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Investigation on the Feasibility of Composite Coil Spring for Automotive Applications

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***Abstract*—**This paper demonstrates the feasibility of replacing the metal coil spring with the composite coil spring. Three different types of springs were made using glass fiber, carbon fiber and combination of glass fiber and carbon fiber. The objective of the study is to reduce the weight of the spring. According to the experimental results the spring rate of the carbon fiber spring is 34% more than the glass fiber spring and 45% more than the glass fiber/carbon fiber spring. The weight of the carbon fiber spring is 18% less than the glass fiber spring, 15% less than the Glass fiber/carbon fiber spring and 80% less than the steel spring.

***Keywords*—**Carbon fiber, Glass fiber, Helical composite spring, spring rate.

I. INTRODUCTION

Springs are crucial suspension elements on automobiles which are necessary to minimize the vertical vibrations, impacts and bumps due to road irregularities and create a comfortable ride. Coil springs are commonly used for automobile suspension and industrial applications. The fuel efficiency and emission gas regulations of automobiles are two important issues in these days. The best way to increase the fuel efficiency is to reduce the weight of the automobiles by employing composite materials in the structure of the automobiles. Metal coil springs can be replaced by composite springs because of weight reduction and corrosion resistance. Metal coil springs cannot withstand high temperature. At high temperature where it is required to operate composite springs are used. Metal springs have several advantages, they are very cheap to produce and can be produced in almost all kinds of measures and in a very broad range of stiffness. Since the composite materials are anisotropic in nature, the design and manufacture of composite springs are difficult. Therefore the application of composite materials in springs is not yet popular. However they are used in the suspension system of the automobiles [1].

For the purpose of saving energy and improving the performance of the shock absorbers, with light weight and high quality, composite materials have to be used for today's vehicles. With the more no of electric vehicles and hybrid vehicles are entering into the market in the present scenario, it has become essential to go for the light components for improving the efficiency.

Because composite springs have some advantages over the metal springs, many researchers are actively involved in the study of composite springs. Chang-Hsuan Chiu et al [2] have conducted the experiment on mechanical behavior of helical composite springs. They have made the springs with different material structures like, unidirectional laminates, rubber core unidirectional laminates, unidirectional laminates with a braided outer layer, and rubber core unidirectional laminate with a braided outer layer.

Henry and c. Robert have tried to replace the metal coil spring of a Rover saloon car using carbon fiber [3]. P.K. Mallick has fabricated and conducted the performance test on the composite elliptic springs [4].

The composite leaf springs are successfully used in the suspension of the light vehicles [5]. 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 [6]. 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 [7] like, propeller shaft, drive shafts [8]-[9], bumper beam [10], side door impact beam [11], universal joints, bearings, brakes [12].

The literature survey has revealed that, only prototype composite springs were prepared and tested for the performance. Since the time consumed for the manufacturing of the composite springs is more, the standard and simple method of mass production of composite coil springs is required from the economical point of view.

In this study a spring from the two wheeler is taken for replacement. Glass fiber and carbon fibers are used for the manufacture of composite coil springs. The principal advantage of fiber reinforced polymer matrix composites for automobile parts is weight savings, part consolidation, and

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improvement in NVH (noise, vibration and harshness). The absence of corrosion problems, which lowers maintenance cost for automobile parts, enables the use of fiber reinforced polymeric composite.

Three types of springs were manufactured in this study with glass fibers [GF], carbon fibers [CF], glass fiber/carbon fiber [GF/CF] roving. These springs were tested for spring rate and other parameters. The results show the feasibility of composite springs for light vehicle applications.

II. Principles of Cylindrical Helical Springs

A Specific strain energy

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

$$U = \frac{\sigma^2}{\rho E} \tag{1}$$

This indicates that a material with lower young's modulus (E) or density (ρ) will have higher specific strain energy under the same stress (σ) condition [B]. Thus the composite materials offer high strength and light weight.

B The spring constant of a cylindrical helical spring

Fig.1 represents when a cylindrical helical spring with rectangular cross section is under the action of an applied compression force W, the primary reaction force on the coil is torsion and thus induces shear stresses on the cross section. For homogeneous and isotropic materials, both the spring constant, K, and the induced shear stress under torsion, τ, for rectangular wire spring can be approximately derived as [13]:

$$K = \frac{W}{\delta} = \frac{Gb^3(t-0.56b)}{2.45nD^3} \tag{2}$$

$$\tau = \frac{K'WD(1.5t+0.9b)}{b^2t^2} \tag{3}$$

$$K' = \frac{4c-1}{4c-4} + \frac{0.615}{c} \tag{4}$$

Where and in Fig. 1, W is the applied load on spring (N); D, the mean coil diameter (mm); L, the free length (mm); δ , the deflection (mm); G, the modulus of rigidity (N/mm^2); n, the no of active coils in the spring; t, the side length of rectangular cross section (mm) parallel to the axis of the spring, b, the width of the spring perpendicular to the axis and c is D/t. It is found from "(2)" that the magnitude of the spring constant of the cylindrical helical spring with a rectangular cross section is related to the mean coil diameter, the no of active coils and the side length of rectangular cross-section, as well as the modulus of rigidity of the material used.

