Study the Possibility of using Fiber and Polymer Composite Materials in Helical Spring Manufacturing

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Abstract. This work deals with studying the possibility of introducing new material into the spring manufacturing and study the properties of this spring and the load-carrying capacity when it is facing compression load. Then, specifying the application that this new composite spring could be used for. One of the applications of springs are in the suspension system, and the primary demand that the designers of automobiles are looking for is improving fuel efficiency, which may be related to the weight of the vehicle. In this research, the steel spring has been replaced by glass and carbon fibers composite with polyester resin as a matrix material. Theoretical analysis has been conducted and numerical analysis of spring was performed using ANSYS WORKBENCH to simulate the spring under axial compression load. A comparison between the theoretical and numerical deflection results has been made to predict the best material that can be used for replacement the steel spring. The second part of the research is the selection of materials and the utilized mold in the manufacturing process of the composite helical compression spring by using fibers, it was found that carbon fiber spring has results near to steel spring with stiffness 5.66 and steel 5.49 and glass composite spring 5.018 and carbon composite deflection was less than the glass composite deflection.

Keywords. Spring design, Composite material, Carbon fiber, Glass fiber, Spring analysis.

1. Introduction

Spring is defined as an elastic object which is deflected under different load conditions, and the spring response is represented by elongation or compression. There are many types of springs which may be classified according to their shapes into helical, flat, and dish. Another type of classification is according to the load applied (Haralem, S. and Elango, M 2014) [1]. Helical spring is widely used in different verity fields such as automobiles, aircrafts, combustion engines, doors locking. One of the spring applications is in the suspension system. Suspension system is an essential part of automobiles, which is responsible for easy and comfortable riding. Suspension system mainly consists of a helical compression spring and shock absorber. The spring is usually made of conventional material (steel, chrome vanadium, stainless steel etc). However, with industrial development, new material have been used in spring manufacturing. In this study, a helical compression spring has been fabricated by using carbon and glass fiber with polyester resin. These new materials have been used in the fabrication of spring in order to reduce the weight of vehicles and high strength, stiffness, and corrosion resistance.
However, it is expensive. Composite materials may be defined as a combination of two or more materials in such a way that give better properties of their virtues while reducing the extent of the effect of insufficiency. The notion of composite materials is attributed to the making of nature and was not invented by humans. As an example, wood is an example of natural composite materials polymer-polymer (reinforcement cellulose –resinous matrix). Composite materials have been developed in the last century, which provide the engineers with a new class of materials and tools to use them advantageously. Composite materials provide high strength, stiffness, wear, corrosion resistance, and lightweight properties (Harris, B, 1999) [2]. Much researches have been done on analysis, design, and fabrication of helical springs for different applications( P. Dhanapal. et al. (2018)) [3]. This study describe the design and comparative analysis using standard empirical formula and ANSYS of steel spring with the glass and carbon fiber epoxy materials. Carbon fiber has a maximum deflection, however, the circular cross-section was considered. The load acting on the entire rear suspension system was 1000 N. The rear suspension system comprises of a pair of shock absorbers. Hence the load on one suspension in the rear is half of the entire load, which is 500 N. This load was applied on the spring in static structural analysis for which the deflection the Von-Mises stress is studied. For carbon epoxy spring, it found that the maximum deflection under static load is 22.264 mm, but for steel spring21.145mm and Von-Mises stress is 392.8 Mpa for carbon, 392.57 Mpa for steel. Strain Von-Mises is 0.002 for carbon, 0.0018 for steel. The theoretical and experimental analyses show that the carbon epoxy has the maximum deflection. Akash Bahtt, et al 2016 [4] have designed two samples of spring; in the first the plain steel spring has been used to manufacture the spring with the following properties: allowable shear stress is 420Mpa, modulus of rigidity (G) is80 Kn/mm², modulus of elasticity (E) is 210 Kn/mm². E-glass is used to design another helical spring. It was concluded that the yield strength in compression E-Glass is 756 Mpa, while the yield strength in tension is 2415 Mpa. Hence after carrying out the analysis of the designed spring using ANSYS, it is found that the values of deflection and stress are within the permissible limit. The maximum value of the deflection obtained is 24.536mm, which is less than 25 mm. Hence the design is safe under deflection. Bhatt, et al (2016) have investigated one of the a significant problem that is faced by automobile industries in the recent few decades, which is the fuel efficiency, as it is related to the weight of the vehicle [5]. This had led to more research for lightweight materials with the same mechanical properties as that of the conventional materials. Two different composite springs were designed and manufactured using E-glass/epoxy with a volume fraction of 60% and a 19 mm diameter. For carbon/epoxy volume of 50% and the diameter of 17 mm and compared with conventional steel material. The linear static analysis was carried out to determine the total deformation and shear stress. The deformation and stress analysis was carried at each 500N, 750N, and 1000N. The ANSYS deflection results were very close for the three springs. However, the experimental result of the manufactured spring showed a little difference in the value of deflection because of different dimension. Burgul and Kulkarni (2015) have studied the static and fatigue analysis of compression spring used for IC Engine valves [6]. The analysis was carried out using simulation software for better design features, better performance and long life. The made modifications on the original spring gave better results, which is represented by decreasing deflection from 14.08 mm to11.25 mm, maximum shear stress (318.04 to 250.30), and an increase in the maximum fatigue life from 1.14e4 to 7.40e4. Also, the application of the composite material in a high range of engineering structure has given good results with low cost for manufacturing. Of these applications are the vibration of a plate with different reinforcement fiber effect [7-8], buckling behavior for a plate structure with different parameters effect [9-14], fatigue life with the effect of reinforcement powder materials [15], and finally, application of composite materials with prosthetic and orthotic structure [16-21].

