Optimization of Steel Helical Spring by Composite Spring

Mehdi Bakhshesh[1] and Majid Bakhshesh[2]
[1,2]Department of Mechanical Engineering, Behbahan branch, Islamic Azad University, Behbahan, Iran
[1]mehdi.bakhshesh@yahoo.com

***Abstract*—Springs that can reserve high level of potential energy, have undeniable role in industries. Helical spring is the most common element that has been used in car suspension system. In this research, steel helical spring related to light vehicle suspension system under the effect of a uniform loading has been studied and finite element analysis has been compared with analytical solution. Afterwards, steel spring has been replaced by three different composite helical springs including E-glass/Epoxy, Carbon/Epoxy and Kevlar/Epoxy. Spring weight, maximum stress and deflection have been compared with steel helical spring and factors of safety under the effect of applied loads have been calculated. It has been shown that spring optimization by material spring changing causes reduction of spring weight and maximum stress considerably. In any case, with changing fiber angle relative to spring axial, composite spring properties have been investigated.**

***Keywords*–** Helical Spring, Stress, Steel and Composite

I. INTRODUCTION

Helical springs are simple forms of springs, commonly used for the suspension system in wheeled vehicles.

Vehicle suspension system is made out of springs that have basic role in power transfer, vehicle motion and driving. Therefore, springs performance optimization plays important role in improvement of car dynamic. The automobile industry tends to improve the comfort of user and reach appropriate balance of comfort riding qualities and economy. There is increased interested in the replacement of steel helical spring with composite helical spring due to high strength to weight ratio. On the other hand, there is a limitation at the amount of applied loads in springs. The increase in applied load makes problem at geometrical alignment of car height and erodes other parts of car. So, springs design in point of strength and durability is very important. Reduction of spring weight is also principal parameter in improvement of car dynamic. By replacement of steel helical spring with composite helical spring will reduce spring weight in addition to resistance raise under the effect of applied loads. In this research, a static analysis is employed to investigate behavior of steel and composite helical spring related to light vehicle suspension system. Steel spring has been replaced by three different composite helical in ANSYS software and results have been compared with analytical solution. The objective is to compare the load carrying capacity, stiffness and weight savings of composite helical spring with that of steel helical spring. Advanced composite fibers such as glass, carbon and Kevlar-reinforced suitable resins, are expected to be widely used in vehicle suspension system application so that spring of different shapes can be obtained. This refers to the high specific strength (strength – to- density ratio) and high specific modules (modules – to- density ratio) of this advanced composite materials.

Although epoxy is relatively sensitive to moisture, it has better mechanical property relative to other polyesters.

The method used for the production of the springs is a variation of the RTM (Resin Transfer Molding) process. Through this method, the dry braids are positioned in the mold before being impregnated with the resin, making production very clean. In this case, an open mold consisting of a helically grooved mandrel is used, and the braids are impregnated by plunging in a bowl filled with resin. The production process can be explained in few steps:

A silicon tube is filled with stand in order to let the braids keep a circular shape when winded. The braids are then wound around the mold. The mold is put in the oven to warm up together with the resin, in order to facilitate the impregnation. The resin is cured while turning on its axis. This allows the resin in excess to be equally removed from the spring. After the curing time the mold is then easily removable from the mold.

Many studies are carried out to investigate the behavior of composite springs. Senthil Kumart and Vijayarangan investigated behavior of composite leaf spring for light passenger vehicles. Their studies included design and experimental analysis of composite multi leaf spring made of glass fiber reinforced polymer. Static analysis of 2-D model of conventional leaf spring was performed using ANSYS and compared with experimental results. Compared to steel spring, the composite leaf spring was found to have lesser stress, higher stiffness and higher natural frequency than that of existing steel leaf spring and weight of spring was reduced by using optimized composite leaf spring [1].

Senthil Kumart and Vijayarangan studied fatigue life ofsteel and composite leaf spring for light passenger vehicles and concluded that fatigue life of composite leaf spring was more than that of conventional steel leaf spring [2]. V. Yildirim investigated the free vibration problem of unidirectional composite cylindrical helical springs theoretically as a continuous system considering the rotary inertia, shear and axial deformation effects. The theoretical results were verified with the values obtained theoretically and experimentally for straight beams and helical springs. In their study , the effects of the number of active loops, the helix pitch angle and material types on the first six natural frequencies of helical springs with circular section and fixed–fixed ends, were investigated [3]. Gobbi and Mastinue designed composite helical spring with a hollow circular section. In their study, the technical specifications, (e.g. stiffness, maximum deflection) were given and the method allows defining the spring geometrical and mechanical parameters in order to get the best compromise among spring performances (minimum mass, maximum strength) with constraints on local and global stability and on resonance frequency [4]. An optimization study on helical compression springs has been performed by Azzam. The objective functions and constrains were mathematically formulated to minimize the spring weight and maximize the spring stiffness by changing composite material [5].