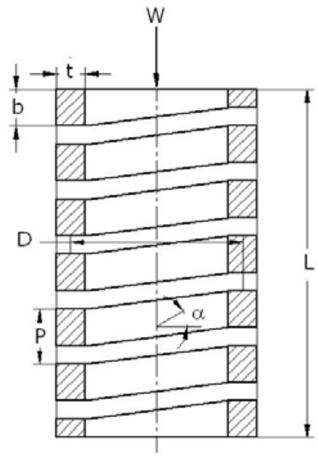

Fig. 1 Schematic diagram of the cylindrical helical spring with rectangular cross section.

III. Fabrication of Composite Coil Springs

A. Selection of materials:

The fibers chosen for the spring design are E-glass in the form of roving and PAN based carbon fiber roving due to their high extensibility, toughness and low cost. In order to facilitate the wetting of fibers, epoxy resin with 2 h pot life is selected. L-552/K-552 Lapox epoxy system for laminating applications is used. They exhibit good mechanical strength both static and dynamic.

B. Properties of material.

E-Glass Fibers:
Shear modulus: 15 GPa
Fiber strength: 3.45 GPa
Elongation: 4.88%
Tensile modulus: 81.4 GPa
Density: 2.6g/cc

Carbon Fiber:
Shear modulus: 30GPa
Fiber strength: 4.5GPa
Tensile modulus: 300 GPa
Elongation: 1.7%
Density: 1.8g/cc

Epoxy Resin:
Modulus of elasticity: 3.45 GPa

Tensile strength: 69 Mpa
Specific strength : 36Mpa
Ductility : 4%

C. Fabrication of composite coil springs.

Composite springs were 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. (Fig 2). This mandrel is fixed in the lathe chuck. A mould 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 24 hours. 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. Fig 3 shows the fibers wound on the mandrel. Fig 4 shows the cross sectional view of spring with mandrel. Fig 5 shows the fabricated composite coil springs. The fabricated spring is having the dimensions L=200mm, D=47mm, n=10, b=10mm, t=8mm and pitch=20mm.

Fig. 2 Mandrel having the profile of the spring

Fig. 3 Fibers wound on the mandrel

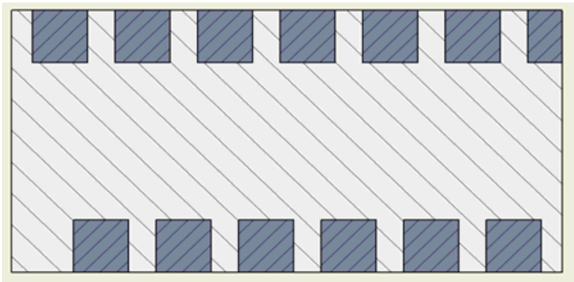

Fig. 4 Sectional view of the composite spring with the mandrel

Fig. 5 The fabricated springs

IV. TESTING OF COMPOSITE SPRINGS

A. Measurement of spring rate, failure load and maximum compression.

The spring constant of a helical spring can be determined at 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 composite spring

The failure load and the maximum compression of a helical composite spring are also evaluated to ensure its safe use.

In this study, a spring testing machine which automatically records the deflection and load applied on the spring is used. The load deflection curve can be drawn from these data. The spring rate, maximum compression and failure load can be evaluated from the load deflection curve. A special fixture is used to hold the spring in the machine.

B. Measurement of fiber volume fraction.

The fiber volume fraction of the spring is measured by the test conducted as per ASTM D 3171. The fiber weight fraction and fiber volume fraction can be calculated from the formula:

$$W_f = \frac{W_1}{W_2} X100\% \quad (5)$$

$$Vf = \frac{W_f / \rho_f}{W_f / \rho_f + W_r / \rho_r} x100\% \quad (6)$$

Where W_f is the fiber weight fraction (%), W_1, the weight of fiber (g), W_2, the weight of specimen (g), V_f, fiber volume fraction (%), W_r, the resin weight fraction (%), ρ_f, the density of fiber (g/cm^3) and ρ_r, is the density of resin, (g/cm^3). The mechanical properties of the three types of composite springs are listed in Table I.

