LITERATURE SURVEY AND PROBLEM FORMULATION

4.1 INTRODUCTION

Like most other fundamental mechanisms, metal springs have existed since the bronze Age. Even before metals, wood was used as a flexible structural member in archery bows and military catapults. Precision springs first became a necessity during the Renaissance with the advent of accurate timepieces. The fourteenth century saw the development of precise clocks which revolutionized celestial navigation. World exploration and conquest by the European colonial powers continued to provide an impetus to the clockmakers about the new inventions. Firearms were another area that pushed spring development.

The eighteenth century dawn of the industrial revolution raised the need for large, accurate, and inexpensive springs. But clockmakers springs were often hand-made, and now springs need to be mass-produced. Manufacturing methodologies were developed so that today springs are ubiquitous. Computer-controlled wire and sheet metal bending machines now allow custom springs to be tooled within weeks.

Springs are crucial suspension elements in automobiles necessary to minimize the vertical vibrations, impact and bumps due to road irregularities. Springs are being used in the automobiles since the inception of the automobiles which dates back to 1940. Till date the research on the production of the better springs for use in automobiles is being continued to improve the performance of the automobiles and to reduce the weight of the springs to improve the fuel efficiency. There are two types of springs used in automobiles, one is leaf spring and the other is helical spring. Leaf springs are used for the suspension of the automobiles. Helical springs are used as suspension and valve springs. The literature is now available on the investigation of the steel springs, materials for springs, stress analysis of springs, finite element analysis of springs, failure analysis of springs, fatigue analysis of springs, composite materials for automobile parts, composite elliptic springs, composite leaf springs and
composite helical springs. Patents obtained on the composite springs are discussed. The review of literature helps in defining the problem of the current investigation.

4.2 LITERATURE REVIEW ON STEEL SPRINGS

Traditionally springs are made of metallic materials which are easily available and can be manufactured easily. Spring materials are available in different varieties and wire sizes. These standard wire sizes give the required properties of the spring materials. However, the investigation on finding the new materials is still in progress. Till date many researchers are investigating on the characteristics of these metallic springs and combining the different compositions and configurations to improve the performance, reduce the weight and to increase their life. The following paragraphs review the work done on steel springs and failure analysis of steel springs.

C.A. Calder et al [7] have conducted the experiments on the helical springs by mounting the strain gauges on the inner radius of the spring. The experiment provides the opportunity to mount gauges on a curved surface with limited access. It is an application for rosette gauges, switch and balance unit, a digital read out and use of an Instron or similar test machine. Stresses acting on the springs can be determined with the mounted gages.

W.G. Jiang et al [8] have created a general and accurate finite element model for helical springs subject to axial loads (extension or/and torsion). Due to the establishment of precise boundary conditions, only a slice of the wire cross-section needs to be modeled hence more accurate results can be achieved. As an example, an application to a circular cross-sectional spring is analyzed. FEM results agree well with the analytical models for the tension and torsion Springs as the helical angle and the ratio of wire radius to coil radius tends to zero.

K.V. Sudhakar [9] has worked on the failure analysis of an automobile valve spring which failed in service. The fractured surfaces as well as the surface of the spring material close to the fractured surface were examined in a scanning electron microscope at suitable magnifications. Optical microscopy was performed to evaluate the basic microstructure of the as-received material.
Detailed electron microscope studies have indicated that the failure was due to the presence of nonmetallic inclusions near the surface of the spring material.

Dammak Fakhreddine [10] has used the finite element method for the stress analysis of isotropic cylindrical helical spring. The efficient two node finite element model, with six degrees of freedom per node, was developed and was capable to model the total behavior of a helical spring.

Michel Langa et al [11] of Allevard resin an Auto suspensions company, a subsidiary of the Italian society group, has developed a suspension coil spring and rubber insulator system design methodology. The particular aim is to identify more robust optimization criteria seeking compromise between ride control handling & NVH. The results obtained underline the importance of integrating the rubber insulators for optimal spring performance with regard to road-holding qualities and low frequency vibration comfort, while filtering the spring modes such as friction and drift in particular, in the case of McPherson suspension.

Josef Salwinski et al [12] have reviewed the stress calculation methods in helical springs with rectangular cross-section wire and have demonstrated that the methods described in literature lead to a very close accuracy. Also, the modern construction of the helical spring machined from tubular blanks is presented. It is indicated, using finite-element method, that existing classical spring with open end stress calculating methods, are not suitable for springs with capped ends because stress calculated from them are much smaller than the real ones.

R.K. Luo et al [13] have worked on the fatigue failure analysis of anti-vibration rubber spring. Rubber springs are widely used in industry as anti-vibration components giving many years of service. The metacone type of rubber spring is well established to control vertical and lateral movements.

C. Berger et al [14] have conducted very high cycle fatigue tests on helical compression springs which respond to external compressive forces with torsional stresses. The results of this investigation can add an important contribution to the experience of fatigue behavior in the very high cycle regime. Most investigations performed on that field deal with specimens under tensile or rotating bending load. The springs tested were manufactured of Si–Cr-alloyed valve spring wire with a wire diameter between 2 and 5 mm, shot-peened and preset. Compared to the fatigue limits evaluated in fatigue tests on these springs up to $10^7$ cycles
substantial decrease in fatigue strength are to be observed if the fatigue tests are continued up to $10^8$ cycles or even more. It is obvious that nucleations of fractures tend to occur below the surface, if fractures happen after more than $10^7$ cycles. Investigations of broken springs by scanning electron microscope show a typical appearance of fracture initiation sites without non-metallic inclusions at the nucleations of fracture.