2. Materials and method

The experimental procedure includes firstly, manufacturing the spring sample by composite materials [22-25], and then testing its composite by the required tests [26-29]. Two types of fibers have been
chosen to fabricate the spring. These fibers were in the form of two-dimensional plane weave made of fiberglass and one-dimensional weave made of carbon and the polyester resin as a matrix material. The fibers properties are listed in Table 1 and the properties of polyester also listed in Table 1. Polyester has been used to facilitate the wetting of these fibers. In order to fabricate the circular helical spring, these mats were dis-assembled into single strings. These yarn has consisted of small-diameter filament ranged from (1-100 micrometer) and these yarn are grouped to form a bundle of fibers. This bundle has a length of 150cm and 1.5cm diameter. Then, prepare the polyester resin mixture with its hardener at a specified amount, and the mixture has to be mixed very well to ensure that there is no bubble in this mixture, as shown in Figure 1. After that, immerse the bundle of fiber in the polyester mixture and wrap the fibers in two the grooves of the internal part of the mold. It takes about 48 hours to completely solidified at 27 C. For this purpose, a special mold has been used to fabricate the circular cross-sectional area helical compression composite spring, as shown in figure 2 and figure 3.

| Properties       | Glass  | Carbon | Polyester |
|------------------|--------|--------|-----------|
| Density          | 2.5g/cc| 1.5    | 1.3g/cc   |
| Poisson ratio    | 0.33   | 0.32   | 0.33      |
| Young's modulus  | 72Gpa  | 230Gpa | 3.1Gpa    |
| Shear modulus    | 30Gpa  | 50Gpa  | 1.1Gpa    |
| Ultimate tensile | 2400Mpa| 3530Mpa| 40Mpa     |

**Figure 1.** Mold and the used equipment.

**Figure 2.** Glass composite spring.
3. Theoretical consideration

In the case of the cylindrical helical spring with the circular cross-sectional area under the action of compression load, the primary reactions produced in the spring wire are torsional stress on the wire of spring and then the shear stress on the cross-section, as shown in Equation (1)[2]. The main considerations in spring design were the deflection and stiffness of the spring. The deflection equation may be driven from the strain energy equation and according to Castiglione’s theorem as described in Equation (4) [30]. Other parameters may be calculated are shear stress and deflection:

\[ \tau = \frac{8PD}{\pi d^3} + \frac{4P}{\pi d^2} \]  
\[ C = \frac{D}{d} \]  
\[ Kw = \frac{4C-1}{4C-4} + \frac{0.612}{2C} \]