TABLE I
THE MECHANICAL PROPERTIES OF THE THREE TYPES OF SPRINGS.

Material type	GF	CF	GF/CF
Spring rate (N/mm)	3.17	4.81	2.62
Failure load (N)	766	1177	647
Maximum compression (mm)	80	90	70
Fiber volume fraction (%)	60.25	60.30	61.25
Weight of spring (g)	205.43	168.82	198.72

V. EXPERIMENTAL RESULTS AND DISCUSSION

The objective of this research is to find the feasibility of replacing metal coil springs with the composite coil springs. Three types of composite springs were manufactured to study the use of composite materials. In order to improve relative reliability of the experimental results three sets of springs were fabricated in each type and tests were conducted on these springs. The average values of these test results were taken for analysis.

The average values of the load and deflection rates of the three types of springs are given in table II. the load deflection curves of the three types of springs are shown in Fig 6. The spring rates are calculated from the load deflection curves and are shown in Fig 7. As observed from the results the spring rates of the carbon fiber springs are 34% more than the glass fiber spring and 45% more than the CF/GF spring. This is due to the more strength of the carbon fiber compared to glass fiber. Due to imperfect bonding of glass fiber and carbon fibers, the spring rates obtained by GF/CF springs are less.

The failure loads and maximum compression of the three types of springs is shown in Fig 8 and Fig 9. Again the failure load of the carbon fiber spring is 35% more than the carbon fiber spring and 45% more than the GF/CF spring. The maximum compression of the carbon fiber spring is more than the other two types of springs due to its high strength. The weight of the carbon fiber spring is 18% less than glass fiber spring and 15% less than the GF/CF spring. Weight of all three types of composite springs is approximately 80% less than the steel spring.

It is evident from the above results the spring rate, failure load, maximum compression of the spring depends upon the material characteristics. Since the properties of carbon fiber are high specific tensile strength, high modulus, low density, low coefficient of thermal expansion, heat resistant, chemical stability, and self lubricity the springs made from these fibers exhibit better properties.

TABLE II
THE AVERAGE VALUES OF THE LOAD AND DEFLECTIONS OF THE THREE TYPES OF SPRINGS

Sl no	Deflection (mm)	Load (N)		
		GF	CF	GF/CF
1	5	11.77	19.62	13.73
2	10	27.46	44.62	26.48
3	15	44.14	67.68	39.24
4	20	61.8	93.19	51.99
5	25	77.49	116.73	64.74
6	30	94.17	141.26	77.49
7	35	109.87	166.77	90.25
8	40	125.56	192.27	102.02
9	45	142.24	213.85	115.75
10	50	157.94	239.35	127.53
11	55	174.61	264.87	140.28
12	60	192.27	289.39	153.03
13	65	207.97	314.9	165.78
14	70	223.66	340.4	178.54
15	75	239.36	365.91	191.29
16	80	255.06	387.49	204.04

