is to minimize the weight of the helical coil spring of Bajaj without reducing the strain energy and keeping good the stiffness of the spring. This is done by comparing the existing conventional steel spring with composite materials. Two composite materials (Carbon/Epoxy and Carbon/Carbon Nanotube/Epoxy) are selected by their advanced mechanical, and physical properties. Properties of each composite components are taken from previously experimental and analytical done literature reviews. Using rule of mixtures and Halpin-Tsai equations for unidirectional ply, mechanical properties of both composite are determined. From literature reviews composite mixture has good properties for 60% of fiber. So the volume fraction of carbon fiber for Carbon/Epoxy is 60%, and for the hybrid composite Carbon/CNT/Epoxy the volume fraction is 1% Carbon Nanotube fiber is added, 59% carbon fiber and the remaining 40% is Matrix (Epoxy Risen). Three dimensional helical coil spring is modeled using CATIA V5R19 and analyzed using ANSYS Workbench17.2.to compare the parameters (Shear stress, Fatigue life, Strain Energy and Deformation) of existing steel spring with Carbon/Epoxy and Carbon/ Carbon Nanotube /Epoxy composites. As a result for the same dimension of coil spring, the weight of Carbon/ Carbon Nanotube /Epoxy, Carbon/Epoxy coil spring is 81% and 80.5% lighter than steel coil spring. But the deflection of both composite coil springs is increased, so to increase the deflection of composite coil spring the dimension of the coil spring is modified. For the modified coil spring, Shear stress is reduced, Strain energy is still better than the steel one. And the result shows Carbon/Carbon Nanotube/Epoxy composite better satisfies the objective of the research than the steel and Carbon/Epoxy composite. Therefore, Carbon/ Carbon Nanotube /Epoxy composite is selected as coil spring material.

***Keywords**: Coil spring, Carbon Nanotube, Carbon/CNT/Epoxy, Carbon/Epoxy, deformation, ANSYS*

LIST OF ABBREVIATIONS

CATIA	*Computer Aided Three dimension Interactive Application.*
ANSYS	*Analysis system*
CAE	*Computer Aided Engineering*
CAD	*Computer Aided Design*
FDE	*Fatigue Data Editing*
FEA	*Finite Element Analysis*
FEM	*Finite Element Method*
CNT	*Carbon Nanotube*
TWV	*Three Wheeled Vehicle*
3D	*Three Dimension*
FWT	*Filament Winding Technique*
GFRP	*Glass Fiber Reinforced polymer*
FRP	*Fiber Reinforced polymer*
SMA	*Shape Memory Alloy*
CFRP	*Carbon Fiber Reinforced polymer*
SP ST GRD II	*Special Steel Grade II*
SWCNT	*Single Wall Carbon Nanotube*
MWCNTS	*Multi Wall Carbon Nanotube*
DWNT	*Double Wall Carbon Nanotube*
CVD	*Chemical Vapor Deposition*
CCVD	*Catalytic Chemical Vapor Deposition*
PE	*Plasma Enhanced*

MPECVD	*Microwave Plasma Enhanced Chemical Vapor Deposition*
RF-CVD	*Radiofrequency Chemical Vapor Deposition*
HFCVD	*Hot-Filament Chemical Vapor Deposition*
MMCs	*Metal Matrix Composites*
ROM	*Rule of Mixture*
fc	*Carbon fiber*
fCNT	*Carbon Nanotube fiber*
Gpa	*Giga Pascal*
MPa	*Mega Pascal*
HROM	*Hybrid Rule of Mixture*
RE	*Rear Engine*
LF	*Free Length*
P	*Properties*
p	*pitch*
f	*fiber*
m	*matrix*
c	*composite*
Ls	*Solid Length*
IGES	*Initial Graphics Exchange Specification*
CMCs	*Ceramic Matrix Composites*
PMCs	*Polymer Matrix Composites*

NOMENCLATURE

D	*Mean coil diameter*
d	*Wire diameter*
N	*Active number of turns*
p	*Pitch of the coil*
C	*spring index*
w	*Weight of spring*
τ	*Shear stress*
τ_{max}	*Maximum Shear stress*
K_w	*Wahl's factor*
δ	*Deflection*
G_m	*Shear modulus of matrix*
K	*Spring rate/ spring stiffness*
F	*Load*
U	*Strain energy*
σ	*Normal stress*
ρ	*Density*
E	*Young's modulus*
W_f	*Weight fraction of the fiber*
W_m	*Weight fraction of the matrix*
w_c	*Weight fraction of the composite*
V_f	*Volume fraction of the fiber*
V_m	*Volume fraction of the matrix*

V_c	*Volume fraction of the composite*
ρ_c	*Density of composite*
ρ_f	*Density of fiber*
ρ_m	*Density of matrix*
P_f	*Property of fiber*
P_m	*Property of matrix*
P_c	*Property of composite*
ε_f	*Fiber strain*
ε_m	*Matrix strain*
ε_c	*Composite strain*
σ_f	*Fiber normal stress*
σ_m	*Matrix normal stress*
σ_c	*Composite normal stress*
E_f	*Fiber Young's modulus*
E_m	*Matrix Young's modulus*
E_c	*Composite Young's modulus*
A_f	*Cross section area of fiber*
A_m	*Cross section area of matrix.*
A_c	*Cross section area of composite*
E_1	*Longitudinal Young's Modulus of composite material*
E_2	*Transvers Young's Modulus of composite material*
G_{12}	*In plane shear stress*
ν_{12}	*Major Poisson's ration*

ξ	*Curve fitting parameter*
σt_l	*Tensile strength of a single ply in longitudinal direction*
σt_f	*Tensile strength of fiber*
σt_m	*Tensile strength of matrix*
σc_l	*Compressive strength of a single ply in longitudinal direction*
σc_f	*Compressive strength of fiber*
σc_m	*Compressive strength of matrix*
V_{fC}	*Volume fraction of carbon fiber*
V_{fCNT}	*Volume fraction of Carbon nanotube (CNT) fiber*
E_{fC}	*Young's Modulus of carbon fiber*
E_{fCNT}	*Young's Modulus of Carbon nanotube (CNT) fiber*
σl_{ut}	*Longitudinal ultimate strength of composite*
σt_{fc}	*Tensile strength of carbon fiber*
σt_{fCNT}	*Tensile strength of Carbon nanotube (CNT)fiber*
σc_{fc}	*Compressive strength of carbon fiber*
σc_{fCNT}	*Compressive strength of Carbon nanotube (CNT)fiber*
ν_{fc}	*Carbon fiber poison's ratio*
ν_{fCNT}	*Carbon nanotube fiber poison's ratio*

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CHAPTER ONE

1. INTRODUCTION

1.1. Background

The name Bajaj is originated in India and appeared in Ethiopia a years ago. The name Bajaj is derived from the brand that produces them. They made their first appearance in Dire Dawa. Now a day, Bajajs are expanding their outreach across all the major cities, towns and even in the rural parts of Ethiopia. Although they are not common visible in the inner city area of Addis Ababa, these small three wheeled vehicles have become regular transportation system in most towns across the country. Despite Bajaj's are most transportation system in our country, due to the topographic environment their life time is less compared to other countries. Irregularity of road in our country causes heavy vibration and uncomfortable ride and this can reduce the life time and performance of the Bajaj's parts.

The suspension system is used to observe the vibrations from shock loads due to irregularities of the road surface. [1] The vehicles must have a good suspension system that can deliver a good ride and good human comfort. Suspension system separate the axle from the vehicle chassis, so that any road irregularities are not transmitted directly to the driver and the load on the vehicle. [2] Therefore, the suspension system performance of the vehicles should be maximized to reduce the damage and vibration. The main functions of suspension systems in vehicles are to isolate the structure and the occupants from shocks and vibrations generated by the road surface. The suspension system requires elastic resistance to absorb the road shocks and this job is fulfilled by the suspension coil springs.

The primary functions for suspension systems are; [3]

- Provide vertical compliance so the wheels can follow the uneven road, isolating the chassis from roughness in the road.
- Maintain the wheels in the proper steer and camber attitudes to the road surface.
- React to the control forces produced by the tires longitudinal (acceleration and braking) forces.

Helical coil spring

It is made up of the wire coil in the form of spring. A helical spring is a spiral wound wire with a constant coil diameter and uniform pitch. The most common form of helical spring is the compression spring but tension springs are also widely used. Helical springs are generally made from round wire. It is comparatively rare for springs to be made from square or rectangular sections. The strength of the steel used is one of the most important criteria to consider in designing spring. The two most basic requirements of a coil spring design are an acceptable stress level and the desired spring rate. To minimize weight, size, and cost, we usually design springs to the highest stress level that will not result in significant long term "set." Stress is usually considered before spring rate, in designing a spring, because stress involves mean diameter (D) and wire diameter (d), but not number of coils (N). [4]

Types of helical springs

Open coiled springs: It is also known as compression spring. In helical springs the gaps between the successive coils is larger. It is made of round wire and wrapped in cylindrical shape with constant pitch between the coils. By applying the load the spring contracts in action. They are designed to resist being compressed. A typical use for compression coil springs is in vehicles suspension.

Closed coiled springs: It is known as tension or extension. It has some means of transferring the load from the support to the body by means of some arrangement. It stretches apart to create load. The gap between the successive coils is small. The wire is coiled in a sequence that the turn is at right angle to the axis of the spring. The spring is loaded along the axis. [5]

Helical coil springs are simple forms of springs, commonly used for the suspension system in vehicles. [6] They are generally used in automobile suspension system and industrial applications. Springs are crucial suspension elements and these are necessary to minimize the vertical vibrations, impacts and bumps due to road irregularities and create a comfortable ride. [7] Metal coils springs can be replaced by composite springs because of weight reduction and corrosion resistance. Composite coil springs can be manufactured using carbon/graphite/glass fibers and resin impregnation. These composite coil springs, compared to standard metal coil springs reduces weight. [8]

It is well known that, the spring of the suspension system plays an important role for a smooth and jerk free ride. So it required to design the springs very precisely. The use of conventional steel as spring increases the weight and with the current scenario the automobile manufacturers are interested in replacing steel springs with light weight composite materials.

Spring rate

The spring rate (or suspension rate) is a component in setting the vehicle's ride height or its location in the suspension stroke. When a spring is compressed or stretched, the force it exerts is proportional to its change in length. The spring rate or spring constant of a spring is the change in the force it exerts, divided by the change in deflection of the spring. Vehicles which carry heavy loads will often have heavier springs to compensate for the additional weight that would otherwise collapse a vehicle to the bottom of its travel (stroke). [9]

$$Mathematically \quad k = -\frac{F}{x} \qquad (1)$$

Negative sign indicates direction of applied force and forces exerted by spring are opposite. Spring rate is confined to a narrow interval by the weight of the vehicle, load the vehicle will carry, and to a lesser extent by suspension geometry and performance desires.

Specific strain energy

The main factor to be considered in the design of spring is the strain energy of a material used. Specific strain energy in the material can generally be expressed as

$$U = \frac{\sigma^2}{\rho E} \qquad (2)$$

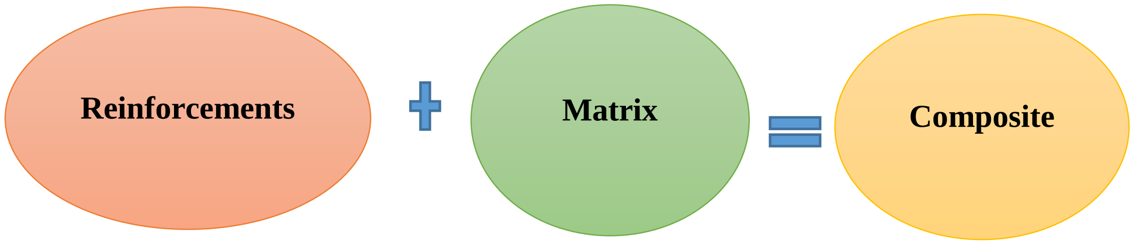
This indicates that a material with lower young's modulus or density will have higher specific strain energy under the same stress condition. Thus a materials with smaller density and less young's modulus which offer high strength and light weight is needed. [10], [11]

Composite materials

Composite materials are combination of materials that consist of a discreet constituent (the reinforcement) distributed in a continuous phase (the matrix) and that derive their distinguishing characteristics from the properties and behavior, geometry and arrangements of constituents and from the properties of the boundaries between the constituents. [12]

Man-made composites have existed for a long time. The first evidences of a manmade composite is appeared in the Egyptian era, where straw and mud were mixed and burnt together by Israelites in order to obtain tougher bricks for construction. Another example of composite materials from the Egyptian era is papyrus, where layers of stems of the papyrus plant were stacked in perpendicular directions in order to manufacture paper with enough resistance to be written on and handled without falling apart, thus creating the first man-made laminate. [13]

Composite materials have two components: the reinforcement and the matrix. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. The matrix material surrounds and supports the reinforcement materials and maintains their relative positions. A combination of the two produces material properties unavailable from the individual constituent materials, while the wide variety of available matrix and strengthening materials allows the designer of the product or structure to choose an optimum combination. Both the constituents are arranged intimately such that one or more discontinuous phases are embedded in the continuous phase.



✓ High strength ✓ High stiffness ✓ Low density	✓ Good shear properties ✓ Low density	✓ High strength ✓ High stiffness ✓ Good shear properties ✓ Low density

Figure 1-1: Composite components [14]

Classification of the composite materials

Composites can be classified based on its reinforcement and its matrix. According to [15] generally composite materials based on the reinforcement they classified as shown in figure below.

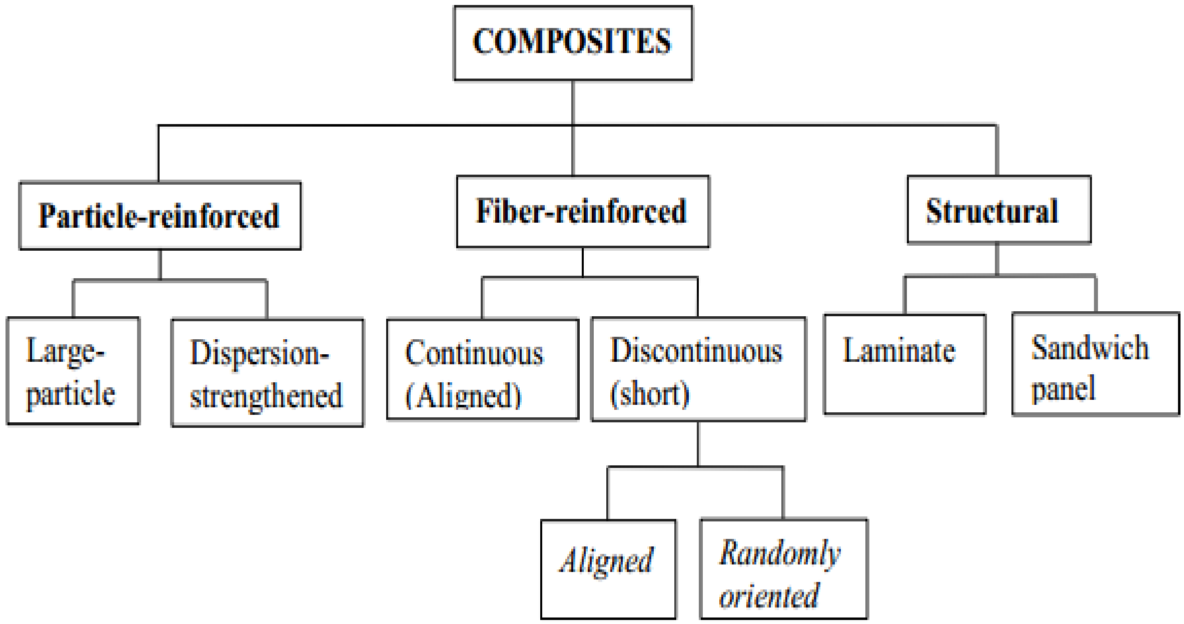


Figure 1-2: composite classification based on reinforcement [15], [16]

Based on matrix composites are classified as:

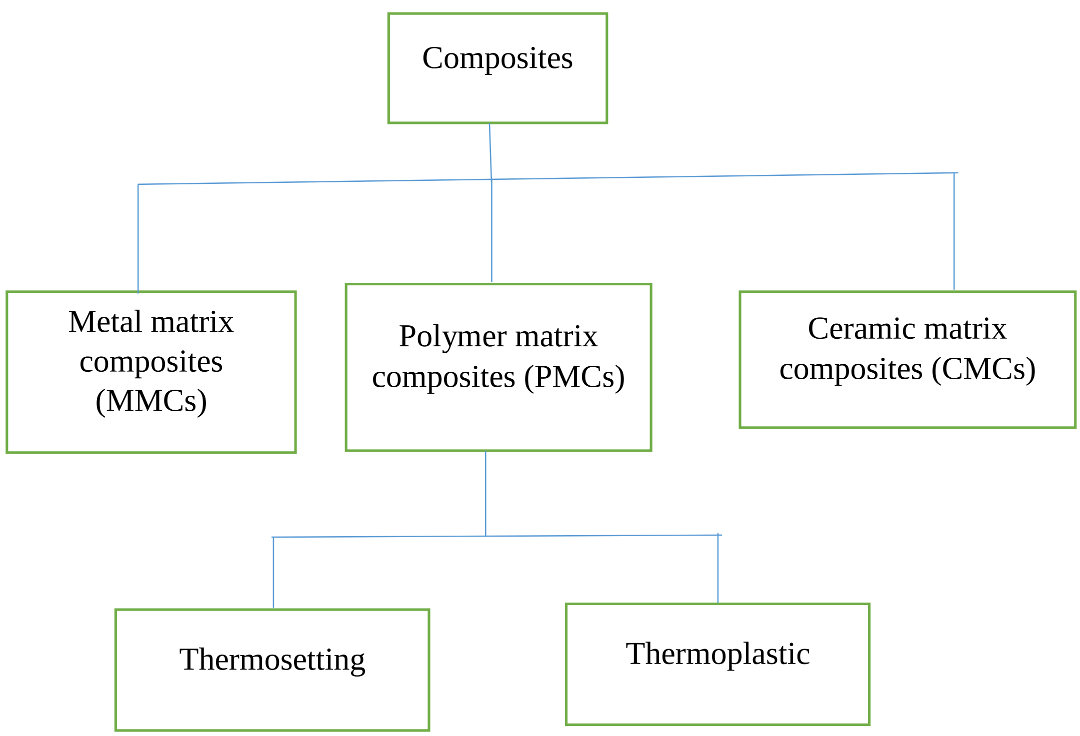


Figure 1-3: Classification of composites based on matrixes [48], [15]

Metal Matrix Composites: Metal matrices are generally used up to 1000^{0}C They have improved thermal resistance as compared to pure metals and alloys. They also have high ductility, strength and fracture toughness. They have superior electrical, thermal conductivity and magnetic properties. Due to a low thermal expansion coefficient, they also possess a high dimensional stability. High density, complicated fabrication processes and high cost of production are the disadvantages of Metal matrices.

Ceramic Matrix Composites: Ceramics are used to refer to a wide variety of nonmetallic inorganic materials. They are generally processed at high temperatures. Most notable properties of CMCs include high resistance to heat, chemical abrasion and wear. Due to these reasons, it is also difficult to fabricate them economically. CMCs can be used up to temperatures of 1500^{0}C. The main objective of using CMCs is to get increased toughness.

Polymer Matrix Composites: This is the most widely used group of matrices. A polymer is a long chain molecule having one or more repeating units of atoms joined together by strong covalent bonds. In solid state, the polymer the polymer molecules may be visualized as being frozen in space. They may either be oriented in a random fashion (amorphous polymers) or in a mixture of random fashion and orderly fashion (as found in semi - crystalline polymers). They have extremely good properties such as high stiffness and fracture toughness, good corrosion and abrasion resistance.

Polymer matrix composites are the subject of growing interest in recent times due to the immense versatility in their applications. They can further be classified into the following two types:

Thermosetting Resins: The most commonly used resins are Epoxy, Unsaturated Polyester and Vinyl Ester. The liquid resin is generally converted into a hard solid by the process of chemical cross linking. This leads to the formation of a tightly bound three dimensional network, which lend s the strength to the polymer block. The mechanical properties of various resins depend on the molecular units making up the networks. They also depend on the length and density of the cross links. The most notable property of the thermosetting resins is they have lower strains to failure. These may be essentially considered to be brittle materials.

Thermoplastics: These polymers do not have a cross linked structure. They derive their strength and stiffness characteristics from the properties of the individual monomer units as well as the very high molecular weight. The advantage of thermoplastics is that in amorphous thermoplastics, there is a high concentration of molecular entanglements. These act like cross-links. Although, a degree of molecular order an d alignment can be seen in semi crystalline materials. Heating of thermoplastics leads to the disentanglement of molecules and thus it turns from solid to a slightly liquid (viscous) state. An amorphous Viscous liquid is formed on heating the crystalline materials. These materials have anisotropic properties. They have good chemical resistance and good thermal stability. Many thermoplastics are also resistant to water absorption. The most common property is that all thermoplastics undergo large deformation before the final fracture. Commonly used thermoplastics are Nylon, polypropylene, acrylics. [17]

1.2. Statement of the problem

Coil spring is one of the basic component of suspension system of Bajaj. The material used for coil spring of Bajaj is usually a plain carbon steel having 0.9 to 1% carbon. Suspension Spring coil made from this alloy steel has high weight relative to composites and its strain energy is low. This high weight of coil spring increases fuel consumption the vehicle. To reduce the weight and increase strain energy of the coil spring, a material with small density and Young's modulus is needed. As composite materials have high strength to weight ratio, automobile industries has great interest for replacement of steel components by composite parts.

To overcome this gap, composite materials having advanced mechanical properties (High strength, High modulus of elasticity and low mass density) is selected to replace the existing steel coil spring. Two composite materials (carbon reinforced epoxy, carbon fiber reinforced-carbon nanotube (CNT) additive composite) are selected by their advanced properties to replace the steel coil spring by comparing using finite element method.

1.3. Objectives

1.3.1. General objective

- The general objective of this research is weight reduction with adequate strength and stiffness of coil spring for front suspension of Bajaj using composite materials.

1.3.2. Specific objective

The specific objective of this research is to:

- Select a suitable composite material so as to reduce weight and to give high performance.
- Analyze the mixture the composition each composite
- Modify the existing design suitable for composite coil spring.
- Reduce stress (shear stress) acting on the coil spring.
- optimize the load caring capacity of the coil spring
- Compare analytical values and ANSYS values of coil spring.

1.4. Scope and Limitations

The design of the existing Steel spring is evaluated using computational (theoretical) methodology while engaging suitable CAE tools. The geometry of the spring is the input for this work which shall undergo Finite Element Analysis to determine its fatigue life. This work is designed for RE engine BAJAJ suspension coil spring, and experimental investigations is not conducted. Instead a reasonable data that was already done by appropriate experiments are taken. The model is considered as Static structure. The model of the coil spring is not manufactured; instead the system is analyzed by ANSYS Workbench.

1.5. Methodology

The procedure to perform the objective of this research is generally summarize as:

- **Data collection:** Datum are collected by measuring the existing coil spring, and reading Journals and other Printed Papers; datum are referred for understanding the previous work done.
- The properties of existing material for coil spring are studied to identify and optimize material for the new design. Study is undertaken to identify and select better material than the conventional steel to improve performance of the coil spring.
- **Material selection:** based on the factors that are considered for the performance of coil spring materials are selected to replace steel spring**.**
- **Analysis for the composite materials and coil spring using analytical formulas**
- Using Micromechanics properties of composite materials are determined.
- In order to check the life time (fatigue life) of the coil spring S-N curve is calculated analytically.
- 3D Coil spring model is created by CATIA V5R19.
- Finite Element analysis including Fatigue life, stress and deformation analysis is made by ANSYS 17.2 workbench by importing the 3D modeled in CATIA V5R19 in the form of IGES.
- Results are captured in the form of output parameters (response) like maximum deflection of spring, maximum shear stress and the fatigue life of the spring (number of cycles).

In general activities used to perform the objectives of this research are summarized in the following methodology flow chart.

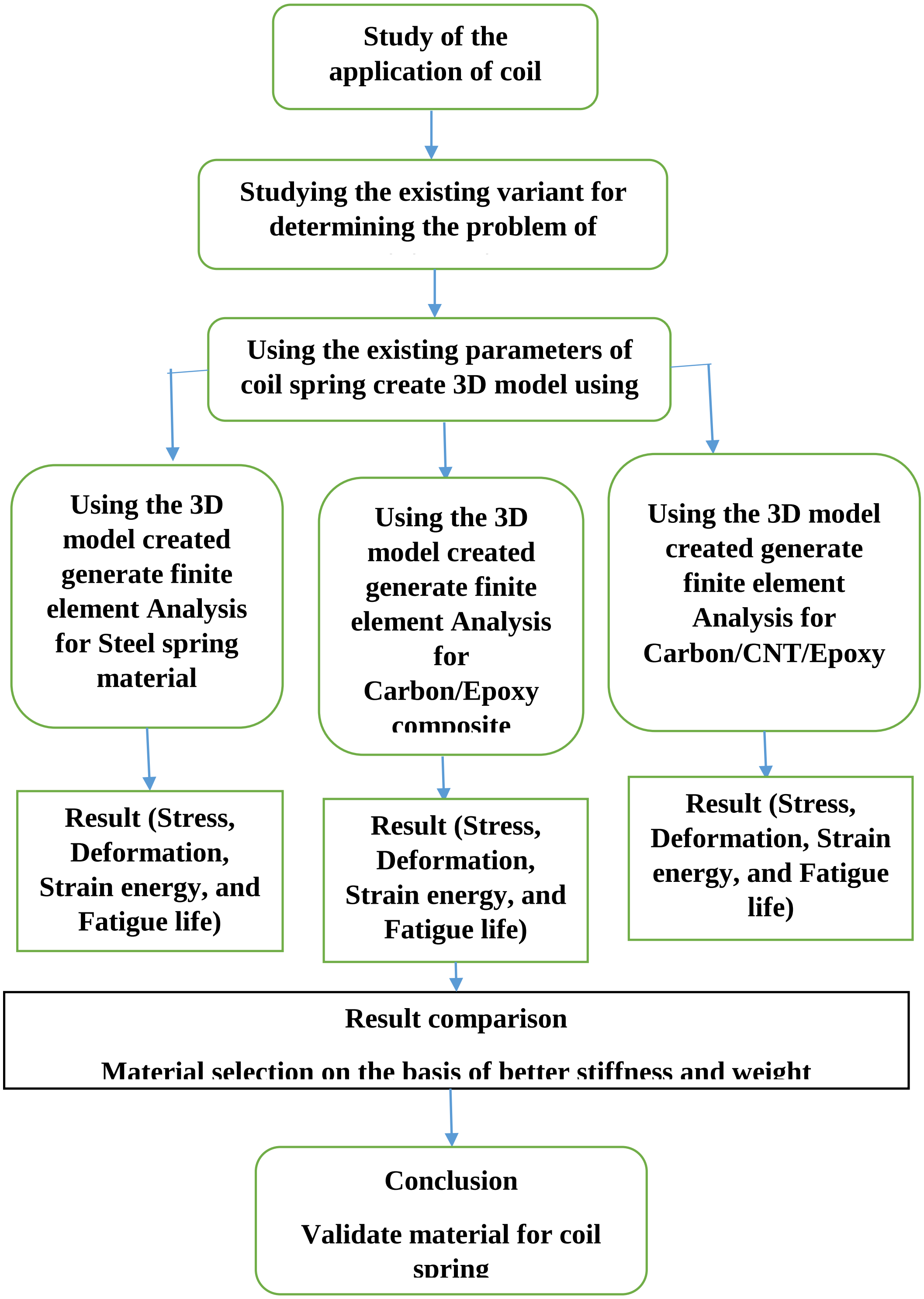


Figure 1-4: Methodology flow chart of the research

1.6. Organization of the Thesis

This work is organized in five chapters. The first chapter is Introduction and deals with brief description of thesis background, composite materials, problem of the statement, general and specific objectives, limitation and methodologies of the study. The second chapter presents literature review on the past helical coil spring materials and it's analysis type. In this chapter different literatures related to helical coil spring are reviewed. The third chapter deals with materials, design methods and conditions which focused on selection of materials, specifications/dimensions of helical coil spring, geometrical modeling and discretization of the model using ANSYS, and the analysis procedure is presented. The fourth chapter covers all the numerical results and discussion of results obtained in the thesis. .And the last chapter devoted to state the conclusions, recommendations and future works of the study.