Results of fatigue tests on a variety of helical springs up to a number of $10^7$ cycles were studied by Bruno Kaiser [15]. These results were obtained in 9 research project which extensively investigated the fatigue properties of helical springs with five different wire diameters (1, 2, 3, 5, and 8mm) up to $10^7$ cycles. The test springs for this project were made out of six different spring materials, two patented cold drawn unalloyed spring steel wires, two oil hardened and tempered spring steel wires and two stainless steel spring wires. The results of these fatigue tests with different mean stresses were statistically evaluated, presented as fatigue strength diagrams. According to Goodman for a test limit of $10^7$ cycles and compared to existing values of standards. Subsequent long run fatigue tests on selected springs were carried out up to a maximum of $1.5 \times 10^7$ cycles, an increase of the stress cycles from $10^7$ to $1.5 \times 10^9$ cycle leads to a remarkable reduction of shot peened springs manufactured from oil hardened and tempered spring steel wires.

L. Del Llano-Vizcaya et al [16] have investigated on the stress relief effect on fatigue and relaxation of compression springs. In the manufacturing process of mechanical springs, high tensile residual stresses are generated which reduces considerably the spring strength and service life. These unfavorable residual stresses are partially eliminated by heat treatment. In this process spring is heated uniformly below the material transformation temperature. An experimental investigation has been conducted to asses the stress relief influences on helical spring fatigue properties. First S-N curves were determined for springs treated under different conditions (time and temp) on a testing machine specially designed to do this task. Next the stress relief effect on the spring relaxation induced by cyclic loading was evaluated. Finally, residual stresses were measured on the inner and outer coil surfaces to analyze the effect of heat treatment and the most suitable heat treatment conditions (time range and temp
level) were obtained. These parameters give rise to the highest fatigue resistance with minimum spring relaxation.

S.K. Das et al [17] have conducted investigation on the premature failure of suspension coil springs of a passenger car which fails within few months after being put into service. Besides visual examination, other experimental techniques used for the investigation were (a) micro-structural analysis fractography by scanning electron microscope (SEM) (b) inclusion rating by optical microscope (c) Hardness testing (d) Residual stress measurement by X-Ray diffraction (XRD) and (e) Instrumental chemical analysis. Inherent material defect in association with deficient processing led to the failure of the springs. The spring failed prematurely due to the inadequate shot peening process used to impart residual compressive stresses on the surface. The presence of excessive outside inclusions in the steel might have also aggravated the case.

I.B. Eryyurek et al [18] have investigated on the failure analysis of the suspension spring of a light duty truck. The failure of the rear suspension spring is analyzed in detail. The rear axle suspension system of the truck and fractured flat spring is investigated. Fracture surface, mechanical and chemical properties and microstructure of the spring material is analyzed. Forces acting on the spring are determined and strength calculations are carried out. Later, failure behavior and cause of fracture is revealed after careful analysis of microstructure and results of calculations.

Y. Prawto et al [19] have investigated on the failure analysis of automotive suspension coil springs. This paper discusses several case studies, of suspension spring failure. The failures discussed concern insufficient load-carrying capacity, raw material defects such as excessive inclusion levels and manufacturing defects such as delayed quench cracking, also discussed are failures due to complex stress conditions and chemically induced failures (FEA) of stress distributions around typical failure initiation sites are also discussed. Failure sources are Raw materials, defects, surface imperfections, improper heat treatment, corrosion, and decarburization.

Design and failure modes of automotive suspension springs, were investigated by Y. Prawoto, et al [20]. This paper discusses about automotive suspension coil springs and their fundamental stress distribution, material
characteristics manufacturing and common failures, as well as parameters influencing the quality of coil springs.

Y. Akiniwa et al [21] have studied on the fatigue strength of spring steel under axial and torsional loading in the very high cycle regime. The fatigue strength of oil-tempered Si–Cr steel for valve springs was investigated. The fatigue strength of the spring steel was successfully measured using ultrasonic fatigue testing.

Bai-yan He et al [22] have studied the cause of a passenger car’s damper spring tower early failure. Inspection of the road surface, tire inflation pressure, suspension, and service load are done first in order to determine the further test procedures and analysis methods. The static stress of the spring tower caused by the body weight is calculated by finite element model. Public road tests with an equipped car are carried out to simulate the real usage by the customers. With the measured strain signals of different test conditions and local strain–life method, fatigue life prediction is made. The calculated fatigue life coincides with the actual failure mileage, and it turns out that the broken spring damper causes the early failure of the spring tower. It is suggested that more emphasis should be taken on the durability design and test of the spring damper.

R. Rivera, A et al [23] determined the premature rupture of a spring from an elevator door control mechanism. The study is based on the general methodology applicable to failure analysis. The results obtained in the experimental analysis and the analytical calculations lead to the conclusion that the failure of the spring was caused by a mechanical fatigue mechanism whose origin is related to the presence of the periphery of the material of inclusions and superficial folds (stress concentrators), probably abbreviated by the tensional state derived from the lack of alignment in the application of the load on the spring with respect to its axial axis.

The above papers reveal that the failure of the springs occurred due to the inclusion of the materials, surface defects and the excess stresses acting on the spring. The method of determining the stresses using strain gages and finite element methods have been discussed.

With the development of new materials and technology, the conventional automobile components were replaced by composite materials in order to reduce
the weight of the vehicles and to improve the fuel efficiency. The investigations on the use of composite materials in the automobiles are discussed here below.

4.3 APPLICATION OF COMPOSITES IN AUTOMOBILES

C. J. Moris et al [24] have studied the use of composites in rear suspension of automobiles. This suspension utilizes a transverse FRP leaf spring to integrate the functions of the production Escort stamped steel lower arms and coil springs. The spring was designed using previously developed composite design procedures. The results show concept feasibility, a vehicle weight saving, good ride, noise, vibration and harshness (NVH) characteristics. A reduction in roll stiffness points out the need for development in the design of the center clamp attachment to the body structure. This study demonstrates the viability and potential of fiber reinforced composites in automotive suspension systems.

