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Original Article

A mechanical behavior study of filament wound composite leaf springs

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Abstract

The mechanical behavior of composite C- and O-shaped glass and carbon fiber epoxy leaf springs were investigated. The composite springs were manufactured via the filament winding method. The effects of design variables such as the spring thickness, fiber orientation, diameter, and clamping positions of the spring on the mechanical response were studied. Compression tests were conducted with a computer based control multi-purpose test suite machine. Test results revealed that O-shaped springs withstood a greater load compared to the C-shaped springs. Carbon fiber springs have much rigidity compared to the glass fiber springs. Increasing spring thickness positively affected the spring capacity. The springs with a smaller diameter exhibited a stiffer response compared to the others. Moreover, placing fibers close to 90º produced the highest spring load. Also, 95º clamping positions showed a better performance during the test. Finite element analysis was conducted using the Abaqus software package. Good agreement between experimental and numerical results was achieved.

Keywords: composite leaf spring, carbon fiber, glass fiber, finite element analysis

1. Introduction

Springs are designed to absorb, store, and release energy. Hence, the strain energy of the spring material becomes a major factor in designing springs. Strain energy (*U*) can be expressed as

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

where ρ is the density, σ the strength, and E the Young's modulus of the spring material. Clearly, from the above expression the material with a lower density and modulus will have a great specific strain energy capacity. Thus, composite materials are good for such applications. Springs in automobiles are used to absorb shock and vibration and prevent direct transfer of the ground forces to the occupants of the vehicle. Springs can also be used to reduce the risk of musculoskeletal damage to an amputee by diminishing the impact to the prosthetic side of the disability. Also, shock absorption of a spring provides a smooth and symmetric gait and relieves strain on the sound side of the disabled body. The use of composite materials yields considerable weight savings without any reduction in load carrying capacity and stiffness of leaf springs.

Several papers and literature reports have been devoted to the application of composite materials in automobiles. The possibility of using composite helical springs in place of steel springs for automotive suspension were investigated and three different types of springs using carbon fiber, glass fiber, and carbon/glass fiber were

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manufactured (Manjunatha & Abdul, 2012). Given much consideration on the geometry, a nine-leaf steel spring was replaced with a double tapered mono-leaf composite spring using finite element analysis (Ekbote, Sadashivappa, & Abdul, 2012). A front suspension leaf spring for a light vehicle was fabricated using a unidirectional E-glass fiber that was roving impregnated with an epoxy resin (Sancaktar & Gratton, 1999). Using the hand lay-up method a mono-leaf composite spring was manufactured with stress and displacement as the design constraints (Deshmukh & Jaju, 2011) and the results of the experimental and finite element analysis were compared. The performance of the double bolted end joint for injection molded glass fiber reinforced polypropylene leaf spring under static and dynamic conditions were investigated (Subramanian & Senthilvelan, 2011). Also the load bearing capacity at the joint and the clearance influence between the composite plate hole and fastener were found to be superior to that of the conventional spring. The effect of a braided outer layer and rubber core of four different helical composite springs were also studied (Chiu, Hwan, Tsai, & Lee, 2007). The stress and resistance to fatigue of the steel spring and composite spring were compared (Yinhuan, Ka, & Zhigao, 2011), whereby the composite spring was found to have less stress and better resistance to fatigue. The bending stresses and displacements were found to be less for an E-glass epoxy composite leaf spring fabricated using the hand lay-up process compared with the conventional spring under similar loading condition (Pozhilarasu & Pillai, 2013). A unidirectional laminate was utilized in manufacturing the E-glass/epoxy composite leaf spring having the same dimensions as the conventional leaf spring (Mouleeswaran & Vijayarangan, 2007). Also, the stiffness and load bearing capacity of the composite spring were experimentally and analytically compared with the steel spring. The composite spring exhibited higher stiffness and less stress concentration. Natural composites can also play an important role in modern technology. The cellulose matrix and silica reinforcement offer high impact strength and high rigidity and when compared to an artificial equivalent their mechanical performance was good (Tucker & Lindsey, 2002). The performance of a natural fiber reinforced composite spring and the glass fiber reinforced composite leaf spring was studied (Kumar, Narayana, & Srinivas, 2013). A lower stress and weight reduction of almost 70% were achieved by the jute fiber reinforced composite spring. Using the same dimensions and number of leaves of the steel spring, a leaf spring was manufactured via E-glass/epoxy unidirectional laminates (Ashok, Mallikarjun, & Mamilla, 2012). The stiffness, weight reduction and bearing capacity of the springs were investigated. The composite spring showed better performance compared to the conventional leaf spring. A single leaf glass fiber reinforced plastic spring was designed with thickness as the variable parameter and with the same geometrical and mechanical properties as the multi-leaf steel spring (Pradeep, Vikram, & Naveenchandran, 2012). Considering the thickness and width as the variables in the study, a single leaf fiber reinforced plastic spring was designed and fabricated (Nadargi, Gaikwad, & Sulakhe, 2012). Verification of the stresses and displacement of the experimental and analytical results were carried out using ANSYS software. The composite spring had low stress and a high natural frequency compared to the steel spring with about 85% lower weight. The dead weight of a steel spring can be reduced if replaced by composite materials. The dynamic response of a filament wound E-glass/epoxy pipe was reported (Gemi, Kayrici, Uludag, Gemi, & Sahin, 2018) and the results showed that as the impact velocity increased, the force and rebound energy values increased. The impact behavior was investigated of hybrid functionally graded composite pipes subjected to various internal pressures (Gemi, Kara, & Avci, 2016). The authors revealed that, increasing the impact energy subsequently lead to increased maximum deflection and contact force as well as absorbed energy. Furthermore, a decrease of the absorbed energy was observed as the carbon fiber content decreased along the radial direction of the pipe.