By substituting Equation (1 b) and Equation (2) in Equation (1a) we get the following shear stress equation:

\[ y = \frac{8NFD^3}{d^6} \]  
\[ U = \frac{T^2L}{2GJ} + \frac{F^2L}{2AE} \]

Substituting \( T=FD/2, L=ND\pi, A=\pi d^2/2, J=\pi d^4/32 \) in Equation (4a) and get the following:

\[ U = \frac{4F^2D^3N}{d^6G} + \frac{2F^2DN}{d^2G} \]

From Casigliano’s theorem \( y = \frac{\partial U}{\partial F} \), then drive the strain energy equation and arrange it to get the deflection equation as in Equation (5)

\[ y = \frac{8PD^3N}{Gd^4} \]

for stiffness or spring rate, which may be defined as the rate of force applied longitudinal deflection as in Equation (6)

\[ K = \frac{d^4G}{4D^3N} \]

Where;

\( P \): load (N); \( D \): mean diameter (mm); \( d \): wire diameter (mm); \( Kw \): Wahl's factor; \( \partial \): deflection (mm); \( G \): shear modulus (Mpa) and \( N=Na \): number of active coils.
4. Numerical simulation

The simulation consisted of the design of spring by SolidWork 17.0 software through helix and sweep features. Then, importing the design into ANSYS WORKBENCH 16.0. However, the modeling of spring includes many steps:

- Introducing the properties of materials to the program through the program library [31-33].
- Then, importing the geometry to ANSYS [34-36], the design is created according to specification in Table 2. Then, two plates were added at the top and bottom of the spring for fixation. The fixation method of spring was thus fixed from the bottom and free from the top, and the load is applied axially in compression, as shown in Figure 4.

![Figure 4. The boundary condition of the designed spring.](image)

- Then, generate mesh [37-40], by default with total nodes of 9677 and total elements of 1830, with two-element types (tetrahedron and hexahedron) to mesh the plates and the spring, as shown in Figure 5.

![Figure 5. Meshing the model.](image)
Then, perform the static structural analysis and modal analysis for both glass and carbon composite spring.

| The type of measurement | Dimension (mm) |
|-------------------------|----------------|
| Outer diameter          | 100            |
| Wier diameter           | 15             |
| Pitch                   | 40             |
| Total length            | 170            |
| Number of total coil    | 5              |

Table 2. Spring specification.

5. Results and discussion
The same design was preformed for both the carbon and glass fiber composite springs and compared with the steel spring used in a three-wheeler shock absorber. The weight of the three-wheeler vehicle is 356 kg. The load should be divided equally between the rear and front wheels. The front wheels have two springs, so the load is applied on a single spring only, which is approximately 880 N. The theoretical and numerical deflections values for glass fiber under different loads (500, 750, 1000 N) are higher than the deflection of carbon fiber reinforced composite spring. A linear relationship has been obtained between the deflections and loads, as shown in Figure 6 and Table 3. Deflection mainly depends on the shear modulus of material and this explains the variation in deflection values between the glass and carbon springs. Maximum shear stress is distributed at the inner surface of the spring, as shown in Figure 7A and 7B and Table 4, with a maximum value of 101Mpa under load 1000N for glass composite spring and 111.9 Mpa for carbon composite spring, as shown in Figure 8 and 9. The properties of composite material under shear load depend on the matrix behavior in transferring stresses across the composite layers and for better behavior under shear load the resin must exhibit adhesion properties and good mechanical features [41-46]. These values of force were selected to experts the properties of each spring as shown in table 5,6 and 7. Modal analysis has been performed, and the results have been presented in Figure 10A and 10B and Table 8 with a maximum frequency of 69.129 and a minimum frequency of 6.0093Hz for glass composite spring, and a maximum frequency of 89.96 and a minimum frequency of 8.074Hz for carbon, as shown in Table 9 and 10, and Figure 11.

Figure 6. Load deflection curve for the three considered springs.
Figure 7. A. Numerical results on glass composite spring under 750N load.
**Figure 7.** B. Numerical results of carbon composite spring under load 750 N.