Seong sik Cheon et al [25] have developed the composite bumper beam for passenger cars. In this work, a new composite bumper that has two pads at the ends of the bumper was developed. The two pads were designed to hit the front two tyres of the car when the bumper brackets collapsed during collision. The end of the bumper beam was designed to have a tapered section to absorb energy by progressive buckling when the pads hit the rims of wheels after collapsing tyres. The composite bumper beam was made of glass fibre fabric epoxy composite material except the elbow section. The elbow section was made of carbon fibre epoxy composite material to increase bending stiffness. From the static bending test of the prototype composite bumper, it was found that the weight of the composite bumper beam was only 30% that of the steel bumper beam without sacrificing the static bending strength.

Seong Sik Cheon et al [26] have developed the Composite side door impact beam for passenger cars. In this study, the side-door impact beam for passenger cars was developed using glass-fibre-reinforced composite materials as metals usually have a lower capacity of impact absorption energy at low temperature compared with that of glass-fibre-reinforced composite materials. Static tests were carried out to determine the optimum fibre stacking sequences and cross-sectional thickness for the composite impact beams taking consideration of the weight saving ratio compared to the high strength steel. Dynamic tests were
carried out at several different temperatures using the pneumatic impact tester, which was developed to investigate the dynamic characteristics of impact beams at a speed of 30 mph.

Naveen Rastogi [27] has developed composite drive shafts for automotive applications; this work presents a comprehensive approach to design drive shafts for automotive applications.

Polymer Matrix composites (PMC) such as carbon/epoxy or glass/epoxy or their hybrids have been successfully used as propeller shafts to transfer torsional loads in many aerospace applications. Apart from higher specific stiffness and strength, the PMCs also offer superior vibration damping and fatigue characteristics as well as excellent corrosion resistance over metals.

In the past two decades or so automotive industry has also evaluated composite materials for driveshaft applications. The first high volume, true automotive application of aerospace technology was the driveshaft developed by Spicer U-joint divisions of Dana Corporation. Following an earlier driveshaft introduction on 1985 Ford Ecoline van Models, the Spicer product continued to see growth on GM pickup trucks during 1988-1992.

Carbon Composite Brake Materials were developed by Christopher Byrne [28]. Carbon-carbon composites used in friction systems are becoming increasingly popular in aircrafts, owing to their combination of low weight and high performance. Their current acceptance as brake materials is somewhat restrained due to two factors: cost and performance variations. Many manufacturers are taking steps towards improving their cost efficiency by utilizing lower cost precursor fibers and processing methodologies. At the same time, modifications to material properties are made to address performance issues of oxidation, wear, and variation of effectiveness.

Three-dimensional fiber-reinforced polymer composites made by the textile processes of weaving, braiding, stitching and knitting have tremendous potential for improving the performance of composite structures and reducing their cost of manufacture [29].

Thermoplastic Composite Pressure vessels for deep water marine applications were developed by Ali Yousefpour [30] et al. A general design and analysis methodology is presented for the development of thick-wall thermoplastic composite pressure vessels for deep-water marine applications. A
parametric study was performed to determine the optimum tapered radius, initial radial clearance, and plug length of the plug-supported end-caps employed here as end-closures since it was found that these optimum parameters could improve the performance of the composite pressure vessels by minimizing bending and shear stresses near the ends. Stress and buckling of nonlinear finite element analyses (FEA) were performed taking hygrothermal effects into account.

A one-piece hybrid aluminum/composite drive shaft for a rear wheel drive automobile was developed with a new manufacturing method [31]. The composite materials were stacked on the inner surface of the aluminum tube and co-cured to prevent the hybrid shaft from being damaged by external impact and moisture. The optimal stacking sequence for the composite stacked on the inner surface of the aluminum tube was determined considering the thermal residual stress induced during co-curing operation. A press fit joining method between the steel yoke with protrusions on its surface and the aluminum tube was developed to increase the reliability of joining and to reduce manufacturing cost. The mass of the manufactured hybrid aluminum/composite drive shaft was 3.3 kg, which was only 25% of the conventional steel drive shaft. The static torque capability and the fundamental natural frequency were 4320 Nm and 9390 rpm respectively, which exceeded the design requirements.

The novel application examples of composite structures to components for the robots, machine tools and automobiles are addressed considering the stiffness design issues of composite structures [32].

The carbon fiber composite rotating boring bar has made the deeper hole boring of engine cylinder blocks possible with four times higher machining speed due to its high specific flexural stiffness than the conventional tungsten boring bar.

The composite one-piece propeller (or drive) shaft has been developed to substitute conventional two-piece metal propeller shafts for rear wheel drive cars. In order to reduce the material cost of carbon fiber, the propeller shaft was manufactured as a hybrid shaft in which the inside aluminum shaft transmits the required torque, while the outside carbon fiber layer increases the fundamental vibration natural frequency over 6500 rpm.

Fiber reinforced polymer matrix composites are being increasingly considered for use in civil infrastructure [33]. They have tremendous applicability to bridge
systems ranging from use in seismic retrofit and strengthening of existing structural components, to use in new systems, either in all composite form, or in conjunction with conventional construction materials.

HyeongYeol Kim et al [34] have designed GFRP deck for prototype of a steel I-girder bridge using the proposed deck profile. The design and analysis of a pultruded GFRP deck system for highway bridges are briefly presented in this paper.

The above research papers show the application of composite materials for automobile parts, pressure vessels and structural elements. The results of these papers encourage the use of composite materials in spring applications.

4.4 COMPOSITE MATERIALS FOR SPRING APPLICATIONS

4.4.1 PROPERTIES OF MATERIALS

The use of composite materials as a spring material requires certain characteristics. The prime among those is the shear modulus of the composite materials. This property can be determined by various methods. Another factor is the energy absorption capacity of the composite materials. Researchers have investigated on these parameters. Few of them are discussed in the following paragraphs.