CHAPTER TWO

2. LITERATURE REVIEW

In this research the papers reviewed to study and understand the previously done works related to coil springs are classified based on materials, geometry, and manufacturing methods.

2.1. Materials

In this sub title papers that are done by replacing the existing Steel coil spring by another materials are reviewed.

Anil Antony Sequeira, Ram Kishan Singh, and Ganesh K Shettiet al [18] in their paper they discussed the behavior of carbon and Kevlar composite helical spring and steel helical spring with related to light vehicle suspension system investigated by a static analysis. Aim of their study to compare the mechanical properties of composite helical spring with steel helical spring in area like load carrying capacity, stiffness and weight saving of FRP composite spring. Design parameters, such as outer and inner coil diameters, pitch length, height etc., of three helical springs were chosen the same. They investigated some mechanical behavior of all springs by numerically in ANSYS software. Mesh size, number of nodes and number of elements have been determined equal for all helical spring in the ANSYS. Their researches show that the specific modulus (young's modulus (E) upon mass density of the material (ρ)) of CFRP composite spring is the highest and Kevlar FRP (KFRP) is lowest. Load and deflection characteristics of steel spring have been found better than composite ones. However, mass of the KFRP helical spring has been determined less than CFRP and steel ones. The weight of the CFRP spring is very low compared to the steel spring and it is very beneficial to use carbon spring instead of steel spring to reduce the overall weight of the related mechanical systems.

Nijssen, R.P.L et al [19], Fiber volume fraction may have determinable effect of properties of composite materials. A schematic of variation in fiber reinforced composite with amount of fiber volume fraction is shown in figure 2-1. Typically fiber share 30% to 75% of volume of composites. At low fiber volume fraction, matrix properties are dominant while at high fiber volume percentage, behavior of composite is controlled by the fiber properties. Tensile strength increases with increase the fiber contents while compressive strength is high at low fiber contents and deceases with increasing fiber volume fraction.

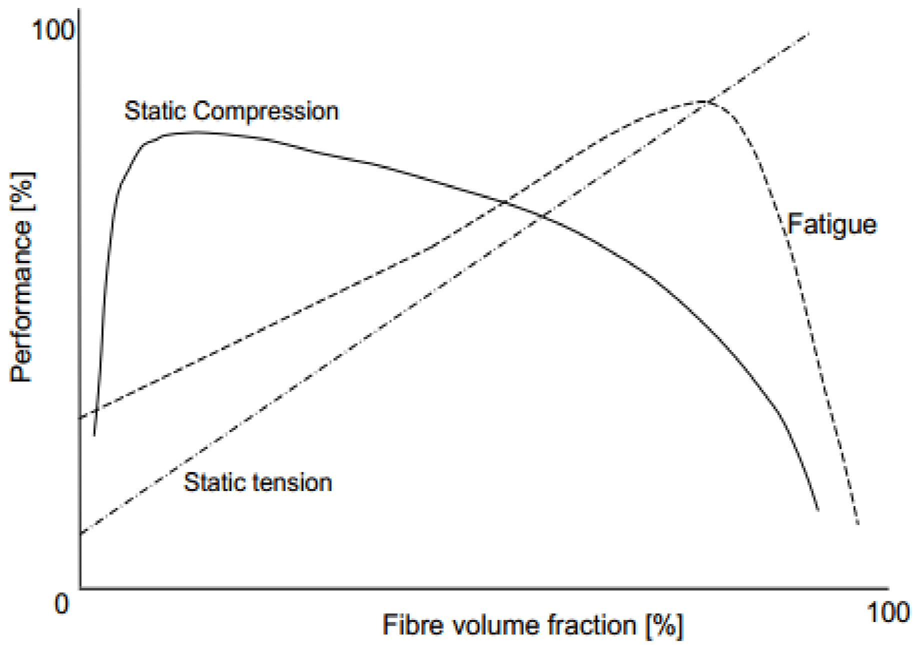


Figure 2-1: Effect of fiber contents on performance of composite materials [19]

Mehdi Bakhshesh et al [6] have studied result found by comparing steel spring with composite helical spring it has been found to have lesser stress and has the most value when fiber position has been considered to be in direction of loading. Also weight of spring has been reduced shown that changing percentage of fiber, especially at Carbon/Epoxy composite, does not affect spring weight.

P.R. Jadhav, N.P. Doshi, and U.D. Gulhane et al [20] in this research steel coil spring is replaced by composite material. Numerical results have been compared with theoretical results and found to be in good agreement in three different composite helical springs. Compared to steel coil spring, the composite helical/coil spring has been found to have lesser stress. Weight of spring has reduced and has been shown that changing percentage of fiber, especially at Carbon/Epoxy composite, does not affect spring weight.

Chang Hsuan Chiu et al, [21]explained about four types of helical compression springs made of unidirectional laminates, rubber core unidirectional laminates, unidirectional laminates with a braided outer layer, and rubber core unidirectional laminates with a braided outer layer respectively. The results indicates that the helical composite coil springs with a rubber core has 12% more load carrying capacity while for the spring with BUR has 18% more load carrying capacity along with the improvement of 16% in spring constant.

Comparison of software and theoretical analyses of coil spring made of SP ST GRD II material suggested the suitability for optimum design. . The stress (shear stress) and deformation produced in the spring at the loading condition is in limit so it is safe. Relative error of maximum shear stress ranging from 6 to 10 % with reference to the applied load compared with the values calculated by using simple analytical formulae which were found in reference books and handbooks. Shear stress is having maximum value at the inner side of every coil which shows stress distribution clearly. From above analysis it is observed that the stiffness of the suspension spring is increased which increases load carrying capacity of the system. Because of the reducing number of turns the weight of the spring is reduced. It has been observed that the weight of the system is reduced up to 9% for same loading conditions. Therefore, the light weight system is achieved which will help to increase the fuel efficiency of the TWV. The load carrying capacity also increased by 11%. Based on the modeling and analyses conclude that the new design is suitable for used so it can be implement. In general, Weight of the spring is reduced by reducing number of coil spring turns and replacing the conventional steel material by SP ST GRD II (special steel grade II). [22] [23] Fundamental stress distribution, materials characteristic, manufacturing and common failures of automotive coil spring is analyzed. An in depth discussion on the parameters influencing the quality of coil springs is also presented. To assure that a coil spring serves its design, failure analysis of broken coil springs is valuable both for the short and long term agenda of car manufacturer and parts suppliers. This paper discusses several case studies of suspension spring failures. The failures presented range from the very basic including insufficient load carrying capacity, raw material defects such as excessive inclusion levels, and manufacturing defects such as delayed quench cracking, to failures due to complex stress usage and chemically induced failure. FEA of stress distributions around typical failure initiation sites are also presented. The fatigue stress, life cycle and shear stress of helical compression spring is analyzed by various research methods such as Theoretical, Numerical, Experimental and FEM methods. [24], [25]

Ganesh Bhimrao Jadhav et al [26] Glass fiber epoxy resin is used in place of conventional spring steel. The cause of implementing combination of steel and composite material is the low stiffness of single composite spring, which limits its application to light vehicles. Fuel efficiency of automobiles can be maximized by lowering the weight of the vehicle. The spring of the suspension system plays an important role for a smooth and jerk free ride. So it is required to design the springs very precisely. The use of conventional steel as spring increases the weight and manufacturing process energy required is more so manufacturers are willing to use composite materials light in weight and also have corrosion resistance, it can also withstand high temperature. Manufacturing composite material is quite costlier than the steel spring. The use of composite material is beneficial if manufacturing process is standardized it can increase the efficiency of the vehicle adherence overcome the material cost.

2.2. Geometry

In this sub title previously done papers by changing the specifications such as changing the diameter of coil spring or wire of the coil spring, changing the number of coils, and changing the cross section are reviewed.

Andrea Shaggier, and Igor Spinella et al [27], they contributes to enhancing the performances of SMA actuators by proposing a new SMA helical spring with a hollow section. The hollow spring is modeled, then it is constructed, and finally it is tested in compression to compare its performances with those of a spring with a solid cross section of equal stiffness and strength. Emptied of the inefficient material from its center the hollow spring features a lower mass 37% less.

2.3. Finite element method

Manish Dakhore et al [28], has studied value of stress found to be more at the critical section of the spring as indicated by red color. Hence possibility of failure is more at that section compared to other section of spring. This paper discusses about locomotive suspension coil springs, their fundamental stress distribution and materials characteristic. The analysis of locomotive spring is carried out by considering cases, when the locomotive at the straight path, curved path and on uphill. This paper also discusses the Experimental analysis of a helical suspension spring by using strain gauge. The stress analysis for the forces obtained and for modal and harmonic response has been carried out by FEA using ANSYS.

P.S.Valsange et al [29], have been presented the review of fundamental stress distribution, characteristic of helical coil springs. An in depth discussion on the parameters influencing the quality of coil springs is also presented. Factors affecting strength of coil spring, FEA. Approaches by the researchers for coil spring analysis are also studied. Reduction in weight is a need of automobile industry. Thus the springs are to be designed for higher stresses with small dimensions. This requires critical design of coil springs. This leads to critical material and manufacturing processes. Decarburization that was not a major issue in the past now becomes essential, to have better spring design.

Tausif M. Mulla et al [30] , studied elastic behavior and the stress analysis of springs employed in the Three Wheeler Vehicle's (TWV) front automotive suspension is studied. The results obtained by a fully 3D Finite Element Analysis (FEA) also highlighted the poor accuracy that can be provided by the classical spring model when dealing with these spring geometries. Relatively small errors on maximum shear stress ranging from 1.5 to 4 per cent, with reference to the applied loads, are obtained when compared with the values calculated by using simple analytical model or formula. The stress distribution clearly shows that the shear stress is maximum at the inner side of every coil. The distribution of the stress is also similar in every coil. So the probability of failure of spring is the same in every coil except end turns. In such case residual stress in every coil may be important factor which influence the failure.

Erol Sancakkar, and Mathieu Gratton et al [31], in their research they observe composite leaf springs are successfully used in the suspension of the light vehicles. The fibers used in these are unidirectional E-glass due to their high extensibility, toughness and low cost. The composite leaf spring is designed and analyzed using ANSYS. The results showed that an optimum spring width decreases hyperbolically and the thickness increases linearly from the spring eye towards the axle seat. Compare to steel springs the optimized composite spring has strength that are much lower, the natural frequency is high and the spring weight is nearly 80% lower. The use of composite materials can be extended to conventional automotive parts like, propeller shaft, drive shafts, bumper beam, side door impact beam, universal joints, bearings, brakes. [31]

2.4. Manufacturing Method

According to [32] Composites springs are manufactured by the filament winding method. All the three types of springs were manufactured by the same method. A mandrel having the profile of the spring is prepared first. This mandrel is fixed in the lathe chuck. A mold release agent like silicone gel is applied on the mandrel. Glass fiber roving/carbon fiber roving is dipped in the measured quantity of resin and wound on the mandrel by rotating it on a lathe. After the complete winding of the roving in the profile of the mandrel a shrink tape is wound on the mandrel. This shrink tape applies the required pressure on the material. The mandrel along with the material and the shrink tape is cured in atmospheric temperature for 24hours. After curing shrink tape is removed. The excess resin on the surface of the spring is removed by filing. The cured spring is removed from the mandrel by rotating in the reverse direction.

According to [12], [33] Helical coil spring can manufactured and fabricated by glass fiber reinforced epoxy composite. This can be manufactured by FWT (Filament Winding Technique), filament winding and hand lay-up because of simple and low cost. In this research, a mandrel, which is re-usable, easy to fabricate and very convenient for the fabrication, is prepared by mild steel material. In this method of manufacturing curing process has determined as two hours for composite spring. The weight of GFRP composite helical spring is 40% less than steel spring. Failure analysis of GFRP helical coil spring is investigated by both numerically and experimentally. Failure load and deflection of GFRP and steel springs can be determined by universal testing machine. Failure load of composite spring is higher than steel one. According to results, GFRP helical spring is 25% stronger and 200% expensive than steel helical spring. However, GFRP composite spring has lower stiffness than the equivalent steel one

Summary

The above literature review presents that the helical compression springs becomes quite necessary to do the complete stress analysis of the spring. These springs undergo the fluctuating loading over the service life. In addition, FEM software has been use for performing meshing simulation. Almost in all of the above cases, fatigue stress, shear stress calculation play more significant role in the design of helical compression springs. Different study shows that shear stress and deflection equation is used for calculating the number of active turns and mean diameter in helical compression springs. Composite materials are used instead of steel coil spring, it reduces the weight of the spring. Hallow compression spring are compared with solid steel coil springs.

As we can understand form the literature review, the use of conventional steel in coil spring increases weight of the spring, and this increase fuel consumption of the vehicle. In addition, Coil spring made up of some composite materials such as Glass fiber reinforced proxy composite has very less weight than the conventional steel weight but the stiffness is less than the of the steel. Glass fiber reinforced epoxy has lower stiffness property. In addition, pure (without any additive) Glass fiber reinforced proxy material is not good for impact load and over load caring capacity. Therefor we can increase the stiffness of composite material by using addition additives.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Materials

Two types of composite materials are selected to replace the existing conventional steel by comparison. The first one is a hybrid composite of two fibers, carbon and carbon nanotube fiber with a single matrix of Epoxy Risen. The second composite is a Carbon fiber reinforced epoxy material with single fiber (carbon fiber) and single matrix (Epoxy Risen).

The composites listed in the above are selected because of their properties for the application of compression coil spring. Therefore the details of each composites component are studied and explained as follow.

The Reinforcement (fiber)

A reinforcing material, which is usually in a fiber form, adds strength and thickness to the bulk material, this is often known as the reinforcement. The reinforcing fibers give composites stiffness and excellent strength to weight ratios. A polymer to which directional fibers have been added is much stronger in the fiber direction than the polymer without fibers. Perpendicular to the fiber direction, the increase in stiffness is less pronounced. The strength in that direction is smaller, since the fibers act as stress concentrators. In practice, fibers are often incorporated in different directions. [34] [35] Some of the commonly used fibers and their properties, advantages and disadvantages are summarized in table below:

Table 3-1: Advantages and disadvantages of reinforced fibers [36]

Fiber	Advantageous	Disadvantageous
E – glass	• High strength • Low cost	• Low stiffness • Short fatigue life • High temperature sensitivity
Armide (Kevlar)	• High tensile strength • Low density	• Low compressive strength • High moisture absorption
Boron	• High stiffness • High compressive strength	• High cost
Carbon	• High strength • High stiffness	• Moderately high cost
Graphite	• Very high stiffness	• Low strength • High cost
Ceramic (silicon carbide, alumina)	• High stiffness • High use temperature	• Low strength • High cost

Fibers Selection for Polymer Matrix Composite

What fiber factors contribute to the mechanical performance of a composite? Fibers are the principal constituents in a fiber-reinforced composite material. They occupy the largest volume fraction in a composite laminate and share the major portion of the load acting on a composite structure. Proper selection of the fiber type, fiber volume fraction, fiber length, and fiber orientation is very important. [37]

Four fiber factors contribute to the mechanical performance of a composite:

• ***Length:*** The fibers can be long or short. Long, continuous fibers are easy to orient and process, but short fibers cannot be controlled fully for proper orientation. Long fibers provide many benefits over short fibers. These include impact resistance, low shrinkage, improved surface finish, and dimensional stability. However, short fibers provide low cost, are easy to work with, and have fast cycle time fabrication procedures. Short fibers have fewer flaws and therefore have higher strength.

• ***Orientation:*** Fibers oriented in one direction give very high stiffness and strength in that direction. If the fibers are oriented in more than one direction, such as in a mat, there will be high stiffness and strength in the directions of the fiber orientations. However, for the same volume of fibers per unit volume of the composite, it cannot match the stiffness and strength of unidirectional composites.

• ***Shape:*** The most common shape of fibers is circular because handling and manufacturing them is easy. Hexagon and square shaped fibers are possible, but their advantages of strength and high packing factors do not outweigh the difficulty in handling and processing.

• ***Material:*** The material of the fiber directly influences the mechanical performance of a composite. Fibers are generally expected to have high elastic moduli and strengths. This expectation and cost have been key factors in the graphite, aramids, and glass dominating the fiber market for composites.

Role of Fiber in composite Includes: To enhance stiffness, to enhance strength, to provide crack-bridging, and to enhance thermal resistance. Detail explanation such as definition, types and synthesis method of fibers selected for this project are explained as follow.

Carbon fiber

Carbon fibers are the new breed of high strength materials made of graphitic and non-crystalline regions. Of all reinforcing fibers, carbon fibers offer the highest specific modulus and strength.

Additionally, carbon fibers have the ability to retain its tensile strength even at high temperatures and are independent of moisture. Carbon fibers do not necessarily break under stress in contrast to glass and other organic polymer fibers. Carbon fibers are very versatile, because of their extremely high strength to weight and stiffness to weight ratios. Moreover, they are chemically inert, electrically conductive and infusible. The stiffness and modulus of elasticity of carbon fibers can range from glass to three times that of steel. [38]

Carbon nanotube

Carbon nanotubes are unique tubular structures of nanometer diameter and large length to diameter ratio. Carbon Nanotubes (CNTs) are allotropes of carbon with a nanostructure that can have a length-to-diameter ratio greater than 1,000,000. [39] The nanotubes may consist of one up to Tens and hundreds of concentric shells of carbons with adjacent shells separation of approximately 0.34 nm. Nanotubes are long, thin cylinders of carbon, they are 100 times stronger than steel, very flexible, and have unique electrical properties. Their electrical properties change with diameter, "twist", and number of walls. Carbon nanotube can be either conducting or semiconducting in their electrical behavior.

Due to their exceptional mechanical, thermal and electrical properties, in addition to low density with respect to the class of organic and inorganic tubes, carbon nanotubes (CNTs) are extremely promising for the development of high performance nanostructured materials. They are broadly classified as single walled carbon nanotubes and multi walled carbon nanotubes.

Single-Wall Carbon Nanotubes (SWNTs)

Most single walled carbon nanotubes (SWCNT) have a diameter of close to 1 nanometer, with a tube length that can be many millions of times longer. The structure of a SWCNT can be conceptualized by wrapping a one-atom-thick layer of graphite called graphene into a seamless cylinder. The way the graphene sheet is wrapped is represented by a pair of indices (n, m) called the chiral vector. The integer‘s n and m denote the number of unit vectors along two direction s in the honeycomb crystal lattice of graphene. If m = 0, the Nanotubes are called "zigzag‖, which is named for the pattern of hexagons as we move on circumference of the tube. If n = m, the Nanotubes are called "armchair", which describes one of the two confirmers of cyclohexene a hexagon of carbon atoms. Otherwise, they are called "chiral", in which the m value lies between zigzag and armchair structures. The word chiral means handedness and it indicates that the tubes may twist in either direction. [39]

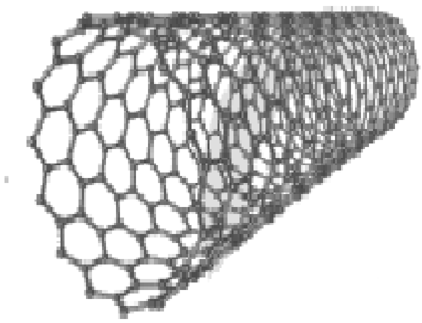


Figure 3-1: Single walled Carbon Nanotube

Multiple Walled Carbon Nanotubes (MWCNTs)

There are two models which can be used to describe the structures of multi-walled nanotubes. In the Russian Doll model, sheets of graphite are arranged in concentric cylinders, e.g. a single-walled nanotube (SWCNT) within a larger single-walled nanotube. In the Parchment model, a single sheet of graphite is rolled in around itself, resembling a scroll of parchment or a rolled newspaper. The interlayer distance in multi-walled nanotubes is close to the distance between graphene layers in graphite, approximately 3.3 Å (330ηm). The special place of double walled carbon nanotubes (DWNT) must be emphasized here because their morphology and properties are similar to SWNT but their resistance to chemicals is significantly improved. This is especially important when functionalization is required (this means grafting of chemical functions at the surface of the nanotubes) to add new properties to the CNT. In the case of SWNT, covalent functionalization will break some C=C double bonds, leaving "holes" in the structure on the nanotube and thus modifying both its mechanical and electrical properties. In the case of DWNT, only the outer wall is modified. DWNT synthesis on the gram-scale was first proposed in 2003 by the CCVD technique, from the selective reduction of oxide solutions in methane and hydrogen. [39]

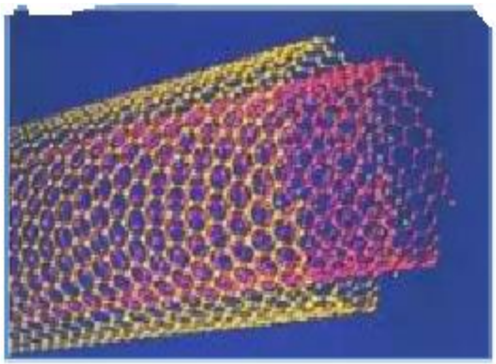


Figure 3-2: Double-wall Carbon Nanotubes (DWCNT)

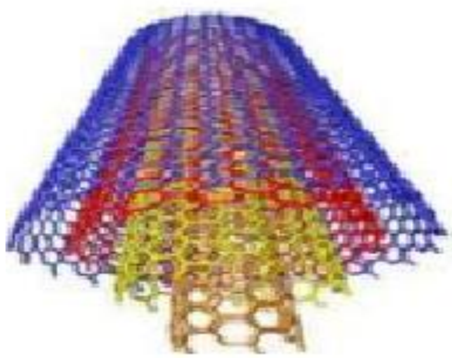


Figure 3-3: Multi walled Carbon Nanotubes (MWCNT

Synthesis Carbon nanotube

There are several techniques that used for fabricating CNT structures which mainly involve gas phase processes. According [40], [41] the most common methods used produce CNTs are: (1) the chemical vapor deposition (CVD) technique, (2) the laser-ablation technique, and (3) the carbon arc-discharge technique.

Electric arc discharge

The most common and easiest way to produce CNTs is the carbon arc discharge method. Using this method, a complex mixture of components is produced that separates the CNTs from soot and the catalytic metals. Arc vaporization is used to produce CNTs by placing two carbon rods from end to end, separated by an approximate distance of 1 mm, placed in an enclosure. At low pressure, the enclosure is usually filled with inert gas. A high temperature discharge between two electrodes is created by applying a direct current of 50 to 100 A. The surface of the carbon electrodes is vaporized by the high temperature discharge and finally forms a small rod-shaped electrode. The production of CNTs in high yield primarily depends on the uniformity of the plasma arc. The arc discharge method with liquid nitrogen can also be used to produce CNTs. Arc-discharge technique uses higher temperatures (above 1,700°C) for CNT synthesis which typically causes the expansion of CNTs with fewer structural defects in comparison with other methods. [40] [42]

Chemical vapor deposition

One of standard methods for production of carbon nanotubes is chemical vapor deposition or CVD. There are many different types of CVD such as catalytic chemical vapor deposition (CCVD) either thermal or plasma enhanced (PE) oxygen assisted CVD, water assisted CVD, microwave plasma (MPECVD), radiofrequency CVD (RF-CVD), or hot-filament (HFCVD). But catalytic chemical vapor deposition (CCVD) is currently the standard technique for the synthesis of carbon nanotubes. This technique allows CNTs to expand on different of materials and involves the chemical breakdown of a hydrocarbon on a substrate. The main process of growing carbon nanotubes in this method as same as arc discharge method also is exciting carbon atoms that are in contact with metallic catalyst particles. For all intents and purposes, tubes are drilled into silicon and also implanted with iron nanoparticles at the bottom. After that, a hydrocarbon such as acetylene is heated and decomposed onto the substrate. Since the carbon is able to make contact with the metal particles implanted in the holes, it initiates to create nanotubes which are a ‘template’ from the shape of the tunnel. [40]

As compared with laser ablation, CCVD is an economically practical method for large-scale and quite pure CNT production and so the important advantage of CVD are high purity obtained material and easy control of the reaction course.

According [40] the difference between single walled carbon nanotubes and multi walled carbon nanotubes is summarized as shown in the table below.

Single walled carbon nanotube	Multi walled carbon nanotube
• Single layer of graphene • Catalyst is required for synthesis • Bulk synthesis is difficult as it requires proper control over growth and atmospheric condition. • Purity is poor • A chance of defect is more during functionalization • Less accumulation in the body • Characterization and evaluation is easy • It can be easily twisted and is more pliable	• Multiple layers of graphene • Can be produced without catalyst • Bulk synthesis is easy • Purity is high • A chance of defect is less but once occurred it is difficult to improve. • More accumulation in the body • It has very complex structure • It cannot be easily twisted

Table 3-2: Comparison between single walled carbon nanotubes and multi walled carbon nanotubes

The matrix

To utilize high strength and stiffness of fibers in a monolithic composite material suitable for engineering applications, fibers are bound with a matrix material whose strength and stiffness are, naturally, much lower than those of fibers (otherwise, no fibers would be necessary).

Matrix material provide the final shape of the composite structure and govern the parameters of the manufacturing process.

Optimal combination of fiber and matrix properties should satisfy a set of operational and manufacturing requirements that sometimes are of a contradictory nature and have not been completely met yet in existing composites.

First of all, the stiffness of the matrix should correspond to the stiffness of the fibers and be sufficient to provide uniform loading of fibers. The fibers are usually characterized with relatively high scatter of strength that could be increasing due to the damage of the fibers caused by the processing equipment. Naturally, fracture of the weakest or damaged fiber should not result in material failure. Instead, the matrix should evenly redistribute the load from the broken fiber to the adjacent ones and then load the broken fiber at a distance from the cross-section at which it failed.

The higher is the matrix stiffness, the smaller is this distance, and the less is the influence of damaged fibers on material strength and stiffness (which should be the case). [15]

Resins Selection for Polymer Matrix Composite

What are the matrix factors that contribute to the mechanical performance of composites?

Use of fibers by themselves is limited, with the exceptions of ropes and cables. Therefore, fibers are used as reinforcement to matrices. The matrix functions include binding the fibers together, protecting fibers from the environment, shielding from damage due to handling, and distributing the load to fibers. Although matrices by themselves generally have low mechanical properties compared to those of fibers, the matrix influences many mechanical properties of the composite. These properties include transverse modulus and strength, shear modulus and strength, compressive strength, inter laminar shear strength, thermal expansion coefficient, thermal resistance, and fatigue strength.