For several decades, various techniques have been used to manufacture fiber reinforced composite materials like hand layup, resin transfer molding, pultrusion, filament winding techniques (Gemi, Koroglu, & Ashour, 2018; Tarakcioglu, Gemi, & Yapici, 2005), and compression molding. This work intends to use the filament winding technique using glass and carbon fiber as reinforcement because it is a fast method for laying materials down. The aim of this work was to investigate the mechanical behavior of manufactured C- and O-shaped composite springs.

2. Materials Selection and Fabrication

2.1 Materials selection

The fibers chosen for the C-shaped and O-shaped springs design were FWR6 E-glass fiber due to its high extensibility, good unwinding properties, fast and complete wet-out, and high mechanical properties, and 6K A-38 carbon fiber because of its toughness, excellent mechanical properties, and light weight. A laminating resin (L285) and hardener (H287) were selected as the matrix material and were mixed in a ratio of 100:40. Table 1 shows the specifications of the laminating resin and hardener used.

2.2 Fabrication

The manufacturing technique followed in this work was the filament winding process. A computer based control Flexwind machine was used for automatic winding under a certain amount of tension in a very precise and controlled manner over the mandrel. Aluminum tubes were used as the mandrels and a releasing gel was rubbed on the mandrel three times at 20 min intervals. The multiple fiber tows were fed to fiber creels, flow via various guides and a resin bath and then out of a payout system onto the mandrel. After the completion of winding, the specimens were wrapped with a Teflon, blanket and plastic-tape and kept for curing at room tempera-

Table 1. Specifications of the resin L 285 and hardener 287.

	Laminating resin L 285	Hardener 287
Density (g/cm^3)	1.18–1.23	0.93–0.96
Viscosity (mPas]	600–900	80-120
Epoxy equivalent (g/equivalent)	155–170	-
Epoxy value (equivalent/1000g)	0.59–0.65	-
Amine value (mg KOH/g)	-	450–500
Refractory index	1.525–1.5300	1.4950–1.4990

ture for 2 days to absorb the excess resin. The specimens were then put in an oven at 60 °C for 15 h to solidify the resin using Hexion L285/H287. When the resin was finally firm and cured, the mandrel was removed to complete the process. This stage of production is important because it provides and assures the highest quality for further analysis. After curing, the O-shaped spring was cut from the mandrel at a desire width, and all the C-shaped springs were cut 45º from the O-shaped spring (Figure 1).

3. Experimental Methods

Experiments were conducted using a multipurpose test suite machine (Instron-43). The static compression tests on the specimens (C- and O-shaped springs) were carried out and ASTM D575-91 standard was employed. In each regular interval, the machine automatically recorded the raw data of the applied load and the corresponding compression and thus generated the load-displacement curve for each specimen. To improve relative credibility of the experimental results, three sets of springs were used in each experiment and tests were carried out on these springs. The average values of the test results were taken for analysis. Figure 2 shows the experimental set-up for the C- and O-shaped springs.