II. SOLID MODELING OF METAL HELICAL SPRING

Helical springs have the characteristic parameters that affect their behaviors. In addition to the physical properties of its material, the wire diameter (d), loop diameter (D), number of loops (N_a) and the distance between two consecutive loops (P) are the parameters that affect the behavior of spring. These parameters have been illustrated in Fig. 1.

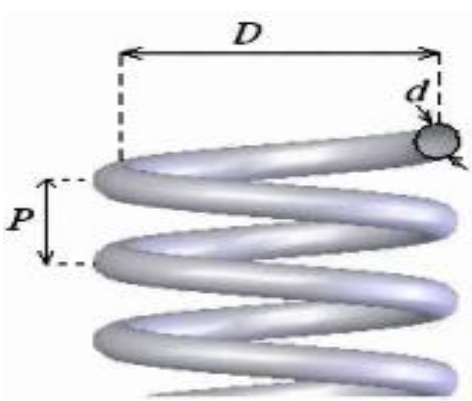

Fig. 1.The parameters of helical spring

Specifications of helical spring related suspension light vehicle is shown in Table 1.

Table 1: Helical spring specifications

Mid diameter(D)	145 mm
Wire diameter(d)	13mm
Active loops numbers	6.5
Spring height	440mm
Maximum force	3KN
Maximum deflection	222mm

Before analysis of helical spring, the rate of spring, shear modulus and poison coefficient are needed to be calculated.

$$K = \frac{F}{Z} \quad (1)$$

$$G = \frac{8D^3 N_a K}{d^4} \quad (2)$$

$$\nu = \frac{E}{2G} - 1 \quad (3)$$

Where K is spring stiffness constant,$F$is static force,Z is Axial displacement,G is shear modulus, D is mid diameter of spring, N_a is number of active loops, d is wire diameter and ν is coefficient of poison and E is elasticity module.

III. SIMULATION OF STEEL HELICAL SPRING

Spring Geometry is modeled in SOLIDWORKS Software and then is analyzed under uniform loading condition in ANSYS Software. Axial displacement and shear stress have been compared with analytical results. Load is in direction of spring axis and is exerted on the one end of spring and other end is fixed in X, Y and Z directions. Meshes with different resolutions are generated to insure grid independence. Mesh of spring and its loading has been illustrated in Fig. 2.

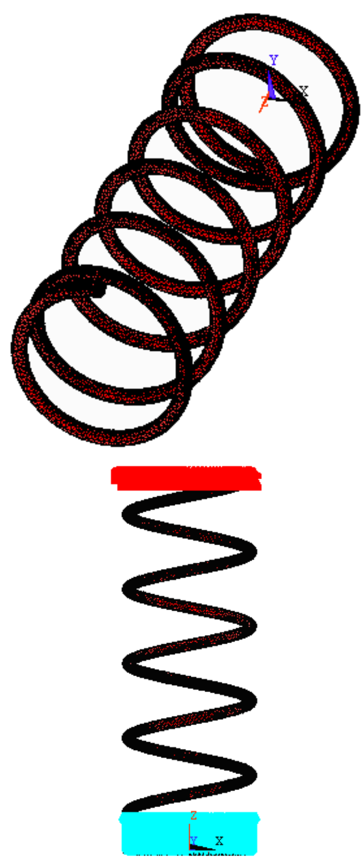

Fig. 2. Manner of mesh and loading in spring

Element selected for this analysis is SOLID45. SHELL element does not show stress variation in the course of diameter. BEAM element represented stress along the length only and doesn't show other information about stress.SOLID92 is a pyramid element that increases time of calculations and it has error in nonlinear complex models. Therefore, a cubic SOLID45 element has been used in the stress analysis. This element is defined by eight nodes having three degrees of freedom at each node: translations in nodal x, y and z directions. Axial and lateral displacements have been shown in Fig. 3 and Fig. 4.