Other than the fiber and the matrix, what other factors influence the mechanical performance of a composite? Other factors include the fiber–matrix interface. It determines how well the matrix transfers the load to the fibers. Chemical, mechanical, and reaction bonding may form the interface. In most cases, more than one type of bonding occurs.

• **Chemical bonding** is formed between the fiber surface and the matrix. Some fibers bond naturally to the matrix and others do not. Coupling agents are often added to form a chemical bond. (Coupling agents are compounds applied to fiber surfaces to improve the bond between the fiber and matrix.

• **The natural roughness or etching** of the fiber surface causing interlocking may form a mechanical bond between the fiber and matrix.

• If the **thermal expansion coefficient** of the matrix is higher than that of the fiber, and the manufacturing temperatures are higher than the operating temperatures, the matrix will radially shrink more than the fiber. This causes the matrix to compress around the fiber.

• **Reaction bonding** occurs when atoms or molecules of the fiber and the matrix diffuse into each other at the interface. This inter diffusion often creates a distinct interfacial layer, called the interphase, with different properties from that of the fiber or the matrix. Although this thin interfacial layer helps to form a bond, it also forms micro cracks in the fiber. These micro cracks reduce the strength of the fiber and thus that of the composite.

Role Matrix in Composite includes; binding fibers together, protect the individual fibers from damage by external environment, act as a medium to transmit and distribute external applied stress to fibers, and serves as barrier to crack propagation

Epoxy resins

Composite fibers are nothing without introducing epoxy. Although reinforcing fibers are used in many applications, epoxy is the substrate that will be dealing with. The substrate materials are used to bind whatever strengthening fiber is being used and to lock them in position so they can stay in position to do their job. Then for this composite fibers epoxy is as a substrate material.

In general, epoxy resins have very good adhesive properties, superior mechanical properties i.e. strength and stiffness, better resistance to fatigue and micro cracking, well resistant to water penetration, Faster curing at room temperature, and Good chemical resistance properties. [43]

Macro-Mechanics of Lamina

For better understanding of the micromechanics of lamina, the knowledge of the material Properties is essential. Therefore, the type of materials to find material Constants are discussed first.

Types of materials:

The materials are classified based on the behavior for a particular loading condition. These includes:

I. Anisotropic materials
II. Monoclinic materials
III. Orthotropic materials
IV. Transversely isotropic materials
V. Isotropic materials

Orthotropic materials:

There are three mutually orthogonal planes of material property symmetry in an orthotropic material. Fiber-reinforced composites, in general, contain the three orthogonal planes of material property symmetry and are classified as orthotropic materials. The intersections of these three planes of symmetry are called the principal material directions. The material behavior is called as especially orthotropic, when the normal stresses are applied in the principal material directions. Otherwise, it is called as general orthotropic which behaves almost equivalent to anisotropic material.

There are nine independent elastic constants in the stiffness matrix as given below for orthotropic material.

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} \qquad (3)$$

From the stress-strain relationship it is clear that normal stresses applied in one of the principal material directions on an orthotropic material cause elongation in the direction of the applied stresses and contractions in the other two transverse directions. However, normal stresses applied in any directions other than the principal material directions create both extensional and shear deformations.

Transversely isotropic materials:

If a material has axes of symmetry in its longitudinal axis and all directions perpendicular to its longitudinal axis (i.e., more than three mutually perpendicular axes of symmetry) then such material is transversely isotropic. (e.g., unidirectional composites). There are five independent elastic constants for these materials.

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{(C_{11}+C_{12})}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} \quad (4)$$

Table 3-3: Elastic constants of different materials

Material	Three dimensional		Two dimensional	
	Number of non-zero constants	Number of independent constants	Number of non-zero constants	Number of independent constants
Anisotropic	36	21	9	6
Generally Orthotropic	36	9	9	4
Specially Orthotropic	12	9	5	4
Transversely Isotropic	12	5	5	4
Isotropic	12	2	5	2

Advantage and disadvantage of composite materials

The advantage of composite material is that, if well designed, they usually exhibit the best qualities of their components or constituents and often some qualities neither constituent possesses. some of the properties that can be improved by forming a composite materials are; strength, stiffness, corrosion resistance, wear resistance, attractiveness, weight, fatigue life, temperature dependent behavior, thermal insulation, thermal conductivity, and acoustic insulation. [44]

Table 3-4: Advantage and dis advantage of composite materials [34],

Advantages of Composites	Disadvantages of Composites
• Excellent strength to weight ratios compared with traditional materials. • Resistant to corrosion. • Allows a greater flexibility with designs. • Low thermal expansion. • Very uniform in its structure, providing reliability in manufacture and use. • Weather resistance. • Directional strength. • Non-magnetic	• Expensive to manufacture. • As they are mostly produced with thermosetting polymers they cannot be reshaped. • When damaged they are difficult to repair due to the fibers being mixed in the matrix. • Difficult to produce to required properties requiring extensive design and testing.

Existing coil spring material

Table 3-5: Properties of hard drawn spring Steel [23], [45], [46]

Properties	Values
Young’s modulus (GPa)	207
Density (kg/m^3)	7850
Poisson’s ratio	0.35
Tensile strength (MPa)	1014-1950
Modulus of Rigidity (GPa)	71.420

Properties of Newly selected materials

Commonly used fibers are carbon fibers, glass fibers, natural fibers etc. Among these fiber types, the carbon fiber has been selected because Carbon Fibers have a high strength-to-weight ratio when tested in the direction of the fibers while E-glass has a lower strength-to-weight ratio, in addition to this carbon fiber is corrosion resistant, chemically stable, high modulus of elasticity, good adhesion to polymer, and has good fatigue strength.

Due to their advanced properties the following Materials are selected;

Carbon fiber properties

Carbon fibers are the new breed of high strength materials made of graphitic and non-crystalline regions. Of all reinforcing fibers, carbon fibers offer the highest specific modulus and strength.

Table 3-6: properties of Carbon fiber [8], [47], [48], [32]

No.	Property	Value
1	Young’s modulus (GPa)	230
2	Tensile Strength (GPa)	3.6
3	Density (g/cm^3)	1.75
4	Shear modulus (GPa)	50
5	Poisson’s ratio	0.2
6	Compressive strength (GPa)	1.2

3.1.1.1. Carbon nanotube properties

Carbon nanotubes are unique tubular structures of nanometer diameter and large length/diameter ratio. As explained in the introduction parts CNTs are selected for their advanced properties. And the properties of both SWCNTs and MWCNTs are summarized in the tables below.

Table 3-7: properties of Carbon nanotube (Single wall nanotube) [39], [49], [50], [40]

No.	Property	Value
1	Young's modulus (GPa)	1054
2	Tensile Strength (GPa)	30
3	Density (g/cm^3)	1.4
4	Shear modulus(GPa)	400
5	Poisson's ratio	0.19
6	Diameter of Single wall carbon nanotube (nm)	0.02

Table 3-8: properties of Carbon nanotube (Multi walled carbon nanotube) [49], [50], [51], [40]

No.	Property	Value
1	Young's modulus (GPa)	1200
2	Tensile Strength (GPa)	63
3	Density (g/cm^3)	1.4
4	Shear modulus (GPa)	546
5	Poisson's ratio	0.19

Epoxy resins Properties

In general, epoxy resins have very good adhesive properties, superior mechanical properties i.e. strength and stiffness, better resistance to fatigue and micro cracking, well resistant to water penetration, Faster curing at room temperature, and Good chemical resistance properties. [43]

Table 3-9: properties of Epoxy Risen [48], [8], [52], [53]

No.	Property	Value
1	Young's modulus (GPa)	3.45
2	Tensile Strength (GPa)	1.3
3	Density (g/cm^3)	1.2
4	Shear modulus (GPa)	1.6
5	Poisson's ratio	0.4
6	Compressive strength (GPa)	0.19
7	Flexural yield strength (GPa)	0.125
8	Glass transition temperature (^{0}C)	120 -130

3.2. Methods and conditions

3.2.1. Composite material design

Rule of Mixtures

Composite properties can be predicted using a micro-mechanics approach termed the rule of mixtures.

Micromechanics is determining unknown properties of the composite based on known properties of the fiber and matrix.

Assumptions

- ✓ Fibers are uniformly distributed throughout the matrix.
- ✓ Perfect bonding between fibers and matrix.
- ✓ Matrix is free of voids.

Applied loads are either parallel or normal to the fiber direction.

- ✓ Lamina is initially in a stress-free state (no residual stresses).
- ✓ Fiber and matrix behave as linearly elastic materials.

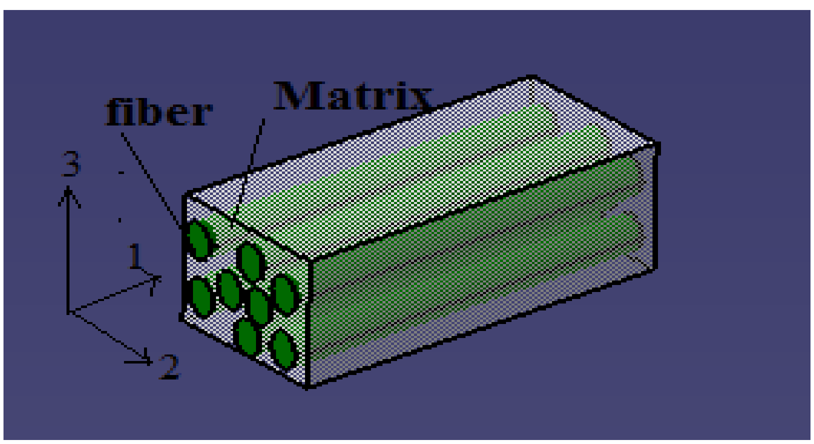


Figure 3-4: composite material representation with orthographic position

3.2.1.1. Mechanical properties of determination of Carbon/ Epoxy composite

Weight fraction of the fiber is defined as (Wf): [54]

$$Wf = \frac{weight\ of\ fiber}{total\ weight} = \frac{wf}{Wt} = \quad (5\ )$$

Weight fraction of matrix is defined as (Wm):

$$Wm = \frac{weight\ of\ matrix}{total\ weight} = \frac{Wm}{Wt} = \frac{Wm}{Wm+Wf} \quad (6)$$

$$Wf\ +\ Wm\ =\ wc\ =\ 1 \quad (7)$$

Volume fraction of the fiber component is defined as (V_f):

$$V_f\ = \frac{V_f}{V_c} = \frac{volume\ of\ fiber\ component}{volume\ of\ composite} \quad (8)$$

Volume fraction of the matrix component is defined as (V_m):

$$V_m\ = \frac{V_m}{V_c} = \frac{volume\ of\ matrix\ component}{volume\ of\ composite} \quad (9)$$

The sum of the volume fractions of all constituents in a composite must be equal to one. In this work two types of materials are selected. For the first one, composite materials two components system consisting of one fiber and one matrix, then, the total volume of the composite is:

$$Vc\ =\ Vf\ +\ Vm, hence\ Vm\ =\ 1 - Vf \quad (10)$$

Similarly the weight fractions Wf and Wm of the fiber and matrix respectively can be defined in terms of the fiber weight wf, the matrix weight, wm and the composite weight, wc. Hence,

$$Wf\ = \frac{wf}{wc}, \quad Wm\ = \frac{wm}{wc} \quad (11)$$

$$Wm\ =\ 1 - Wf \quad (12)$$

Composite Density

The density of the composite in terms of volume fraction can be found by considering the weight of the composite to be composed of the weights of their constituent,

$$Wc = Wf + Wm \tag{13}$$

The weights can be expressed in terms of their respective densities and volumes,

$$\rho cVc = \rho fVf + \rho mVm \tag{14}$$

Applying the definitions of volume fraction the density of the composite, ρc can be expressed in terms of the fiber density, ρf and the matrix density ρm as:

$$\rho c = \rho fVf + \rho mVm \tag{15}$$

Table 3-10: Effect of Volume fraction of carbon fiber

Fiber percentage	Conventional steel spring weight(kg)	Carbon/epoxy composite density(g/cm^3)	Carbon/epoxy composite spring mass(kg)	
0.5	2.02	1.475	0.379	
0.6	2.02	1.53	0.393	
0.7	2.02	1.583	0.407	
0.8	2.02	1.64	0.422	

According to different literatures and experiments the volume fraction of fiber to matrix of 60/40 has better chemical and physical properties for a mixtures. So using table 3-10 and literature reviews in this project the following volume fractions are taken.

Volume fraction of fiber = 0.6, volume fraction of matrix material (epoxy) = 0.4, density of carbon fiber = 1.75 g/cm^3 and density of epoxy = 1.2 g/cm^3 from the table.

Now calculate the density of composite carbon/epoxy material (ρc):

$$\boldsymbol{\rho c = 1.53 g/cm^3}$$

Based on ROM longitudinal and transverse properties of the composite material (Pc) can be estimated by:

$$P_c = P_f V_f = P_m V_m \qquad (16)$$

Where: Pf & Pm = property of fiber and property of matrix material respectively.

This equation is easily understood by considering the analogy of calculating the stiffness of two springs connected in parallel. [14]

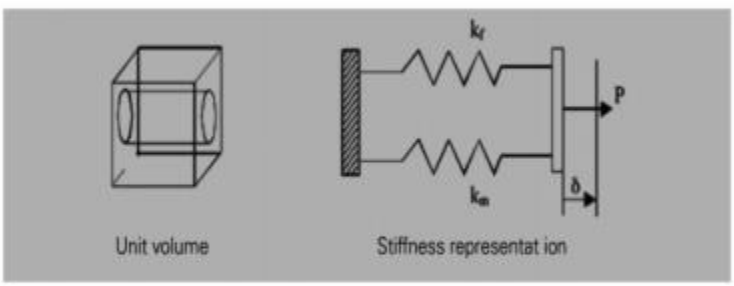


Figure 3-5: Physical model for the longitudinal properties of a composite.

For properties perpendicular to fiber direction the calculation becomes a little more sophisticated, dependent on the fiber shape and fiber content, but a good estimate can be obtained using the model of two springs connected in series: [14]

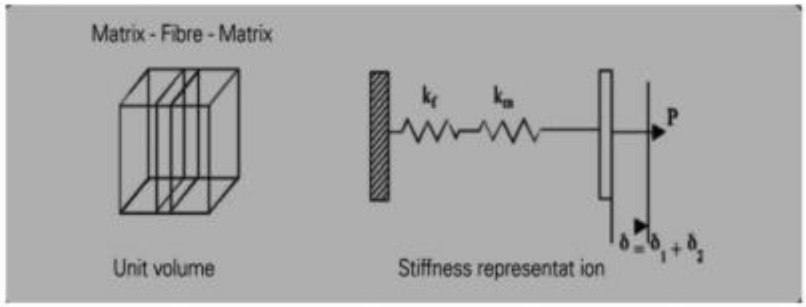


Figure 3-6: physical model for the transverse properties of a composite.

With this model, the total deformation at a point of load application in a direction perpendicular to fiber direction is the sum of the deflections in the fiber and the matrix. The resulting expression for transverse property of a composite is:

$$\frac{1}{Pc} = \frac{V_f}{P_f} + \frac{V_m}{P_m} \quad (17)$$

Longitudinal modulus (E_1) for Carbon/epoxy composite: [54]

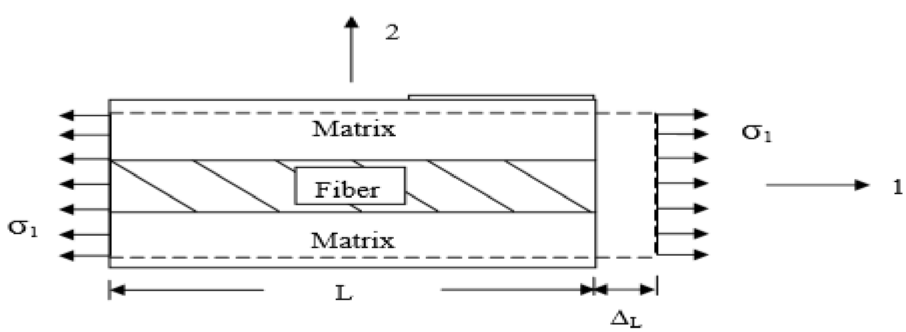


Figure 3-7: Load parallel to fiber direction

Equal strain assumption:

$$\varepsilon_c = \varepsilon_f = \varepsilon_m \quad (18)$$

Static equilibrium requires that the total resultant force on the element must equal the sum of the forces acting on the fiber and matrix

$$\sigma_c * A_c = \sigma_f * A_f + \sigma_m * A_m$$

$$\sigma_c = \sigma_f \frac{A_f}{A_c} + \sigma_m \frac{A_m}{A_c} \tag{19}$$

Then we can also say that volume fractions are expressed as:

$$V_f = \frac{A_f}{A_c}, \qquad V_m = \frac{A_m}{A_c} \tag{20}$$

Invoking Hook's law we get:

$$E_c * \varepsilon_c = E_f * \varepsilon_f * V_f + E_m * \varepsilon_m * V_m \tag{21}$$

Then, to have strain compatibility, using equation (22) the average strains in the composite, fiber, and matrix along the longitudinal direction are equal.

Therefore:

$$E_1 = Ef \times Vf + Em \times Vm \tag{23}$$

$$\boldsymbol{E_1 = 139.8Gpa}$$

Transverse modulus (E_2) for carbon/Epoxy composite:

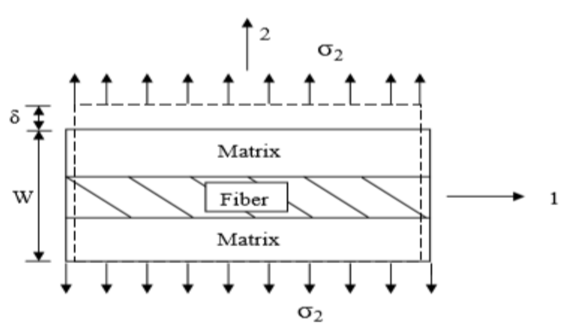


Figure 3-8: Load perpendicular to fiber

Geometric compatibility requires that the total transverse composite displacement in the 2-direction (transvers), δc, must equal the sum of the corresponding transverse displacements in the fiber, δf, and the matrix, δm.

$$Therefore,\ \delta c\ =\ \delta f+\ \delta m \tag{24}$$

$$But,\ \varepsilon f\ = \frac{\delta 2}{Ef}, and\ \varepsilon m = \frac{\delta 2}{Em} \tag{25}$$

$$\delta c = \varepsilon 2 * W = Vf * W * \varepsilon f + Vm * W * \varepsilon m \tag{26}$$

$$or\ \varepsilon 2 = Vf * \varepsilon f + +Vm * \varepsilon m \tag{27}$$

Invoking Hooke's Law:

$$\frac{\delta c}{Ec} = \frac{\delta f}{Ef}Vf + \frac{\delta m}{Em}Vm \tag{28}$$

$$but\ \delta c = \delta f\ = \delta m \tag{29}$$

Therefore,

$$\frac{1}{EC} = \frac{1}{E_f}V_f + \frac{1}{E_m}V_m \tag{30}$$

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \tag{31}$$

$$Or\ E_2\ = Ec = \frac{Ef * Em}{Vf * Em + Vm * Ef} \tag{32}$$

$$\boldsymbol{E_2 = 10.93GPa}$$

Shear modulus for carbon/Epoxy composite:

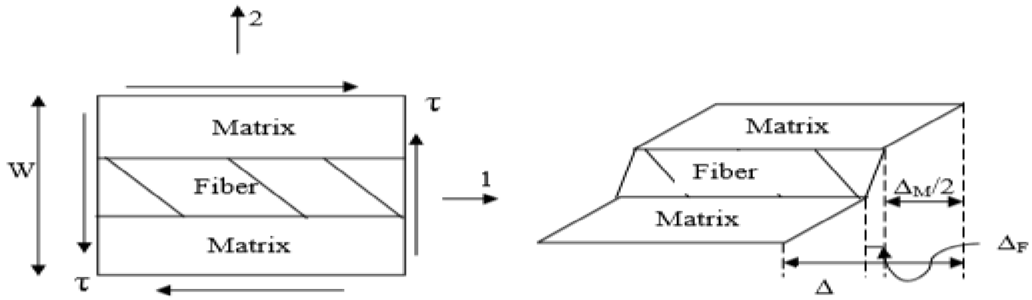


Figure 3-9: Shear deformation

Major Poisson's ration (v_{12})

$$v12 = v_f \times V_f + v_m \times V_m \qquad (33)$$

$$v12 = 0.28$$

$$v21 = v12\frac{E_2}{E_1} \qquad (34)$$

$$v21 = 0.022$$

In plane Shear modulus (G_{12})

$$G_{12} = \frac{Gm*Gf}{Vm*Gf+Vf*Gm} \qquad (35)$$

$$G_{12} = 3.817GPa$$

According to [8]general method to estimate the properties E_2 and G_{12} involves the use of semi-empirical equations that are adjusted to match experimental results such as the Halpin-Tsai equation. For the transverse modulus, the Halpin-Tsai equation is:

$$\frac{E_2}{E_m} = \frac{1+\xi(\eta V_f)}{1-(\eta V_f)} \qquad (36)$$

$where$

$$\eta = \frac{\left(\frac{E_{fc}}{E_m}\right)-1}{\left(\frac{E_{fc}}{E_m}\right)+\xi} \qquad (37)$$

$, and\ \boldsymbol{\xi}\ \ is\ \ a\ \ curve\ fitting\ \ parameter$ Which is dependent on the fiber packing arrangement. The corresponding equation for G_{12} is obtained by replacing Young's moduli E_2, E_f and E_m in the above equation by shear moduli G_{12}, G_f and G_m respectively.

$$\frac{G_{12}}{G_m} = \frac{1+\xi(\eta V_{fc})}{1-(\eta V_{fc})} \qquad (38)$$

$$similarly\ \eta = \frac{\left(\frac{G_{fc}}{G_m}\right)-1}{\left(\frac{G_{fc}}{G_m}\right)+\xi} \qquad (39)$$

By substituting for the hybrid composite we use $\xi = 2$ for transverse modulus E_2 and $\xi = 1.01$ for G_{12}

$$\mathbf{E_2 = \ 17.376GPa}$$

$$\mathbf{G_{12} = \ 7.14Gpa}$$

$$G_{23} = \frac{E_2}{2(1+v_{23})} \qquad (40)$$

$$where\ \ v_{23} = 1 - v_{21} - \frac{E_2}{3k} \qquad (41)$$

$$v_{23} = \mathbf{0.77}$$

K= bulk modulus of the composite

$$k = \left[\frac{f}{k_f} + \frac{(1-f)}{k_m}\right]^{-1} \qquad (42)$$

$$k = \boldsymbol{17.71Gpa}$$

$$k_f = \frac{E_f}{3(1-2v_f)} \tag{43}$$

$$k_f = \mathbf{191.67}\boldsymbol{Gpa}$$

$$k_m = \frac{E_m}{3(1-2v_m)} \tag{44}$$

$$k_m = \mathbf{7.5}\boldsymbol{Gpa}$$

$$G_{23} = \mathbf{3.864}\boldsymbol{Gpa}$$

According to [8] the Halpin-Tsai equation for the transverse modulus best matches for experimental results. Therefore the transverse modulus values are:

$$\mathbf{E_2 = \ 17.376GPa}$$

$$\mathbf{G_{12} = \ 7.14Gpa}$$

According to ROM of the stress of the composite is given as: [35]

Tensile strength of a single ply in longitudinal direction:

$$\sigma t_l \ = \ \sigma t_f \, V_f \ + \ \sigma t_m \, V_m \tag{45}$$

$$\sigma t_l = \mathbf{2.68}\boldsymbol{Gpa}$$

Tensile strength of a single ply in transverse direction:

$$\frac{\mathbf{1}}{\sigma t_t} = \frac{V_f}{\sigma t_f} + \frac{V_m}{\sigma t_m} \tag{46}$$

$$\sigma t_t = \mathbf{0.306}\boldsymbol{Gpa}$$

Compressive strength of a single ply in longitudinal direction:

$$\sigma c_l = \sigma c_f V_f + \sigma c_m V_m \tag{47}$$

$$\sigma c_l = \mathbf{0.796\ GPa}$$

Compressive strength of a single ply in transverse direction:

$$\frac{1}{\sigma ct} = \frac{Vf}{\sigma c_f} + \frac{Vm}{\sigma cm} \tag{48}$$

$$\sigma ct = \mathbf{0.384\ Gpa}$$

3.2.1.2. Mechanical properties of determination of Carbon/CNT/Epoxy composite

Longitudinal Modulus for Carbon/CNT/Epoxy composite

Static equilibrium requires that the total resultant force on the element must equal the sum of the forces acting on the fiber and matrix

Therefore, for two fibers equation (16) will expanded in to:

$$\sigma c * A_C = \sigma_{fC} * A_{fC} + \sigma_{fCNT} * A_{fCNT} + \sigma_m * A_m$$

$$\sigma_C = \sigma_{fC}\frac{A_{fC}}{A_C} + \sigma_{fCNT}\frac{A_{fCNT}}{A_C} + \sigma_m\frac{A_m}{A_C} \tag{49}$$

Where σ_C= composite longitudinal stress

$\sigma_{fC} = strength\ carbon$ fiber longitudinal stress

$\sigma_{fCNT} = strength\ of\ CNT$ fiber longitudinal stress

$\sigma_m =$ matrix longitudinal stress

A_C=composite cross section area

A_{fC} = fiber1 cross section

A_{fCNT} = fiber2 cross section

A_m = matrix cross section

Then we can also say that volume fractions are expressed as:

$$V_{fC} = \frac{A_{fC}}{A_C}, V_{fCNT} = \frac{A_{fCNT}}{A_C} and, V_m = \frac{A_m}{A_C} \tag{50}$$

Where $V_m =$ volume fraction of matrix

$V_{fC} =$ volume fraction of carbon fiber

$V_{fCNT} =$ volume fraction of CNT fiber

Invoking hook's for two fibers and a matrix law we get

$$E_C * \varepsilon_c = E_{fC} * \varepsilon_{fC} * V_{fC} + E_{fCNT} * \varepsilon_{fCNT} * V_{fCNT} + Em * \varepsilon_m * V_m \tag{51}$$

Then, to have strain compatibility, we have to assume that the average strains in the composite, fiber, and matrix along the longitudinal direction are equal.

Therefore,

$$E_C = E1 = E_{fC} * V_{fC} + E_{fCNT} * V_{fCNT} + E_m * V_m \tag{52}$$

$$V_{fC} + V_{fCNT} + V_m = 1 \tag{53}$$

$$E1 = \sum_{k=1}^{n}((Efi)(Vfi) + (Emi)(Vmi)) \tag{54}$$

Substituting the elastic modulus of each fiber, matric and volume fractions:

E1= 149.08Gpa

Therefore, the fraction of load carried by fibers in a unidirectional continuous fiber lamina is

$$\frac{Pf}{Pc} = \frac{\sigma f * Vf}{\sigma f * Vf + \sigma m * Vm} = \frac{Ef * Vf}{Ef * Vf + Em * Vm} = \frac{\frac{Ef}{Em} Vf}{\frac{Ef}{Em} Vf + Vm} \tag{55}$$

In general, fiber failure strain is lower than the matrix failure strain. Assuming all fibers have the same strength, the tensile rupture of fibers will determine the rupture in the composite.