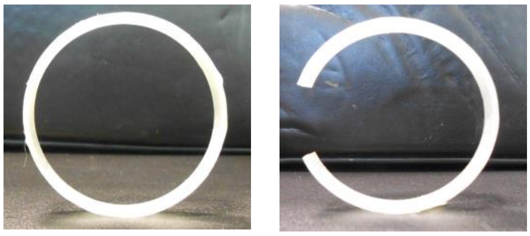
4. Results and Discussion

In this experimental study, the average measured load-displacement curves are presented. The results were categorized into thickness effect, diameter effect, fiber orientation effect, and clamping position of the spring. From the results obtained, the load bearing capacity of the carbon fiber springs was better compared to the glass fiber springs in both the C- and O-shapes for all four different experiments. This is as a result of the high strength of the carbon fiber. Also, the O-shaped springs exhibited a better performance in terms of load bearing capability than the C-shaped springs. The thickness, diameter, width, and the placement of the C-shaped spring were found to be influential on the performance of both the carbon and glass fiber epoxy springs.

4.1 Effects of spring thickness

In this process, the springs were fabricated at an 80º fiber orientation. All load-displacement curves of the C-shaped springs exhibited a linear increase at the beginning. The initial slope of the curve was much smaller compared to the second stage. The slope of the load-displacement curve represents the spring stiffness. It is believed that small displacements applied to the C-shaped spring did not provide full tension of the fiber reinforcement along the perimeters of the C-shaped spring (Figure 3a). Subsequently, vertical displacement applied to the spring came to a critical value and the fibers became active. Stiffness of the spring changed dramatically and the load-displacement curve rose exponentially. The three layers of the springs clearly bore much load compared to the one- and two-layer springs which was due to the rigidity and thickness of the layers.

The load-displacement behavior of O-shaped springs was quite different than the C-shaped springs. At the beginning, it started as a linear curve and then the slope of the linear curve decreased in the second stage. In third stage, the slope increased back to the same slope seen in the first stage (Figure 3b). Overall, the response was quite close to linear behavior. For the O-shaped springs, due to the fiber reinforcement tension, the compression started immediately. Hence, linear behavior continued up to the end of the test.



(a)

(b)

Figure 1. O-shaped and 45º cut C-shaped springs made of (a) glass fiber and (b) carbon fiber.

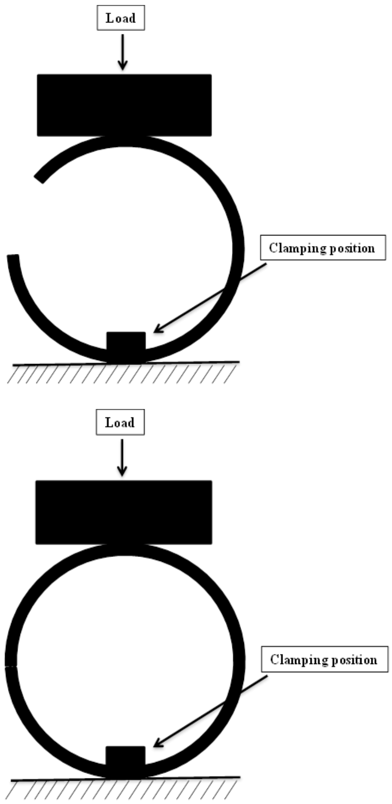
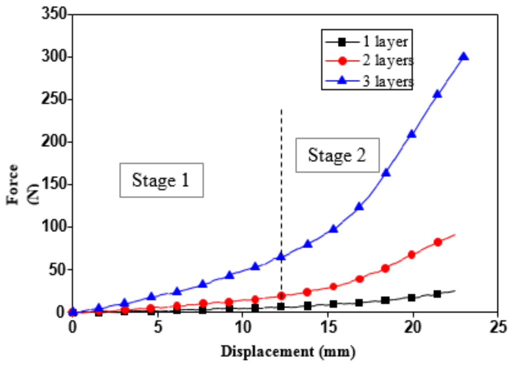
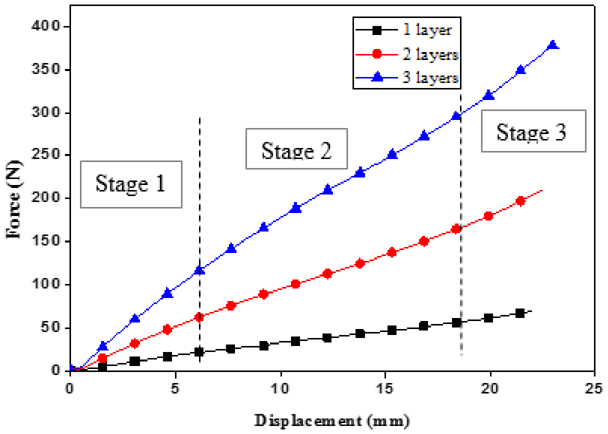


Figure 2. Experimental set up for C- and O-shaped springs.



