# EXPERIMENTAL AND NUMERICAL APPROACH TO STUDY THE MECHANICAL BEHAVIOR OF THE FILAMENT WOUND COMPOSITE LEAF SPRING

by

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in

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# APPROVAL PAGE

This is to certify that I have read the thesis entitled "Experimental and Numerical approach to study the mechanical behavior of the filament wound composite leaf spring" by Abubakar Gambo Muhammad and that in my opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Material Science and Mechanical Engineering, the Graduate Institute of Science and Engineering, Melikşah University.

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**EXPERIMENTAL AND NUMERICAL APPROACH TO STUDY THE MECHANICAL BEHAVIOR OF THE FILAMENT WOUND COMPOSITE LEAF SPRING**

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MSc Thesis- Material Science and Mechanical Engineering
June 2014

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## ABSTRACT

In this study, mechanical behavior of composite C and O shape glass and carbon fiber epoxy leaf spring were investigated. The composite springs were manufactured via filament winding method. The effect of design variables such as the spring thickness, fiber orientation and the diameter of the spring on the mechanical response were studied. Compression tests were conducted with a computer based control Multi-Purpose Test Suite (MTS) machine. Test results revealed that O shape springs withstand much load compared to the C shape springs. Carbon fiber springs have much rigidity compared to the glass fiber springs. Increasing spring thickness positively affected the spring capacity. The springs with smaller diameter exhibited stiffer response compared to others. Placing fibers close to 90$^{o}$, produced highest spring load. Finite Element Analysis was conducted using Abaqus software package. Good agreement between experimental and numerical results was achieved.

**Keywords:** Composite leaf spring, carbon fiber, glass fiber, Finite Element Analysis

**FILAMENT YARA KOMPOZİT YAPRAK YAY MEKANİK DAVRANIŞLARINI İNCELEMEK İÇİN DENEYSEL VE SAYISAL YAKLAŞIM**

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## ÖZ

Bu çalışmada elyaf sarım yöntemiyle üretilen O ve C şeklindeki cam ve karbon elyaf takviyeli kompozit yaprak yayların mekanik davranışları incelendi. Yay kalınlığı, elyaf takviye açısı ve yay çapı gibi tasarım parametrelerinin yayın mekanik davranışına etkileri incelendi. Yaylar üzerinde bası deneyleri MTS üniversal cihazı yardımıyla gerçekleştirildi. Elde edilen sonuçlar O şeklindeki yayların C şeklindeki yaylara göre daha yüksek kuvvet dayanımı olduğunu gösterdi. Karbon yaylar cama göre daha mukavemetli fakat rijittiler. Kompozit yay kalınlığı arttıkça yayın dayanım kuvvetinde artış gözlendi. Çapın küçülmesi yayın daha rijit davranmasına ve yüksek dayanım kuvveti göstermesine neden oldu. Elyaf doğrultusunun 90$^{o}$'ye yakın olması durumunda yayın dayanımının arttığı gözlendi. Abaqus yazılım paketi kullanılarak sonlu elemanlar yöntemi yardımıyla yayların mekanik davranışları simüle edildi. Deneysel ve nümerik sonuçlar arasında uyumluluk tespit edildi.

**Anahtar Kelimeler:** Kompozit yaprak yaylar, karbon fiber, cam fiber, Sonlu elemanlar yöntemi

## DEDICATION

This thesis is dedicated to my lovely parents Gambo Muhammad and Halima Abdullah, who have been a source of encouragement and inspiration throughout my life. Your prayer indeed keeps paving a smooth way for me to reach the level I am now.

A special feeling of gratitude to my mentor, the Executive Governor of Kano state, Eng. Dr. Rabiu Musa Kwankwaso, who gave me this golden opportunity to study abroad.

I also, dedicate this to my colleagues, friends and family members whose word of encouragement and advice still ring in my ear. I will always appreciate all they have done.

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# CHAPTER ONE

# INTRODUCTION

The word composite means ‘made of distinct parts or substances. Naturally, a composite material is a material that consists of two or more distinct constituents which are bound together to form an integral unit. In nature, composite materials have been in existed for millions of years. Wood, bamboo and bone are just a few examples of the naturally occurring composite materials. Man has learned to fabricate composite materials relatively recently. Perhaps, one of the first evidence of a man made composite material is the mud-block reinforced with straws. The composite materials fabrication technology has since progressed from straw reinforced mud-blocks to man-made metallic matrix and carbon-carbon composite materials [1].

## 1.1 Types of Composite materials

Composite materials are not new; most of the natural biological materials are composites. Composites may be further categorized by their constituent materials or by the processing methods. Below are the six general classification of composite material [2].

- Natural composite
- Biocomposite
- Carbon-Carbon composite
- Metal matrix composite
- Ceramic matrix composite
- Polymer matrix composite

**Natural composite**

Many of nature's structural elements tend to be formed of composite materials. The examples of these are bamboo tree, wood, horn, bone, and shell of crustacean. The reinforcement of the animals composite (tooth for example) is made from polysaccharide or calcium salt, and the matrix material is often protein. Also, bone is reinforced with a brittle high modulus apatite crystals bound together with ductile organic collagen fibers (Figure 1.1). The honeycomb core structure of the bird's bone gives the stiffness required to carry the muscle load enables them to flight without weighing too much [2].

**Fig. 1.1** Bone as natural composite.

**Biocomposite**

Majority of the biocomposites are natural structural materials, but also include artificial composites produced using synthetic resin and reinforcement fiber. Like coconut, banana, bamboo fibers. Their major applications are biomedical composite such as artificial hip joint mounting as shown in Figure 1.2, artificial inner ear bones which can restore hearing to profoundly deaf, and cosmetics [2].

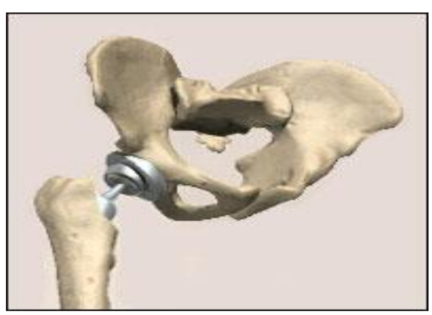


**Fig.1.2** Artificial hip joint.

**Carbon-carbon composite**

The matrix and the reinforcement of carbon-carbon composites are made from carbon. The matrix is transferred into the reinforcing material either as a liquid or by chemical vapor deposition. The material is densified in a controlled atmosphere at high temperature to produce the composite material. Carbon-carbon composites are expensive but are use in applications like aircraft disc brake, automobile clutch (as shown in Figure 1.3), and racing motorcycles brake where they work under extreme temperature. Other applications include throats, nozzles and trust tubes for rocket motors [2].

**Fig.1.3** A car clutch made of carbon-carbon composite.

**Metal matrix composite**

Metal matrix composites are produced by adding up of reinforcing particles to molten metal by the infiltration of molten metal into a fibrous or particulate perform. They perform much better than metals in terms of creep resistance, wear resistance, and enhanced elevated-temperature properties. Their major applications are inclined towards the exotic; the antenna booms on the Hubble Space Telescope as shown in Figure 1.4. Due to low thermal expansivity, high thermal conductivity, and good mechanical properties metal matrix composites make a good candidate for power electronics packaging. The complex fabrication techniques, and high costs limited their service experience [2].

**Fig. 1.4** Hubble space telescope.

**Ceramic matrix composite**

Ceramic matrix composites have a matrix made of ceramic such as alumina calcium, alumino silicate reinforced by fibers such as silicon carbide or carbon. Ceramic matrix composite fail catastrophically under tensile or impact loading, due to their low fracture toughness. This fracture toughness can be increased by reinforcing ceramics with fibers such as carbon or silicon carbide. Ceramic matrix composites have advantages such as high strength, hardness, high service temperature limits, low density and chemical inertness. Their main applications (as can be seen in Figure 1.5) include grinder tools, cutting tool inserts in oxidizing and high-temperature environments [3].

**Fig. 1.5** Grinder composite disc.

**Polymer matrix composite**

Polymer matrix composites (PMCs) are the most common advanced composites consist of a polymer such as epoxy, polyester, and urethane, reinforced by thin diameter fibers. Their high strength, low cost and simple manufacturing principles are the reasons why they are the most common composites. Polymers are classified as thermosets and thermoplastics. After curing, thermosets are insoluble and because the chains are rigidly joined with strong covalent bonds. While, thermoplastics at high temperatures and pressure are formable, because the bonds are weak. Examples of thermoset include epoxies, phenolics, polyesters, and polyamide; and typical examples of thermoplastics include polystyrene, polyethylene, polyether–ether–ketone, and polyphenylene sulfide [3]. Polymer matrix composites dominate the composite world market by almost 75% by value or by tonnage [2]. Figure 1.6 shows some of their applications.

**Fig.1.6** Bullet proof vest and helmet.

## 1.2 Advantage of composite materials

An obvious advantage that the fiber reinforced composite materials have over the conventional engineering materials such as steel, aluminum, copper etc. are:

- High specific strength
- High specific modulus
- Light weight
- Good corrosion resistance
- Retain the strength and stiffness of the structure at an ultra-high temperature
- Improved fatigue and impact resistance

## 1.3 Disadvantages

- Fibers are expensive
- Manufacturing parts is both labor intensive and expensive
- Manufacturing process is slow
- Joining composite parts is difficult
- Don’t like concentrated point load
- Difficult to repair.

### 1.4 Applications

The outstanding features which make composite materials advantageous over metals are the specific strength and modulus. The specific strength is the ratio of the material strength to the material density and the specific modulus is the young modulus per unit material density. High specific modulus and specific strength have very important implications on the engineering application of composite material. This means that, composite materials are strong, stiff and light in weight. Such characteristics are desirable in many applications [1]:

**Aircraft**: examples as shown in Figure 1.1 of the composite materials in military aircraft are F111 wing pivot fitting, Vought A-7 speed brake, graphite-epoxy used in manufacturing the vertical fin, the wings and horizontal tail surface of the Boing F-18, landing gear door, helicopter rotor etc.