Therefore, estimation of longitudinal tensile strength could be calculated as:

$$\sigma_{lut} = \sigma_{ut} Vf + \sigma_m Vm \tag{56}$$

Where, σ_{FU} is the fiber tensile strength and σ_M is matrox stress at fiber failure strain . Fore effective reinforecment of matrix (i. e., $\sigma_{MU\leq} \leq \sigma_{LTU}$), the Vf must be greater $than\ the\ critical\ value\ defined\ as$:

$$critical\ Vf = \frac{\sigma_{MU\_}\sigma_M}{\sigma_{FU\_}\sigma_M} \tag{57}$$

Tensile strength of a single ply in longitudinal direction:

$$\sigma t_{\ l} = \sigma t_{fc}\, V_{\ fC} + \sigma t_{fCNT}\, V_{\ fCNT} + \sigma t_m\, V_{\ m} \tag{58}$$

$$\sigma t_{\ l} = \mathbf{4.144}\boldsymbol{Pa}$$

Compressive strength of a single ply in longitudinal direction:

$$\sigma c_l = \sigma c_{f1}\, V_{\ fC} + \sigma c_{f2}\, V_{\ fCNT} + \sigma c_m\, V_{\ m} \tag{59}$$

$$\sigma cl \ = \mathbf{2.1}\boldsymbol{GPa}$$

Transverse Modulus of Carbon/CNT/Epoxy composite:

Using fig 3-6, geometric compatibility requires that the total transverse composite displacement in the 2-direction (transvers), δc, must equal the sum of the corresponding transverse displacements in the fiber, δf, and the matrix, δm.

$$Therefore,\ \delta_c = \delta_f + \delta_m \qquad (60)$$

$$But,\ \varepsilon f = \frac{\delta 2}{Ef},\ and\ \varepsilon m = \frac{\delta 2}{Em} \qquad (61)$$

$$\delta c = \varepsilon 2 * W = V_{fC} * W * \varepsilon_{fC} + V_{fCNT} * W * \varepsilon_{fCNT} + Vm * W * \varepsilon m \qquad (62)$$

$$or\ \varepsilon 2 = V_{fC} * \varepsilon_{fC} + V_{fCNT} * \varepsilon_{fCNT} + Vm * \varepsilon m \qquad (63)$$

Invoking Hooke's Law:

$$\frac{\delta c}{Ec} = \frac{\delta f1}{Ef1} V_{fc} + \frac{\delta f2}{Ef2} V_{fCNT} + \frac{\delta m}{Em} V_m \qquad (64)$$

$$but\ \delta c = \delta_{fc} = \delta_{fCNT} = \delta_m \qquad (65)$$

Therefore,

$$\frac{1}{E_2} = \frac{1}{E_{fc}} + \frac{1}{E_{fCNT}} V_{fCNT} + \frac{1}{Em} Vm \qquad (66)$$

$$Or\ E_2 = E_c = \frac{E_{fc} * E_{fCNT} * Em}{V_{fc} * E_{fCNT} * Em + V_{fcNT} * E_{fC} * Em + Vm * E_{fc} * E_{fCNT}} \qquad (67)$$

E2=<u>10.97Gpa</u>

Using Halpin-Tsai equation similarly stated as in equation (35) and (37) for Carbon/carbon nanotube/epoxy is expressed by:

$$\frac{E_2}{E_m} = \frac{1+\xi(\eta_c V_{fc}+\eta_{CNT} V_{fcNT})}{1-(\eta_c V_{fc}+\eta_{CNT} V_{fcNT})} \qquad (68)$$

$$\eta_c = \frac{\left(\frac{E_{fC}}{E_m}\right)-1}{\left(\frac{E_{fC}}{E_m}\right)+\xi} \qquad (69$$

$$\eta_{CNT} = \frac{\left(\frac{E_{fCNT}}{E_m}\right)-1}{\left(\frac{E_{fCNT}}{E_m}\right)+\xi} \qquad (70)$$

$$\boldsymbol{E_2 = 14GPa}$$

Poisson's Ratio

$$v12 = v_{fc} * V_{fc} + v_{fcNT} * V_{fcNT} + v_m * V_m \qquad (71)$$

V12=0.33

$$and\ v21 = \frac{E2}{E1} v12 \qquad (72)$$

V12=0.0153

Shear Modulus

From figure 3-7, the shear modulus of the Carbon/CNT/Epoxy is determined as follow.

$$\gamma m = \frac{\tau}{Gm}, \gamma f1 = \frac{\tau}{Gf1}, \ \ and\ \gamma f2 = \frac{\tau}{Gf2} \qquad (73)$$

Total shear deformation on a macroscopic scale would be

$$\Delta = \gamma * m \qquad (74)$$

On a macroscopic scale

$$\begin{cases} \Delta\mathrm{m} = \mathrm{Vm} * \mathrm{W} * \gamma m \\ \Delta\mathrm{f1} = \mathrm{Vf1} * \mathrm{W} * \gamma f1 \;\; and \\ \Delta\mathrm{f2} = \mathrm{Vf2} * \mathrm{W} * \gamma f2 \end{cases} \tag{75}$$

$$Then\ because\ \Delta = \Delta m + \Delta f1 + \Delta f2 \tag{76}$$

$and\ dividing\ by\ W, we\ get$

$$\gamma = Vm * \gamma m + V_{fc} * \gamma f1 + V_{fCNT} * \gamma f2 \tag{77}$$

$$but\ \ \gamma = \frac{\tau}{G12}, therfore\ \frac{\tau}{G12} = Vm\frac{\tau}{Gm} + V_{fc}\frac{\tau}{G_{fc}} + V_{fCNT}\frac{\tau}{G_{fCNT}} \tag{78}$$

$$or\ \frac{1}{G12} = V_m\frac{1}{Gm} + V_{fc}\frac{1}{G_{fc}} + V_{fCNT}\frac{1}{G_{fCNT}} \tag{79}$$

$$G12 = \frac{Gm*G_{fc}*G_{fCNT}}{V_m*G_{fc}*G_{fCNT}+V_{fc}*Gm*G_{fCNT}+V_{fCNT}*Gm*G_{fc}} \tag{80}$$

G12=3.84Gpa

$$\frac{G_{12}}{G_m} = \frac{1+\xi(\eta_c V_{fc}+\eta_{CNT}V_{fCNT})}{1-(\eta_c V_{fc}+\eta_{CNT}V_{fCNT})} \tag{81}$$

$$\eta_c = \frac{\left(\frac{G_{fC}}{G_m}\right)-1}{\left(\frac{G_{fC}}{E_m}\right)+\xi} \tag{82}$$

$$\eta_{CNT} = \frac{\left(\frac{G_{fCNT}}{G_m}\right)-1}{\left(\frac{G_{fCNT}}{G_m}\right)+\xi} \tag{83}$$

$$\boldsymbol{G_{12} = 7.4GPa}$$

Therefore the Transverse shear modulus

$$\boldsymbol{G_{12} = 7.4GPa}$$

This is because the Halpin-Tsai equation is best for transvers shear modulus.

A material is called transversely isotropic if its behavior in the 2-direction is identical to its behavior in the 3-direction. For this case $E_2 = E_3,\ v_{12} = v_{13}, and\ G_{12} = G_{13}$ in addition we have the following relation:

$$k_{f1} = \frac{E_{fc}}{3(1-2v_{fc})} = \mathbf{191.67}\boldsymbol{Gpa} \qquad k_{f2} = \frac{E_{fCNT}}{3(1-2v_{fCNT})} = \mathbf{537.63}\boldsymbol{Gpa}$$

$k_m = \frac{E_m}{3(1-2v_m)} = \mathbf{7.5}\boldsymbol{Gpa}$

$$V23 = \mathbf{0.78}$$

$$G_{23} = \frac{E_2}{2(1+v_{23})} = \mathbf{5.5}\boldsymbol{Gpa}$$

Tensile strength of a single ply in transverse direction:

$$\frac{\mathbf{1}}{\sigma tt} = \frac{V_{fc}}{\sigma t_{fc}} + \frac{V_{fCNT}}{\sigma t_{fCNT}} + \frac{Vm}{\sigma tm} \tag{84}$$

Compressive strength of a single ply in transverse direction:

$$\frac{\mathbf{1}}{\sigma ct} = \frac{V_{fc}}{\sigma c_{fc}} + \frac{V_{fCNT}}{\sigma c_{fCNT}} + \frac{Vm}{\sigma cm} \tag{85}$$

The summarized mechanical properties of both composite materials (Carbon/Epoxy and Carbon/CNT/Epoxy) is shown in table 3-7, and 3-8.

Table 3-11: Calculated properties of carbon/epoxy laminated composite (@ Vf = 60%)

No.	**Material properties**	**Symbol**	**Value**
1	Young modulus 1-direction (GPa)	E1	139.8
2	Young modulus 2-direction (GPa)	E2	17.37
3	Young modulus 3-direction (GPa)	E3	17.37
4	Tensile Strength 1-direction (GPa)	σ_{t1}	2.68
5	Tensile Strength 2-direction (GPa)	σ_{t2}	0.306
6	Tensile Strength 3-direction (GPa)	σ_{t3}	0.306
7	Compressive Strength in 1-direction (GPa)	σ_{c1}	1.20
8	Compressive Strength in 2-direction (GPa)	σ_{c2}	0.384
9	Compressive Strength in 3-direction (GPa)	σ_{cc3}	0.384
10	Shear modulus in 12-direction (GPa)	G_{12}	7.14
11	Shear modulus in 23-direction (GPa)	G_{23}	3.08
12	Shear modulus in 13-direction (GPa)	G_{13}	7.14
13	poisons ratio 12	υ_{12}	0.28
14	poisons ratio 23	υ_{23}	0.77
15	poisons ratio 13	υ_{13}	0.28
16	Density (g/cm^3)	ρ	1.53

The table in the above shows the calculate properties of the new composite carbon/epoxy composite at 60% of carbon fiber.

Table 3-12: Calculated properties of carbon/epoxy with CNT additive laminated hybrid composite (@ Vf2= 1%)

No.	**Material properties**	**Symbol**	**Value**
1	Young modulus 1-direction (GPa)	E1	149.08
2	Young modulus 2-direction (GPa)	E2	14
3	Young modulus 3-direction (GPa)	E3	14
4	Tensile Strength 1-direction (GPa)	σ_{t1}	4.144
5	Tensile Strength 2-direction (GPa)	σ_{t2}	0.309
6	Tensile Strength 3-direction (GPa)	σ_{t3}	0.309
7	Compressive Strength in 1-direction (GPa)	σ_{c1}	2.12
8	Compressive Strength in 2-direction (GPa)	σ_{c2}	0.384
9	Compressive Strength in 3-direction (GPa)	σ_{cc3}	0.384
10	Shear modulus in 12-direction (GPa)	G_{12}	7.4
11	Shear modulus in 23-direction (GPa)	G_{23}	5.5
12	Shear modulus in 13-direction (GPa)	G_{13}	7.4
13	poisons ratio 12	υ_{12}	0.33
14	poisons ratio 23	υ_{23}	0.78
15	poisons ratio 13	υ_{13}	0.33
16	Density (g/cm^3)	ρ	1.5

In the above table 3-8 and 3-7 shows the summary of composite properties of both materials Carbon/Epoxy and Carbon/CNT/Epoxy respectively. These properties are calculated by using rule of mixture and Halpin-Tsai equation.

Using these properties summarized in the above, analysis is made for the coil spring by using ANSYS workbench.

3.2.2. Ply property analysis

Most of the composite materials are made by stacking several distinct layers of unidirectional laminas or ply [33]. Each lamina or ply is made of the same constituent materials, matrix and fiber. Figure 3 representing a unidirectional lamina with respective longitudinal and transverse directions. So, to model a composite material in it is important to calculate the stiffness of the individual lamina.

The stiffness of the lamina and laminate depends on three factors:

1. Volume fraction of the matrix and fiber.
2. Type of reinforcement used, continuous or discontinuous fiber used.
3. Orientation of fibers with respect to a common reference axis.

A single layer of these products is called a lamina or ply. The thickness of a single ply formed by using unidirectional fibers ranges from about 0.12 to 0.20 mm, whereas the thickness of a single ply of a woven or braided fabric ranges from about 0.25 to 0.40 mm. obviously, a single composite ply is quite thin. To produce a composite structure with significant thickness, many plies are stacked together to form a composite laminate.

Conceptually any number of plies may be used in the laminate, but in practice, the number of plies usually ranges from about 10 plies to (in unusual cases) perhaps as many as 200 plies. The fiber represents the reinforcing material in these composites. [54]

3.2.3. Coil spring Design

3.2.3.1. Specification

Table 3-13: Specifications of coil spring [55]

No.	**Specification**	**Value**
	General information	
1	Model of the vehicle	Bajaj RE
2	Kerb weight	307 kg
3	Cubic capacity	447.3 cc
4	Power(engine)	6.19kw@3400rpm
5	Torque (engine)	19.4Nm@2600rpm
6	Number of passengers	4
	Existing coil spring parameters	
1	Outer diameter of the spring, Do	66.88mm
2	Core diameter of the spring, Di	42.88mm
3	Wire diameter of the spring, d	12mm
5	Free length of the spring	210mm
6	Number of active coils	11
7	Total number of turns	13

Total mass =kerb mass plus mass of passenger's including the driver

Mt=307kg+ (4x75kg) assuming the average weight of man is 75kg

$$= 607kg.$$

Total weight is then

$$= 607x9.81$$

$$= 5954.67\text{N}$$

The axial load applied on the coil spring is assumed to one third of total weight. Therefore the load on the coil spring F is:

$$F = \frac{5954.67\text{N}}{3} = 1984.89N$$

3.2.3.2. Fatigue Loading of Helical Compression Springs

According to [56], springs are almost always subject to fatigue loading. In many instances the number of cycles of required life may be small, say, several thousand for a padlock spring or a toggle-switch spring. But the valve spring of an automotive engine must sustain millions of cycles of operation without failure; so it must be designed for infinite life.

FATIGUE OF COMPOSITES

Fatigue properties of a material are its response to cyclic loading. Fatigue strength is lower than static strength. On a macro- scale fatigue failures appear to occur with little or no gross plastic deformation, however a micro examination of the fatigued surface often reveals evidence of plastic deformation. Fatigue life depends on stress level, state of stress, mode of cycling, process history, and environmental condition.

The effect of mean stress on fatigue strength

The fatigue strength for a given cyclic life time at any load amplitude depends upon the mean stress, sm. For the same given fatigue life it is evident that the stress amplitude, σ_a (fatigue strength) must be reduced as the mean stress is increased. To avoid having to make fatigue measurements at all possible mean loads, an empirical method called the Goodman plot is commonly employed. The so- called "Goodman Line" is just a linear reduction in the fatigue strength (the stress amplitude for a given fatigue life) with increasing mean stress at a rate proportional to the ratio of the fatigue strength at zero mean stress, σ_a^o (fully reversed loading) to the tensile strength, σ_{UT} . The Goodman relation is thus expressed as;

$$\frac{\sigma_a}{\sigma_a^o} = 1 - \frac{\sigma_m}{\sigma_{UT}} \qquad (86)$$

For polymer composites a modification of the Goodman line is needed to more accurately predict the effect of mean stress on fatigue strength. In this modification, the Goodman - Boller line uses the stress rupture strength at the time corresponding to the cyclic life, σ_a for the x - axis intercept instead of the tensile strength. The Goodman - Boller relation is thus

$$\frac{\sigma_a}{\sigma_a^o} = 1 - \frac{\sigma_m}{\sigma_C} \qquad (87)$$

A helical coil spring force-deflection characteristic is ideally linear. Practically, it is nearly so, but not at each end of the force-deflection curve. The spring force is not reproducible for very small deflections, and near closure, nonlinear behavior begins as the number of active turns diminishes as coils begin to touch. The designer confines the spring's operating point to the central 75 percent of the curve between no load, $F = 0$, and closure, $F = Fs$. Thus, the maximum operating force should be limited to $Fmax \leq \frac{7}{8}Fs$. Defining the fractional overrun to closure as ξ, where:

$$Fs \ = (1 + \xi)Fmax \qquad (88)$$

It follows that

$$Fs \ = (1 + \xi)Fmax = (1 + \xi)(\frac{7}{8})Fs \qquad (89)$$

Thus, it is recommended that ξ≥0.15. So taking $\xi = 0.15$

$$\mathbf{Fs = 2KN}$$

Helical springs are usually assembled with a preload so that the working load is additional. The worst condition, then, would occur when there is no preload, that is, when $\tau_{min} = 0$. now, we define;

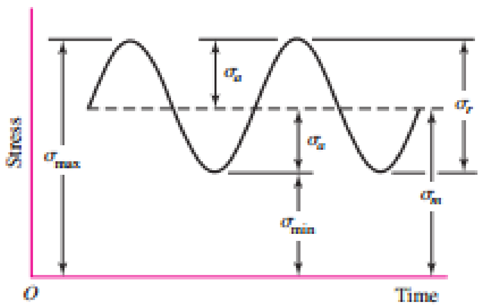


Figure 3-10: The stress-time for helical springs [56]

$$Fa = \frac{Fmax - Fmin}{2} \quad (90)$$

$$Fm = \frac{Fmax + Fmin}{2} \quad (91)$$

$Assuming\ fully\ reversed, Fa = 1000N, and\ Fm = 1000N$

Where the subscripts have the same meaning as those of Fig3-7 when applied to the axial spring force F. Then the shear stress amplitude is

$$\tau_a = K_B \frac{8F_aD}{\pi d^3} \quad (92)$$

Where, KB $= \frac{4C+2}{4C-3}$

The midrange shear stress is given by the equation

$$\tau_m = K_B \frac{8F_mD}{\pi d^3} \quad (93)$$

Shearing ultimate strength is estimated from

$$\tau_{su} = 0.67\sigma_{ut} \tag{94}$$

S-N curve fatigue properties

The S-N curve the most popular method of characterizing the fatigue behavior of composite materials. Several empirical equations exist for describing S-N curves. Most are based on the classical power law that gives a straight line in a log-log plot of the fatigue data, but some possess refinements to account for mean stress or the ratio of maximum stress to minimum stress.

S-N curve for steel spring

Table 3-14: Number of cycles versus alternating stress of Steel spring

Number of cycles	Alternating stress
10	4028.050577
20	3458.345002
50	2826.972046
100	2427.140488
200	2083.858933
2000	1255.649176
10000	881.2414472
20000	756.6034477
100000	531.0004816
200000	455.8986603
1000000	319.9594304

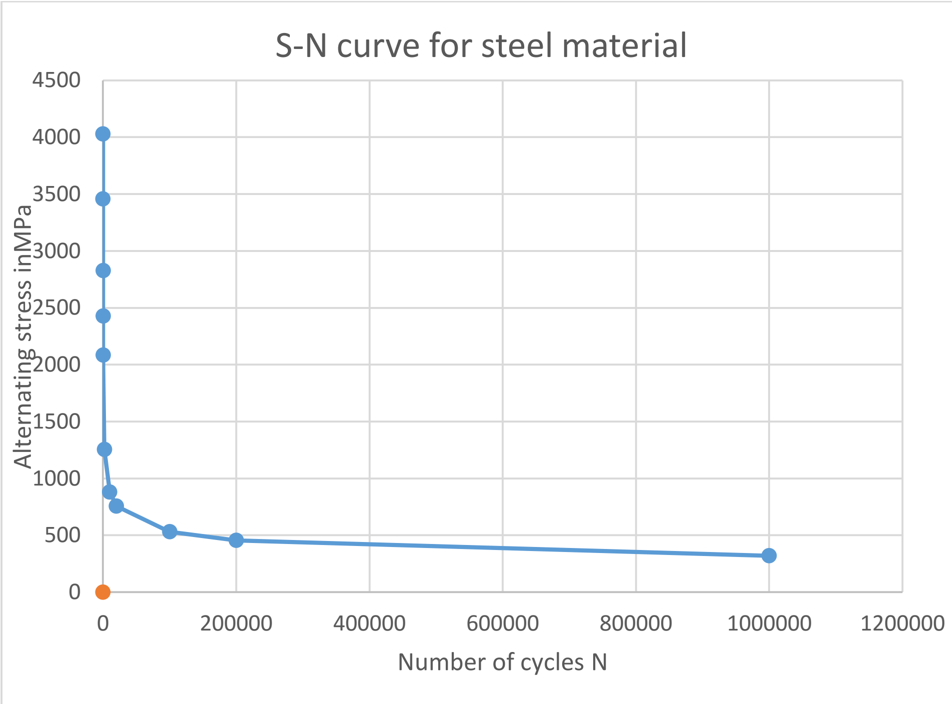


Figure 3-11: S-N curve of Steel spring

S-N curve for composite

One of the simpler equations used to describe the fatigue behavior of several composite materials is as follows: [57],

$$\sigma_A = \sigma_{ut} - b * log\ N \qquad (95)$$

Where σ_A is the maximum applied stress, σ_u is the static strength (ultimate strength), b is a constant and N is the number of cycles to failure.

For Carbon/Epoxy composite material ultimate strength σ_u is $2680 Mpa$. The S-N curve is predicted considering the figure bellow:

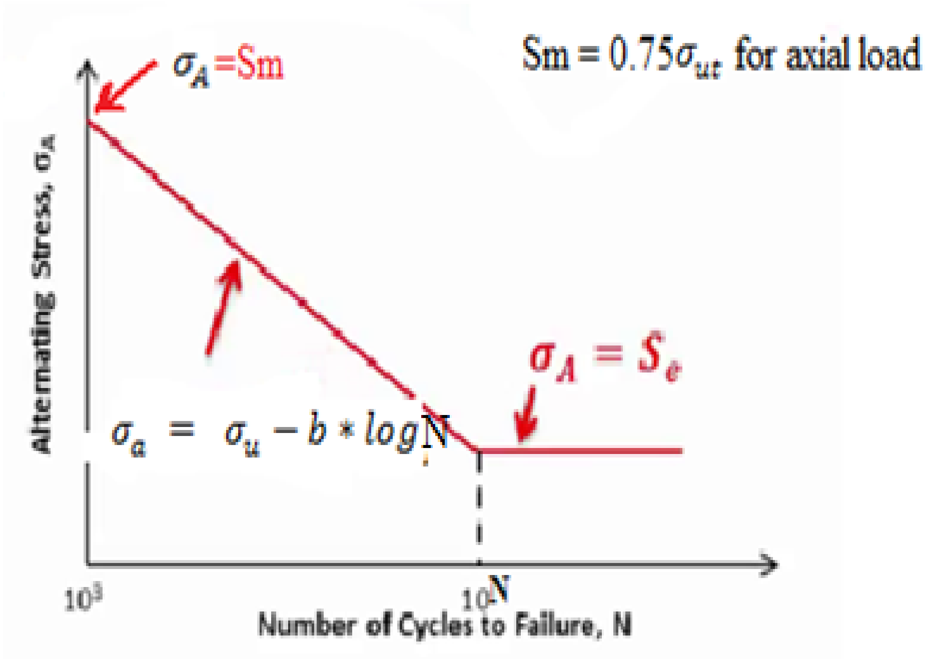


Figure 3-12: S-N curve representation [58]

$Sm = 0.75\sigma_{ut} = 2010Mpa$

At $N = 10^3, \sigma_A = Sm$

Therefore, the constant is calculated by substituting $\sigma_A = 2010Mpa\ and\ \sigma_{ut} = 2680Mpa$

Hence $b = 223.33$

The equation of S-N curve becomes:

$$\sigma_A = 2680\text{Mpa} - 223.33 * \log N$$

Similarly the S-N curve equation for Carbon/CNT/Epoxy material is given by:

$$\sigma_A = 4144\text{Mpa} - 345.33 * \log N$$

We can compare the composite materials based on their alternating stress as shown in Table 3-10

Table 3-15: Number of cycles versus alternating stress of both composites

Number of cycles	Alternative stress for Carbon/epoxy	Alternative stress for Carbon/CNT/epoxy
10	2456.67	3798.67
100	2233.34	3453.34
1000	2010.01	3108.01
10000	1786.68	2762.68
100000	1563.35	2417.35
1000000	1340.02	2072.02
10000000	1116.69	1726.69
1E+08	893.36	1381.36
1E+09	670.03	1036.03
1E+10	446.7	690.7
2E+10	379.06	586.74
2E+11	223.37	345.37

S-N curve for both materials is shown in graph in bellow. The red color line is S-N curve for Carbon/CNT/Epoxy material and the lower one with blue color is Carbon/Epoxy composite material. From the S-N graph we can clearly see that the Carbon/CNT/Epoxy has better life than the Carbon/Epoxy composite material.

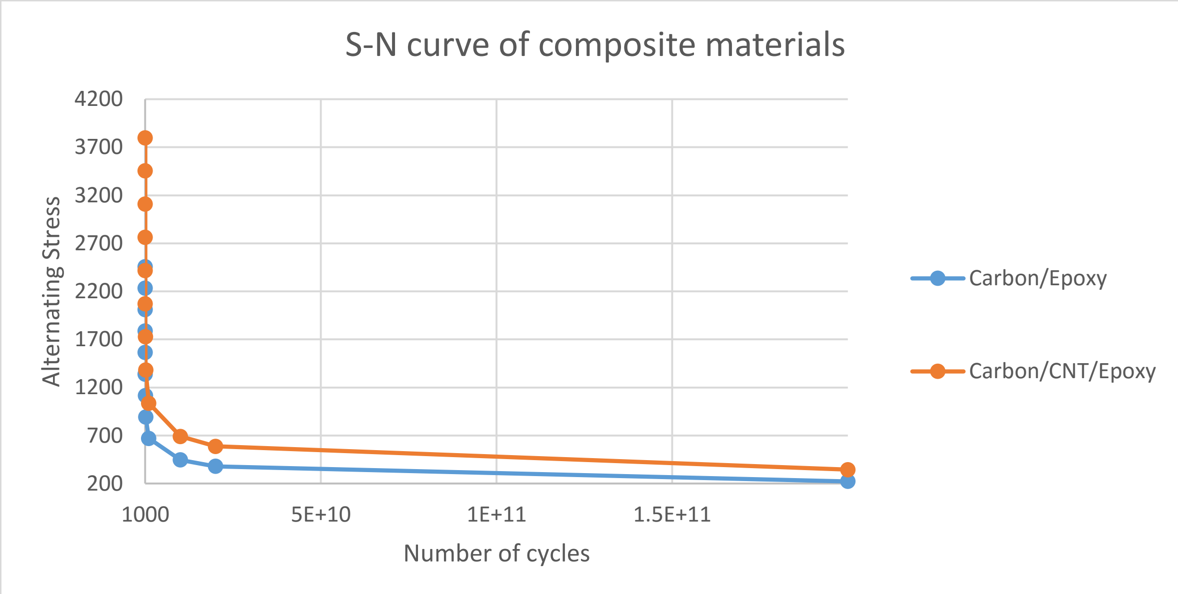


Figure 3-13: S-N curve comparison for both composites

3.2.3.3. Terms used in Compression Springs

The following terms used in connection with compression springs are important from the subject point of view. [58]

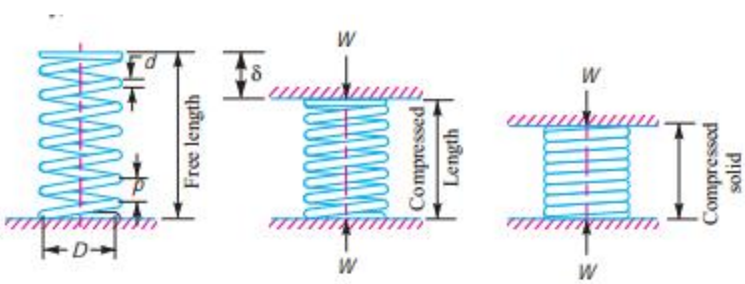


Figure 3-14: Terms used in Compression Springs [58]

1. ***Solid length***; when the compression spring is compressed until the coils come in contact with each other, then the spring is said to be solid. The solid length of a spring is the product of total number of coils and the diameter of the wire. Mathematically, Solid length of the spring, [58]

$$LS = Nt\ X\ d \qquad (96)$$

$$\boldsymbol{Ls = 144mm}$$

Where $Nt = Total\ number\ of\ coils, and$

$$d = Diameter\ of\ the\ wire.$$

2. ***Free length***; the free length of a compression spring, is the length of the spring in the free or unloaded condition. It is equal to the solid length plus the maximum deflection or compression of the spring and the clearance between the adjacent coils (when fully compressed). [58]

Mathematically

$$\text{LF} = \text{Solid length} + \text{Maximum compression} + \text{Clearance between adjacent coils}$$

(Or clash allowance)

$$= Nt\ X\ d + \delta max + 0.15\delta\ max \qquad (97)$$

The following relation may also be used to find the free length of the spring,

$$i.e. LF = Nt\ X\ d + \delta max + (N - 1) \times 1\ mm \qquad (98)$$

In this expression, the clearance between the two adjacent coils is taken as 1 mm.