(a)



(b)

Figure 3. Graph of three different glass fiber layers: (a) C-shaped springs and (b) O-shaped springs.

4.2 Effects of fiber orientation

The effects of fiber orientation on the response of the glass fiber and carbon fiber reinforced springs were investigated. The load bearing capacity of carbon and glass spring wound at 88º was better than those wound at 70º and 80º. If the fibers are placed along a longitudinal direction, they contributed fully to the load bearing and were found to be effusively tensioned. When placed at an angle other than 90º, their load bearing capacity was divided into longitudinal and transverse components and the bearing capability of the load reduced. Figure 4 shows the fiber orientation direction on the mandrel.

Although placing the fibers along 90º was best for load capacity, the spring was very weak under bending loading in the transverse direction. Therefore, a winding angle near the 90º direction would be the best for spring performance without jeopardizing bending capacity in the transverse direction. Figure 5a and Figure 5b depict the load-displacement graphs of the three different fiber orientations for C-shaped carbon fiber and glass fiber springs. The curves displayed almost a similar pattern for fiber orientations at 70º and 80º with the average higher forces of 68 N and 127 N, respectively, in favor of the carbon fiber springs. However, for the 88º fiber orientation the glass fiber spring exhibited more rigidity compared to the carbon fiber springs. The reason behind this could be the glass fiber spring wound at 88º is thicker due to the excess epoxy on it.

The O-shaped spring with 88º carbon fiber orientation exhibited almost a linear behavior compared to the 88º glass fiber orientation but with less displacement as it cracked before further displacement. Because of the high extensibility of the glass fiber, the 88º glass fiber orientation spring deflected much. Moreover, large variations were observed between the 88º, 80º, and 70º fiber orientations which were also due to the load applied along the 88º fiber orientations (Figure 6a and Figure 6b).

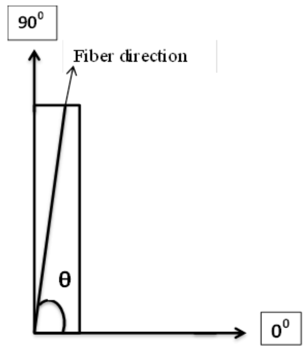
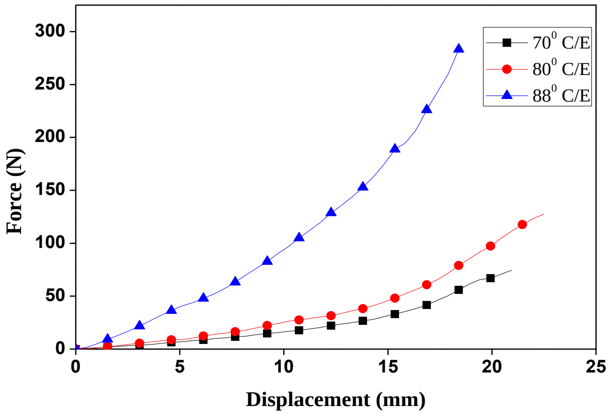
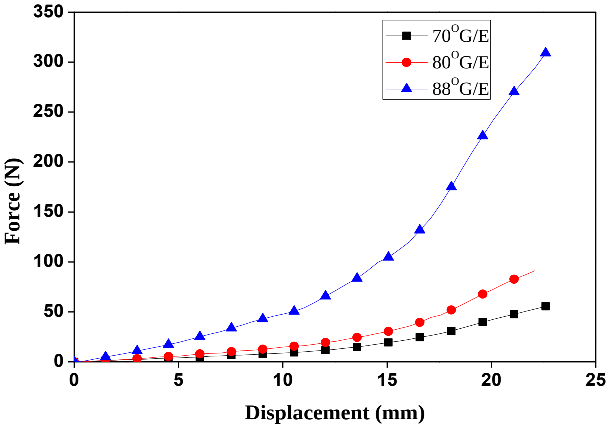


Figure 4. Fiber orientation on the mandrel.



(a)



(b)

Figure 5. Three different fiber orientations for C-shaped springs: (a) carbon fiber springs and (b) glass fiber springs.