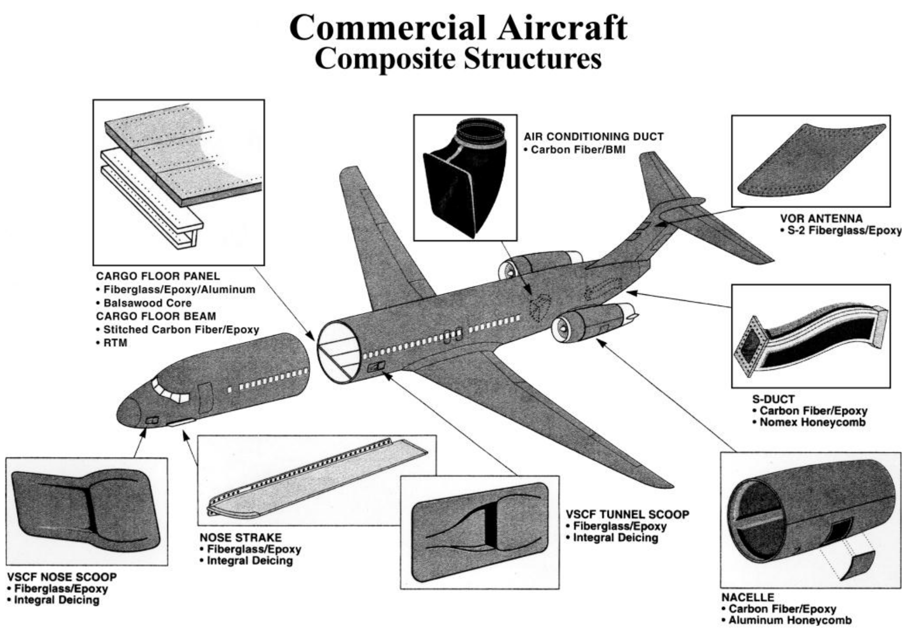



**Fig.1.7** Commercial aircraft composite structure (Courtesy of Composites Horizon, Inc.)

**Space:** The weight saving by structural components of composite material can directly be translated into fuel saving which in other hand makes the operation of space vehicle more economical. Examples as shown in Figure 1.8, are the graphite epoxy used in space vehicles antenna and to stabilize and support the Hubble space Telescope.

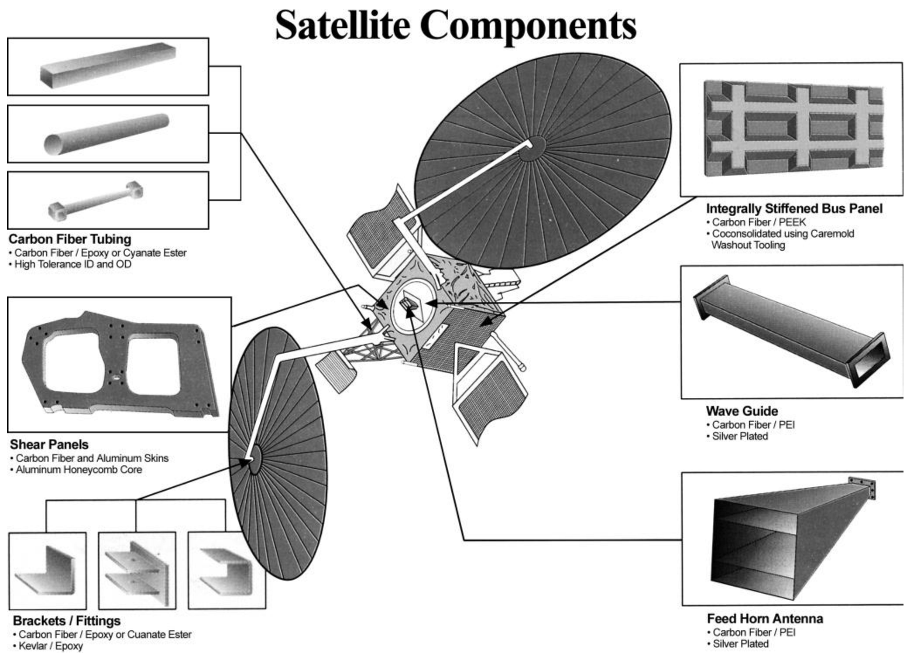



**Fig. 1.8** Components of composite used in satellite applications
(Courtesy of Composites Horizon, Inc.)

**Automobile:** In automobile industry, individual car parts such as leaf spring, driveshaft, door, bonnet, and bumper manufactured by polymer matrix composite have proven production records of high weight savings, low cost, and high production rates that can satisfy body mass reduction requirements to achieve fuel economy goals. Steel leaf springs for example for the 1980 Chevrolet Corvette weighed 19 kg, whereas the 1981 and later composite springs weighed 3.6 kg [4].

**Military:** Due to the high stiffness, good impact resistance and good energy absorption of the aramid fiber and Dupont Kevlar fiber make them strong candidate for manufacturing bullet proof vest, bullet proof helmet, jet fighters body components as shown in Figure 1.9, and armour vehicles.

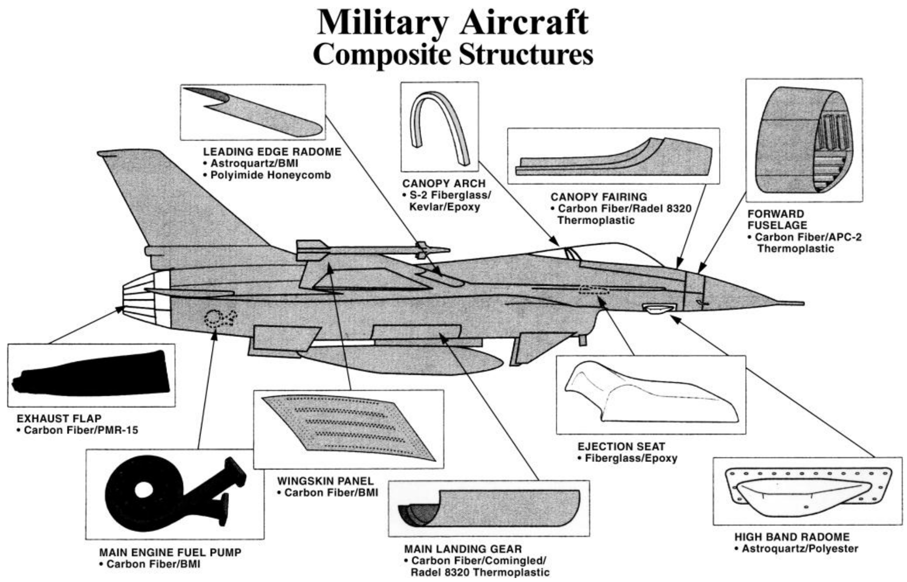



**Fig.1.9** Structures of composite used in military aircraft (Courtesy of Composites Horizon, Inc.)

**Commercial:** Replacing the metals sporting good like in tennis racquets, golf club shafts, ice hockey sticks, ski poles, snow board and race bicycles decrease the dead weight and improve the compatibility. It also reduces the stress concentration at joints of metal frames.

## 1.5 Fibers and Matrix

### Fibers

Fibers consist of thousands of filaments each filament having a diameter ranging from 5 to 15 micrometers [5]. Fibers are the main load carrier. The strength and stiffness properties of composite materials are generally determined by the fiber strength. They offer a constant controlled orientation load path. The fibers can be woven into cloth, bonded together into continuous filament mat (CFM), by means of a thermoplastic binder, or loosely twisted into bundles for use in pultrusion or filament winding. Below are the examples of the fibers used in manufacturing composite materials;

- Glass fiber: The filaments are produced by pulling the glass (eg. Silicon and sodium carbonate, at temperature of about $1000^0$C) through the small hole of a plate made from platinum alloy

- Carbon fiber: The filament of polyacrilontrile or pith obtained from filtrate of petroleum products at high temperature of about $300^0$C are oxidized, then further heated to $1500^0$C in nitrogen atmosphere
- Aramid: Dupont developed the aramid based organic fiber commonly known as Kevlar. Due to their covalent bonding, organics like aramids offer good potential to produce materials that are tough, strong in tension and light.
- Boron: consist of boron deposited by chemical vapor deposition of around 12 μm tungsten core. Boron fiber can be used to repair the fatigue cracks and impact damage in aeroplanes using vacuum bagged boron epoxy composites
- Natural fiber: They are obtained from plants; flax, jute, kenaf and hemp are the examples of them. Their physical properties vary between species, age of the plants, fiber extraction and growing condition.

**Table 1.1** Properties of some fibers [2].

| | Specific density | Tensile strength ($GN/m^2$) | Specific tensile strength | Tensile modulus ($GN/m^2$) | Specific tensile modulus |
|---|---|---|---|---|---|
| Hemp | | 0.895 | | 25.1 | |
| Flax | 1.2 | 2.0 | 1.6 | 85.0 | 71 |
| Kenaf | | 1.191 | | 60.0 | |
| E Glass | 2.6 | 3.5 | 1.35 | 72.0 | 28 |
| Carbon | 1.75 | 3.0 | 1.71 | 235.0 | 134 |
| Kevlar 49 | 1.44 | 3.9 | 2.71 | 131.0 | 91 |

**Matrix**

The fibers or any reinforcements used in manufacturing composite materials are of small use, except they are bounded together to take the shape of structure that can carry loads. This binder material is called matrix. The main functions of the matrix are the protection of the fibers, support of the fibers, stress transfer between the broken fibers, equally distribute load to the fibers etc. Moreover, properties such as shear stress, transverse tensile, heat resistance from environment are all closely related to matrix .The matrix materials can be metals, polymers, ceramics and carbon.

Thermoplastic and thermoset resin:

Polymers are usually classified into thermoplastic or thermosetting. The main difference between the two is that thermoplastics are totally polymerised in their raw state. Basically, there is no chemical reaction involved in processing. After cured, thermoplastics can be melted. This means that, applying heat can melt the polymer, and they can be solidified via cooling, which in turn can be reshaped and reformed. Moreover, ease of processing when compared with thermosets, no chemical reaction is needed in curing the parts make thermoplastic materials favorite for high volume applications. Thermoplastics have properties such as; toughness, high thermal expansion coefficient, recyclable, low working temperature etc.

Thermosets are typically in a solid or resinous liquid state before use. They are not totally polymerized in their raw state. To achieve curing, most of the thermosets need the used of extra component, this often termed a curing agent. Applying heat and pressure can cause the polymer to undergo a softening phase during which it will flow simply and thus can be impregnated into long fiber reinforcements followed via a chemical reaction carrying out the polymerization, cross-linking. Thermoset polymers have an extremely cross linked structure after cured and thus can no longer be made to flow. Re-applying of heat can degrade the resin. Thermoset polymers in some cases, when cured produce mainly polymer molecules which can then be processed thermally after cure.

A synthetic resin used as composite materials should have high mechanical properties, heat resistance, dielectric properties, and non-aging performance, and can also be fabricated easily.

**Phenolic resin**: in industrial production phenolic resin is one of the earliest resins; it has characteristics such as, solidifying under heat condition without the addition of curing agent, alkali or acid may be capable to promote the curing reaction; separation of small molecules through the process of resin curing, therefore curing of resin should be carried out in high pressure, good water resistance, volume shrinkage is large of curing, resin adhesion on fiber is not good enough, good compression performance of the curing resin, ablation resistance properties, and chemical resistance. But the resin is brittle and low fracture elongation. Therefore a large amount of phenolic resins are used within molding powder and molding compound of short fiber [6].