H. Ho, M.Y. Tsai et al [35] have compared, three popular test methods for determining the shear modulus of composite materials. Three popular shear tests—the 10° off-axis, the ±45° tensile and the losipescu specimen tested in the modified Wyoming fixture—for shear modulus measurement are evaluated for a graphite-epoxy composite material system. A comparison of the shear stress-strain response for each test method is made using conventional strain gage instrumentation and moire interferometry. The uniformity and purity of the strain fields in the test sections of the specimens are discussed, and the shear responses obtained from each test technique are presented and compared. For accurate measurement of the shear modulus, the 90° losipescu specimen is recommended.

An inverse parameter identification technique using a modified losipescu shear test (MIST) has been developed for determining the viscoelastic interlaminar shear modulus of composite laminates [36]. The main component of

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the technique involves minimizing the difference between an experimentally measured and a numerically determined creep response at various elevated temperatures by varying the interlaminar shear modulus terms in the numerical model. Consequently, the ‘optimum’ model for the viscoelastic interlaminar shear modulus can be found at each temperature.

A. Chan et al [37] have determined the elastic interlaminar shear modulus of fiber reinforced composite laminates. An inverse parameter identification technique using a modified losipescu shear test has been developed for determining viscoelastic interlaminar shear modulus of composites. The technique involves minimizing the difference between an experimentally measured and a numerically determined material response by varying the interlaminar shear modulus in the numerical model.

Experimental assessment of energy absorption capability of carbon-epoxy and glass-epoxy composites was studied by Stanislaw Ochelski [38]. The influence of the factors such as fiber reinforcement type, type of structure, geometry and shape of the specimens, orientation of fibers in a layer and stacking sequence of layers on the energy absorption capability is analyzed.

4.4.2 COMPOSITE CYLINDRICAL AND CIRCULAR SPRINGS

Some researchers have investigated on the use of composite materials for cylindrical springs, circular springs and cylindrical springs of arbitrary shape. The summary of these papers are discussed in the following paragraphs.

C.K. So, P.C. Tse et al [39] have studied the mechanical behavior of composite cylindrical springs. Cylindrical springs were manufactured by circumferential winding of E-glass woven cloth impregnated with epoxy resin on a PVC mandrel and cured at 80$^\circ$C for 24 hours. The compression tests were conducted on springs, as per ASTM standards, and linear load deflection curves were obtained. Initially as the load increases a non linear curve is obtained with the appearance of interlaminar shear cracks. Theoretical predicted spring rates were slightly higher than the experimental spring rates. The failure loads were also recorded. Electrical resistance strain gauges were mounted on the inside and outside surfaces of spring, to measure the strain distributions. A theoretical analysis of the composite cylindrical spring based on the minimum potential
energy has been presented and is validated by experimental data obtained for especially orthotropic composite springs.

Theoretical analysis of the bending of symmetric laminated composite springs by considering the exact expression of the moment curvature relationship for beams based on the equivalent flexible rigidity is presented. Large deflection study has been conducted and the deformed shapes of the springs are classified into stages according to the load and are governed by the theories of nodal and undulating elastica [40]. This analysis provides basic information about the design of composite springs. Tests on composite spring have shown that the use of present large deflection analysis or finite element analysis to predict mechanical behavior of composite springs in the third or final stage can be misleading without considering plastic deformation composite material with improved toughness and strength are thus needed to verify the final stage of deflection.

V. Yildrim [41] has studied the free vibration of uniaxial composite cylindrical helical springs with circular section. The free vibration problem of unidirectional composite cylindrical helical spring is modeled theoretically as a continuous system considering the rotary inertia, shear and axial deformation affects the first order shear deformation theory is employed in the mathematical model. The theoretical results are verified with the reported values, which were obtained theoretically and experimentally for straight beams and helical springs.

Theoretical expressions based on the principle of minimum potential energy are presented which describe the stiffness of mid-surface symmetric, woven composite circular springs with extended flat contact surfaces subjected to unidirectional line and surface loading configurations [42]. Three dimensional finite-element analysis has been employed to study the transfer shearing effects. Eighteen woven fibre/epoxy composite circular springs with extended flat contact surfaces in different radii and thickness were fabricated and tested. Comparison studies of the results obtained from both the analytical and numerical modes are made with experimental data, and the results are found to be satisfactory. The semi included angle of the flat contact surface is vital parameter to spring stiffness of the composite spring. In the present work, a theory is developed from complementary strain energy and castigilliano's second theorem to predict the spring stiffness of mid-surface symmetric, woven composite circular springs with
extended flat contact surfaces under unidirectional line and surface configurations.

The feasibility of utilizing nickel-titanium alloy wires in altering the spring rates of a composite circular spring [43] is discussed. Three-dimensional finite element analysis has been employed to study the transverse shearing effects. Reduction in spring stiffness at elevated temperature can be prevented by inclusion of nickel-titanium alloy wire in a composite structure. The relationships between the spring stiffness at different temperatures and geometry were illustrated.

Large deflections of a range of mid-surface-symmetric, woven composite circular springs with extended flat contact surfaces subject to unidirectional line and surface-loading configurations were studied experimentally and modeled numerically [44]. Finite element analysis was employed to study the load–deflection and strain distribution characteristics. Eighteen woven fibre/epoxy composite circular springs covering a range of different radii and thicknesses were fabricated and tested. Comparison of the results obtained experimentally with the numerical models show good agreement. Correlation curves of the normalized ultimate load versus normalized geometrical parameters of the springs were established successfully. These curves can be used to predict the ultimate load according to the springs geometry and mechanical properties.

The dynamic behavior of composite coil springs of arbitrary shape is investigated [45]. The Timoshenko beam theory is adopted in the derivation of the governing equation. The material of the rod is assumed to be homogeneous, linear elastic and anisotropic. The effects of the ratio maximum diameter of the cylinder/ thickness ($D_{\text{max}}/d$), the number of active turns ($n$), the helix pitch angle ($a$) and the ratio of the minimum to maximum cylinder radii ($R_{\min}/R_{\max}$) on the dynamic behavior of the composite barrel and hyperboloidal springs are investigated. The free and forced vibrations of composite coil springs of arbitrary shape such as barrel and hyperboloidal springs are analyzed through various examples.