3. ***Spring index***. The spring index is defined as the ratio of the mean diameter of the coil to the diameter of the wire.

Mathematically,

$$Spring\ index, C = \frac{D\prime}{d} \qquad (99)$$

Where D' = Mean diameter of the coil, and $\text{D} = \text{Do} - \text{d} = \mathbf{54.88mm}$

d = Diameter of the wire.

$C = \frac{D}{d} =$ **4.573** for existing coil spring

4. ***Spring rate***. The spring rate (or stiffness or spring constant) is defined as the load required per unit deflection of the spring.
   Mathematically,

$$Spring\ rate, k = \frac{F}{\delta} \qquad (100)$$

$$Where \quad F = Load, and$$
$$\delta = Deflection\ of\ the\ spring.$$

5. Pitch. The pitch of the coil is defined as the axial distance between adjacent coils in uncompressed state. Mathematically,

$$Pitch\ of\ the\ coil, p = \frac{Free\ length}{N-1} \qquad (101)$$

The pitch of the coil may also be obtained by using the following relation, i.e. Pitch of the coil,

$$p = \frac{Lf - Ls}{Nt} + d \qquad (102)$$

Where

$$Lf = Free\ length\ of\ the\ spring,$$

$$Ls = Solid\ length\ of\ the\ spring,$$

$$Nt = Total\ number\ of\ coils, and$$

$$d = Diameter\ of\ the\ wire.$$

$$\boldsymbol{p = 17.5mm}$$

In choosing the pitch of the coils, the following points should be noted:

(a) The pitch of the coils should be such that if the spring is accidently or carelessly compressed, the stress does not increase the yield point stress in torsion.

(b) The spring should not close up before the maximum service load is reached.

3.2.3.4. Stresses in Helical Springs

The flexing of a helical spring creates torsion in the wire and the force applied induces a direct stress. The maximum stress in the wire may be computed by super position.

The result is:

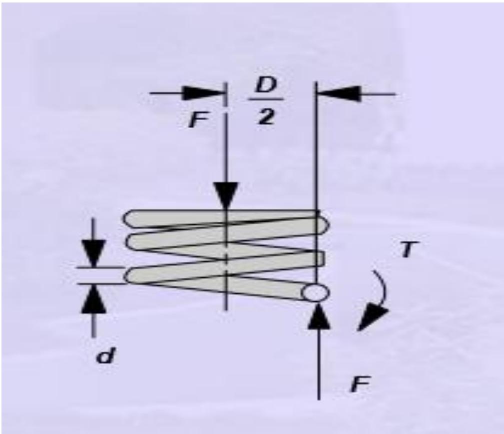


Figure 3-15: Helix spring free body diagram

The spring is under the action of two forces; the axial force (F) and the twisting moment (T) which can be seen in Figure 3-9.

$$\tau_{max} = + \frac{+Tr}{J} + \frac{F}{A} \qquad (103)$$

Replacing the terms;

$$T = \frac{FD}{2} \tag{104}$$

$$r = \frac{d}{2} \tag{105}$$

$$J = \frac{\pi d^4}{32} \quad and \tag{106}$$

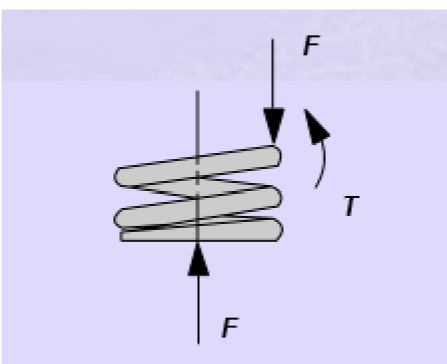
$$A = \frac{\pi d^2}{4} \tag{107}$$

So the torsional shear stress;

$$\tau_1 = \frac{8FD}{\pi d^3} \tag{108}$$

The direct shear stress due to axial load F;

$$\tau_2 = \frac{8F}{\pi d^2} \tag{109}$$



The resultant shear stress in the wire becomes;

$$\tau = \tau_1 \pm \tau_2 = \frac{8FD}{\pi d^3} \pm \frac{8F}{\pi d^2} \tag{110}$$

Positive sign is for the inner edge and negative sign is for the outer edge of the wire.

As a result, the maximum shear stress;

$$\tau_{max} = \tau_1 + \tau_2 = \frac{8FD}{\pi d^3} + \frac{8F}{\pi d^2} \qquad (111)$$

And rearranging,

$$\tau_{max} = K_s \frac{8FD}{\pi d^3} \; or \; \tau_{max} = K_s \frac{8FC}{\pi d^2} \qquad (112)$$

Where Ks is the shear-stress correction factor and is defined by the equation:

$$K_s = \frac{2C+1}{2C} \qquad (113)$$

$K_s = 1.109$

Therefore the shear stress for design load of F=200N is:

$$\tau = K_s \frac{8FC}{\pi d^2} = \mathbf{180MPa}$$

Curvature Effect

According [58], the curvature of the wire increases the stress on the inside of the spring, an effect very similar to stress concentration but due to shifting of the neutral axis away from the geometric center, as could be observed in curved beams. Consequently the stress on the inside surface of the wire of the spring, increases but decreases it only slightly on the outside. The curvature stress is highly localized that it is very important only fatigue if is present.

This effect can be neglected for static loading, because local yielding with the first application of the load will relieve it. The combined effect of direct shear and curvature correction is accounted by Wahl's correction factor and is given as:

$$\tau_{max} = K_w \frac{8FD}{\pi d^3} \qquad (114)$$

The combined effect of direct shear and curvature correction is accounted by Wahl's correction factor and is given as: [59]

$$K_w = \frac{4C-1}{4C-4} + \frac{0.615}{C} \qquad (115)$$

$$\boldsymbol{K_w = 1.344}$$

$$\boldsymbol{\tau_{max} = 217.6\text{MPa}}$$

The values of K for a given spring index (C) may be obtained from the graph as shown in

Figure 3-10 [58]

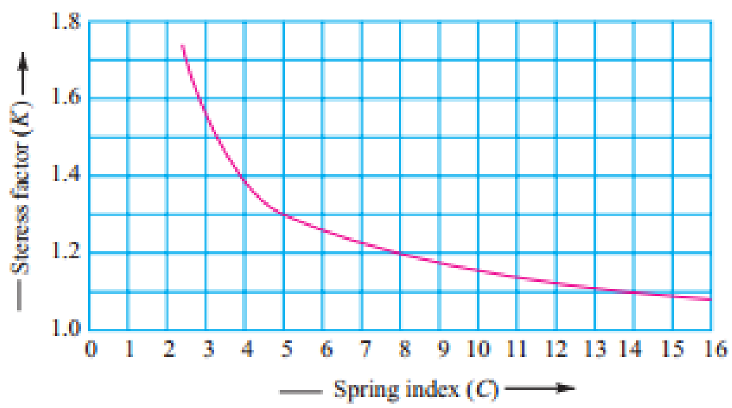


Figure 3-16: Wahl's stress factor for helical springs. [58]

3.2.3.5. Deflection and Stiffness of the spring

A systems strain energy is related to its force deflection behavior and using the Castiglione's theorem the deflection of a spring can be estimated using the strain energy stored in it. The total strain energy for a helical spring is composed of torsional component and a shear component. The shear component is quite negligible, and the final equation is, [58]

$$u = \frac{T^2}{2G} * \frac{Ls}{J} + \frac{F^2}{2A} * \frac{1}{G} \qquad (116)$$

The spring rate and hence:

$$T = F\frac{D}{2};\ Ls = \pi DN: J = \pi * \frac{d^4}{32}\ and\ A = \pi\frac{d^2}{4}$$

Where N is the number of active coils. The deflection in the spring, using Castiglione's theorem

$$\delta = \frac{\partial U}{\partial F} = \frac{8FD^3N}{Gd^4} \qquad (117)$$

Substituting $C = \frac{D}{d}$ and rearranging

$$\delta = \frac{8FD^3N}{Gd^4}\left(1 + \frac{1}{2C^2}\right) \qquad (118)$$

For design load of 2000N, the deflection for the steel spring and the composites is:

$$\delta = \frac{8FD^3N}{Gd^4}\left(1 + \frac{1}{2C^2}\right)$$

Shear modulus G is 7666.6Mpa, 7400Mpa, and 7100Mpa for steel spring, Carbon/CNT/Epoxy and Carbon /Epoxy respectively.

Substituting the coil spring specifications and shear modulus, deflection for Steel material is 19.032mm. For Carbon/CNT/Epoxy and Carbon/Epoxy composite is 215.67 mm and 250mm respectively.

From this result deformation of composite spring is too big comparing with steel spring. Therefore, by optimizing the geometry of the coil spring; deformation can be reduced by decreasing mean diameter, increasing wire diameter or reducing number of coils.

Development of Optimization Method of the Helical Spring

Optimization, in general sense, refers to the process of minimizing or maximizing the costs/benefits of some objective function over a period of time.

Design variables

Design variables are parameters that are chosen to describe the design of a system. Design variables are controlled by the designers. For computational design optimization of helical spring, objective function and constraints must be expressed as a function of design variables.

In this study a circular cross section spring is considered. Three geometrical proprieties of the spring are chosen as design variables, namely, the wire diameter d, the mean diameter of coil spring, and active coil number Na.

These parameters are presented in the design parameters vector:

$$\{X\} = (x_1\ x_2\ x_3)^T = (d\ D\ N_a)^T \qquad (119)$$

The other parameters are supposed fixes.

Constraints conditions

Constraints are the conditions that must be met in the optimum design and include restrictions on design variables. These constraints define boundaries of the feasible and infeasible design space domain.

Following hypotheses are assumed to be taken:

- The wire section is and remains circular.
- The ends of the springs are ground and strengthened to make a perpendicular plans to the spring axis to support it without friction.

Condition of shear stress

When helical spring is loaded by axial force, shear stress is exerted in the spring wire. By using superposition, the shear stress in the inside fiber of the spring can be computed. In order to avoid the structure damage, when the spring is loaded with an axial force F, the condition of shear stress is, the maximum shear stress τ_{max} should be less than the allowable shear resistance R_{pg} [61]

$$\tau_{max} = 1.66\left(\frac{d}{D}\right)^{0.16}\frac{8F_{max}D}{\pi d^3} \leq R_{pg} \qquad (120)$$

R_{pg} is taken as shear stress of steel coil spring

F_{max} is the maximum axial load. So the condition of the shear stress can be expressed as follow;

$$c_1(x): -R_{pg} + 4.23F_{max}\frac{x_2^{0.84}}{x_1^{2.84}} \leq 0 \qquad (121)$$

Condition of maximum axial deflection

When a helical spring is loaded by the axial force F, deflection is also exerted in spring. To obtain the equation for the deflection of a helical spring, an element of wire formed by two adjacent cross sections is considered. An element, the length of it is dx, cut from wire of diameter d. This element is on the surface of wire which is parallel to the spring axis. When loaded by force F and after deformation it will rotate through the angle and occupy the new position. The deflection of a wire element is given by [60]:

$$\delta = \frac{8FD^2(N_a+2)\sqrt{(\pi D)^2+p^2}}{G\pi d^4} \qquad (122)$$

To ensure that the axial deflection is less than the maximum axial deflection, the maximum load that leads to the expected maximum axial deflection should be larger than the working force $F_{max} \geq F$.So the condition of the maximum axial deflection can be expressed by the following equation[60]

$$c_2(x): \frac{G\pi f {x_1}^4}{8{x_2}^2(x_3+2)\sqrt{(\pi x_2)^2+p^2}} - F_{max} \leq 0 \qquad (123)$$

Condition of fatigue strength

The spring designed for variable stresses with a great number of cycles should be checked for resistance to fatigue. When a spring is subjected to alternating forces F_{min} to F_{max} the stresses for spring are obtained from these two equations

$$\tau_{min} = K\frac{8F_{min}D}{\pi d^3} \qquad \tau_{max} = K\frac{8F_{max}D}{\pi d^3} \qquad (124)$$

So the fatigue strength condition can be defined in this equation

$$c_3(x): S - \frac{0.33\sigma_B x_1^{2.84}}{4.23F_{max}x_2^{0.84}} - 0.75\frac{F_{min}}{F_{max}} \leq 0 \qquad (125)$$

Considering the three conditions $c_1(x)$, $c_2(x)$ and $c_3(x)$ explained in equations 121, 123, and 125 in the above the coil spring is modified in to the followng shown in table 3-16.

Error and trial mated is used to satisfy the three conditions to optimize the weight of the coil spring for the composites.

The coil specification are modified as shown in table below:

Table 3-16: Modified coil spring specifications

Specifications	values
Mean diameter of coil	52mm
Wire diameter	19mm
Total number of turns	9

Now calculate the deformation of modified coil spring:

For Carbon/CNT/Epoxy deformation at axial load of 2000N is $\boldsymbol{\delta 1}$

$$\boldsymbol{\delta 1 = 18.75mm}$$

And for Carbon/Epoxy the deformation is $\boldsymbol{\delta 2}$

$$\boldsymbol{\delta 2 = 22mm}$$

Therefore, the spring rate or spring stiffness is defined by:

$$K = \frac{F}{\delta} \qquad (126)$$

Therefore the spring rate are 105.086N/mm, 90.9N/mm and 106.67N/mm for Steel, Carbon/epoxy, and Carbon/CNT/Epoxy coil springs respectively.

3.2.3.6. End Construction

Coil compression springs generally use four different types of ends. These are illustrated in Figure below. And Table shows how the type of end used affects the number of coils and the spring length. For important applications the ends of springs should always be of both squared and ground, because a better or even transfer of the load is obtained.

Therefor coil spring for suspension system is squared and ground with;

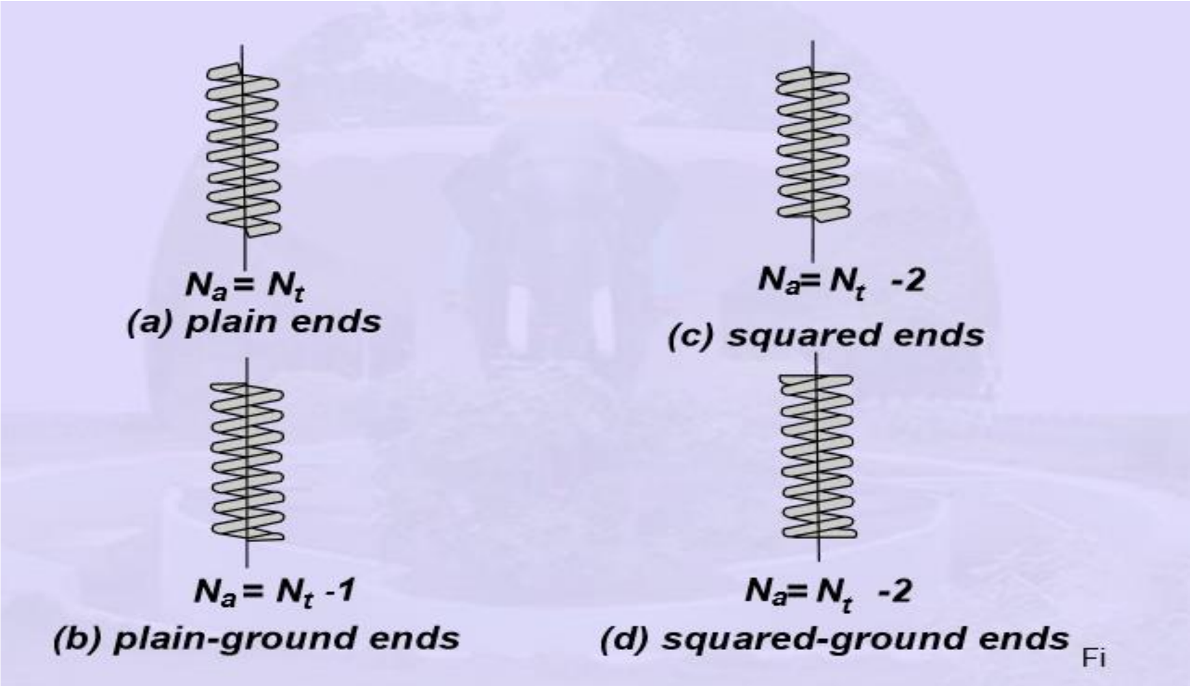


Figure 3-17: Helix coil spring End Construction types

Table 3-17: Summary of coil spring parameter determining formulas [58]

Terms	Plain	Plain and ground	Square or closed	Square and Ground
End coils, N_e	0	1	2	2
Total coils N_t	N_a	$N_a + 1$	$N_a + 2$	$N_a + 2$
Free length, L_f	$pN_a + d$	$P(N_a + 1)$	$pN_a + 3d$	$pN_a + 2d$
Solid length, L_s	$d(N_t + 1)$	dN_t	$d(N_t + 1)$	dN_t
Pitch, p	$(L_f - d)/N_a$	$L_f/(N_a + 1)$	$(L_f - 3d)/N_a$	$(L_f - 2d)/N_a$

Mass of coil spring

Weight of coil spring is density dependent, and is given by the expression:

$$M = \rho V$$

Where ρ is density of the material

V is Volume of coil spring which is found by multiplying Area of coil spring wire by length wire. Volume of steel spring, Carbon/Epoxy and carbon/CNT/Epoxy spring are the same for the existing coil spring specifications.

$Mass\ of\ Steel\ spring\ = 1.975\ kg$

$Mass\ of\ Carbon/Epoxy\ spring = 0.38493\ kg$

$Mass\ of\ carbon/CNT/Epoxy\ spring = 0.37739\ kg$

For modified coil spring the mass increases by some percentages. But still they are lighter than the steel spring.

3.2.4. Helical coil spring modeling and analysis

Using the analytically calculated values, and the parameters in table 3-8, Coil spring is modeled in **CATIA V5R19** as shown in Figure 3-13 below. Then the model is converted in to the **IGES** format which is most suitable and accessible for any other software. Using the **IGES** format the coil spring model from **CATIA V5R19** is imported to **ANSYS Workbench17.2**. Then mesh the coil spring shown in Figure. After meshing boundary conditions and Loading conditions are applied as shown in Figure 3-14 and Figure 3-15 respectively.

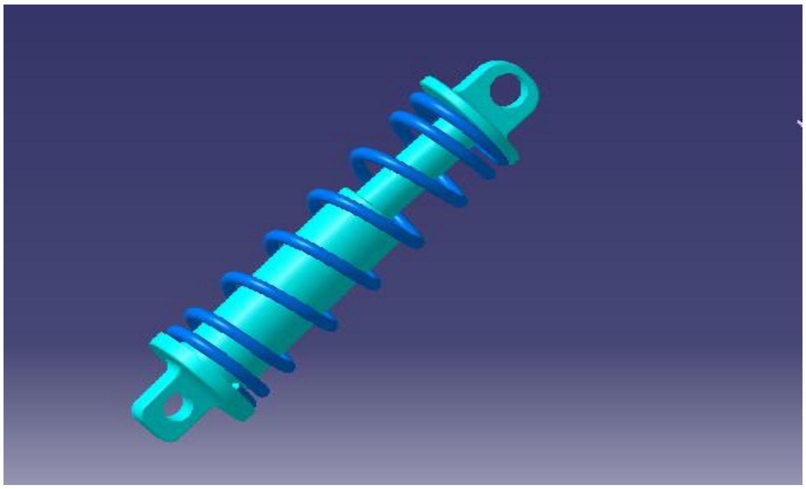


Figure 3-18: Bajaj RE suspension system

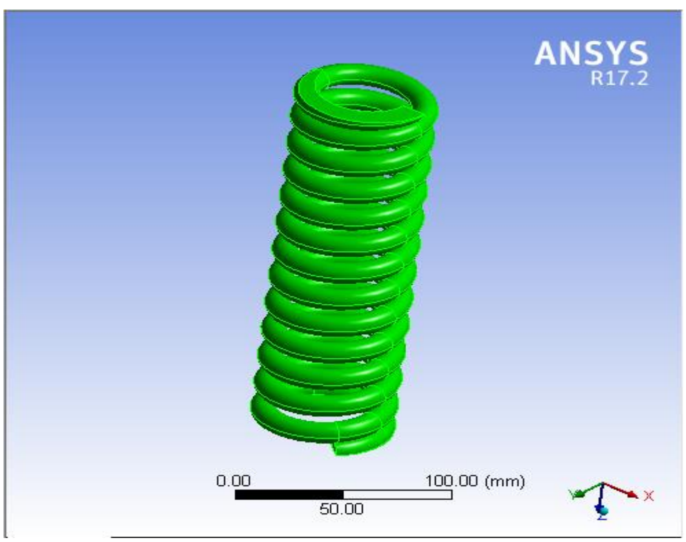


Figure 3-19: Helical coil spring 3D model imported from CATIA

Boundary conditions

To perform static analysis, few constraints are applied to the component as the component contains several degrees of freedom, restriction of few of these degrees of freedom is achieved by applying boundary conditions. In static analysis the helical spring is provided with fixed support constraint at one end and Load of 2000N is applied at the other end for all materials.

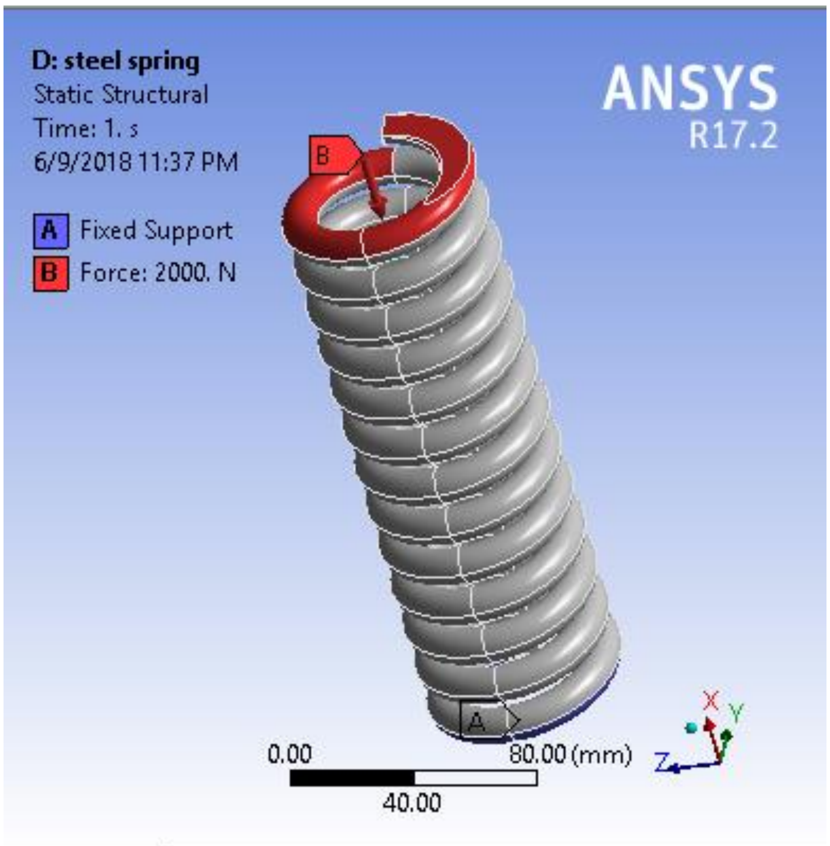


Figure 3-20: Boundary conditions representation of coil spring

Meshing

As shown in the figure in below afine mesh is applied to to get th exact solution of the analysis. For all medels a mesh with element size of 2mm is applied. For steel coil spring and for unmodiefid model of both composites there are 296621 nodes annd 174114 elements. And for the modified model there are 77370 nodes and 43969 elements each elements having a size of 2mm.

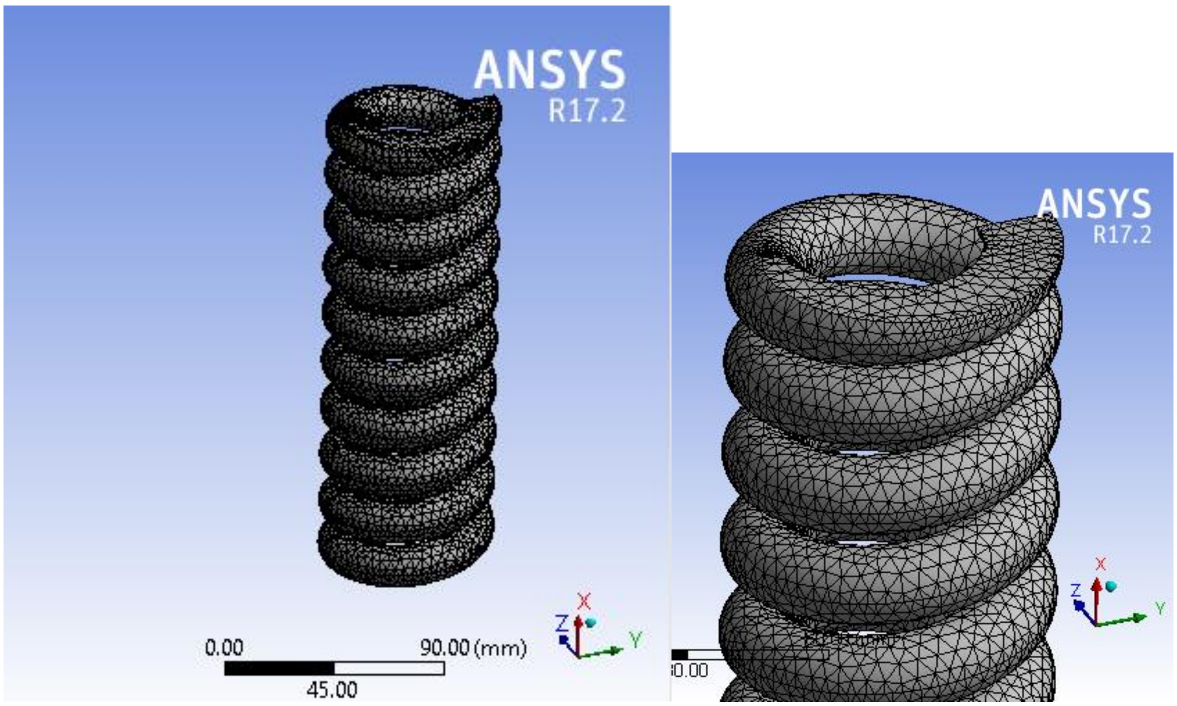


Figure 3-21: Meshing

CHAPTER FOUR

4. RESULT AND DISCUSSION

In this chapter the result of finite element analysis procedure is interpreted and discussed briefly. Since finite element analysis procedures are invariably accompanied by an extensive output of data, it is extremely important that we interpret the results correctly.