**Unsaturated polyester resins**: these are important resin in manufacturing the glass fiber composite materials. They have characteristics of good technology like, mold at atmospheric pressure; can be cure at room temperature. These are their major advantage compared to epoxy and phenolic resin. The mechanical properties of unsaturated polyester resin are not as good as epoxy or phenolic resin, and have lower price than epoxy resin and slightly more expensive than phenolic resin. The major disadvantage of the unsaturated polyester resin is the large curing volumetric shrinkage, poor heat resistance, and it is often used as matrix of carbon fiber composite materials [6].

**Epoxy resins**: these resins have strong bonding with the materials, good dielectric properties, high mechanical strength, and an excellent chemical corrosion resistance. Epoxy resins have wide range applications especially in carbon fiber composite materials and boron fiber composite materials [6].

### 1.6 Composite Manufacturing Processes

The manufacturing processes of composite materials can be subdivided into two main categories. These are manufacturing process for thermoset and manufacturing process for thermoplastic composites. Generally, thermoset composite parts dominate the commercial market. Almost, 75% of all composite products are made from thermoset resin [7]. Below are the description of some of the manufacturing process, their advantages and limitations.

#### (a) Hand Lay- up process

Hand lay-up process is generally categorized into two major methods: prepreg lay-up and wet layup.

**Prepreg lay-up:** It is also called autoclave processing or vacuum bagging process. Prepreg lay-up is very common in aerospace industry. Complicated shapes with high fiber volume fractions can be manufactured using this process. This process is an open molding process which has low-volume capability. Using this process, prepregs are cut, laid down in the required fiber orientation onto a tool, and after that vacuum bagged. The composite with the mold is therefore put inside autoclave after vacuum bagging, later on, heat and pressure will be apply for curing and consolidation of the parts. The prepreg lay-up process required labor intensive. The major application of the prepreg lay up is in aerospace industry and for making archetype parts. Also, wing structures of the airplanes, sporting goods, radomes and yacht parts are produced using this process. Figure 1.10 shows types of aircraft radomes lke sharknose, varying length, conical solid laminates and sandwich constructions using dielectric loaded foam cores.

**Fig. 1.10** Varieties of the aircraft radomes [7].

Some of the manufacturing challenges that are encountered during the prepreg lay-up are;

- Maintaining the fiber orientation accurately is difficult
- Void free parts are difficult to obtain.
- Obtaining parts free from distortion is also difficult.

**Wet lay-up process:** The wet lay-up process is commonly used in marine industry. The process is also a labor intensive. Because of the open mold nature, it has a concern for styrene emission. In wet lay-up process, resins are applied to the mold, and the reinforcements are then placed on top. A roller is then used to impregnate the fiber with the resin. Another reinforcement layer and resin is applied till the desired thickness builds up. The process is flexible and can allow the user to use the parts more efficiently by placing mat materials and varieties of fabrics. Also it is called hand lay-up because of the manual placing of the reinforcement. Commercially, wet lay-up process is broadly used for manufacturing boats, storage tanks, wind mill blades, etc. Due to its process simplicity and little capital investment, the process is widely used for manufacturing prototype parts. Complex shapes can also be manufactured using this process. Figure 1.11 shows A 72-ft yacht and schematic of the wet lay-up process [7].

**Fig 1.11** A 72-ft yacht made from wet lay-up process

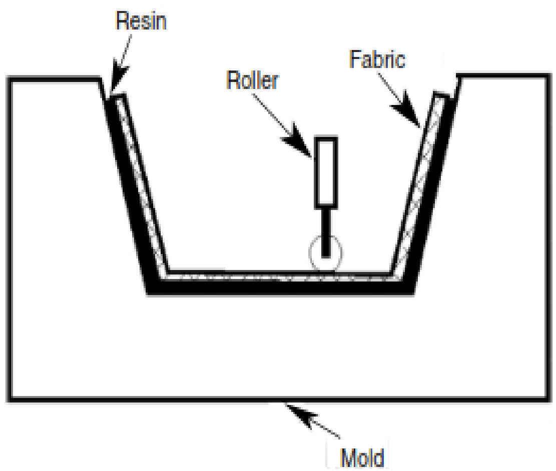



**Fig 1.12** A schematic of the wet lay-up process.

The limitations of the wet lay-up process are:

- Labour intensive of the process
- Styrene emission is involved because of the open mold system
- Quality of the part manufactured is inconsistent from part to part
- The process is not sufficient to manufacture high volume fraction parts

**(b) Spray-up Process**

Spray-up process is a process in which a spray-gun is used to apply reinforcements and resin at the same time with a capacity of 453.59 kg to 816.47 kg material delivered per hour

[7]. The process is similar to the wet lay-up process, but the difference is in the method of applying fiber and resin materials on the mold. The chopped fibers and resin are deposited on the mold using spray-gun as shown in Figure 1.13. The gun concurrently chops the continuous fiber roving

The wet lay-up process is labor intensive because reinforcements and resin in a preset length and then impels it via a resin spray on the mold. Since the resins and reinforcements are applied manually, the spray-up process became a labour intensive process.

Spray-up process is used to manufacture parts in low to medium volume quantities, and small to large conventional parts. Some of the commercial uses are boat hulls, bathtubs, storage tanks, swimming pools, handling equipments, and furniture components.

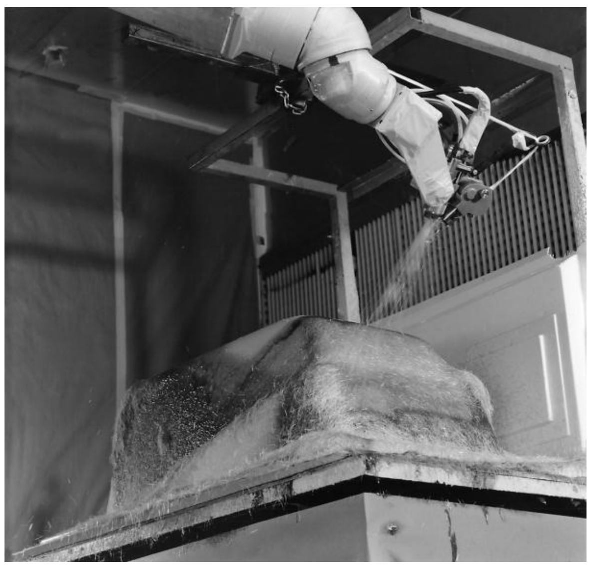


**Fig 1.13** A robotic spray-up in making a bathtub [7].

The spray-up process has limitations such as:

- The fiber volume fraction and thickness are difficult to control
- It is not appropriate for manufacturing high structural parts.
- Styrene emission is also a concern
- It does not give a good surface finish and dimensional control on all the sides of the product.

**(c) Filament winding**

Filament winding is a process whereby resin-impregnated fibers are wound over a rotating mandrel at a desired angle. In this process the mandrel rotates at a particular speed while the carriage unit moves forth and back.  An example of the filament winding process is shown in Figure 1.14. A desired fiber angle is obtained by controlling the motion of the carriage unit and the mandrel. More details are discussed in chapter 3.

**Fig 1.14** A filament winding process.

Majority of the products manufactured using filament winding process are, pressure vessels, tubular structures, pipes, chemical storage tanks, rocket launch tubes etc.

Some parts manufactured using filament wound are shown in Figure 1.5.

**Fig 1.15** Some filament wound parts [8].

Filament winding is suitable for manufacturing hollow shapes. However, it has limitations such as:

- The process is used to produce closed and convex structures. It cannot be used for making open structure like bathtubs.
- It has limited fiber orientation angles. Fiber angles like $0^o$, $5^o$ are not simple to produce.
- Resin content and uniform fiber distribution through thickness of the laminate.

**(d) Pultrusion process**

Pultrusion is a process whereby resin-impregnated fibers are pulled through a die to produce. It is a low-cost, automatic process, and high-volume manufacturing process. Pultrusion is like metal extrusion process, but the difference is that the material is pull instead of being push through the die in extrusion process. Figure 1.16 illustrated a pultrusion process whereby resin impregnated yarns are pulled through a heated die at a constant speed. The material becomes moderately cured as it passes through the heated die.

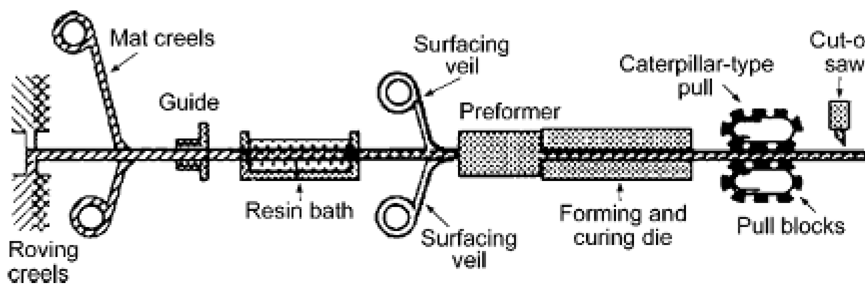



**Fig 1.16** Illustration of pultrusion process.

Pultrusion mainly use to produce hollow structures with invariable cross-sections. Common applications are in making beams, tubes, channels, grating system, light poles, ladders, electrical enclosures, etc. Figure 1.17 shows some pultruded shapes.

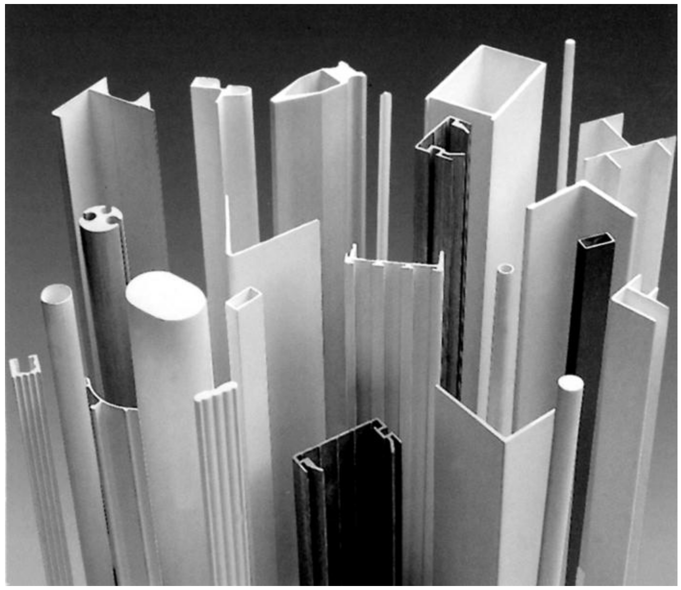


**Fig 1.17** Pultruded shapes.

Components produced using pultruded process, are used in infrastructure and buildings due to their lower product cost. Below are some limitations of the process.