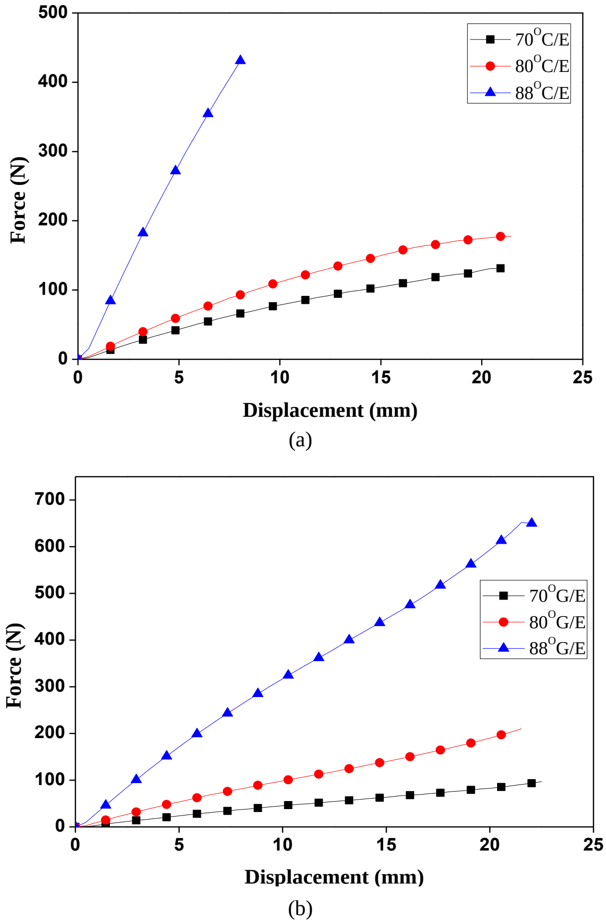


Figure 6. Three different fiber orientations for O-shaped springs: (a) carbon fiber springs and (b) glass fiber springs.

4.3 Effects of the clamping position on the spring

Glass and carbon fiber C-shaped springs with two plies as the spring thickness and 80º fiber orientation were used. Figure 7 shows the different clamping positions of the C-shaped spring during the test. The 95º holding position showed a better load carrying capacity than the 75º and 85º fix positions for the carbon and glass fiber springs, respectively (Figure 8a and Figure 8b). Within the first 10 mm displacement, all of the curves rose linearly with less tension on the fibers. After 10 mm displacement, the gradients elevated abruptly as a result of more tension on the fiber. Even though, both the carbon and glass fiber springs attained almost a similar value of force, the carbon spring had less displacement.

4.4 Finite element analysis

Classical lamination theory was used to evaluate the mechanical behavior of the composite springs. ABAQUS/ computer aided engineering (CAE) was used for modeling and simulating the behavior of the composite springs. Table 2 shows the engineering elastic constants and Poisson's ratio used for the glass and carbon fiber springs based on previous work by the authors (Sevkat & Tumer, 2013). The sizing controls of the mesh used were 0.5 approximate global size, and the curvature control was 0.1 maximum deviation factor with 8 as the approximate number of circles. Figure 9 illustrates the Von Mises equivalent stress for the C- and O-shaped springs. The experimental results were compared with the finite element analysis results for thickness and fiber orientation.

4.5 Effects of thickness

The combined experimental and simulation of the individual graphs for the three layers are shown in Figure 10 for the C- and O-shaped springs. The C-shaped springs