4.4.3 COMPOSITE ELLIPTIC SPRINGS

Elliptic springs are another type of springs which can be used in automobiles in place of helical springs. The load acting on the springs is shear and the
composite materials are poor in withstanding shear load and are strong in the tensile load. This advantage of composite materials is effectively used in the elliptic springs. Many researchers [46-49] have worked on composite elliptic springs. The elliptic composite springs are also easy to manufacture.

Mallick P K [46] has fabricated Fiber reinforced composite elliptic springs and tested. The reinforcing fibers experience tensile and compressive stresses instead of shear. Mechanical performance and failure modes of composite elliptic spring elements under static load conditions are reported. Springs were manufactured by dry winding around a segmented elliptic mandrel. The spring is cured at 300\(^{\circ}\) F for at least 14 hours. Strain gauges were mounted on the inside and outer surfaces of major and minor diameters to measure the strains. Spring rates were calculated from the slopes of the load-deflection curves in the compression tests. The theoretical and experimental values were in good agreement. Failure modes were observed during the compressive loading. Interlaminar shear cracks appeared at the curved wall near the minor diameter, both failure loads and spring rates depend on the thickness of the spring.

G. Goudah et al [47] have also developed composite elliptic springs. Finite-element models were developed to optimize the material and geometry of the composite elliptical spring based on the spring rate, log life and shear stress. The influence of ellipticity ratio on performance of woven roving wrapped composite elliptical spring was investigated both experimentally and numerically, the study demonstrated that composite elliptic spring can be used for light and heavy trucks with substantial weight saving. The results showed that the ellipticity ratio significantly influenced the design parameters. Composite elliptic spring with ellipticity ratio a/b=2 displayed the optimum spring model. Because of the poor resistance to shear stress in the fiber reinforced plastic composites in general, it is essential to control the composites failure by utilizing their strength in principal direction instead of shear. In the case of the new configuration of composite elliptic spring, the layers experience self compression state and the failure is dominated by tensile properties of the fiber eliminating the delamination and overriding the weakness of matrix properties. Material used for this project is woven fiber glass fabrics. The result showed that composite elliptical springs have better fatigue behavior than the conventional composite leaf and coil spring. Elliptical configuration successfully eliminates the hypothesis of delamination. The
fabricated composite elliptic spring was constructed based on the optimization developed from the finite-element analysis which has the ellipticity ratio of \((a/b=2)\) and resulting in substantial saving.

The influence of ellipticity ratio on performance of woven roving wrapped composite elliptical springs has been investigated both experimentally and numerically [48-49]. A series of experiments were conducted for composite elliptical springs with ellipticity ratios \((a/b)\) ranging from one to two. Typical failure histories of their failure mechanism are presented and discussed. In general, this study demonstrated that composites elliptical spring can be used for light and heavy trucks and meet the requirements, together with substantial weight saving. The results showed that the ellipticity ratio significantly influenced the spring rate and failure loads.

**4.4.4 COMPOSITE LEAF SPRINGS**

Leaf springs are another type of springs which are used in automobile suspension. Investigations on utilizing composite materials for leaf springs are carried out successfully and commercial production of these composite leaf springs are successful. Investigations on these springs are discussed below.

Erol Sancaktar [50] et al have designed and developed composite Leaf Springs for Light Vehicle Applications. Design and manufacture of a functional composite spring for solar powered light vehicle is described. Materials Used are, E glass fibers with the layers of Bi-directional fabric, vinyl ester resin, a spring rate of 127N/mm is obtained. Combined spring rate is 63.5N/mm close to the initial design goal of 70N/mm, FEA analysis is also done. Spring stiffness obtained is 74.95N/mm which is close to target/ theoretical value of 70N/mm, (with an approximate difference of 7%) Springs were fabricated using lay up process. Mould is made using polyester resin fiber glass chopped strained material. Spring suspension system (leaf spring) is redesigned.

H.A. Al-Qureshi [51] has developed Automobile Leaf Springs from Composite materials. The suspension spring of a compact car, "a jeep" was selected as a prototype. A single leaf, variable thickness spring of glass fiber reinforced plastic (GFRP) with similar mechanical and geometrical properties to the multileaf steel spring, was designed, fabricated and tested. The testing was performed
experimentally in the laboratory and was followed by the road test. Comparison between the performance of the GFRP and the multileaf steel springs is presented.

The development of a GFRP single leaf spring having constant width, where the stress level at any station in the leaf spring is considered constant due to the parabolic tape of the thickness of the spring, has proved to be very effective. Such a spring normally has lower flexure stress but higher nominal shear stress. In general, this study demonstrated that composites can be used for leaf springs for light trucks (jeeps) and meet the requirements, together with substantial weight saving. However, in the case of automobiles, the significant weight reduction may not cause the technological impact that it would for aircraft. Other work has shown that composite leaf springs have better fatigue behavior than steel springs. Needless to say, the hybridization technique can be used effectively to improve weight saving and performance in the automotive industry.

A steel leaf spring used in the rear suspension of the light passenger cars was analyzed by two analytical and finite element methods [52]. The experimental results verified the analytical and the finite element solutions. The steel leaf spring was replaced with an optimized composite one. Main consideration was given to the optimization of the leaf spring geometry. The objective was to obtain a spring with minimum weight that is capable of carrying given static external forces by constraints limiting stresses and displacements. The results showed that the optimum spring width decreases hyperbolically and the thickness increases linearly form spring edge towards the axle seat. The stress in the composite leaf spring is much lower than that of the steel spring, compared to the steel leaf spring the optimized composite leaf spring without edge limit weighs nearly 80% less than steel spring The natural frequencies of composite leaf spring is higher than that of the steel leaf spring and is far enough from the road frequency to avoid the resonance.