- Only parts with constant cross-section along their length are suitable for the process.
- Parts with thin wall cannot be produced.
- Limited to $0^{o}$ fiber orientation angle.

**(e) Resin Transfer Molding Process**

Resin transfer molding (RTM) process also know as liquid transfer molding process, is a process whereby a preform is placed in the mold cavity. A half of the similar mold is mated to the first half, and then together the two are clamped. A dispensing equipment, pressurized matrix of thermoset resin, color, catalyst, filler etc. are pumped into the mold. The part is then removed after curing.

Resin transfer molding process is applicable for manufacturing small to large sized structures, in small to medium volume quantities. RTM is mainly used in application such as aerospace, automotive, sporting goods etc. The main structures made are doors, helmets, bicycle frames, sport car bodies, aircraft parts, windmill blades etc. as shown in Figure 1.18.

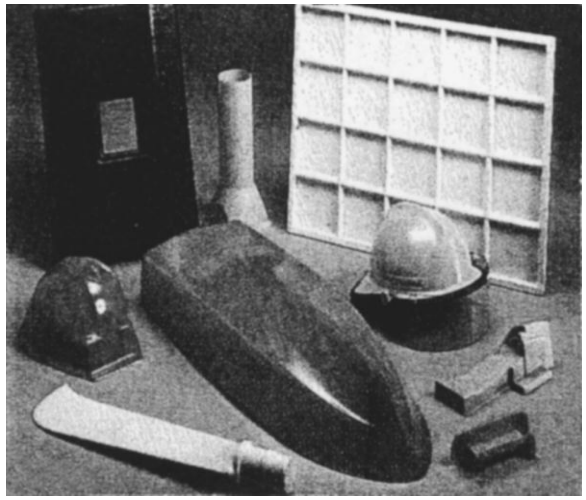


**Fig 1.18** Resin transfer molded parts.

The followings are some limitations of the RTM.

- It requires a precise amount of trial and error experimentation for the manufacturing of complex parts.
- The cost of equipments and tooling are higher than for spray-up and hand lay-up.
- Design of tooling is complex

**(f) Compression Molding Process**

Compression molding is well known in automotive industry because of its high volume facility. It is used in molding large automotive panels. The general raw materials for compression molding are sheet molding compound and bulk molding compound. Compression molding process uses molds that are normally preheated to a temperature of about 140°C. As a result of the movement of the mold as shown in Figure 1.19, the sheet cut into rectangular sizes starts to flow inside the mold and fills the cavity. The entrapped air from the mold, as well as from the rectangular plies is removed due to the flow of the molding. The part is then removed after cure under heat and pressure.

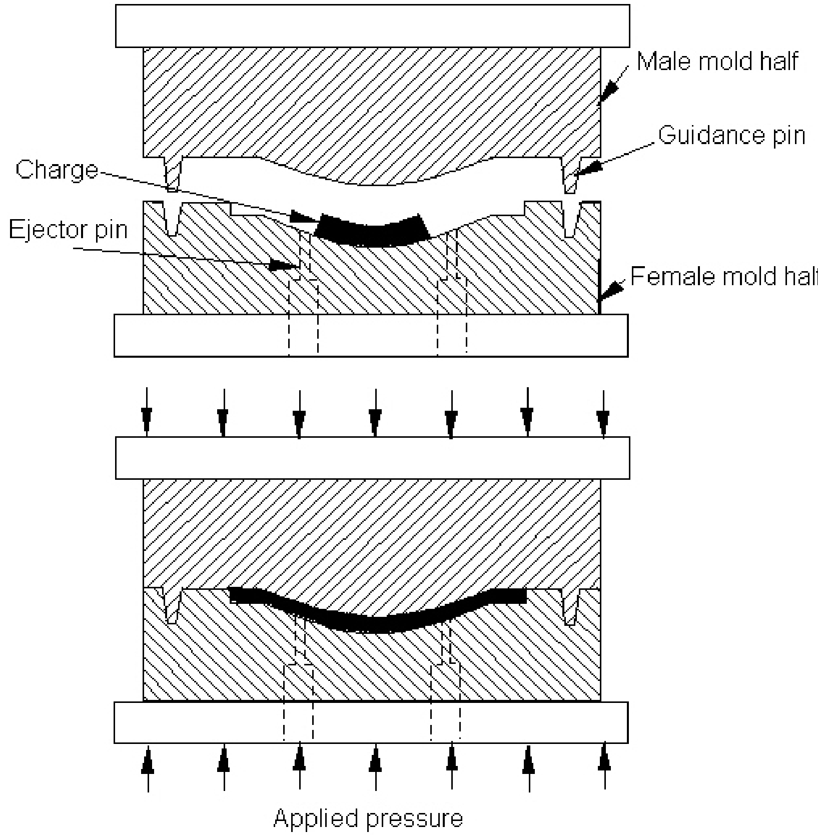



**Fig.1.19** Schematic of compression molding process.

Compression molding of sheet molding components are used for manufacturing one and two piece panels for automotives. Examples of one piece panel are roof panels, and fenders etc., and for the two piece panels are hoods, doors, etc.

The limitations of the compression molding process are:

- Because of its high mold and equipments cost, initial investment is high.
- The process is not convenient for making small number of parts.
- It provides non structural parts.

## 1.7 AIMS AND OBJECTIVES

In this study, the mechanical behavior of the glass and carbon epoxy composite leaf springs in the form of C and O shapes was investigated under static compressive loading. The obtained compression test results were compared and evaluated. The effect of thickness, diameter, and the fiber winding angle on the springs behavior was reported. Finite element analysis was conducted using Abaqus software package. The linear-elastics composite material model was used for simulating the structural behavior of glass epoxy and carbon epoxy C and O shape springs. The sufficient agreement between experimental and numerical results was achieved.

# CHAPTER TWO

## REVIEW OF THE LITERATURE

Springs are designed to absorb, store and release energy. Thus, the strain energy of the spring material becomes a major factor in designing the springs. Strain energy can be express as $U = {\sigma^2}/{\rho E}$, where $\rho$ is the density $\sigma$ the strength, and E the Young's modulus of the spring material. It is clear that, material with lower density and modulus will have a great specific strain energy capacity. Thus, composite materials become good candidate for such applications. Introduction of the composite materials yield significant weight savings without any reduction in load carrying capacity and stiffness of the leaf springs.

Several papers and literatures were devoted to the application of the composite materials in automobiles. Some of these papers are review here.

T. S. Manjunatha and D Abdul Budan [9], carried out an experiment to investigate the possibility of using composite helical spring for automotive suspension instead of steel spring. They manufactured three different types of springs using carbon fiber, glass fiber and glass/carbon fiber in 45 degree fiber orientation. They found that, for the three types of the springs small variation was observed from the curve and that was due to dimensional variation in the fabrication techniques. They further suggested that the variation can be diminished by standardizing the fabrication techniques.

Thippeswamy Ekbote et.al [10], had developed a double tapered mono leaf composite leaf spring in order to replace the nine leaf steel spring with the main consideration given to the geometry using finite element analysis. They concluded that, considering the design variables as width at the center and at the end, and thickness, the multi leaf steel spring has yield large variation of 4% in Von-Mises stress and 6% in displacement. The comparison of the analysis result was carried out using finite element analysis ANSYS software. E. Mahdi and A.M.S. Hamouda [11], had investigated the tension, compression, and cyclic test behaviors of the composite semi-elliptical suspension springs. From their finding they concluded that, the elliptical ratio, and the fiber type have influence on the spring ratio. And a poor ride quality as well as high spring rate was exhibited by the glass-carbon/epoxy elliptical spring compared with to the nonhybrid elliptical spring. Also, a 2% reduction of the composite elliptical spring stroke sides of its original height was observed after millions of fatigue cycles. Erol Sancaktar and Mathieu Gratton [4], described the capabilities of using composite leaf springs produced by unidirectional E-glass rove impregnated with an epoxy resin for light vehicle applications. They fabricated a front suspension leaf spring for a solar and displacement test was conducted on the spring. Finally, they suggested that, the impact forces transferred to the chassis can be reduced by putting a rubber pads on the inner side of the blades to cushion bottoming out of the springs. B.B. Deshmukh and Dr. S. B. Jaju [12], have designed and analyzed the mono composite leaf spring fabricated by hand lay-up method with stress and displacement as the design constraints. The experimental results were compared with the finite element analysis using ANSYS software. After comparing the experimental results with the numerical one, they concluded that, the fiber reinforced composite leaf spring is suitable to replace the conventional leaf spring, because of the light weight and less stress concentration in the glass fiber reinforce leaf spring. C. Subramanian and S. Senthilvelan [13], reported the performance of the double bolted end joint for injection molded glass fiber reinforced polypropylene leaf spring under the static and dynamic condition. They found that under static loading condition the load bearing capacity of the investigated joint is superior to that of leaf spring design load. The clearance influence between the composite plate hole and fastener under the bearing strength of the joint in static loading condition is significant. The low cycle fatigue showed total tension failure form alongside with bearing damage as in static loading situation. Because of the existence of bi-axial stress situation, matrix deformation and matrix fibrillation occurred at the surface of the joint under fatigue as well as static loading.