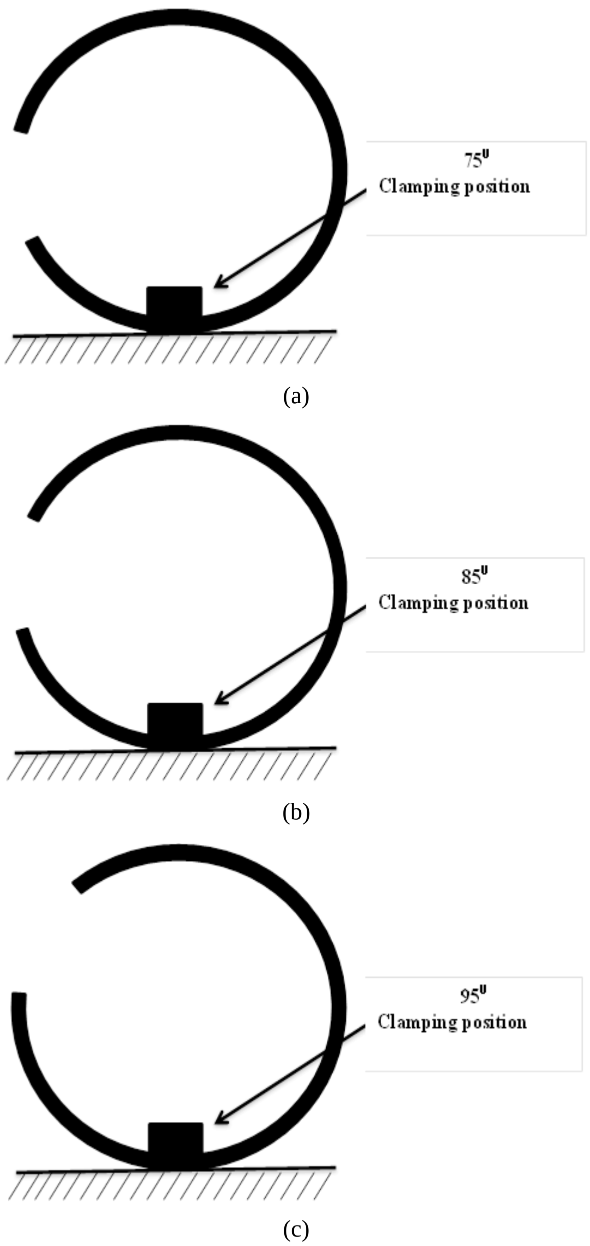
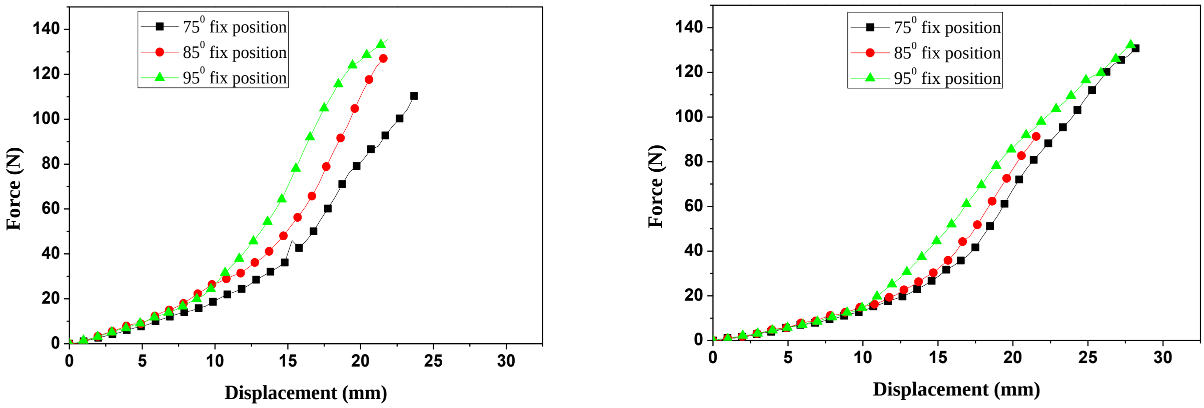


Figure 7. C-shaped springs: Clamping positions at (a) 75º, (b) 85º, and (c) 95º.

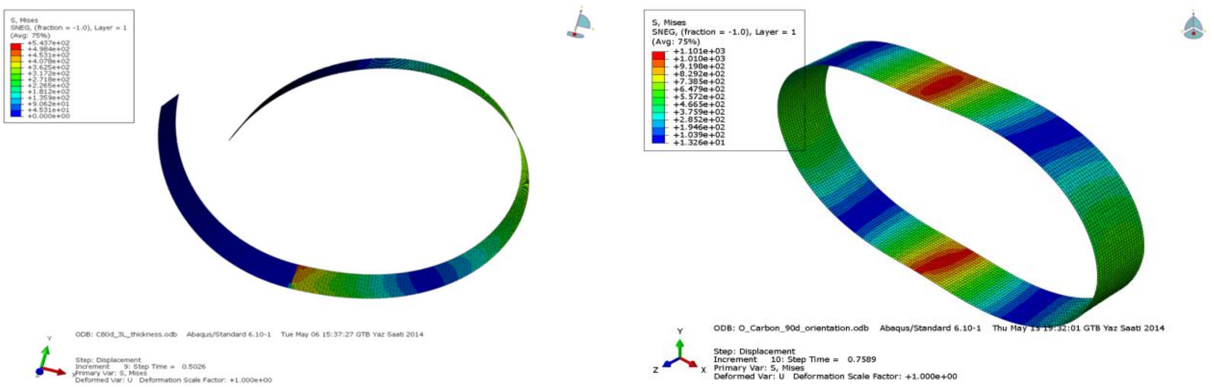
Table 2. Engineering elastic constants and Poisson's ratio of the glass and carbon springs.