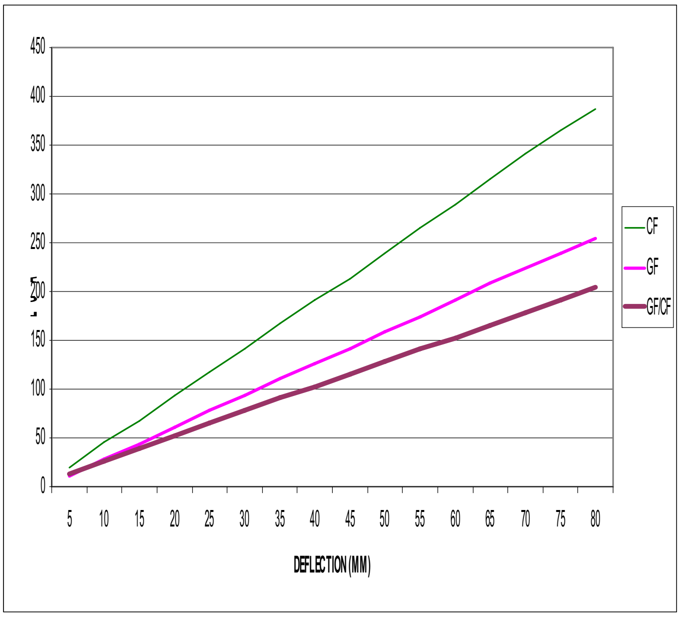

Fig. 6 The load deflection curves of the three types of springs

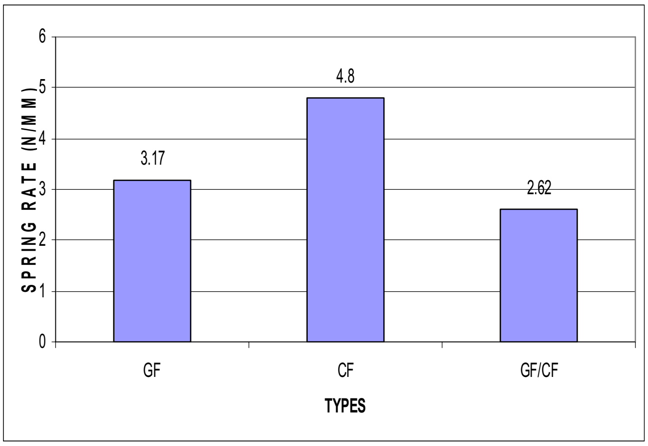

Fig. 7 Spring rates of the three types of springs

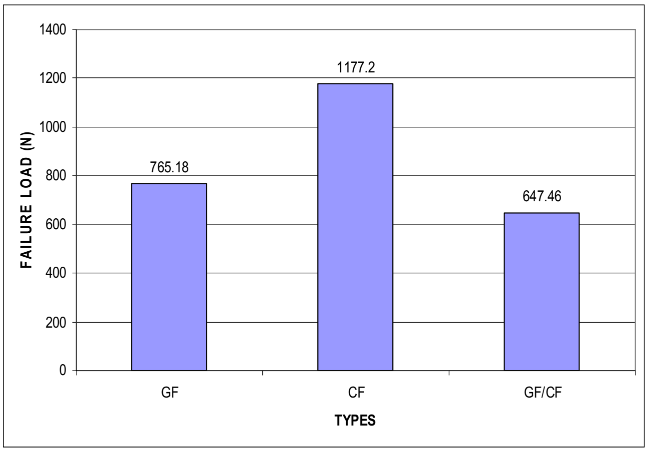

Fig. 8 Failure loads of the three types of springs

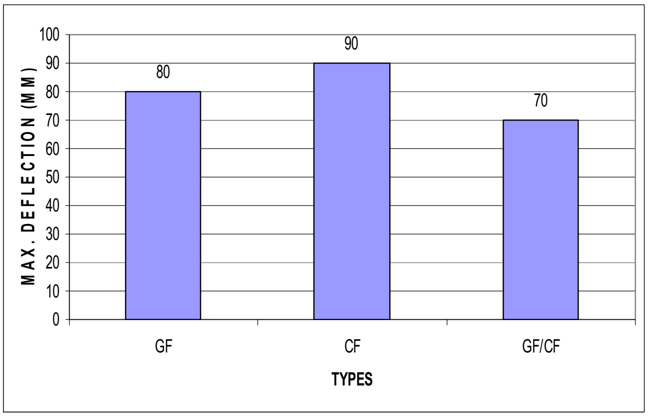

Fig. 9 Maximum compression of the three types of springs

VI. Conclusion

Three types of composite coil springs have been developed in this study; they are lighter than steel spring and the stiffness achieved in these springs are less than the steel spring. (Spring rate of the same dimension steel spring is approximately 14 N /mm and weight of the steel spring is 1.078 kg). The following conclusions can be drawn from the analysis of experimental results of these springs.

The weight of the springs manufactured from carbon fiber roving is less than the glass fiber and glass fiber/carbon fiber roving springs.

The stiffness of the carbon fiber springs is greater than the other two types of composite coil springs.

The springs developed from the glass fiber/carbon fiber rovings does not exhibit a favorable results compare to other two types of springs.

The cost of the glass fiber springs are 25% more than the steel springs and the cost of the carbon fiber springs is 200% more than the steel springs. The selection of the glass fiber or a carbon fiber springs depends upon the cost and application of the spring which can be compensated by saving the fuel from weight reduction.

As compared to steel springs of the same dimensions, the stiffness of composite coil springs is less. In order to increase the stiffness of the spring the dimensions of the composite spring is to be increased which in turn increases the weight of the spring. Hence the application of the composite coil springs can be limited to light vehicles, which requires less spring stiffness, e.g. electric vehicles and hybrid vehicles.

The manufacturing of the composite coil springs is also difficult and time consuming compare to steel spring, however with the use of CNC winding machine and automated process which can be made easy and also the manufacturing cost can be reduced if produced in mass.

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