Chang-Hsuan Chie et.al [14], studied the effect of braided outer layer and rubber core on the mechanical properties of four different types of helical composite springs made form unidirectional laminates, rubber core unidirectional laminate, unidirectional laminate with braided outer layer, and rubber core unidirectional laminate with braided outer layer. Through experimental work, they come up with conclusions that, the compression failure load of the helical composite spring with rubber core increased to about 12% and decreased the amount of prepregs used. The spring constant of the helical composite spring with a braided outer layer is improved about 16%. Its compression failure load increased to about 18%. Also, braided outer layer helical composite spring was observed to have highest mechanical properties amid the four types. Zheng Yinhuan et.al [15], described the comparison between the performance of glass fiber reinforced plastics using the ANSYS software and the steel spring. They concluded that, the stress on steel spring is higher than on the composite spring and its resistance to fatigue (composite spring) is much stronger. And also, using finite element analysis the stress distribution and the deformation of composite leaf spring of each leaf can specifically be found. V Pozhilarasu and T Parameshwaran Pillai [16], fabricated an E-glass/epoxy composite leaf spring using hand lay-up process and compared its performance with conventional leaf spring under similar condition using ANSYS. They concluded that, under the same loading condition the composite leaf spring bending stress and displacement is less when compared with steel spring. M. S. Kumar and S. Vijayarangan [17], studied the static and fatigue analysis of composite multi leaf spring and steel leaf spring. They fabricated the composite leaf spring using E-glass/epoxy unidirectional laminates with the same dimension to conventional leaf spring. The stiffness, load bearing capacity and the weight of the composite leaf spring are compared with that of steel experimentally and analytically. Life data analysis was used for the experimental fatigue analysis of composite multi-leaf spring made from glass fiber. In conclusion, they found that the composite leaf spring has 64.9% higher stiffness, 67.3% lesser stress, 126.9% higher frequency than the steel spring. Also, a higher fatigue life was predicted for composite leaf spring. M. M. Patunkar and D. R. Dolas [18], presented a general study on design and manufacturing, and testing analysis of a mono leaf composite spring. They used a hand lay-up method in manufacturing the glass fiber reinforce composite spring. From their finding they, discussed that, composite leaf spring showed less stresses in comparison with steel leaf spring under similar loading condition, a 33.3% weight reduction of the composite leaf spring compared to steel spring with similar level of performance. Also, the composite leaf spring showed much displacement at maximum loading compared to steel spring. And increasing the thickness increases the load bearing capacity. Ravi Kumar V, et.al [19], compared the performance of natural fiber reinforced composite spring (jute fiber reinforced composite) with the glass fiber reinforced composite leaf spring. They used hand lay-up method in manufacturing process. Analytical results were compared with simulated one for the two types of the leaf springs. Verification of stresses and displacement were compared with analytical and finite element method with ANSYS. They concluded that, the natural fiber reinforced composite spring has lower stress and with 60-70% weight reductions compared to steel spring. And chipping resistance was the disadvantage of jute and glass fiber reinforced composite leaf spring. Dara Ashok, et.al [20], compared the stiffness, weight saving and load bearing capacity of composite leaf spring with steel leaf spring. The composite leaf spring was manufactured with E-glass/epoxy unidirectional laminates and 65Si7 as the material of the steel spring. They used the same number of leaves and dimension for both the composite leaf spring and steel spring, and used the ANSYS software for numerical analysis. From their finding they stated that, composite leaf spring showed better performance than the conventional leaf spring, and can be used to replace the existing leaf spring. R. Pradeep, et.al [21], designed a single leaf glass fiber reinforced plastic spring with thickness as the variable and with the same geometrical and mechanical properties to multi leaf steel spring. Based on long life, shear stress and spring rate, they used a finite element model to improve and optimize the material with total geometry of the composite elliptical spring. At last, they suggested that, using finite element method a 3-D model of composite leaf spring can be analyzed, with respect to riding quality, weight strength and cost, comparison study is to be made between composite leaf spring and steel spring. Yogesh G. Nadargi, et.al [22], designed and fabricated a single leaf fiber reinforced plastic spring with thickness and width as the variables with constant cross sectional area having similar geometrical and mechanical properties. Verification of the stresses and displacement of the experimental with analytical results were carried out using ANSYS software. Their results of finding showed that, hyperbolically width of the spring decrease and the thickness rises linearly from the spring eyes to the axle seat. The composite spring has low stresses and high natural frequency compared to the steel spring, and about 85% lower weight. The dead weight of steel spring can be reduced if replaced by composite one. G. S. Shiva Shankar and Sambagam Vijayarangan [23], used C- computer algorithm language for the designation of constant cross-section leaf spring. Using hand lay-up method, they manufactured a single leaf spring with width, thickness, and constant cross-sectional area of a unidirectional glass fiber reinforced polymer with the same geometrical and mechanical properties to the multi-leaf spring. Stresses and displacements were verified together with experimental and numerical results using ANSYS software. Displacement and stresses are the design constraints. Their conclusion remarks stated mono leaf composite spring which has a constant cross sectional area in which stress point at any position in the leaf spring is regard as constant because of the parabolic nature of the thickness of the spring, proved to be very efficient. Composites leaf springs reach the requirements to be used in light weight vehicles. There is a good agreement between the experimental and analytical results. The performance of composite leaf spring is enriched by the adhesively bonded end joints when compared with bolted joints. B. Vijaya Lakshmi and I. Satyanarayana [24], fabricated unidirectional laminates composite multi-leaf spring using C-glass/epoxy, E-glass/epoxy, and S-glass/epoxy and compared its load bearing capacity, weight and stiffness with the heavy commercial leaf steel spring. Cosmos was used to perform the dynamic and static analysis. Their conclusion remark showed that, considering the 8 leafs analysis conducted, the E-glass/epoxy spring is better than mild steel even though the stresses are little higher than mild steel. While comparing the traditional materials with epoxy materials constituents, the epoxy materials have lower weight. Also, they analyzed a 12 leafs spring in which S-glass showed better results than E-glass, C-glass and mild steel. C. K. Clarke and G. E. Borowski [25], studied and analyzed the failure, residual strength estimates, chemical contamination and rust on the fracture point during accidents for a rear leaf spring in sport vehicles. From their finding they concluded that, spring can be weak due to the segregation of sulfur at the mid-plane, prior to the accident the spring was cracked. The strength of the spring is reduced due to prior cracking and that caused a normal road force to produce rapture. At the start of accidents, rupture is supported by the marks in the wheel wells.

Jadhav Mahesh V, et.al [26], fabricated a mono composite leaf spring that can be used in Maruti 800 vehicle using hand lay-up process, and studied the advantage and fitness of the spring. They compared the conventional EN 47 steel with composite leaf spring under static loading, and analyzed the performance using ANSYS. Weight reduction achievement together with sufficient improve in mechanical properties made composite springs the replacement materials for the convectional steel. N. P. Dhoshi, et.al [27], investigated the possibility of improving the performance as well as reducing the cost of the leaf spring used in tractor trailer. They selected the leaf spring produced by Awachat industries Pvt. Limited. They carried out analysis using ANSYS and compared the result with experimental one. They have concluded with, advantage of using analytical method which can reduce the cost and improve accuracy. Also reducing leaf spring number from 17 to 13 will reduce the weight to about 6 kg and production cost to about 20%.

K. K Jadhao and R. S. Dalu [28], fabricated a spring having constant thickness and width using hand lay-up procedure. Using ANSYS they verified the results of the stresses and displacement with the experimental one. They discussed the weight reduction of the composite spring was obtained to be about 85%, and the stress is quite low for the composite spring. R. B. Charde and D. V. Bhope [29], had studied the evaluation of stress in master leaf using finite element method and strain gauge method. They carried out a stress analysis of the half cantilever master leaf spring without and with extra full length leave. From their finding they come up with conclusion that, stresses on master leaf do not fallow cantilever beam theory, they further suggested that adding one extra full-length leaves to the assembly the theory will be valid. The length of the graduated leaves have a significant effect on the stresses on master leaf. Karthik Badugu, et.al [30], described the manufacturing of fiber glass, its development, and static load test analysis of composite leaf spring made from glass fiber reinforced polymer. They manufactured the E glass/epoxy mono leaf composite spring using hand lay-up techniques. The pro/E was used in modeling the leaf spring and analysis was carried out using ANSYS software. For the same apply load, the stresses and displacement for the composite spring are quite less compared to steel leaf spring. Also, composite spring weight was observed to be less in the range of 70% to 80% than the steel spring. Amrita Srivastava and Sanjay Choudhary [31], investigated the possibility of using natural and synthetic fiber reinforced hybrid composite in place of the synthetic fiber reinforced composite material in automobile spring. They used Jute and E-glass as the woven roving mat reinforcements. From their finding they made conclusion remarks, that replacing the steel leaf spring with jute-E-glass/epoxy can reduce weight up to 55%. The hybrid composite spring has less stress, less displacement compared to steel spring. High elastic strain energy storage capability of the Jute-E-glass/epoxy is observed to be more than that of E-glass and steel. The Jute-E-glass/epoxy hybrid composite spring is less expensive.

This present research work discusses the variables thickness, diameter, orientation angle, and width of the leaf springs in C and O-shapes which are made from composite material. Their force-displacement behaviors were obtained by conducting compression test. Their behavior was simulated using finite element method. The aim of the study is to investigate the possibility of using C-shape and O-shape composite leaf spring in medical applications such as C-walk shoe to support the amputee.

# CHAPTER THREE

# MATERIAL SELECTION, MANUFACTURING AND EXPERIMENTAL PROCEDURE

Springs are designed to absorb, store and release energy. Thus, the strain energy of the spring material becomes a major factor in designing the springs. Strain energy can be express as

$$U = \frac{\sigma^2}{\rho E} \qquad \text{------} \quad (3.1)$$

where $\rho$ is the density $\sigma$ is the strength, and E is the Young's modulus of the spring material. It is clear that, material with lower density and modulus will have a great specific strain energy capacity. Thus, composite materials become good candidate for such applications. Introduction of the composite materials yield significant weight savings without any reduction in load carrying capacity and stiffness of the leaf springs.

## 3.1 Materials

In this section the materials used during the manufacturing are described. The fibers used are FWR6 E-glass fiber, 6K A-38 Carbon fiber, laminating resin L285, and H287 hardener.

**Glass fiber:** due to its high extensibility, good unwinding properties, fast and complete wet-out and high mechanical properties E-glass is chosen in the C and O composite spring manufacturing.

**Table 3.1** Specifications of FWR6 E-glass.

| | |
|---|---|
| Type of glass | E |
| Moisture content % | Max. 0.15 |
| Coupling agent | Silane |
| Loss on ignition (%) | 0.55 ± 0.15 |
| Resin compatibility | Polyester/Vinylester/Epoxy |
| Roving text count (g/1000m) | 600/1200/2400/4800 |
| Filament diameter (μ) | 15/15/17/25 |

**Carbon fiber:** because of its toughness, excellent mechanical properties, light weight etc. A-38 carbon fiber is chosen also in this research work for the manufacturing.

**Table 3.2** Specification properties of the 6K A-38 carbon.

| | | | | | |
|---|---|---|---|---|---|
| Tensile strength | 552 | ksi | 3800 | MPa | ISO 10618 |
| Tensile Modulus | 34.8 | Msi | 240 | GPa | ISO 10618 |
| Strain | 1.6 | % | 1.6 | % | ISO 10618 |
| Density | 0.064 | lbs/in$^3$ | 1.78 | g/cm$^3$ | ISO 10119 |
| Yield | 3.719 | ft/lbs | 400 | g/1000m | ISO 1889 |
| Sizing type & amount | D052 | | 1.0–1.5 | % | ISO 10548 |
| Twist | Never twist | | | | |

**Laminating resin and H 287 hardener:** in order to provide a shape for the manufacturing products, support and protection of the fiber, distribution of the load uniformly to the fiber etc. a matrix is require to perform such work. In this research work, L285 resin and H287 hardener were chose as the matrix material. The resin and hardener were mixed as a ratio of 100 : 40, and table 3.3 and 3.4 showed the specifications of the laminating resin and hardener and their mechanical properties respectively measured at 25$^o$C.