Springs	E_1 (GPa)	E_2 (GPa)	ν_{12}	G_{12}	G_{23}
Glass/epoxy	21.04	6.68	0.33	2.168	2.168
Carbon/epoxy	34.77	6.68	0.33	2.722	2.722



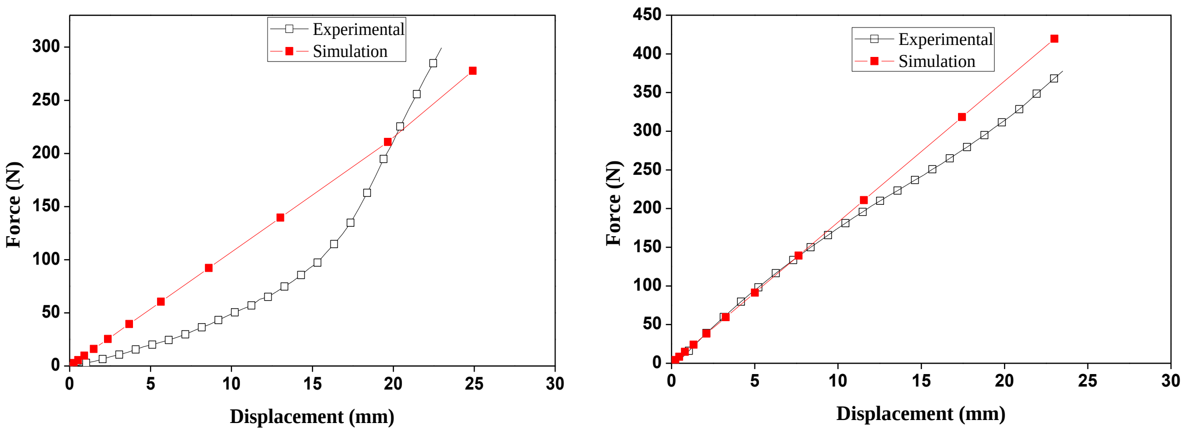
(a) (b)

Figure 8. Different fixing positions for C-shaped springs: (a) carbon fiber springs and (b) glass fiber springs.



(a) (b)

Figure 9. Von Mises equivalent stress for (a) C-shaped spring and (b) O-shaped spring.



(a) (b)

Figure 10. Load-displacement graphs for the combined experimental and finite element analysis of three layers for (a) C-shaped springs and (b) O-shaped springs.

showed a non-linear behavior, while the simulated results showed a linear behavior. This is because the linear elasticity of an orthotropic material is defined by the engineering constants which were used: E_1; E_2; Poison's ratio υ_{12}; and the shear moduli G_{12}, G_{13}, and G_{23} associated with the material's principal direction. This linear elasticity is defined using the ELASTIC option in Abaqus/CAE.

4.6 Effects of fiber orientation

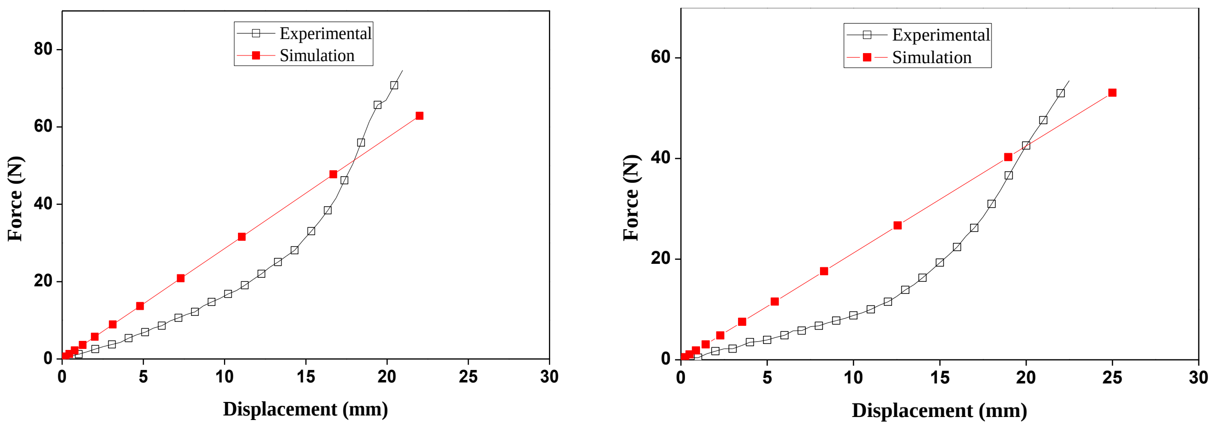
Figure 11 shows the individual graphs of the combined experimental and simulation for the 70º fiber orientations for the carbon and glass fiber composite C-shaped springs. It is clear from the graphs that the carbon spring superseded the glass spring with a force of almost 14 N.