4.1. Results

After applying the boundary conditions and loads on both existing and modified 3D model of the coli spring, results of Deformation, strain energy, maximum shear stress, and Equivalent strain effect at different load is explain using tabular form and graphs.

Deformation Results

The deformation result of the coil spring for the existing steel material and the two composites is as shown in

Table 4-1: Comparison of Steel spring with same specification of composite coil spring

Load(N)	Deflection of existing coil spring model (mm)					
	Steel spring		Carbon/CNT/Epoxy		Carbon/Epoxy	
	FEA	Analytical	FEA	Analytical	FEA	Analytical
100	0.995	0.951539	10.717	10.78098	13.54979	12.6068
500	4.975	4.757695	53.584	53.9049	67.74894	63.034
1000	9.95	9.51539	107.17	107.8098	135.4979	126.068
1500	14.926	14.27309	160.75	161.7147	203.2468	189.102
1600	15.9	15.22462	171.47	172.4957	216.7966	201.7088
2000	19.9	19.03078	214.34	215.6196	270.9958	252.136
2500	24.876	23.78848	267.92	269.5245	338.7447	315.17
3000	29.85	28.54617	321.5	323.4294	406.4937	378.204
3500	34.83	33.30387	375.09	377.3343	474.2426	441.238
4000	39.8	38.06156	428.67	431.2392	541.9915	504.272
5000	49.75	47.57695	535.84	539.049	677.4894	630.34

Table 4-1 shows the deflection comparison of Steel coil spring, Carbon/CNT/Epoxy, and Carbon/Epoxy for existing spring model. This is because Composite materials has less shearing properties than steel materials. So as the result shows the deflection for both composites is very large for higher load. Therefore, composite coil spring is not recommended if the parameters of the coil spring are not modified.

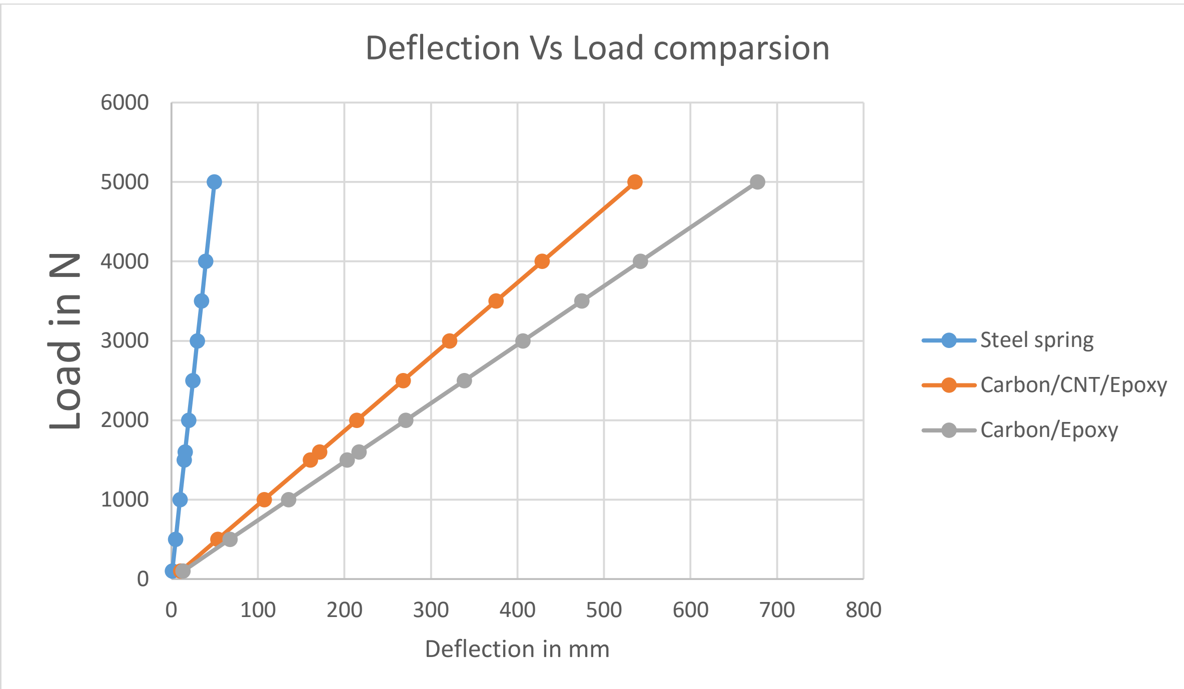


Figure 4-1: Load Versus Deformation for existing coil springs model

Figure 4-1 shows the graphical comparison of deflection for all materials. From the figure, the blue color represents the Steel coil spring deflection, the red color represents deflection of Carbon/CNT/Epoxy and the remaining black color represent for Carbon/Epoxy deflection. So as shown (fig 4-1) in deformation for composite material is larger than steel material. Therefore, modification of the existing specification is needed to reduce the deflection for composite coil spring. Hence, for the modified coil spring model the deformation versus load is shown in figure 4-2.

Table 4-2: Deflection Comparison of Steel spring with Modified composite coil spring model

Load(N)	Deflection of Modified coil spring model (mm)					
	Steel spring		Carbon/CNT/Epoxy		Carbon/Epoxy	
	FEA	Analytical	FEA	Analytical	FEA	Analytical
100	0.995	0.951539	0.96	0.937558	1.3114	1.096
500	4.975	4.757695	4.793	4.687788	6.557	5.48
1000	9.95	9.51539	9.59	9.375576	13.114	10.96
1500	14.926	14.27309	14.38	14.06336	19.671	16.44
1600	15.9	15.22462	15.34	15.00092	20.982	17.536
2000	19.9	19.03078	19.17	18.75115	26.228	21.92
2500	24.876	23.78848	23.97	23.43894	32.785	27.4
3000	29.85	28.54617	28.76	28.12673	39.342	32.88
3500	34.83	33.30387	33.554	32.81452	45.899	38.36
4000	39.8	38.06156	38.347	37.5023	52.456	43.84
5000	49.75	47.57695	47.93	46.87788	65.57	54.8

Table 4-2, shows the deflection result of both FEA and analytical (manually by applying formula) for the modified coil spring model of the three materials. By modifying the existing coil spring deflection of composite coil spring is reduced enough.

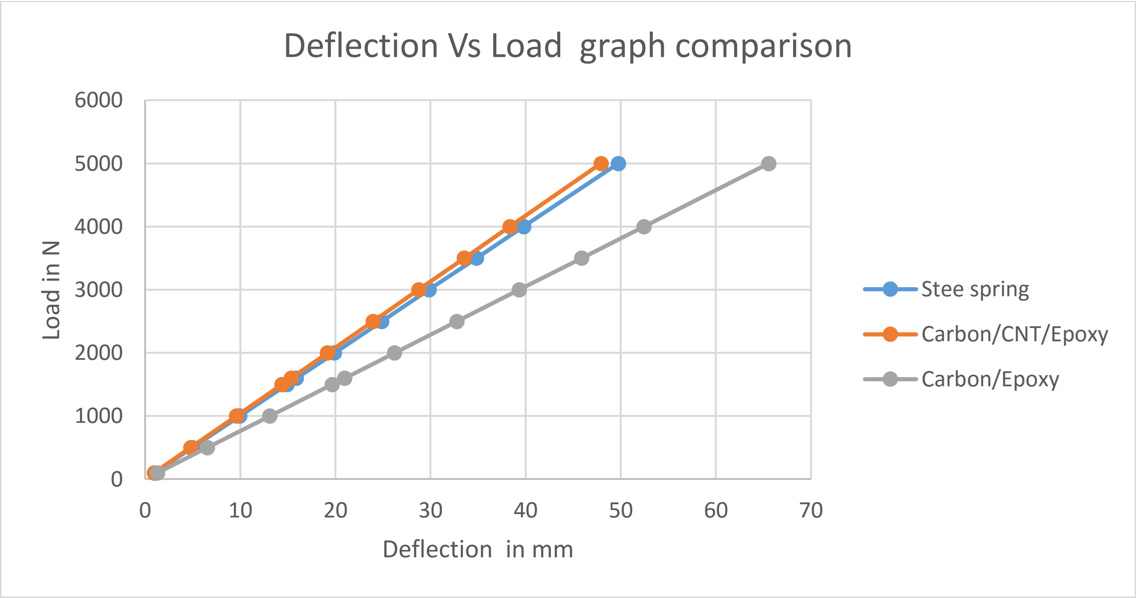


Figure 4-2: Load versus deflection for Modified coil spring

Now as shown in the above graph the deflection of Carbon/CNT/Epoxy is less than both steel coil spring and Carbon/Epoxy.

Maximum shear stress results

Table 4-3: Maximum shear stress comparison for Existing coil spring model

Load(N)	Maximum shear stress of Existing coil spring model (MPa)					
	Steel spring		Carbon/CNT/Epoxy		Carbon/Epoxy	
	FEA	Analytical	FEA	Analytical	FEA	Analytical
100	10.71	10.875	11.172	10.875	11.06	10.875
500	53.53	54.375	55.858	54.375	55.06	54.375
1000	107.1	108.75	111.72	108.75	110.61	108.75
1500	160.6	163.125	167.57	163.125	165.91	163.125
1600	171.3	174	178.75	174	176.97	174
2000	214.1	217.5	223.43	217.5	221.21	217.5
2500	267.6	271.875	279.29	271.875	276.52	271.875
3000	321.2	326.25	335.15	326.25	331.82	326.25
3500	374.7	380.625	391.01	380.625	387.12	380.625
4000	428.2	435	446.86	435	442.42	435
5000	535	543.75	558.58	543.75	553.03	543.75

Table 4-3 shows Maximum shear stress result of the three materials coil spring using both FEA method and analytical method. The result shows that the maximum shear stress for all materials is very similar for existing coil spring model. This because shear stress does not depend on materials properties.

Maximum shear stress is force dependent. As axial compression load increases Maximum shear stress increases. The comparison of maximum shear stress for these three materials for existing coil spring is shown graphically in figure 4-3.

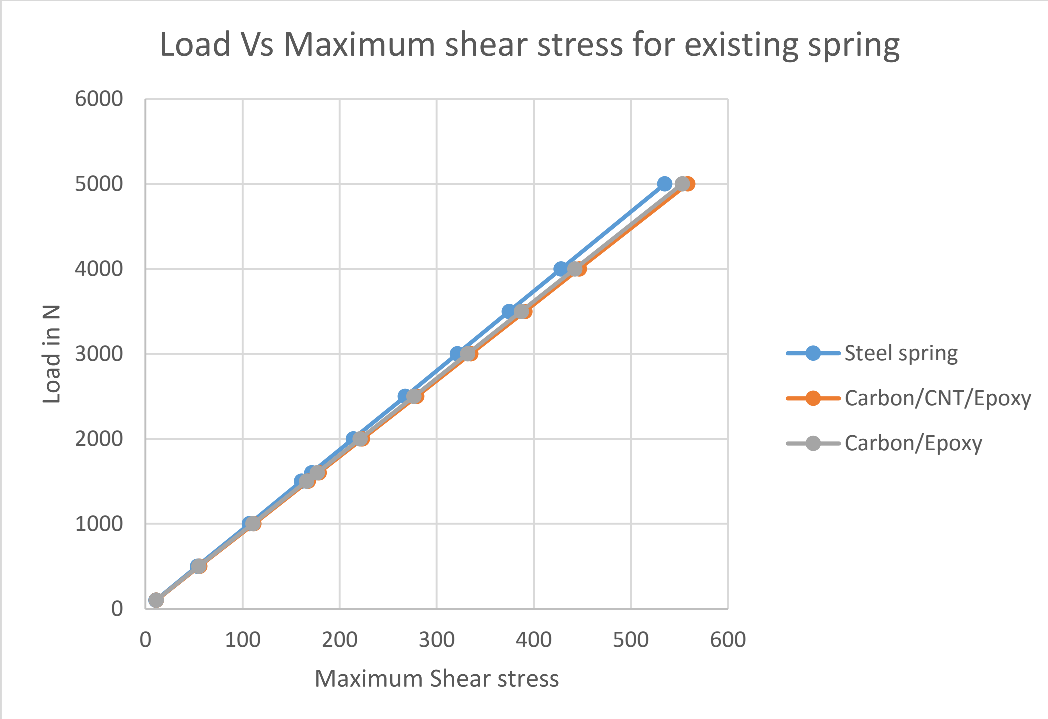


Figure 4-3: Maximum shear stress for Existing coil spring model

The shear stress for the existing coil spring is similar for all materials with 1% average error between materials and 1.56% error between FEA and analytical values.

Table 4-4: Maximum Shear stress comparison of steel with modified coil springs

Load(N)	Maximum shear stress of Modified coil spring model (MPa)					
	Steel spring		Carbon/CNT/Epoxy		Carbon/Epoxy	
	FEA	Analytical	FEA	Analytical	FEA	Analytical
100	10.71	10.875	3.146	3.199959	3.2952	3.199959
500	53.53	54.375	15.732	15.99979	16.476	15.99979
1000	107.1	108.75	31.46	31.99959	32.952	31.99959
1500	160.6	163.125	47.195	47.99938	49.427	47.99938
1600	171.3	174	50.34	51.19934	52.723	51.19934
2000	214.1	217.5	62.926	63.99918	65.903	63.99918
2500	267.6	271.875	78.658	79.99897	82.379	79.99897
3000	321.2	326.25	94.39	95.99877	98.855	95.99877
3500	374.7	380.625	110.12	111.9986	115.33	111.9986
4000	428.2	435	125.85	127.9984	131.81	127.9984
5000	535	543.75	157.32	159.9979	164.76	159.9979

Since the coil spring is modified to reduce the deflection, maximum shear stress has positive impact for the modified coil spring. Maximum shear stress reduces for modified coil spring as shown in table 4-4.

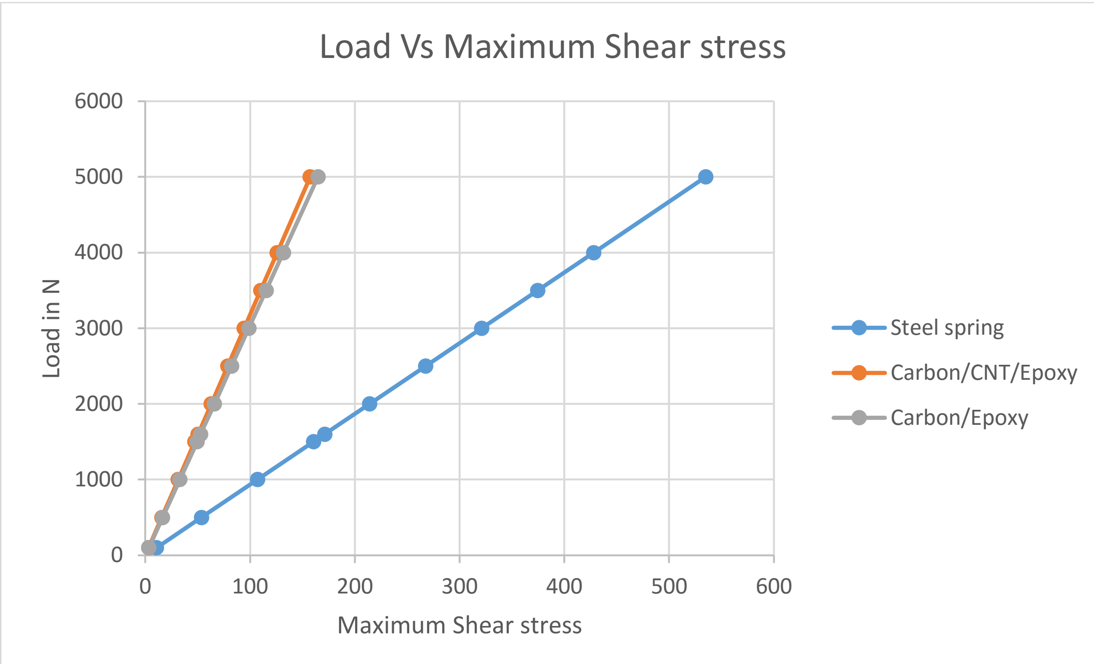


Figure 4-4: Maximum shear stress for modified coil spring model

Figure 4-4 shows the comparison maximum shear stress for modified composite coil spring and maximum shear stress of the existing Steel spring.

As shown from the graph maximum shear stress for composites is smaller than the steel one. Therefor when wire diameter is increased or mean diameter of coil is reduced shear stress reduces. This is because shear stress does not depend on the materials properties but on geometry of coil spring.

Strain Energy

Table 4-5: Strain Energy comparison

Load(N)	Strain Energy for existing coil spring model (mJ)		
	Steel spring	Carbon/CNT/Epoxy	Carbon/Epoxy
100	0.0054	0.04605	0.018
500	0.136	1.1513	0.4531
1000	0.545	4.605	1.81
1500	1.225	10.361	4.078
1600	1.394	11.789	4.64
2000	2.18	18.42	7.25
2500	3.4035	28.781	11.33
3000	4.901	41.445	16.313
3500	6.671	56.412	22.204
4000	8.713	73.68	29
5000	13.61	115.13	45.314

Table 4-5 shows the strain energy result of coil spring for all materials for variable load. Strain energy depends on density, Young's modulus of material and induced stress. Materials with smaller density and Young's modulus has higher strain energy. Therefore composite materials has higher strain energy due to their small density and Young's comparing to Steel spring. As shown in table 4-5, the strain energy for Carbon/CNT/Epoxy is higher than Carbon/Epoxy. In return Carbon/Epoxy has higher strain energy than Steel spring.

The higher strain energy shows the capacity of the coil spring to return to its initial position after deformation due to rough surface of road. So higher strain energy is needed for coil spring design.

So as figure 4-5, and 4-6 shows, Carbon/CNT/Epoxy has higher strain energy for both the existing coil spring and modified coil spring.

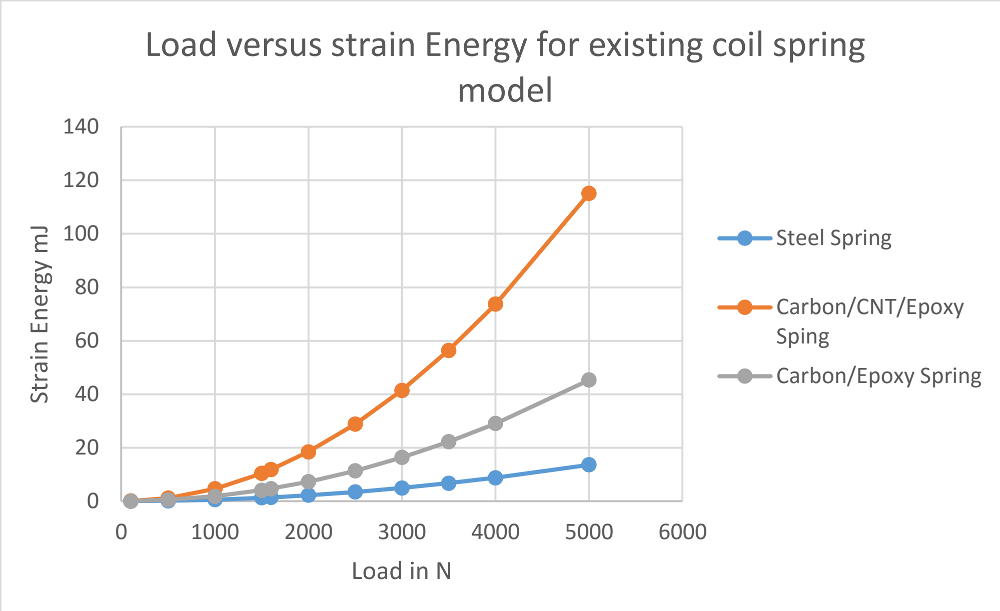


Figure 4-5: Load versus Strain energy comparison

The strain energy graph shows, energy for Carbon/CNT/Epoxy is higher than both Carbon/Epoxy and steel spring.

Table 4-6: Strain Energy comparison for modified spring model

Load(N)	Strain Energy for modified coil spring model(mm)		
	Steel spring	Carbon/CNT/Epoxy	Carbon/Epoxy
100	0.0054	0.005	0.00628
500	0.136	0.174	0.15705
1000	0.545	0.697	0.62818
1500	1.225	1.569	1.4134
1600	1.394	1.8	1.6081
2000	2.18	2.8	2.5127
2500	3.4035	4.36	3.9261
3000	4.901	6.277	5.6536
3500	6.671	8.544	7.6952
4000	8.713	11.16	10.051
5000	13.61	17.44	15.705

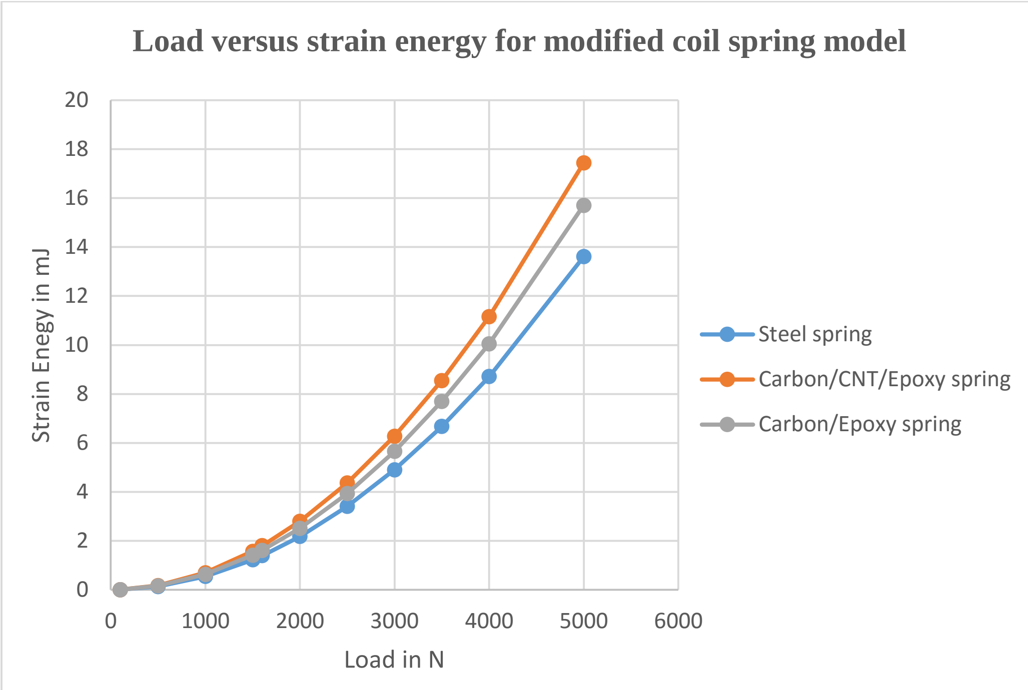


Figure 4-6: Strain Energy graph comparison for modified spring model

For design load of 2000N the comparison of Deflection, Maximum shear stress, and Strain energy developed on both existing model and modified coil spring are shown on fig 4-7, 7-8 and 4-9 respectively.