**Table 3.3** 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 |

**Table 3.4** Mechanical properties for the resin L285 and Hardener 287.

| | |
|---|---|
| Density [g/cn$^3$] | 1.18-1.20 |
| Flexural strength [N/mm$^2$] | 110-120 |
| Modulus of elasticity [kN/mm$^2$] | 3.0-3.3 |
| Tensile strength [N/mm$^2$] | 70-80 |
| Compressive strength [N/mm$^2$] | 120-140 |
| Elongation of break [%] | 5.0-6.5 |
| Impact strength [kJ/m$^2$] | 45-55 |
| Water absorption 24 h[%]<br>at 23$^o$C 7 d[%] | 0.20-0.30<br>0.60-0.80 |

## 3.2 Manufacturing process

The manufacturing process followed in this work was filament winding process. In this method, a computer based control Flexwind machine is used for automatic winding, under amount of tension in a very precise and controlled manner over the mandrel. The mandrel as shown in Figure 3.1 is fixed between the rotor and the support of the flexwind machine.

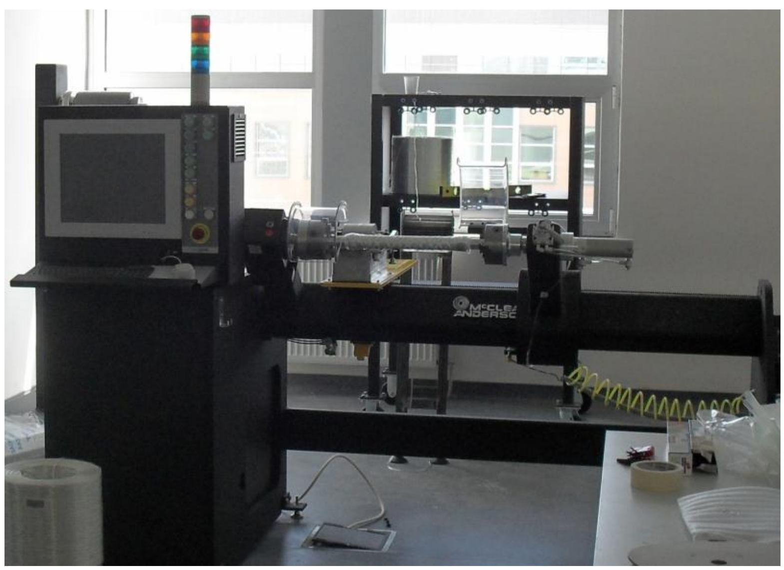
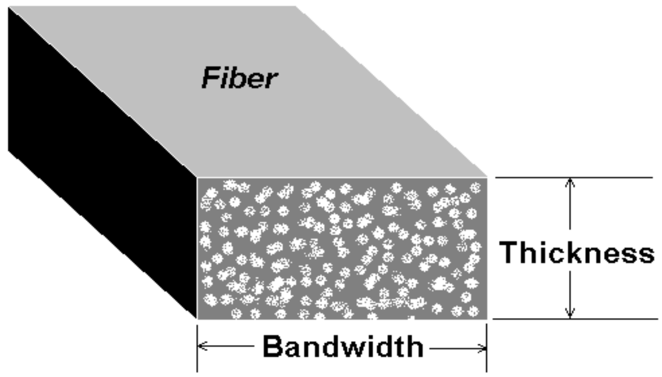
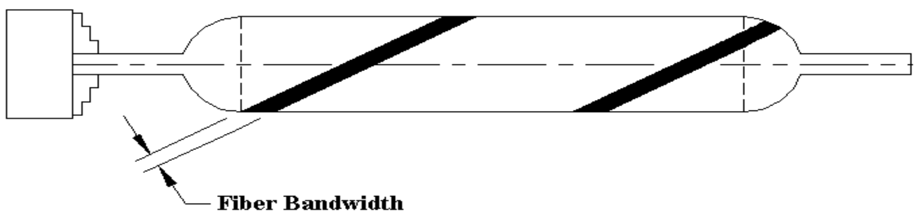


**Fig.3.1** Filament winding machine.

Generally, multiple fiber tows are fed to fiber creels, flow via various guides, via a resin bath and out of a payout system onto the mandrel. This group of fibers all together makes one fiber bandwidth as shown in Figure 3.2 [32].




(a)




(b)

**Fig.3.2** (a) Presentation and (b) definition of fiber bandwidth.

Figure 3.3 showed the basic order from start-up to part execution of the Flexwind.


**Fig.3.3** Flexwind winding control procedures

**Reference:** the machine needed to be reference before loading the Flexwind program and execution. The hardware has ability to track the machine motions. The machine will be aware of all the axis's positions and limits of their motion will be enforced once the machine is referenced.

**Program loading:** selection and loading of a new motion file can be done via a typical windows file open dialog box and clicking on the Open button. The main motion files, together with the auxiliary output files, and with similar name at the same location are loaded automatically.

**Finding path:** after the files had been loaded, the machine may start execution, then a synchronizing of the machine's position to match the fiber path at a desired execution point is set. And this is typically known as find path maneuver.

**Execution of the program:** Once the program is loaded, and the find path maneuver is done, the program can be executed by clicking “Enable” and then “Increase” button. Figure 3.4 showed a Flexwind composite designer screen.

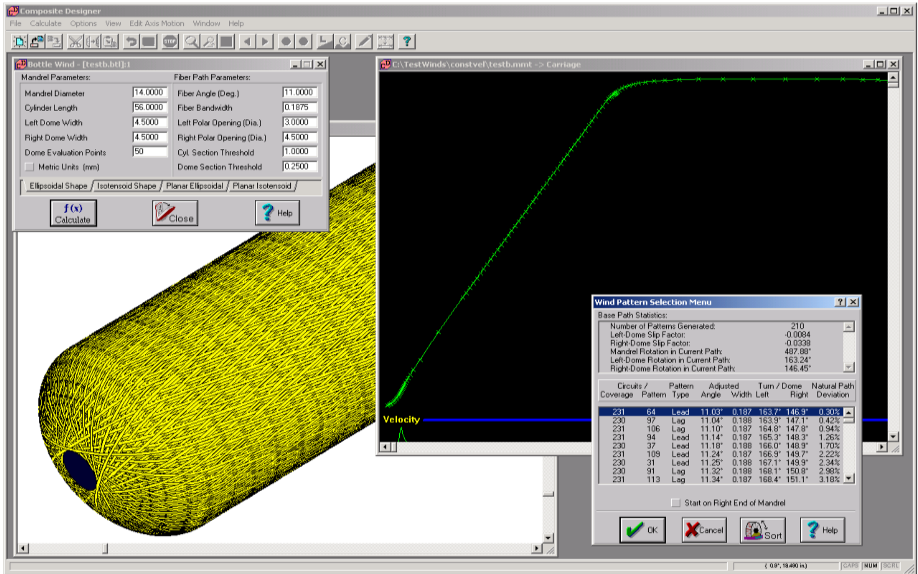


**Fig.3.4** Screen of the typical composite designer.

The steps flowed in this manufacturing of the C and O-shape composite springs are;.

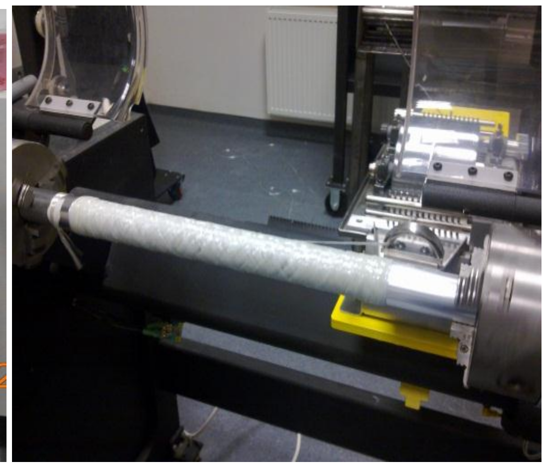

**Fig.3.5** Manufacturing steps

**Applying release gel:** a QZ5111 Ren release gel was applied onto the mandrel three times at 20 minutes interval. This helps to remove the composite component from the mandrel easily after curing.

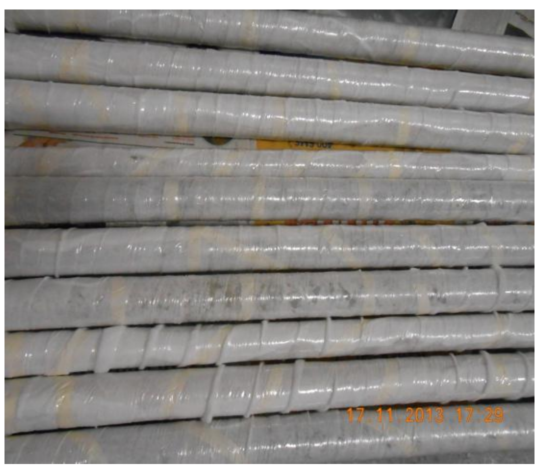
**Filament winding:** after the release gel dried out, the mandrel is mounted on the Flexwind machine and fixed the two edges at the rotor and support strokes. After loading the motion files, setting the reference, and find path maneuver the winding started by clicking Enable button. The desire winding angle, the fiber bandwidth and require number of ply are input in the created program on the machine. This process of winding is continuing until a require thickness of the spring is obtained on the mandrel.

**Curing and Cutting of the specimens:** After the completion of winding, the specimens were wrapped with a teflon, blanket and plastic-tape and kept for curing at room temperature for 2 days. Later on, the specimens were put in an oven at $60^0$ Celsius for 15 hours. After curing, the O-shape spring was cut from the mandrel at a desire width, and all the C-shape springs were cut $45^0$ from the O-shape spring as shown in Figure 3.6.

(a)



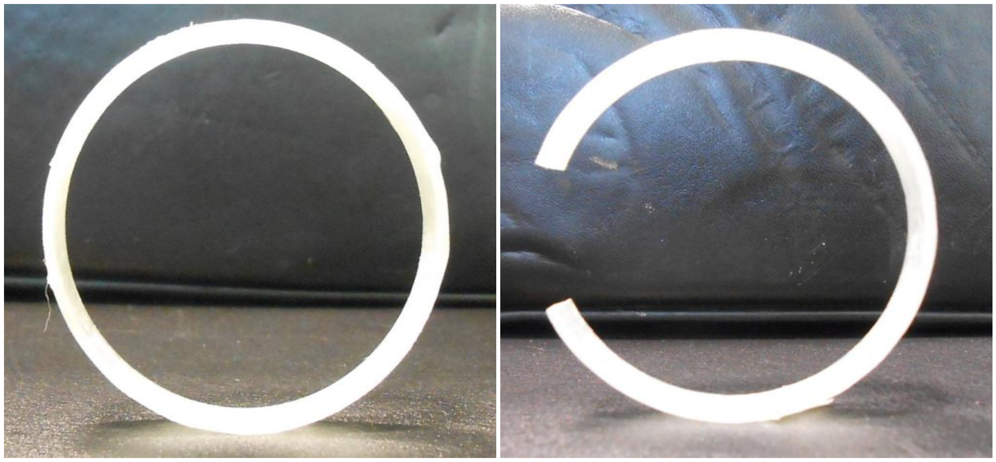
(b)




(c)


(d)

**Fig.3.6** shows (a) release gel on the specimens, (b) filament winder in operation, (c) specimens wrapped with blanket, tapelone, and plastic tape, (d) specimens after curing.