Likewise, in Figure 12 the individual graphs are presented of the combined experimental and simulation for the 70º fiber orientations for carbon and glass fiber composite O-shaped springs. Both springs exhibited virtually a linear behavior with the glass spring having less stiffness compared to the carbon spring. This linear-like behavior of the O-shaped spring attested to its advantages over the C-shaped spring, especially for a spring design to support amputees.

5. Conclusions

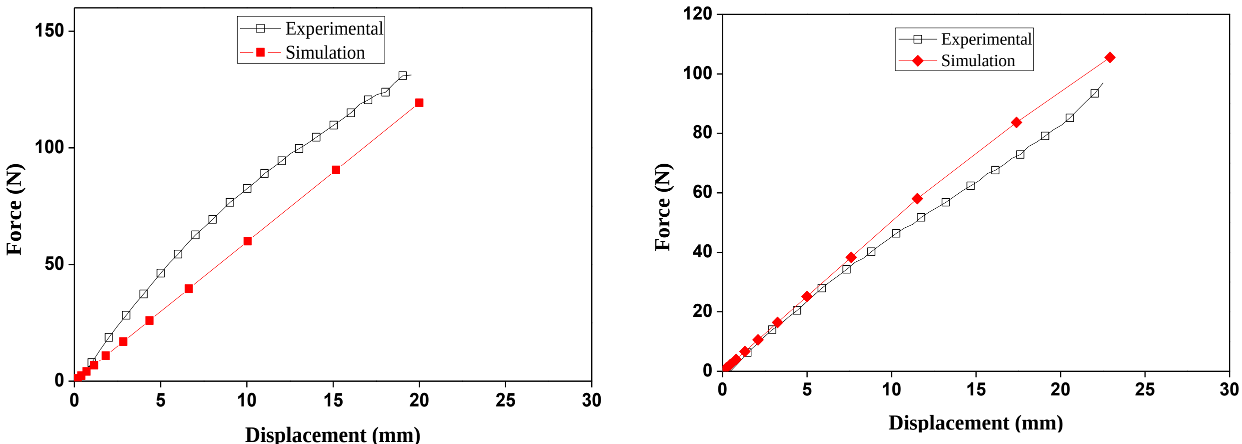
As observed from the experimental results the spring thickness and orientation angle play important roles in the stiffness and load carrying capability of the springs. The O-shaped springs could withstand a greater loading and rigidity compared to the C-shaped springs. Also, the carbon fiber springs could bear more loads but with less displacement compared to the glass fiber springs due to the ductility of the glass fiber. According to the results obtained, it is clear that;

1) The three-layer spring could bear a greater load and stiffness compared to the one-layer and two-layer springs. The load bearing capacities of the three-layer springs were 34% more than the two-layer springs and 75% more than the one-layer springs.



(a) (b)

Figure 11. Load-displacement graphs of the experimental and finite element analysis for 70º fiber orientation C-shaped springs for (a) carbon and (b) glass.



(a) (b)

Figure 12. Load-displacement graphs of the experimental and finite element analysis for 70º fiber orientation O-shaped springs for (a) carbon and (b) glass.

2) The 88º fiber orientation springs withstand more load and exhibited higher stiffness compared to the 80º and 70º fiber orientation springs. The load bearing capacities of the 90º fiber orientation springs were 47% more than the 80º fiber orientation and 62% more than the 70º fiber orientation springs.

3) The springs placed at 95º fix position displayed better load carrying capacity. Springs placed at a 95º fix position could carry a load that was 18% more than a spring placed at 85º and 27% more than a spring placed at a 75º fix position.

4) The finite element analysis using the linear elastic orthotropic material model successfully simulated the behavior of O-shaped springs. However nonlinear load displacement curves produced by C-shaped spring were not simulated sufficiently. This was due to the linear elastic orthotropic material model used for simulations. However, finite element analysis predicted results for the C-shaped spring could still be used for estimating maximum load and general behavior of C-shaped springs.

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