![Numerical results of carbon composite spring under load 750 N.](image)

**Figure 8.** Comparison between theoretical and numerical deflection.

| a. Glass | b. Carbon |
|----------|-----------|

![Comparison between theoretical and numerical deflection.](image)

**Figure 9.** Comparison between theoretical and numerical shear stress.

| a. Glass | b. Carbon |
|----------|-----------|

![Comparison between theoretical and numerical shear stress.](image)
Table 3. Theoretical deflection results.

| Load (N) | Glass (mm) | Carbon (mm) | Steel (mm) |
|----------|------------|-------------|------------|
| 500      | 99.36      | 87.73       | 91.034     |
| 750      | 146.25     | 132.5       | 132.56     |
| 1000     | 199.1      | 175.46      | 182.068    |

Table 4. Theoretical shear stress results.

| Load N | Maximum shear stress |
|--------|----------------------|
| 500    | 40.69                |
| 750    | 56.85                |
| 1000   | 81.38                |

Table 5. Numerical results of glass composite spring.

| Load | Equivalent stress | Equivalent strain | Deformation | Shear stress |
|------|-------------------|-------------------|-------------|-------------|
| 500  | 90.765            | 0.0182            | 102.39      | 50.689      |
| 750  | 136.15            | 0.027             | 153.59      | 76.360      |
| 1000 | 181.5             | 0.0360            | 204.78      | 101.38      |

Table 6. Numerical results of carbon composite spring.

| Load | Equivalent stress | Equivalent strain | Deformation | Shear stress |
|------|-------------------|-------------------|-------------|-------------|
| 500  | 105.28            | 0.015             | 79.031      | 55.952      |
| 750  | 157.92            | 0.0238            | 126.56      | 83.928      |
| 1000 | 210.56            | 0.031             | 162.65      | 111.96      |

Table 7. Numerical results of steel spring.

| Load | Equivalent stress | Equivalent strain | Deformation | Shear stress |
|------|-------------------|-------------------|-------------|-------------|
| 500  | 514.6             | 0.0024            | 81.282      | 274.31      |
| 750  | 666.25            | 0.0258            | 126.56      | 378.41      |
| 1000 | 857.7             | 0.0048            | 162.65      | 494.51      |
Table 8. Stiffness of three springs.

| Item | Steel | Carbon | Glass |
|------|-------|--------|-------|
| Stiffness N/mm | 5.49  | 5.699  | 5.018 |

Table 9. Stiffness composite spring result.

| Item | Theoretical | Numerical |
|------|-------------|-----------|
| Glass | 5.01        | 5.28      |
| carbon | 5.699      | 6.32      |

Table 10. Model results of glass composite spring.

| Mode | Frequency of glass spring(Hz) | Frequency of carbon spring(Hz) |
|------|--------------------------------|-------------------------------|
| 1    | 6.0039                         | 8.074                         |
| 2    | 6.2001                         | 8.193                         |
| 3    | 8.1138                         | 10.647                        |
| 4    | 59.426                         | 76.053                        |
| 5    | 63.296                         | 81.989                        |
| 6    | 69.128                         | 89.962                        |

![stiffness chart](image)

Figure 11. Stiffness comparison of carbon and glass composite springs.

6. Conclusion

1. Steel spring can be effectively replaced by composite spring in specific applications like the suspension system without affecting the performance of the suspension system.
2. Mechanical properties (stress yield, elongation at break, stress at break) of E-glass reinforced polyester composite is higher than that of the carbon reinforced polyester composite.
3. In both cases, carbon and glass fibers composite spring work within the permissible limit. The deflection of both carbon and glass fiber composite is lower than the deflection of steel, so the design is safe.
4. The load capacity of the E-glass reinforced composite spring is higher than the load capacity of the carbon composite spring. E-glass by 1000 N and 763 N for carbon.
5. Numerical results of the mathematical models are represented by total deflection, equivalent (Von-Mesis) stress, equivalent strain, and maximum shear stress induce in spring show variation with the theoretical result; this is due to the manufacturing process.
6. The weight reduction of composite spring is 46% as compared with steel spring. The cost percentage of carbon fiber is 5 times higher than the cost of steel spring, and the percent cost of glass is 30% higher than the cost of steel spring.

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