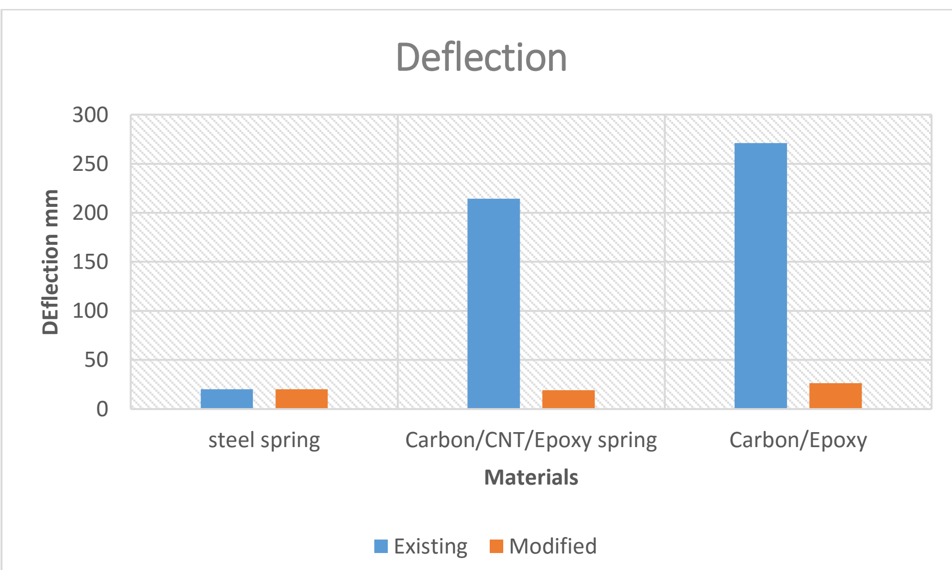


Figure 4-7: Deflection comparison for Existing and Modified

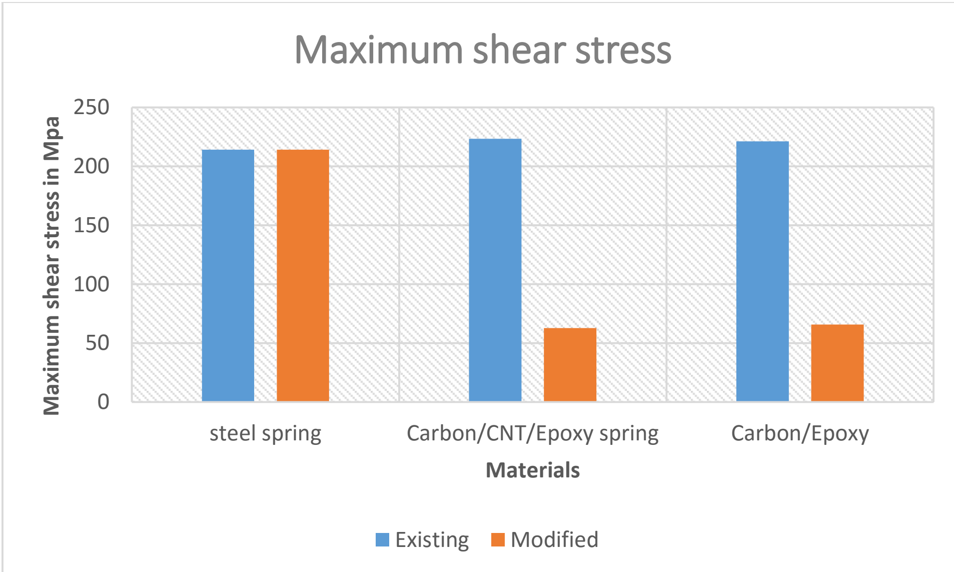


Figure 4-8: Maximum shear Stress comparison of modified and existing model

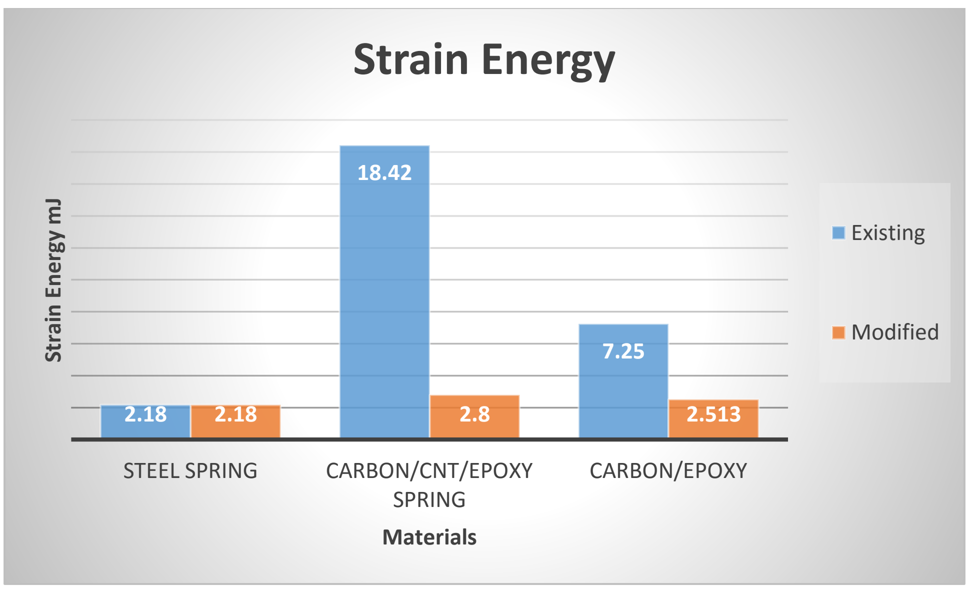


Figure 4-9: Strain energy comparison for existing and modified model

Mass comparison

Table 4-7: Mass comparison of Steel coil spring for existing coil spring

	Mass in kg		
No.	**Materials**	**Existing**	**Modified**
1.	Steel coil spring	1.975	1.975
2.	Carbon/CNT/Epoxy coil spring	0.37739	0.61728
3.	Carbon/Epoxy coil spring	0.38493	0.62963

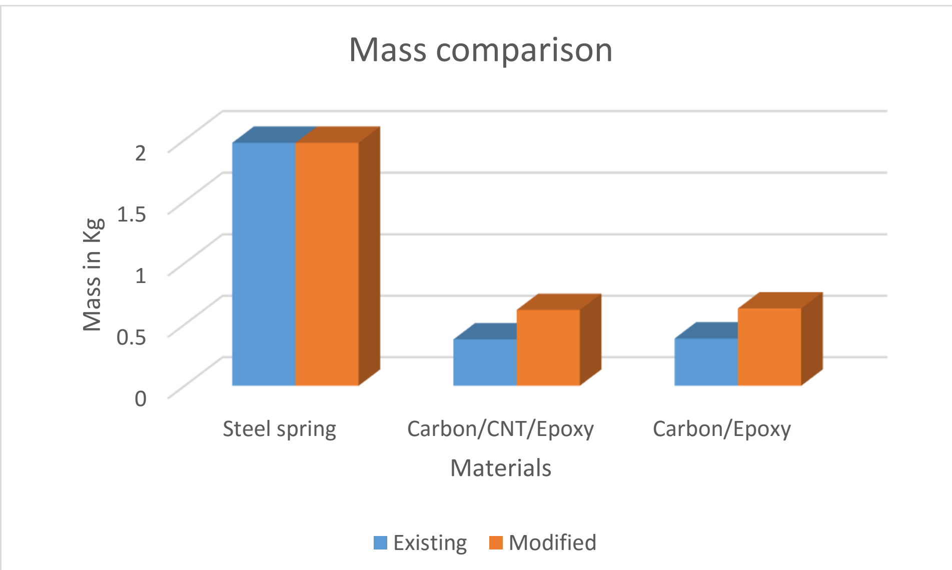


Figure 4-10: Mass comparison

Mass of the Carbon/CNT/Epoxy coil spring is lighter than both steel spring and Carbon/Epoxy for existing and modified coil spring model.

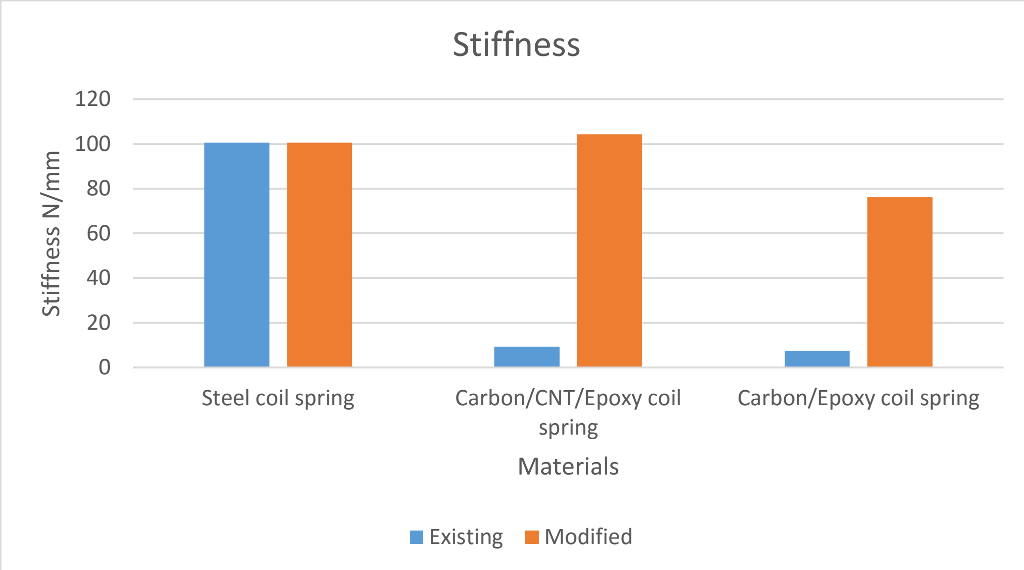


Figure 4-11: Stiffness comparison

Table 4-8: Stiffness comparison of coil spring

	Stiffness		
No.	**Materials**	**Existing**	**Modified**
1.	Steel coil spring	100.5	100.5
2.	Carbon/CNT/Epoxy coil spring	9.331	104.33
3.	Carbon/Epoxy coil spring	7.38	76.25

Fatigue life

The fatigue life for composite is larger than steel spring. This is because fatigue life is related the strength of the materials. Fatigue life for both composite more than 10^9 cycles and for steel spring the fatigue life is 5.0778×10^5cycles.

4.2. Discussion

Table 4-1 and figure 4-1 in the above shows the comparison of deflection for existing Steel Spring and Composite (Carbon/CNT/Epoxy, and carbon epoxy) springs. As the graph shows the deflection of the composite materials is large compare to Steel soring. This because the shear modulus for both Carbon/CNT/Epoxy and Carbon/ Epoxy composite materials is smaller than the Steel material. Figure 4-2 shows the deflection versus deflection for modified coil spring, and the deflection for both composite coil springs is reduced. Increasing the wire diameter of coil spring, reducing diameter of coil spring or reducing number of turns also reduces the maximum shear stresses as shown in figure 4-4. The strain energy of both Carbon/CNT/Epoxy and Carbon/ Epoxy composite coil spring and Steel coil spring is shown in figure 4-5 and 4-6 for both existing and modified spring models. As shown the figure strain energy for composite is less for modified spring than the existing model. But still the strain energy for composites is better than Steel coil spring.

Mass of coil spring is reduced from 1.975kg of Steel spring in to 0.37739kg of the same dimension Carbon/CNT/Epoxy, and for Modified coil spring the lightest coil is 0.61728kg for Carbon/CNT/Epoxy. The mass variation for all materials is explained in figure 4-10. The maximum shear stress in steel coil spring at design load 2000N is 214.1MPa and at same load the same specification for carbon/Epoxy and Carbon/CNT/Epoxy the maximum shear stress is 221.21MPa and 223.43MPa respectively. But for the modified coil spring the maximum shear stresses are 65.926Mpa, and 62.926Mpa for carbon/Epoxy and Carbon/CNT/epoxy respectively. This shows Maximum shear stress developed in Carbon/CNT/Epoxy coil spring is 70% less than Steel spring. Maximum shear Stress of Carbon/Epoxy is 69% less than steel spring. In addition deflection of existing specification for steel, carbon/Epoxy, and Carbon/CNT/Epoxy coil springs are19.9mm, 270.99mm, and 214.34mm respectively. Deflection for modified coil spring of carbon/epoxy is 26.228mm and for carbon/CNT/epoxy 19.17mm. Carbon/CNT/Epoxy is 3.66% less in deflection than steel spring. Similarly the strain energy is 22% higher than the steel coil spring. Therefor Carbon/CNT/epoxy composite spring has better performance than Steel spring and Carbon/Epoxy.

CHAPTER FIVE

5. CONCLUSION, RECOMMENDATION AND FUTURE WORKS

5.1. Conclusion

The objective of this work was to minimize the weight of steel coil spring without reducing the spring rate and strain energy. The design is then carried out by replacing the steel spring by comparing two composites (Carbon/Epoxy, and Carbon/CNT/Epoxy). The coil spring is then analyzed by ANSYS work bench for all these materials. To validate the result analytical calculation is perform, and by comparing the ANSY result with analytical calculations validation is checked.

In general from the design analysis we get the following points:

- Weight of composite coil spring is 80% lighter than the same specification and 69.89% lighter for modified specification than the steel coil spring
- Strain energy of composites is 22% larger than the steel coil spring, for both the existing dimension and modified composite coil spring.
- Maximum shear stress for both composite coil springs is less than the steel coil spring. Shear stress of Carbon/CNT/Epoxy is 70% less than steel spring.
- Deformation for composite is larger for composites for the same dimension as the steel coil spring. But deformation is reduced by 3.67% for modified specifications of the coil spring.
- Since factor safety of the composite is composite is three times larger than Steel coil spring load carrying capacity is higher for Composite springs.

Based on the modelling and analyses it is concluded that the carbon/CNT/Epoxy material is better than carbon/Epoxy for production of helical spring.

5.2. Recommendation

The properties of composite materials, like high strength to weight ratio and high specific stiffness are attractive for the construction of lightweight, fuel efficient and environmental friendly vehicle components. The energy absorption capability of the composite materials in general offers a unique combination of reduced weight and improves failure of the vehicle components. Standing from different aspects, working on composite materials have several advantages. From this point of view, regarding laminated composite coil spring several things can be made and improved in the future in which this study didn’t address.

5.3. Future works

Vibration and dynamic analysis of coil spring is recommended for the future work. Replacing and manufacturing of coil spring by natural fiber like sisal fiber is addressed for the future work.

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Appendix

Properties of commonly used Reinforcements

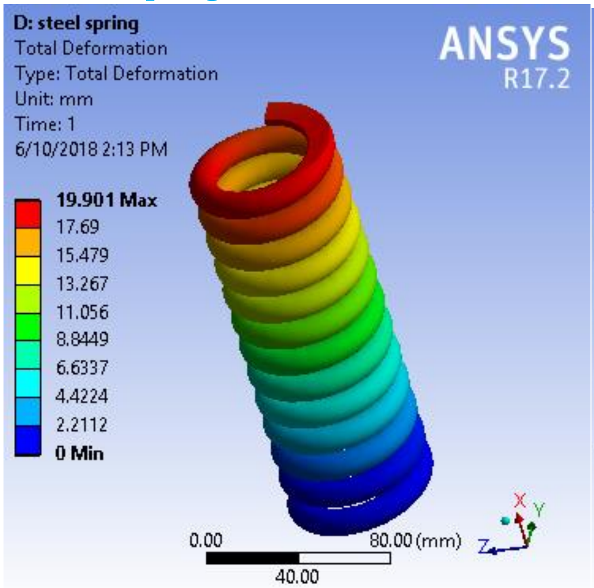
Reinforcements	*Fiber Diameter d(μm)*	*Density ρ(kg/m³)*	*Modulus of Elasticity E(Mpa)*	*Shear Modulus G(Mpa)*	*Poisson Ratio ν*	*Tensile Strength σ_{Ult} (Mpa)*	*Elongation E(%)*	*Coefficient of Thermal Expansion α(°C⁻¹)*	*Coefficient of Thermal Conductivity λ(W/M°C)*	*Heat Capacity c(J/kg°C)*	*Useful Temperature Limit T_{max} (°C)*	*Price 1993 ($/kg)*
"R" glass, high performance	10	2500	86,000		0.2	3200	4	0.3×10^{-5}	1	800	700	14
"E" glass, common applications	16	2600	74,000	30,000	0.25	2500	3.5	0.5×10^{-5}	1	800	700	2
Kevlar 49	12	1450	130,000	12,000	0.4	2900	2.3	-0.2×10^{-5}	0.03	1400		70
"HT" graphite, high strength	7	1750	230,000	50,000	0.3	3200	1.3	0.02×10^{-5}	200 (20°C) 60 (800°C)	800	>1500	70
"HM" graphite, high modulus	6.5	1800	390,000	20,000	0.35	2500	0.6	0.08×10^{-5}	200 (20°C) 60 (800°C)	800	>1500	140
Boron	100	2600	400,000			3400	0.8	0.4×10^{-5}			500	500
Aluminum	20	3700	380,000			1400	0.4		50 (20°C) 7 (800°C)	900	>1000	
Aluminum silicate	10	2600	200,000			3000	1.5					
Silicon carbide	14	2550	200,000			2800	1.3	0.5×10^{-5}			1300	600
Polyethylene		960	100,000			3000					150	

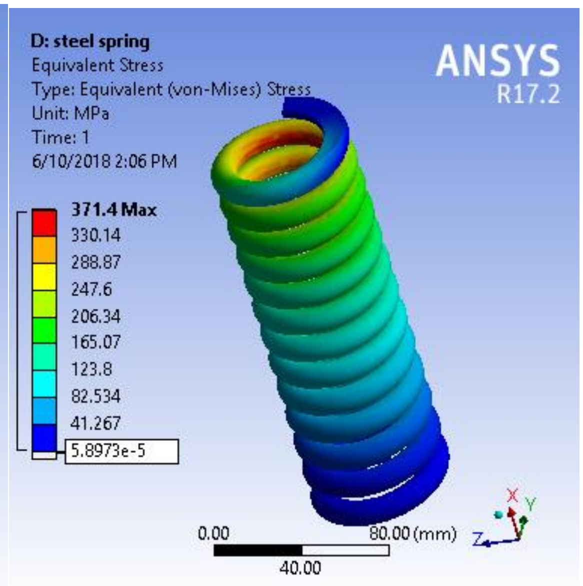
Properties of commonly used Resins

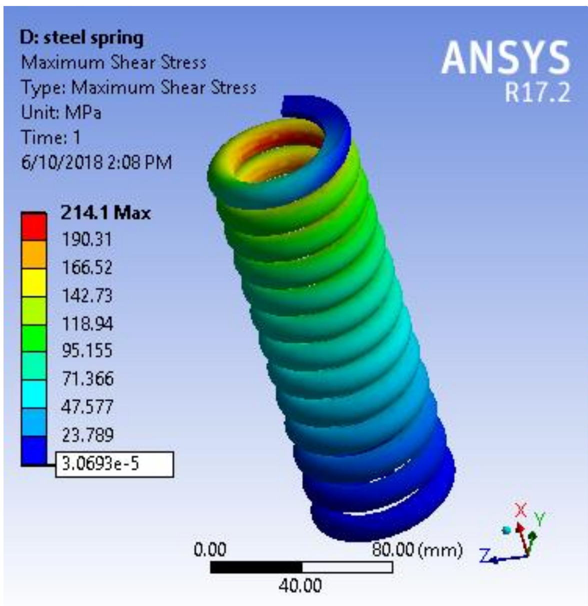
Resins	*Density ρ (kg/m³)*	*Elastic Modulus E(Mpa)*	*Shear Modulus G(Mpa)*	*Poisson Ratio ν*	*Tensile Strength σ_{Ult} (Mpa)*	*Elongation E%*	*Coefficient of Thermal Expansion α(°C⁻¹)*	*Coefficient of Thermal Conductivity λ(W/m°C)*	*Heat Capacity C(J/kg°C)*	*Useful Temperature Limit T_{max} (°C)*	*Price 1993 ($/kg)*
					Thermosets						
Epoxy	1200	4500	1600	0.4	130	2 (100°C) 6 (200°C)	11×10^{-5}	0.2	1000	90 to 200	6 to 20
Phenolic	1300	3000	1100	0.4	70	2.5	1×10^{-5}	0.3	1000	120 to 200	
Polyester	1200	4000	1400	0.4	80	2.5	8×10^{-5}	0.2	1400	60 to 200	2.4
Polycarbonate	1200	2400		0.35	60		6×10^{-5}		1200	120	
Vinylester	1150	3300			75	4	5×10^{-5}			>100	4
Silicone	1100	2200		0.5	35					100 to 350	
Urethane	1100	700 to 7000			30	100				100	4
Polyimide	1400	4000 to 19,000	1100	0.35	70	1	8×10^{-5}	0.2	1000	250 to 300	
					Thermoplastics						
Polypropylene (pp)	900	1200		0.4	30	20 to 400	9×10^{-5}		330	70 to 140	
Polyphenylene sulfone (pps)	1300	4000			65	100	5×10^{-5}			130 to 250	
Polyamide (pa)	1100	2000		0.35	70	200	8×10^{-5}		1200	170	6
Polyether sulfone (pes)	1350	3000			85	60	6×10^{-5}			180	25
Polyetherimide (pei)	1250	3500			105	60	6×10^{-5}	0.2		200	20
Polyether-ether-ketone (peek)	1300	4000			90	50	5×10^{-5}	0.3		140 to 250	96

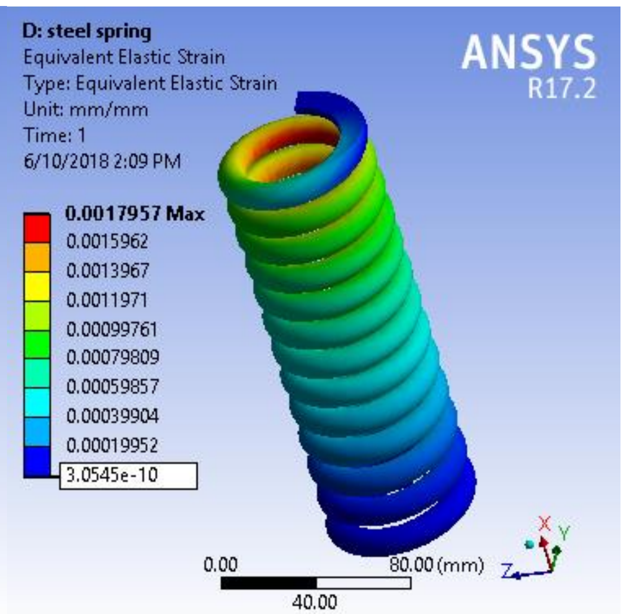
ANSYS results for design load

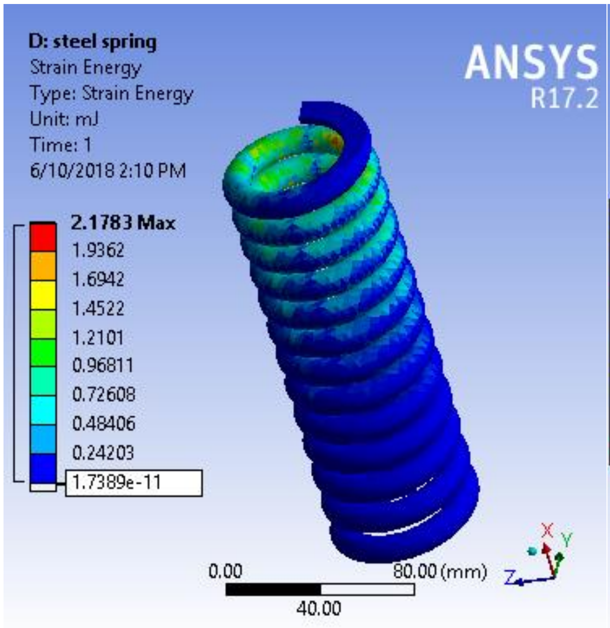
Steel coil spring model results

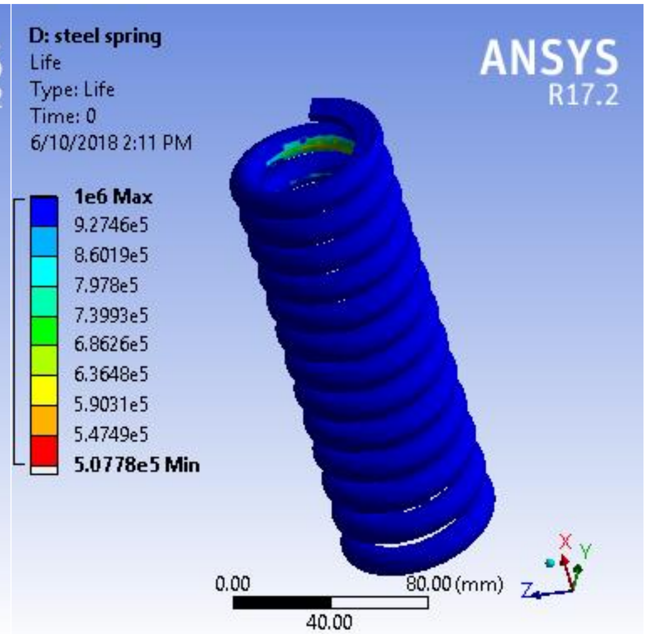




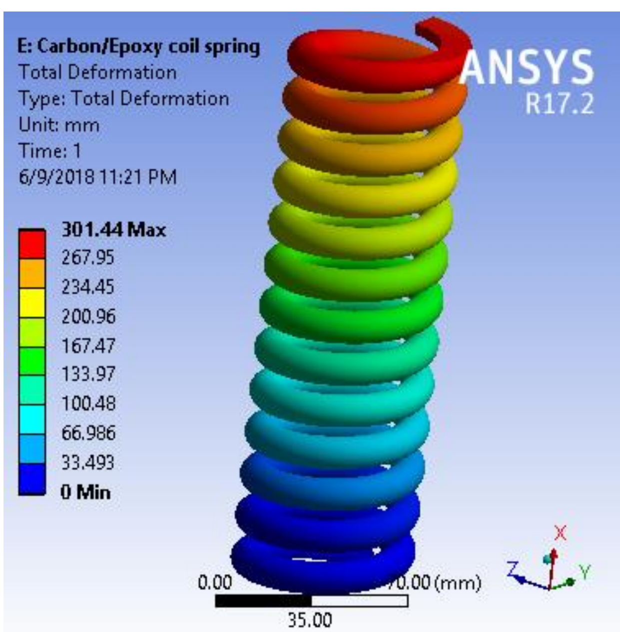


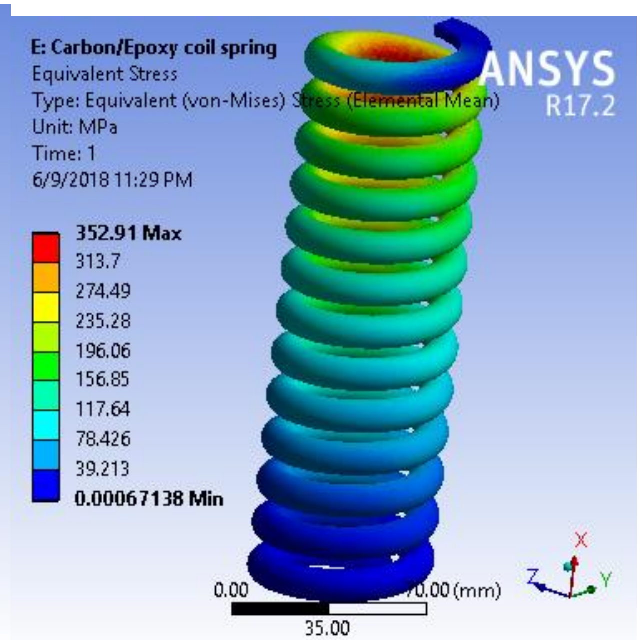


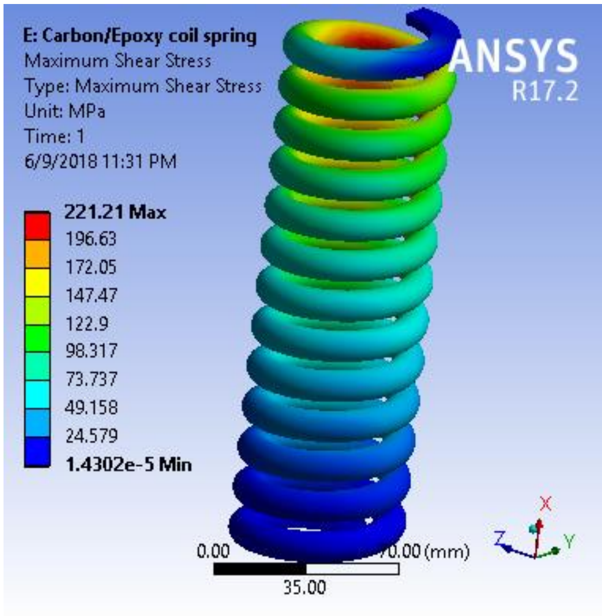


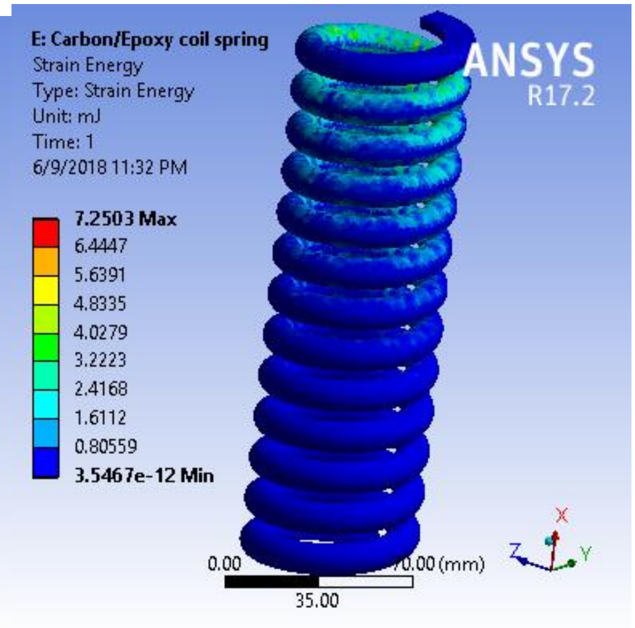


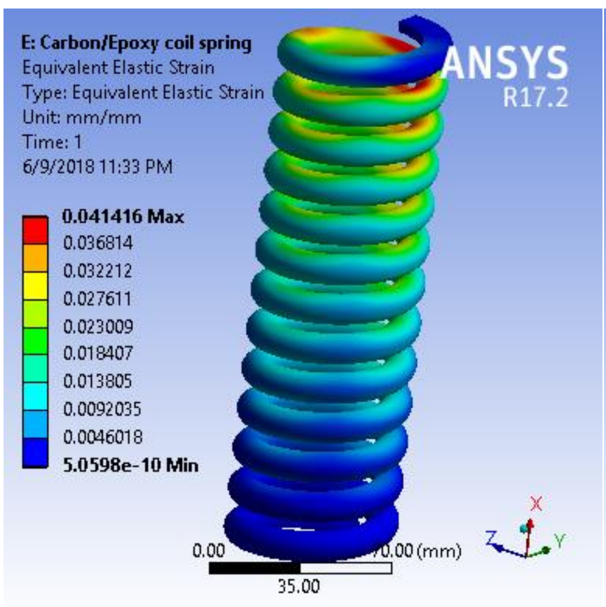
Carbon/Epoxy coil spring results

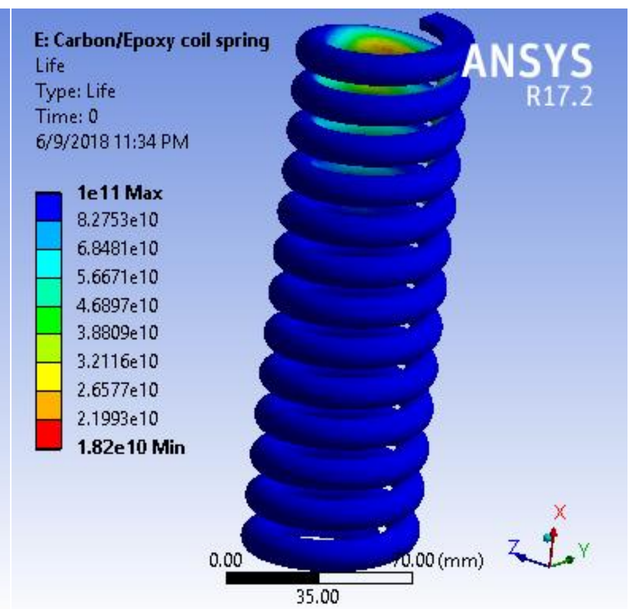


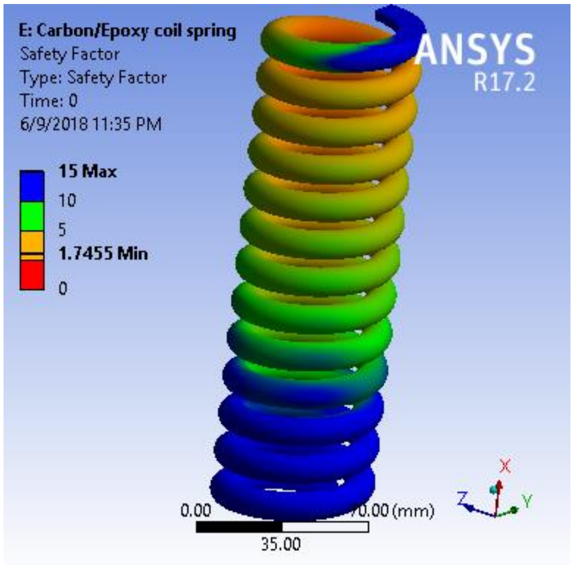



E: Carbon/Epoxy coil spring
Maximum Shear Stress
Type: Maximum Shear Stress
Unit: MPa
Time: 1
6/9/2018 11:31 PM
221.21 Max
196.63
172.05
147.47
122.9
98.317
73.737
49.158
24.579
1.4302e-5 Min
ANSYS
R17.2
0.00
35.00
(mm)
X
Y
Z