(a)

(b)

**Fig.3.7** Shows the O-shapes and 45$^{o}$ cut C-shapes spring made of (a) glass fiber and (b) carbon fiber.

**Experimental Method**

Experiments were conducted using a Multipurpose Test Suite machine (MTS) in which static compression test on the specimens (C and O-shape springs) was carried out. In each regular interval, the machine automatically records the raw data of the applied load and the corresponding compression, and thus generates 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 these test results were taken for analysis.

**Fig.3.8** MTS control machine.

The load bearing capacity, the spring constant can then be evaluated. Generally, the spring rate depends mainly on its shape, material properties and dimensions. Experiments were carried out according to ASTM standards.

# CHAPTER FOUR

# EXPERIMENTAL RESULTS

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

## 4.1 Effect due to the thickness of the springs

All load-displacement curves of the C-shape springs exhibited linear increase at the beginning. 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 the small displacements applied on the C-Spring do not fully tension fiber reinforcement along the perimeters of the C-Shape. Then the vertical displacement applied on the spring comes to the critical value and fibers become active. Stiffness of the spring changes dramatically and the load-displacement curve raises exponentially. The three layers springs clearly bear much load compared to the one and two layers springs, this is due to its rigidity and thickness of the layers (Figure 4.1). During the experiment, pictures of the specimens were snapped at every 5 mm displacement increment and shown in Figure 4.2. The table 4.1 shows the data of the maximum load carried for the C-shape and O-shape spring for the changing thickness experiment.

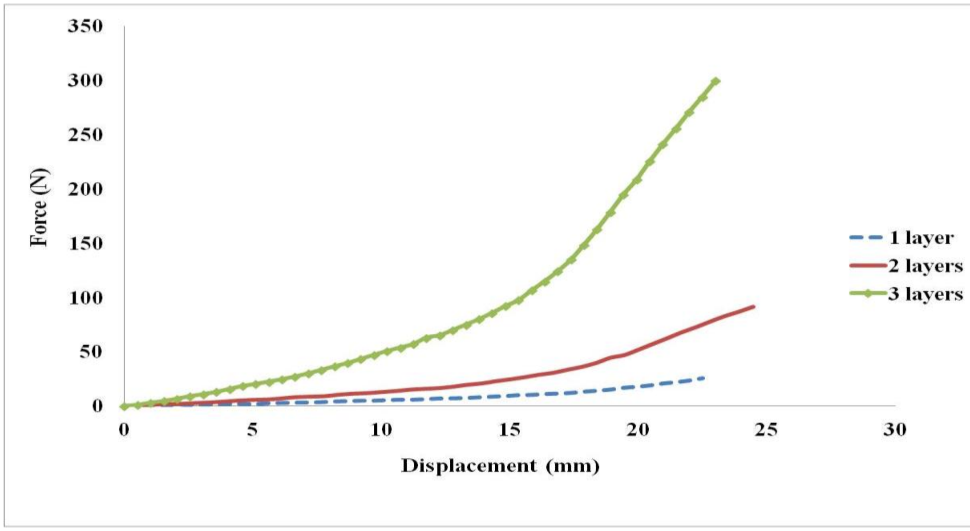
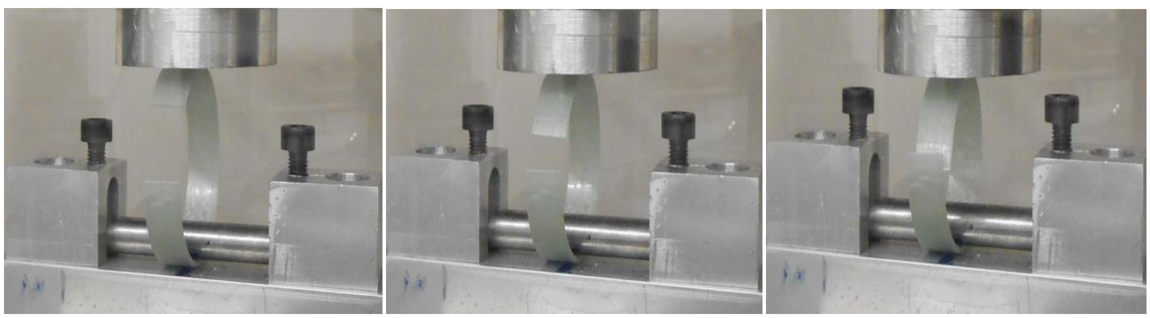



**Fig.4.1** Graph of three different layers glass fiber C-shape springs.

(a) 0 mm (b) 5 mm (c) 10 mm



(d) 15 mm (e) 20 mm (f) 23 mm

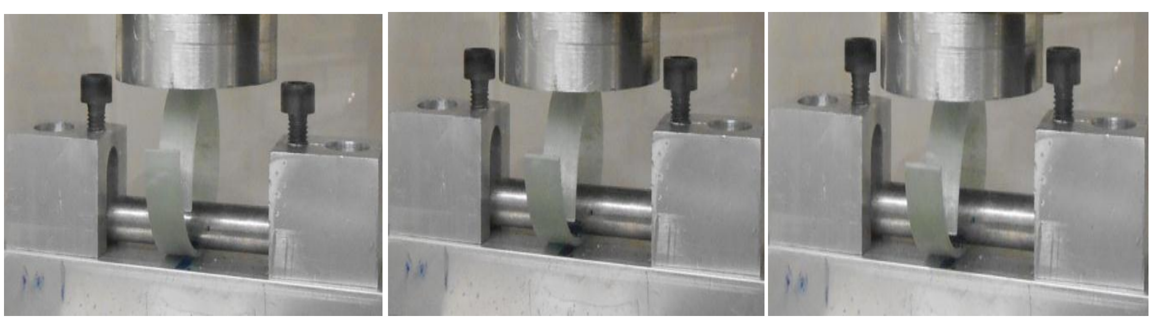


**Fig. 4.2** Pictures of three layers C-shape glass fiber springs snapped at 5 mm displacement interval.

**Table 4.1** Load bearing capacity for three different spring thickness

| Experiment | Spring shape | Fiber | 1 Layer | 2 Layers | 3 Layers |
|---|---|---|---|---|---|
| Changing thickness | C-shape | E-glass | 0.0419 | 0.0958 | 0.3197 |
| | O-shape | E-glass | 0.0831 | 0.2497 | 0.3865 |

Because of their geometry, the load-displacement behavior of O-shape springs, was quite different than C-shape springs. At the beginning, it started as a linear and then slope of the linear curve decreased in second stage. In third stage, slope increased back to the same slope seen in the first stage. Over all response was quite close to linear behavior. For O-shape springs, fiber reinforcement tensioned as soon as the compression starts. Hence, linear behavior continues up to the end of the test. For the one layer spring, a slight drop in the curve is observed; this is caused by a small crack generated on the matrix part (Figure 4.3). Figure 4.4 shows optical pictures of O spring taken during compression test.

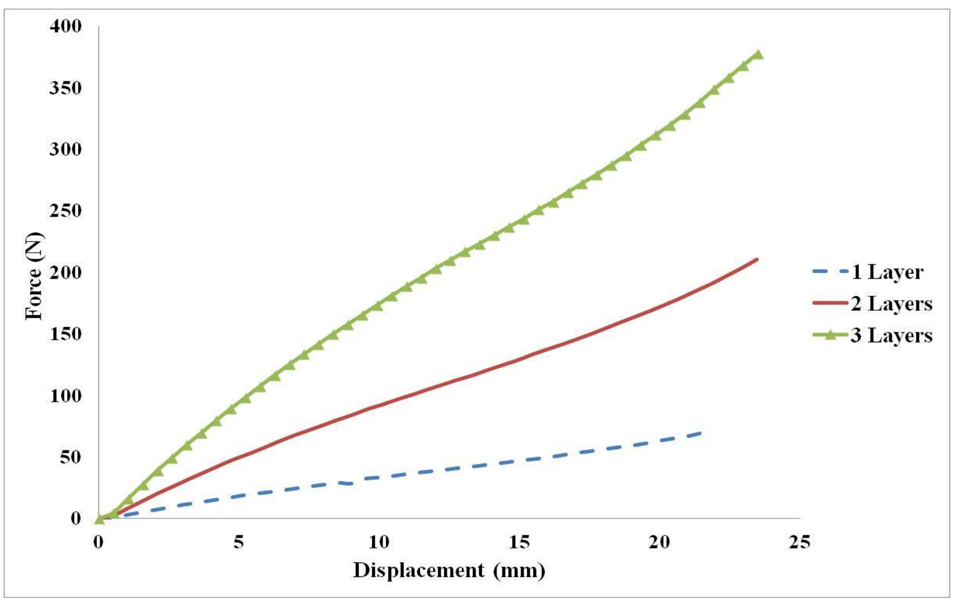
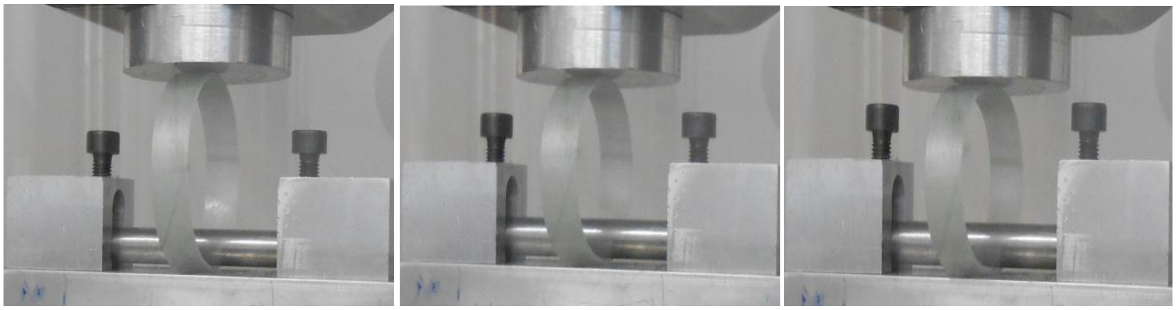