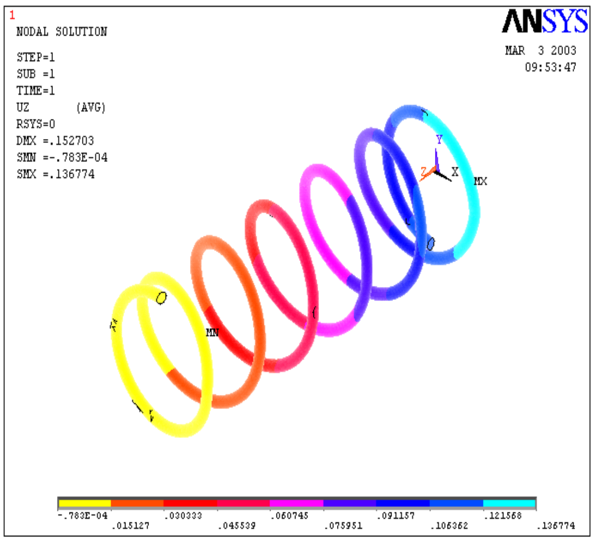

Fig. 3.axial displacement spring

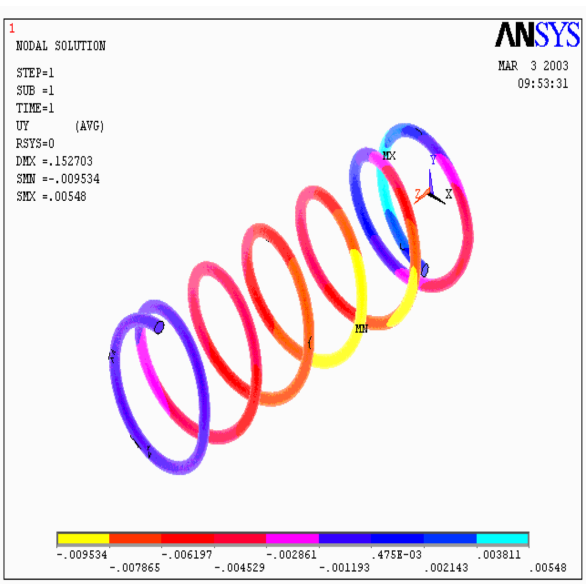

Fig. 4.lateral displacement spring

Fig. 3 and Fig. 4 show that lateral displacement of spring is nominal in compare with longitudinal displacement. This is because that loading is in longitudinal direction and poison coefficient is very small.

Table 2 shows axial displacement and shear stress using finite element method (FEM) and have been compared with analytic results.

Shear stress can be written as:

$$\tau_{xy} = k_w \frac{8FD}{\pi d^3} + \frac{F}{A} \tag{4}$$

Where,$k_w$is shear stress correlation coefficient , $c$is index spring (D/d), F is static force, D is mid diameter of spring, d is wire diameter [6].

$$k_w = \frac{4c-1}{4c-4} + \frac{0.615}{c} \tag{5}$$

Table 2: Displacement and shear stress spring

	Analytic Method	FEM Method	Error %
Axial Displacement (mm)	148	136	8%
Shear Stress (Mpa)	791	697	10.6%

IV. REPLACEMENT STEEL SPRING WITH COMPOSITE SPRING

Steel helical spring has been replaced by three different composite helical springs including E-glass/Epoxy, Carbon/Epoxy and Kevlar/Epoxy. The loading conditions are assumed to be static. Spring Shear stress has been obtained using FEM and has been compared with steel helical spring. Composite spring properties have been studied with changing fiber angle relative to spring axial. The element is SOLID 46, which is a layered version of the 8-nodes structural solid element to model layered thick shell or solids. The element has three degree of freedom at each node and allows up to 250 different material layers.

A. Composite helical spring weight

Before modeling of composite helical spring, its weight has been calculated and compared with steel helical spring. Results for different percentage of fiber have been shown in Table 3. Compared to steel helical spring, Composite helical spring has been found to have lesser weight. Also it is concluded that changing percentage of fiber, especially at Carbon/Epoxy composite, does not affect spring weight.

Table3- weight steel helical and composite comparison

Fiber percentage	Steel spring weight (N)	Glass/Epoxy composite spring weight (N)	Carbon/Epoxy composite spring weight (N)	Kevlar/Epoxy composite spring weight (N)
0.6	30.1	7.75	4.95	5.26
0.7	30.1	8.26	5	5.36
0.8	30.1	8.77	5.05	5.46