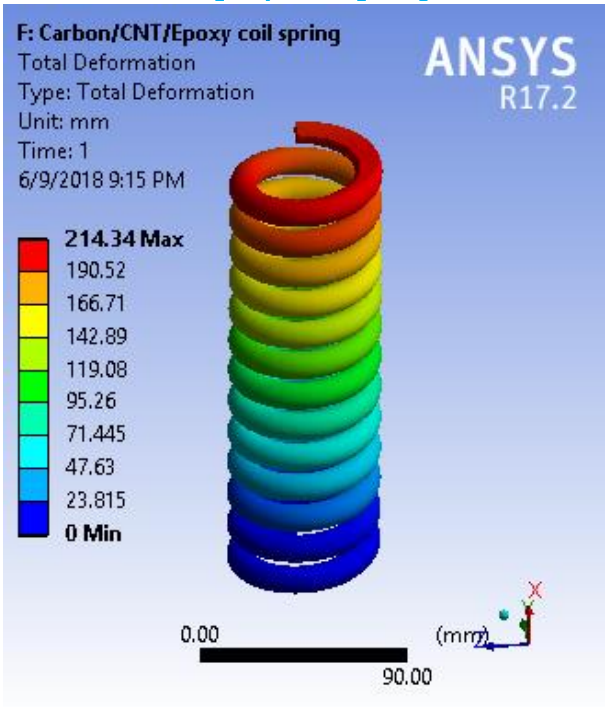

E: Carbon/Epoxy coil spring
Strain Energy
Type: Strain Energy
Unit: mJ
Time: 1
6/9/2018 11:32 PM
7.2503 Max
6.4447
5.6391
4.8335
4.0279
3.2223
2.4168
1.6112
0.80559
3.5467e-12 Min
ANSYS
R17.2
0.00
35.00
(mm)
X
Y
Z

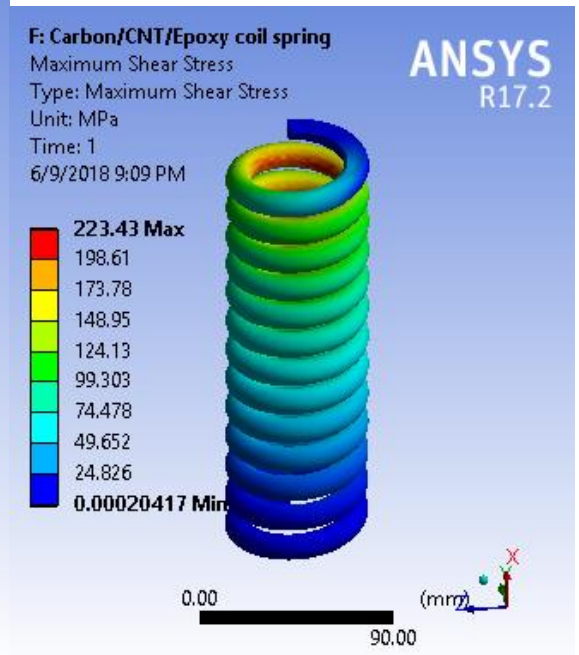

E: Carbon/Epoxy coil spring
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Unit: mm/mm
Time: 1
6/9/2018 11:33 PM
0.041416 Max
0.036814
0.032212
0.027611
0.023009
0.018407
0.013805
0.0092035
0.0046018
5.0598e-10 Min
ANSYS
R17.2
0.00
35.00
(mm)
X
Y
Z

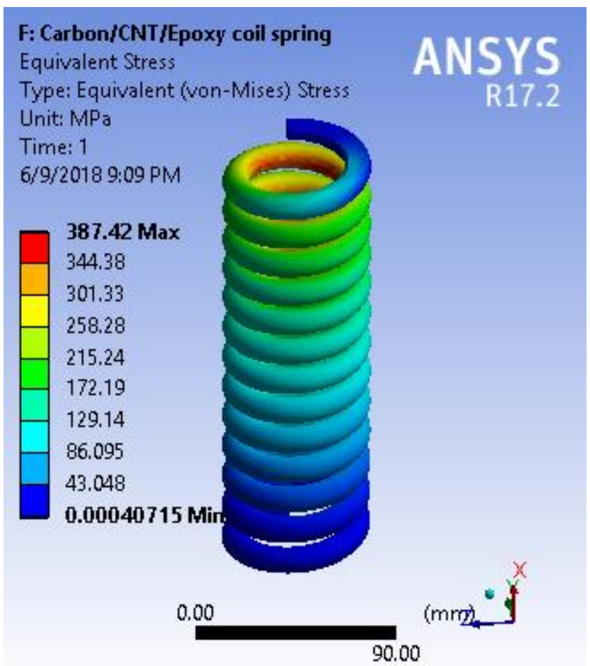

E: Carbon/Epoxy coil spring
Life
Type: Life
Time: 0
6/9/2018 11:34 PM
1e11 Max
8.2753e10
6.8481e10
5.6671e10
4.6897e10
3.8809e10
3.2116e10
2.6577e10
2.1993e10
1.82e10 Min
ANSYS
R17.2
0.00
35.00
(mm)
X
Y
Z

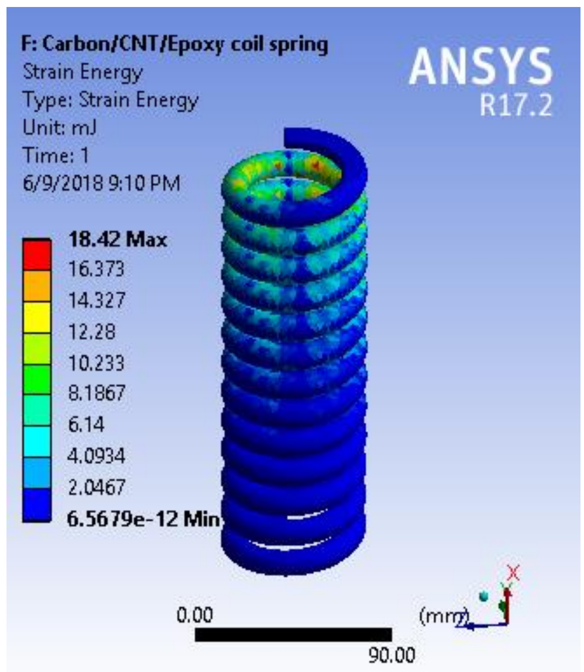

E: Carbon/Epoxy coil spring
Safety Factor
Type: Safety Factor
Time: 0
6/9/2018 11:35 PM
15 Max
10
5
1.7455 Min
0
ANSYS
R17.2
0.00
70.00 (mm)
35.00
X
Y
Z

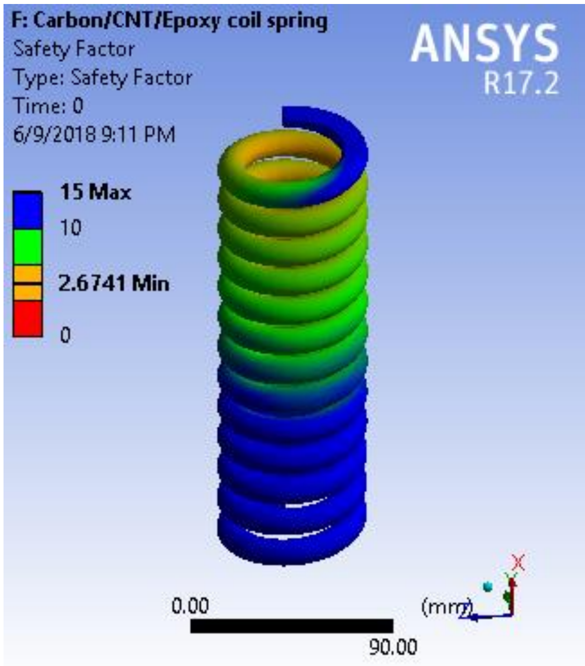
Carbon/CNT/Epoxy coil spring results

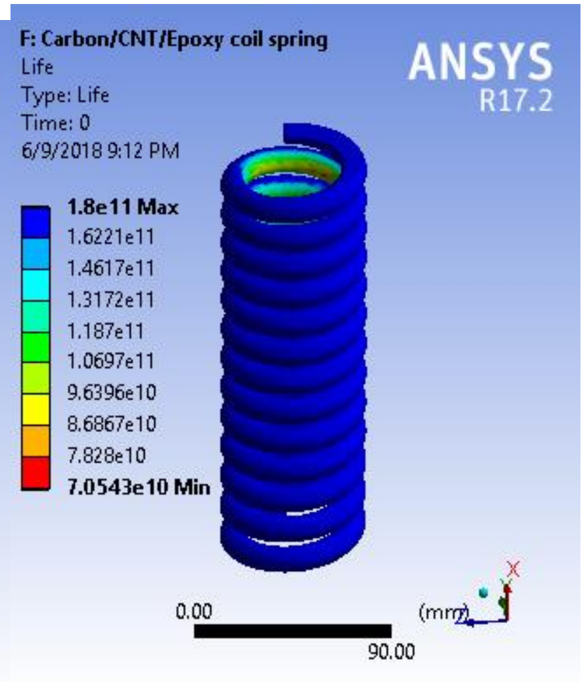




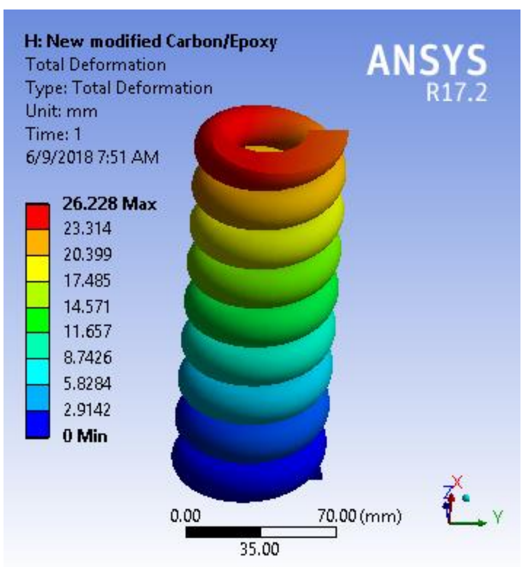


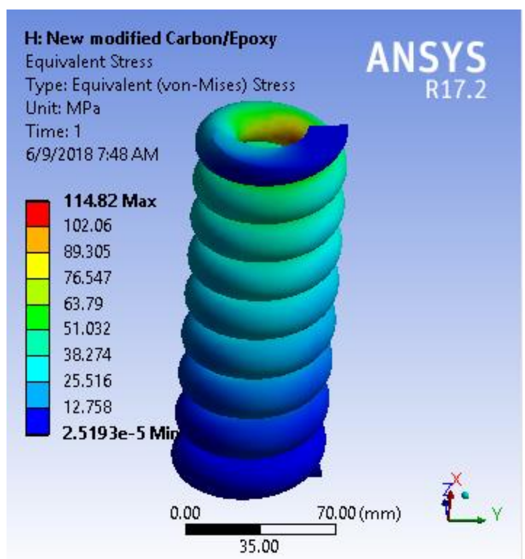


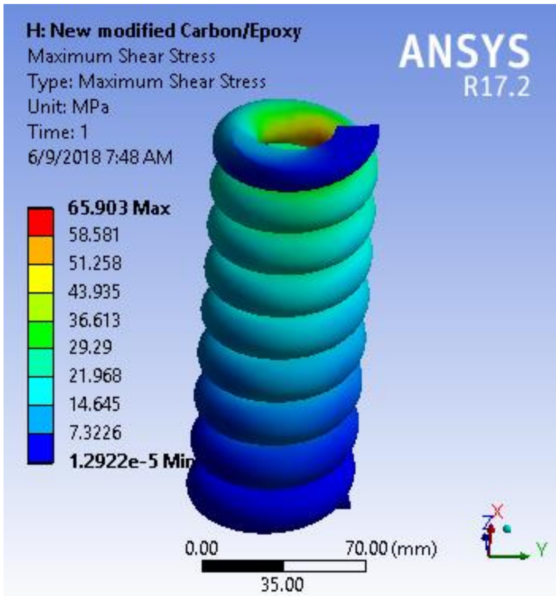


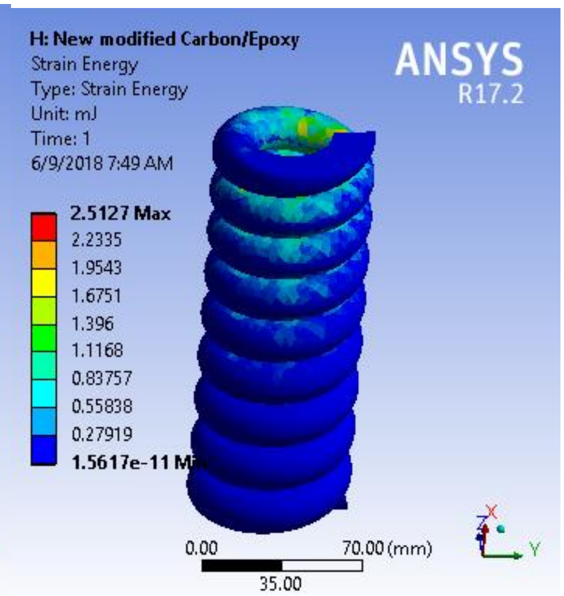


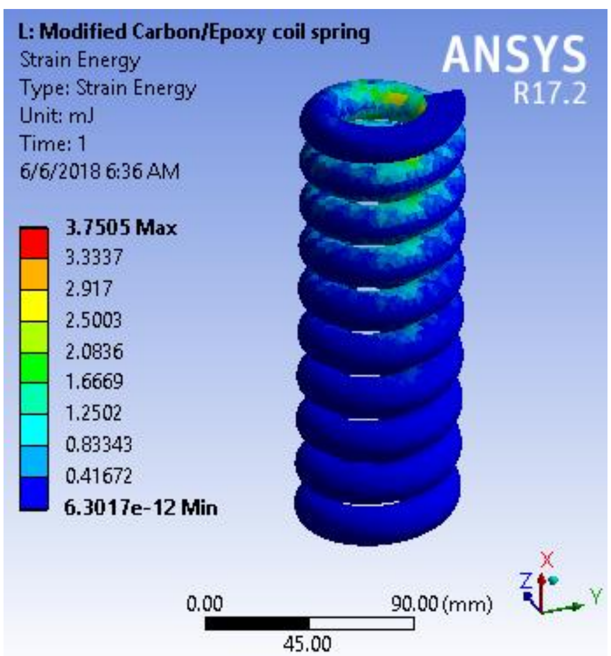
Modified Carbon/Epoxy coil spring model

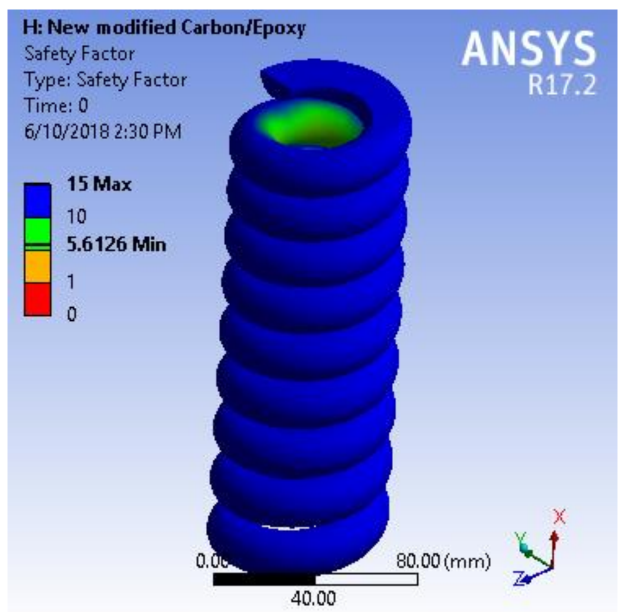




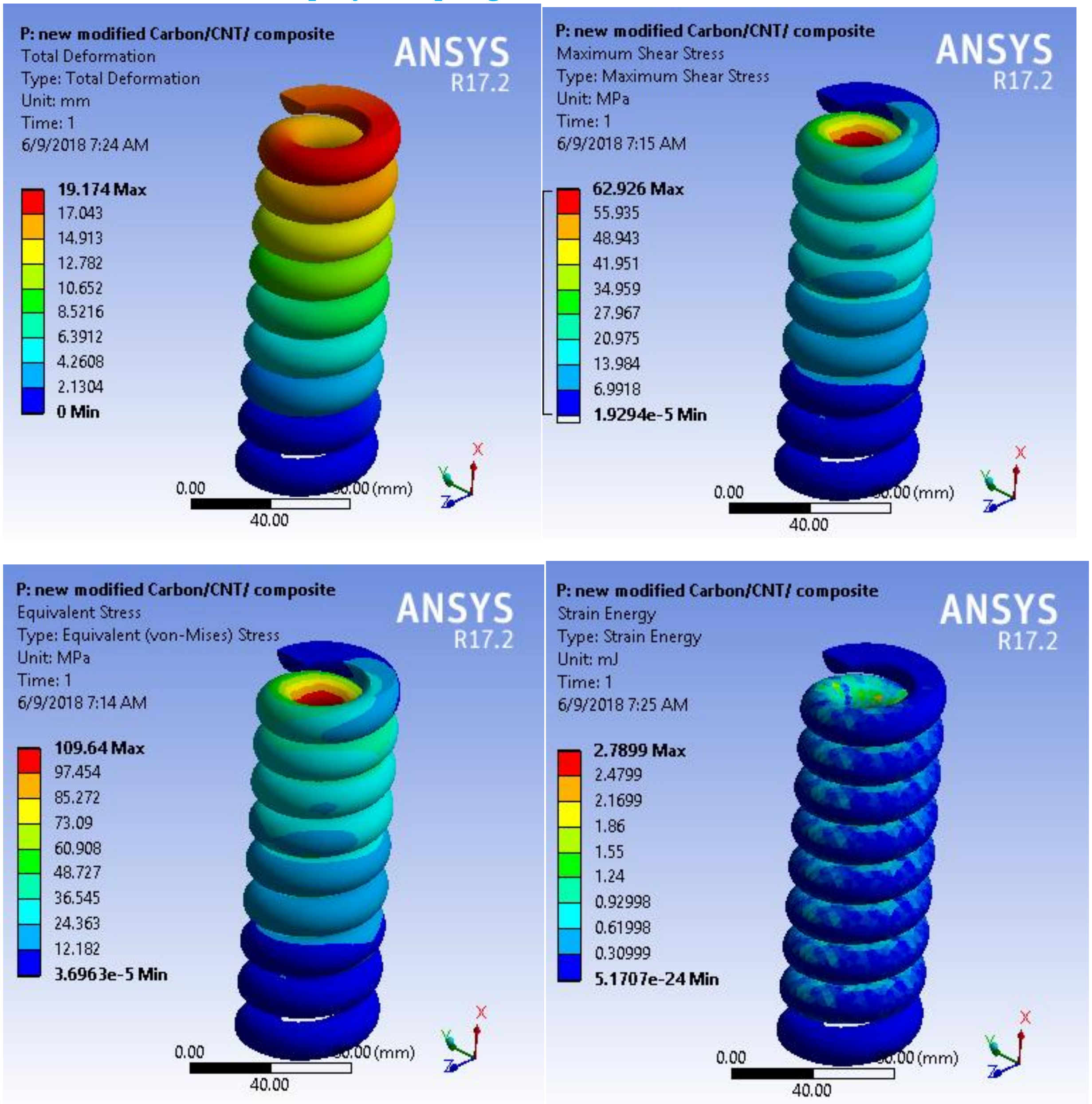

H: New modified Carbon/Epoxy
Maximum Shear Stress
Type: Maximum Shear Stress
Unit: MPa
Time: 1
6/9/2018 7:48 AM
65.903 Max
58.581
51.258
43.935
36.613
29.29
21.968
14.645
7.3226
1.2922e-5 Min
ANSYS
R17.2
0.00
70.00 (mm)
35.00
Z
X
Y

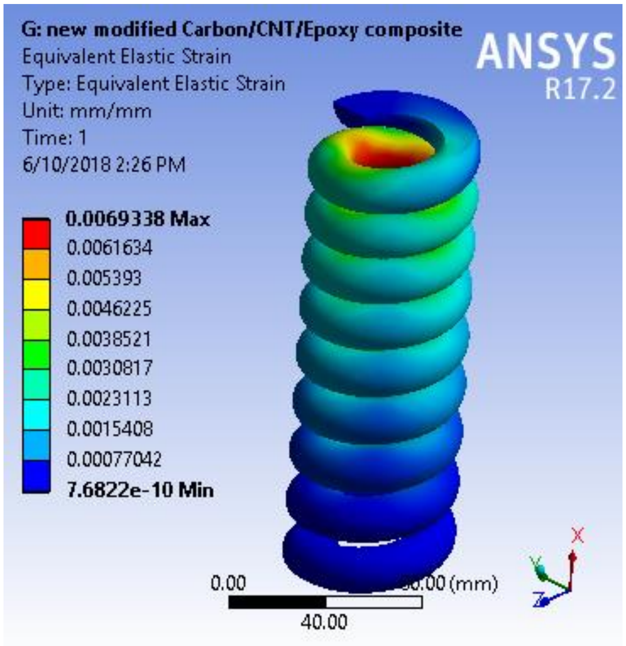

H: New modified Carbon/Epoxy
Strain Energy
Type: Strain Energy
Unit: mJ
Time: 1
6/9/2018 7:49 AM
2.5127 Max
2.2335
1.9543
1.6751
1.396
1.1168
0.83757
0.55838
0.27919
1.5617e-11 Min
ANSYS
R17.2
0.00
70.00 (mm)
35.00
Z
X
Y

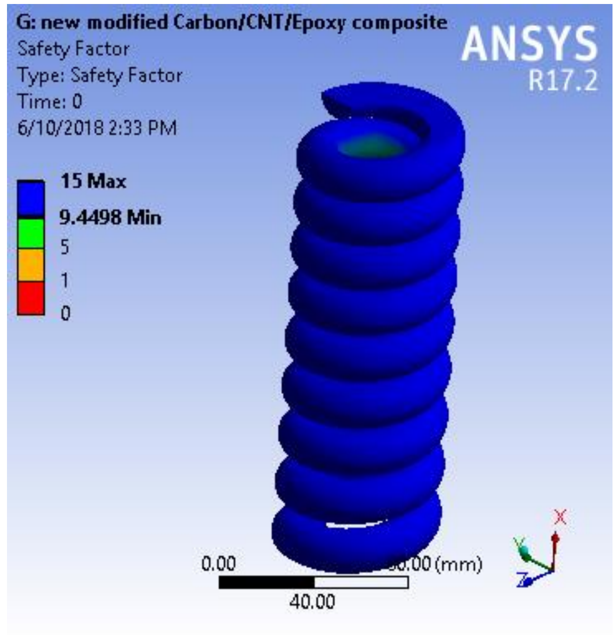

L: Modified Carbon/Epoxy coil spring
Strain Energy
Type: Strain Energy
Unit: mJ
Time: 1
6/6/2018 6:36 AM
3.7505 Max
3.3337
2.917
2.5003
2.0836
1.6669
1.2502
0.83343
0.41672
6.3017e-12 Min
ANSYS
R17.2
0.00
90.00 (mm)
45.00
Z
X
Y


H: New modified Carbon/Epoxy
Safety Factor
Type: Safety Factor
Time: 0
6/10/2018 2:30 PM
15 Max
10
5.6126 Min
1
0
ANSYS
R17.2
80.00 (mm)
40.00
X
Y
Z

Modified Carbon/CNT/Epoxy coil spring model




G: new modified Carbon/CNT/Epoxy composite
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Unit: mm/mm
Time: 1
6/10/2018 2:26 PM
ANSYS
R17.2
0.0069338 Max
0.0061634
0.005393
0.0046225
0.0038521
0.0030817
0.0023113
0.0015408
0.00077042
7.6822e-10 Min
0.00
(mm)
40.00


G: new modified Carbon/CNT/Epoxy composite
Safety Factor
Type: Safety Factor
Time: 0
6/10/2018 2:33 PM
ANSYS
R17.2
15 Max
9.4498 Min
5
1
0
0.00
(mm)
40.00