Gulur Siddaramanna Shiva Shankar et al [53] have developed Mono Composite Leaf Spring for Light Weight Vehicle. A single leaf with variable thickness and width for constant cross-sectional area of unidirectional glass fiber reinforced plastic (GFRP) with similar mechanical and geometric properties to that of multileaf spring was designed, fabricated (hand lay-up technique) and tested. Computer algorithm using C-language has been used for the design of
constant cross-section leaf spring. The results showed that spring width decreases hyperbolically and thickness increases linearly from the spring eyes towards the axle seat. The finite element results using ANSYS software showing stresses and deflection were verified with analytical and experimental results. The design constraints were stresses and displacement. Compared to the steel spring, the composite spring has stresses that are much lower, the natural frequency is higher and the spring weight is nearly 85% lower with bonded end joint and with complete eye unit.

4.4.5 COMPOSITE HELICAL SPRINGS

The actual use of composite materials for helical/coil springs is limited. However some researchers have tried to use the composite materials for these applications. Some have taken patents on developing the composite coil springs. The brief discussion of these researches is given below.

Howard S. Kliger [54] has taken a patent on Carbon Fiber Reinforced Composite Coil Spring. A carbon fiber reinforced composite coil spring is provided which is made from a braid formed of carbon fibers oriented at a preferred angle to the braid axis of approximately $\pm 45^\circ$ and impregnated with a resin which serves as a substantially continuous matrix phase. Longitudinal reinforcing fiber may be incorporated into the braid to prevent it from straightening under longitudinal tension. The carbon fiber reinforced composite coil spring is formed by wrapping the braid, impregnated with a non-solidified resin, within a groove which extends helically along the surface of a helical mandrel and solidifying the resinous matrix material, and then removing the solid composite coil spring from the helical mandrel.

Kenji Hashimoto [55] has taken a patent on manufacturing of fiber-Reinforced Resin Coil Spring. A fiber-reinforced resin coil springs impregnated with thermosetting resin which comprises a resin-impregnated and twisted rod-shaped fiber bundle formed by binding a plurality of fiber wire blanks made of glass or carbon, immersing the fiber bundle and twisting the rod-shaped fiber bundle in a thermosetting resin, and forming coiled twisted rod-shaped fiber bundle from the resin-immersed and rod-shaped fiber bundle. Thus, the resin coil spring
incorporates large elastic energy and high load withstanding capability due to the twisting of the fiber bundle.

Glass fiber hollow springs were fabricated. Method used for the production was variation of resin transfer moulding (RTM) process [56]. A silicon tube is filled with the sand and the glass fiber braid with resin is wound on the tube. This tube along with the glass fiber braids were wound on the mandrel, mandrel is put in an oven to warm. The required curing time was (3hrs 80°C + 8hrs 160°C). Spring is removed after curing and was designed to give a stiffness of 30KN/m, and the results were compared with the FEM results. The production of these springs is a laborious process. Only prototype springs were manufactured. The glass fibers were oriented at ± 45° angle to resist the shear load. The production of springs confirmed only the preliminary feasibility and a low cost mould and tools were used.

J.C. Hendry et al [57] have developed carbon Fiber coil Springs, for the rear suspension of a Rover Saloon for the replacement. Carbon fiber/Epoxy material was selected. Fibers were oriented at ± 45° circumferentially on the spring stock. The method of manufacturing selected spring was braiding. Material used is carbon fiber. Springs were tested in a mechanical spring testing machine and they fail to meet the required stiffness. Fatigue tests were also conducted on these springs.

Kenji Ukal et al have taken a patent on synthetic resin-coated spring and method for making the coated spring [58]. The synthetic resin coating layer contains an olefin polymer modified with an unsaturated carboxylic acid or a derivative thereof. A method for making the coated spring is also described. This invention relates to synthetic resin-coated springs which have a good self-silencing property or damping effect and a good corrosion resistance.

William G. Roeseler [59] has taken a patent on composite coil spring. A helical torsion spring composed of unidirectional graphite fibers encased in an epoxy resin matrix of rectangular cross section. The graphite fibers are longitudinally oriented relative to the core of the coil spring and can be located adjacent to the inner and outer surface of each of the coils. The present invention relates to counterbalance springs, and more particularly, to helical torsion springs.
Overhead sliding doors on aircraft require some sort of counterbalance mechanism to offset the weight of the door so that it can be raised and lowered with relatively minimum manual effort. Because of compactness and reliability, coil spring counterbalances are preferred for such overhead doors. Although conventional material such as steel alloys has been utilized for coil springs, steel alloys are relatively heavy and impose a severe weight penalty if employed in aircraft applications. It has therefore been suggested that titanium alloy springs be utilized instead of more conventional spring materials. Titanium, however, is difficult to work with and is extremely expensive. Additionally, only limited quantities of titanium are available.

Fiber-Reinforced Plastic Springs with Helical Fiber Wind was developed by Mark F. Folsom [60] and a patent was registered. Fiber-reinforced composite springs have a unidirectional fiber wind. In this invention it is a cylindrical torsion bar, or a helical tension or compression spring having a core that is either unreinforced or axial-liner reinforced, and a continuous-fiber reinforced composite cladding having most or all of its fibers helically arrayed around the core. The core may be solid or hollow. The sense of the helical winding is that it places the fibers in tension when the spring is used as intended at fiber winding helix angle of approximately $55^0$ is used with a weak and unreinforced core, while larger or smaller helix angles are used only with a core having sufficient stiffness to resist axial normal stress. By carefully selecting the materials for the core and cladding, as well as utilizing a fiber winding helix angle appropriate to the application, significant advantages over prior art springs are realized in energy per unit-volume, energy per unit-weight, and spring velocity. The present invention relates to composite springs formed of reinforcing fibers embedded in a plastic resin matrix, more particularly the present invention relates to unidirectionally-wound composite torsion bars and helical compression and tension springs. The composite springs of the present invention are formed by winding, at specified angles, matrix-bonded reinforcing fibers around a core material. The core material may or may not be reinforced. Springs according to the present invention are further formed of carefully selected materials to maximize the energy per unit volume, energy per unit weight for a given spring application.