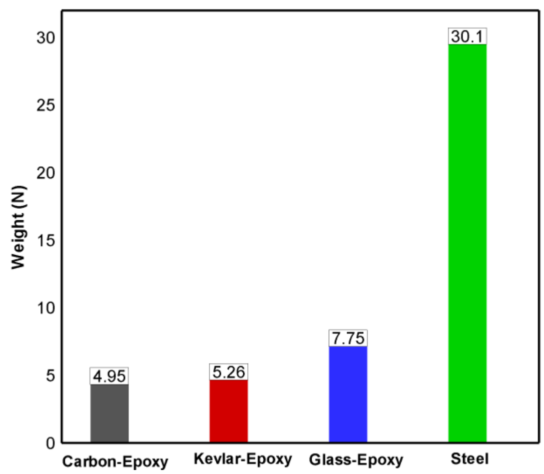

Fig. 5. Comparison of steel and composite spring weight

Helical spring weight can be written as:

$$W = \frac{\pi^2 d^2 D\, N_a\, \rho}{4} \qquad (6)$$

Where, N_a is number of active loops, d is wire diameter. and ρ is weight per volume that can be calculated by:

$$\rho = V_f \rho_f + V_m \rho_m \qquad (7)$$

Where, V_f is volumetric portion of fiber, V_m is volumetric portion of resin, ρ_f is fiber weight per volume and ρ_m is resin weight per volume.

For composite helical spring with 0.6 fiber volumetric portion, three different composite helical springs weight has been graphically compared with steel helical spring in Figure 5. It has been demonstrated that Carbon/Epoxy composite helical spring has lesser weight in comparison with other springs.

B. Direction of Fiber in Composite Helical Spring

Spring strength must be calculated at fiber along and fiber vertical direction and can be written as [7]:

$$E_1 = V_f E_f + V_m E_m \qquad (8)$$

$$E_2 = \frac{E_f\ E_m}{V_f E_f + V_m E_m} \qquad (9)$$

Where, E_1 is strength of composite helical spring at along of fiber and E_2 is its strength in vertical direction of fiber. Fiber volumetric portion is 0.6 and resin volumetric portion is 0.4. Since spring wire diameter is 13 mm, number of layers must be selected in a way that summation of layers thickness is equal to 13 mm. Therefore, number of layers is 26 in which each layer thickness is 0.5 mm.

Angle fiber has been changed so that fiber position has been considered in direction of loading, perpendicular to loading and at angles of 30 and 45 degree relative to applied loads. In any case, three different composite helical springs including E-glass/Epoxy, Carbon/Epoxy and Kevlar/Epoxy have been considered and longitudinal displacement and shear stress have been calculated to analyze the effect of spring material upon spring behavior. It is worth mention that fiber has been placed at the same thickness layers which are parallel relative to each other. Longitudinal displacement under the effect of fiber angle has been shown in Fig. 6.

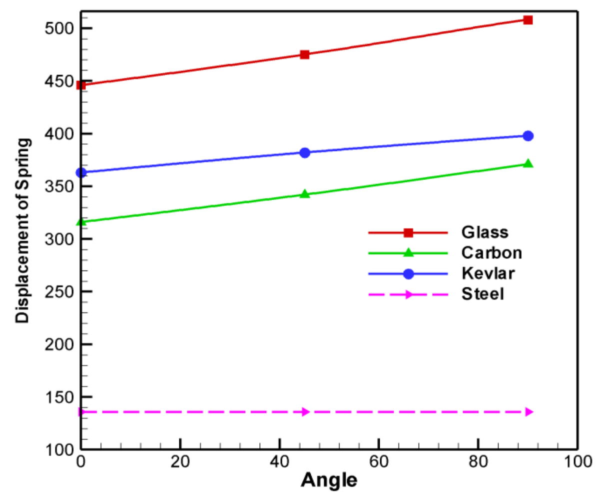

Fig. 6. Longitudinal displacement versus fiber angle

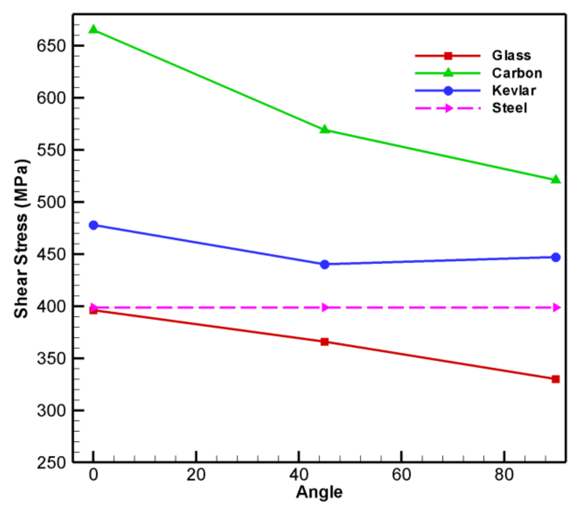

Fig. 7. Shear stress versus fiber angle

Spring has the least longitudinal displacement when fiber position has been considered to be in direction of loading. With changing fiber angle, spring longitudinal displacement increases so that it reaches the greatest value when fiber position has been considered to be perpendicular to loading. Also, Figure 6shows that E-glass/epoxy composite helical spring has the most flexibility and Carbon/Epoxy composite helical spring has the least displacement. It is obvious that longitudinal displacement in composite helical springs is more than that of steel helical spring shown in Fig. 3.

Shear stress under effect of fiber angle has been shown in Fig. 7. Spring has the most Shear stress when fiber position has been considered to be in direction of loading. With changing fiber angle, Shear stress reduces so that it reaches the least value when fiber position has been considered to be perpendicular to loading.

Factors of safety under the effect of applied loads have been calculated with changing fiber angles. Results have been presented in table4 and have been graphically illustrated in Figure 8. At factor of safety calculations, it has been assumed that resin strength is nominal in comparison with fiber strength and can be neglected.

Table 4: Factor of safety with changing fiber angle

Spring Material	Fiber in direction of loading	Fiber at angle of 45 degree relative to applied loads	Fiber perpendicular to loading
E-glass/Epoxy	3.6	3.9	4.2
Carbon/Epoxy	3.53	4.05	4.4
Kevlar/Epoxy	3.46	3.76	4.06

Fig. 8 shows that for a composite helical spring, the most safety factor under the effect of applied loads is related to case that fiber position has been considered to be perpendicular to loading. Also, Carbon/Epoxy composite helical spring has more safety factor at any fiber angle in comparison with other composite helical springs. Therefore, that composite helical spring is more suitable at this aspect.

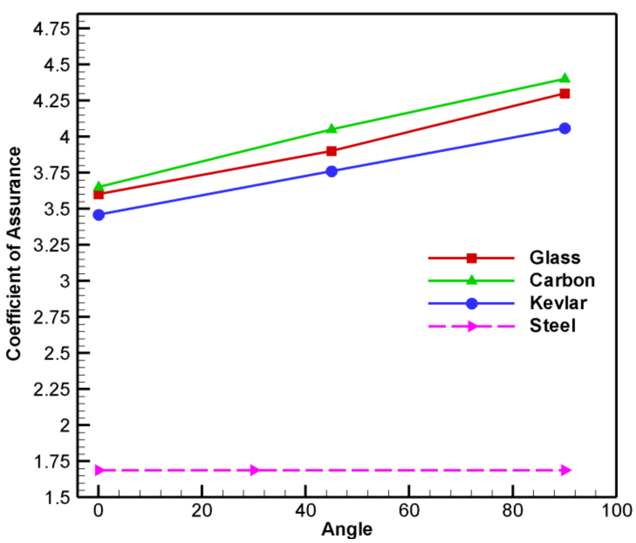

Fig. 8. Safety factor versus fiber angles

V. CONCLUSION

In this paper, a helical steel spring has been replaced by three different composite helical springs. Numerical results have been compared with theoretical results and found to be in good agreement. Compared to steel spring, the composite helical spring has been found to have lesser stress and has the most value when fiber position has been considered to be in direction of loading. Weight of spring has been reduced and has been shown that changing percentage of fiber, especially at Carbon/Epoxy composite, does not affect spring weight. Longitudinal displacement in composite helical spring is more than that of steel helical spring and has the least value when fiber position has been considered to be in direction of loading. The most safety factor is related to case that fiber position has been considered to be perpendicular to loading and it is for Carbon/Epoxy composite helical spring.

REFERENCES

[1] M. Senthil Kumar, S. Vijayarangan,"Design Optimization and Experimental Analysis of Composite Leaf Spring for Light Passenger Vehicles", Journal of Advances in Vibration Engineering, Vol 6, pp. 175-184, 2007.

[2] M. Senthil Kumar, S. Vijayarangan,"Static analysis and fatigue life prediction of steel and composite leaf spring for light passenger vehicles", Journal of Scientific & Industrial Research, Vol 66,pp. 128-134, 2007.

[3] Yildirim, V, "Free vibration of uniaxial composite cylindrical helical springs with circular section", Journal of sound and vibration, Vol 239, pp. 321-333, 2001.

[4] Gobbi, M., Mastinue, G.,"On the optimal design of composite tubular helical springs",Physics and Astronomy, Meccanica, Vol 36, pp. 525-533, 2001.

[5] AZZAM,B. S., "An optimum design for helical spring composite", Journal of proceedings of the institution of mechanical engineers, Vol224, pp. 347-354. 2010.

[6] J.E, *Mechanical Engineering Design*, fifth edition, McGraw Hill publication, 1997.

[7] J. Theodore, *Engineered Material Handbook Composite Composites*, Vol 1, ASME International publication, USA, 1987.