A patent on composite multi-wave compression spring was registered by James T. Hawkins et al [61]. A circular multi-wave composite compression spring
is formed from a carbon fiber reinforced laminate. The circular compression spring is comprised of unidirectional graphite fibers encased in a polymeric resin of generally rectangular cross-section such that adjacent crests and troughs of the waves in adjacent turns of the spring contact each other along a radial line generally extending from the longitudinal axis of the spring. The line contact provides for increased fatigue life and more stable loading of the spring under compression. The carbon fiber reinforced laminate provides comparable strength characteristics similar to configured springs fabricated from conventional materials while providing significantly reduced weight. Furthermore, the composite spring offers increased performance parameters such as increased linearity response over a wider spring deflection range and with insignificant hysteresis.

Takeshi Oguri et al [62] have registered a patent on, Carbon fiber reinforced resin coil spring. In a carbon fiber reinforced coil spring the carbon fibers A and B are oriented at an angle of $+30$ to $+60^\circ$ relative to the axis of the cord of the spring. Further, the ratio $A/B$ of the amount of the fibers A oriented in the compression direction and the fibers B oriented in the tension direction lies within the range of 1.1 and 4.0. This invention relates to a carbon fiber reinforced resin coil spring and more specifically to a coil spring consisting at a spirally wound cord made of carbon fiber reinforced resin.

U.S. Pat No. 2,852,424 proposes a fiber reinforced resin coil spring which is more lightweight than a conventional metal coil spring. The coil spring is made of resin impregnated glass roving which is wound on a mandrel for forming a coiled resin coil spring, the orientation of the reinforced fibers is uniform and is parallel to the axis of the cord.

Japanese Patent Laid Open No. 56-18136 discloses a coil spring in which the orientation of the fibers is chosen relative to the axis of the cord. Namely, all the reinforcing fibers are oriented with respect to the direction in which the fibers are subject to a tensile force when a load is applied to the coil spring. The orientation angle is within the range of $30^\circ$-$60^\circ$ relative to the axis of the cord.

Japanese Patent Laid Open No. 57-11742 discloses a coil spring in which the reinforcing fibers are inclined at a predetermined oblique angle with respect to the axis of the cord. Further, the reinforcing fibers are wound in two different directions so that the two groups of fibers cross over each other, the cross-over
angle at the center in the longitudinal direction being different from the angles at both ends. Such an arrangement of the reinforced fibers allows regulation of torsional rigidity and gives the coil spring a non-linear spring constant.

Takao Nakagawa et al [63] have taken a patent on spring members. A spring member made of a carbon fibers/carbon composite material in which carbon fibers dispersed in a matrix of graphite. The spring member has a spring constant in a range of 0.1 to 25 kg/mm and a density of about 1.5 to 3.0 g/cm³. For use in high temperature severe condition a material is incorporated into the surface of the spring member.

Bertelson [64] has taken a patent on Composite Helical Springs and Process of Manufacture. In this a helical spring is formed by winding a fiber bundle on to a core at a predetermined angle and then winding the wound core on to a groove mold. The fibers have a thermosetting material there on which is cured as the wound core advances along the groove by heating the mold, the mold rotated to achieve the advance. A frictional engagement at the delivery end is set up between the wound core and the groove to pull and stretch the wound core and to thereby optimally orient the fibers before setting.

For the replacement of a metal spring in an acid environment, a glass fiber spring is designed for its better chemical resistant properties [65]. Also its electrical insulating properties are an advantage. The spring is made by covering a sand filled silicon tube with glass braid. When this tube is wound around a mould, the fibers are injected with resin. After curing, the spring is screwed off the mould. To verify the design method, the spring has to be tested for its properties. Spring rate, local strain and the breaking strength are determined. First a suitable clamping is designed which prevents buckling of the spring and breaking of the coil close to the clamping. The required properties could be determined from the test data. The average spring rate is 32.7 for a spring with 13.6 active coils. The maximum deviation of the spring rate is not much (+4.1% and -2.9%). The spring rate is perfectly constant until failure, as expected. The spring rate is 9% higher than predicted, but this is due to the effect of the locking angle of the braid. Because of this, the mean fiber angle is higher and this is fully accountable for the higher spring rate. The strain shows an anomaly with the expected. On the outer side of the coil is the compression strain larger than the tensile which is not expected from the theory. This is not clarified yet. The fiber volume content
(60.8%) looks a little high for a woven material and might indicate voids in the laminate which might cause the high compression strain. The spring remains functional after failure, the broken coils are pressed together and the spring can be compressed. Further, the production method is not suitable for large series, because it’s very time consuming. For small series the method is suitable and its reproducibility is good.

Valeria Antonelli [66] has discussed feasibility study on the production of a composite helical spring to replace the metal spring. Glass fiber raids are used and Resin transfer molding method is used to manufacture composite springs. Optimization has been performed to study the best characteristics for the requirements. Finite element calculations have been done to compare with analytical results.

Erol Sancaktar et al [67] have taken a patent on fiber reinforced composite springs. A fiber-reinforced composite spring comprising a coiled spring wire that comprises a fiber-reinforced core having longitudinal axis, where the core comprises core-reinforcing fiber tows that are twisted about the longitudinal axis of the core, and an outer layer surrounding the fiber-reinforced core, where the outer layer comprises a resin that is devoid of fiber tows. The present invention provides a reinforced composite spring comprising a coiled spring wire that comprises a fiber-reinforced core having longitudinal axis, where the core comprises core-reinforcing fiber tows that are twisted about the longitudinal axis of the core, and an outer layer surrounding the fiber-reinforced core, where the outer layer comprises a resin that is devoid of fiber tows.

Chang-Hsuan Chiu [68] et al have taken a patent on Manufacturing Method for a Composite Coil Spring. A Manufacturing method for a composite coil spring includes the following steps: prepare a mold, winding a coil former around a mandrel of the mould, winding composite material pre-preg, compressing and heating, opening the mold and detaching the mandrel and the coiled coil former.

An experimental investigation into the mechanical behaviors of helical composite springs was done by Chang-Hsuan Chiu [69] et al. In this study, four different types of helical composite springs were made of structures including unidirectional laminates. Rubber core unidirectional laminates, unidirectional laminates with a braided outer layer respectively. It aims to investigate the effects of rubber core and braided outer layer on the mechanical properties of the
aforementioned four helical springs. According to the experimental results, the helical composite spring with a rubber core can increase its failure load in compression by about 12%; while the spring with a braided outer layer can not only increase its failure load in compression by about 18%, but also improves the spring constant by approximately 16%. The helical spring with a BUR structure has the highest mechanical properties among those considered herein, its failure load in compression approximately equals to 336.2 kgf, and the spring constant is almost 16.27 kgf/mm. The four kinds of helical composite springs have been developed in this study, and they are lighter and stiffer than the spring made of commonly used spring steel (both its spring constant and weight are about 7.8 kgf/mm and 49 respectively, of the same volume as the helical composite springs designed in this study).

The fabrication of helical composite springs sounds preliminarily feasible by this research. Helical composite springs have significant advantages over the traditional helical metals springs as discussed in this paper. Therefore, shock absorbers with high performance might be expected to come soon.

A scan of these research works reveals that the investigation on FRP springs to improve their performance, materials and other characteristics are not stopped. Many researchers are trying to use new methodologies, new manufacturing methods and new configurations. Use of new materials like composites has shown promising results on automobile parts. A complete research on use of composites for springs is rarely observed. Only prototype models have been developed. And the fabrication process is very laborious. Composite materials applications for helical springs are very rare. Hence this research focuses on the study of fiber reinforced composite materials for helical spring applications.

4.5. FORMULATION OF THE PROBLEM

The suspension spring is one of the potential items for weight reduction in automobile as it accounts for 10 to 20 percent of the un-sprung weight. This helps in achieving the vehicle with improved riding qualities. It is well known that springs, are designed to absorb and store energy and then release it. Hence, the strain energy of the material becomes a major factor in designing the springs. The relationship of the specific strain energy can be expressed as
U = \frac{s^2}{\rho E}

Where \( \sigma \) is the strength, \( \rho \) the density and \( E \) the Young’s modulus of the spring material.

It can be easily observed that material having lower modulus and density will have a greater specific strain energy capacity. The introduction of composite materials was made it possible to reduce the weight of the leaf spring with out any reduction on load carrying capacity and stiffness [51] since; the composite materials have more elastic strain energy storage capacity and high strength-to-weight ratio as compared to those of steel.

The literature survey has revealed that much amount of work has been carried out on the design and the fabrication of the composite circular springs, elliptic springs and leaf springs. However, the study of helical composite springs is not yet popular, and only few researchers have worked on these springs. The composite springs discussed by these researchers are mainly fiber glass reinforced plastic composites, and no detailed information regarding the manufacturing process was ever provided. Some researchers have taken patent on the fabrication of composite helical springs. They have fabricated the springs with circular cross section. The manufacturing process used is very complicated. Therefore in this work the composite coil springs with rectangular cross section are developed. Simple fabrication techniques are used so as to make it automated. The composite helical springs are fabricated using glass fiber and carbon fiber in the form of fabric and roving as reinforcement and epoxy as matrix material. Epoxy resin is used as matrix material due to its superior mechanical properties.

OBJECTIVES OF THE PRESENT INVESTIGATION:

- To design a composite coil spring with an intention to reduce the weight and to improve the efficiency of an automobile.
- To modify the existing design suitable for composite coil spring.
- To select a suitable composite material so as to reduce weight and to give high performance.
To provide a method of manufacturing a fiber-reinforced resin coil spring with a remarkable simplicity inexpensively.

To determine the simple and suitable fabrication methods for the fabrication of composite coil springs using conventional machine tools and accessories for mass production.

To fabricate the designed composite coil spring in different orientations.

To carry out various tests on composite coil spring to evaluate its performance.

To construct an FEA model.

Comparison of FEA and experimental results.

To determine the best spring among these fabricated springs.

Comparison of composite coil spring with steel spring.

Methodology of Work

- Glass fiber (Bi-Directional Fabric 7 Mil, Roving), PAN based high strength carbon fiber (mat and roving), Epoxy (LAPOX L-12), are used for the fabrication of composite coil spring.

- Nine different types of springs are fabricated in unidirectional, 0/90 and +45 degree orientations using glass fibers, carbon fibers and glass/carbon fibers.

- The volume fraction of fibers and epoxy resin was kept constant i.e. 60:40.

- Composite coil springs are fabricated by using hand lay-up method and filament winding technique.

- Conventional machine tools with attachments are used for the fabrication of springs.

- Suitable type of mandrel has been designed and fabricated.

- Slow curing method at ambient temperature for better bonding is followed.

- Compression tests were conducted on spring testing machine to obtain the load deflection characteristics and to determine the stiffness.

- According to JIS B2704, the spring constant of a helical spring can be determined by two measured points, corresponding to deflection at both
30% and 70% of the full loading, on the load deflection curve from the compression test of a helical spring.

- Volume fractions are determined as per ASTM D 3171 standards.
- Fabricated springs were subjected to maximum load in UTM to determine the braking loads.
- Fatigue testing machine is fabricated to conduct the fatigue tests on the composite springs.
- Fatigue tests were conducted on the composite springs till $10^6$ cycles.
- Stiffness before and after the fatigue tests were compared.
- Stresses acting on the springs were determined.
- Finite element analysis is carried out for the composite coil springs using FE commercial software like Altair Hypermesh7.0 and MSC Nastron2007r1.
- The experimental values are compared with the FEA and analytical results.
- All parameters of springs i.e. energy stored, natural frequency, Buckling factor, were determined.
- The fabricated springs were compared with the steel springs for weight reduction, efficiency, performance and cost and results were analyzed.