**Fig. 4.3** Graph of three different layer glass fiber O-shape springs.

(a) Initial position (b) 5 mm (c) 10 mm



(d) 15 mm (e) 20 mm (f) 23 mm

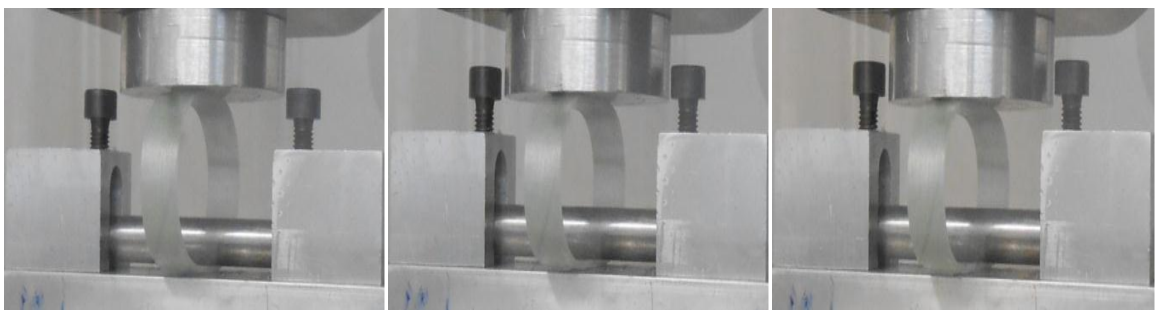


**Fig. 4.4** Pictures of three layers O-shape glass fiber spring snapped at 5 mm displacement interval.

## 4.2 Effect due to changing diameter of the spring

From the results obtained, the smaller diameter 35 mm springs carried much load than the bigger diameter 40 and 50 mm diameter springs with the same thickness and fiber orientation. In this process the springs were fabricated at 70$^{o}$ fiber orientation and with two plies as the thickness.

From the load-displacement graph (Figure 4.5) for the 35, 40, and 50 mm diameter, the 35 mm diameter spring is observed to carried more load but with less displacement, because of its smaller diameter. Also, the 40 mm diameter has less displacement but with much load carrying capability compared to 50 mm diameter. All the C-shape springs start with linear behavior and then increased exponentially. The small diameter of the spring makes it stiffer compared to spring with bigger diameter. Figure 4.6 shows the graphical pictures of the C-shaped spring snapped at 5 mm displacement intervals.

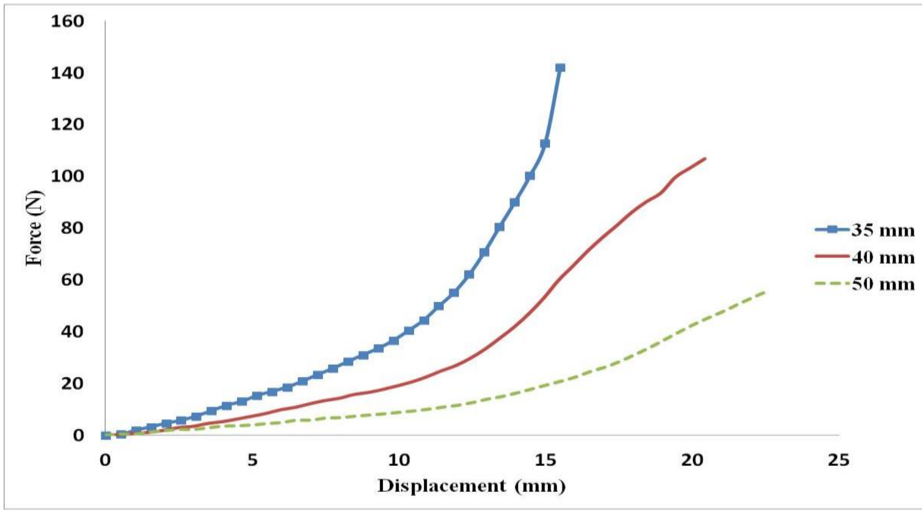



**Fig. 4.5** Graph of three different diameter C-shape glass fiber springs.

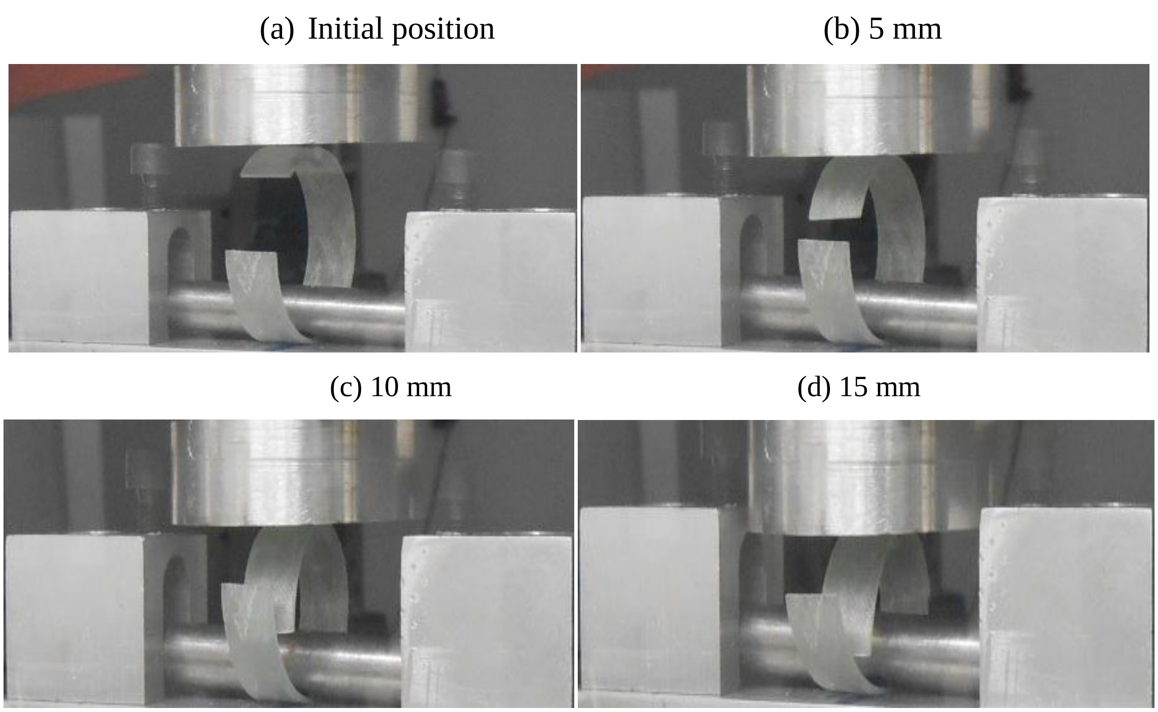



**Fig. 4.6** 35 mm diameter C-shape glass fiber springs snapped at 5 mm displacement interval.

**Table 4.2** Load bearing capacity for the different diameter of the springs

Load (KN)

| Experiment | Spring shape | Fiber | 35 mm | 40 mm | 50 mm |
|---|---|---|---|---|---|
| Changing diameter | C-shape | E-glass | 0.1391 | 0.1039 | 0.0597 |
| | O-shape | E-glass | 0.7183 | 0.1807 | 0.1039 |

Results shown in Figure 4.7 prove that small diameter O-springs exhibited much stiffer response and their maximum load capacity was higher than the others. The O-shape spring with 35 mm diameter carried much load compared to springs with 40 and 50 mm diameter. However its displacement at maximum load was much smaller compared to other two springs. Figure 4.8 shows the pictures of O-shape spring snapped at the interval of 5 mm displacement.

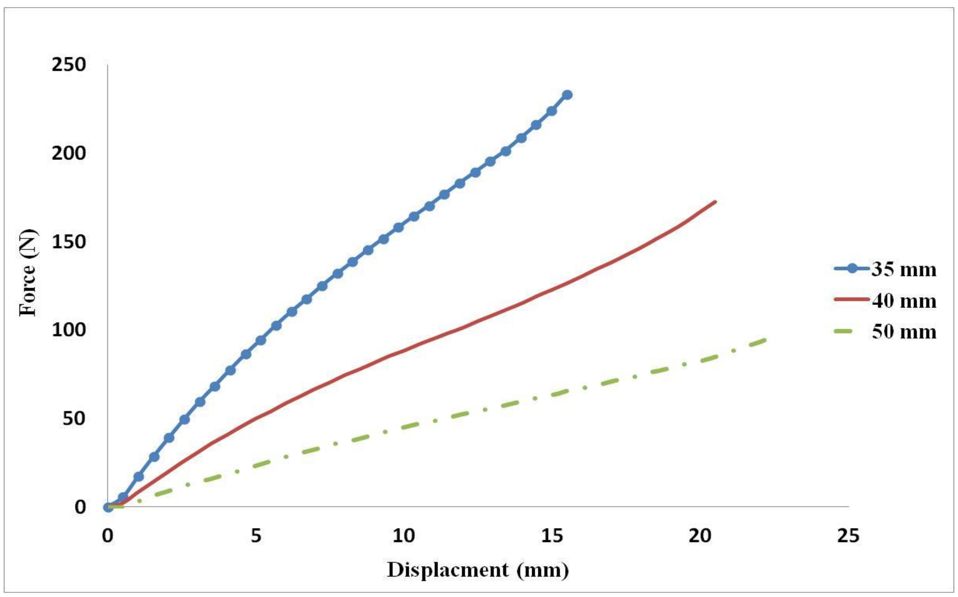
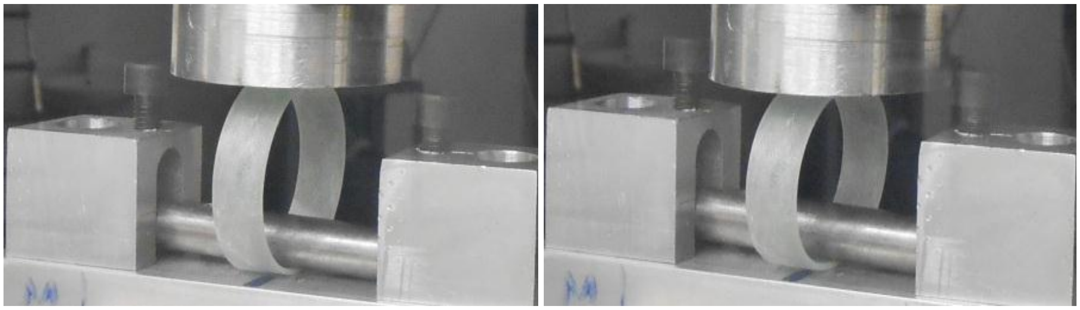



**Fig. 4.7** Load-Displacement graph of three different diameter O-shape glass fiber springs.

(a) Initial position (b) 5 mm



(c) 10 mm (d) 16 mm

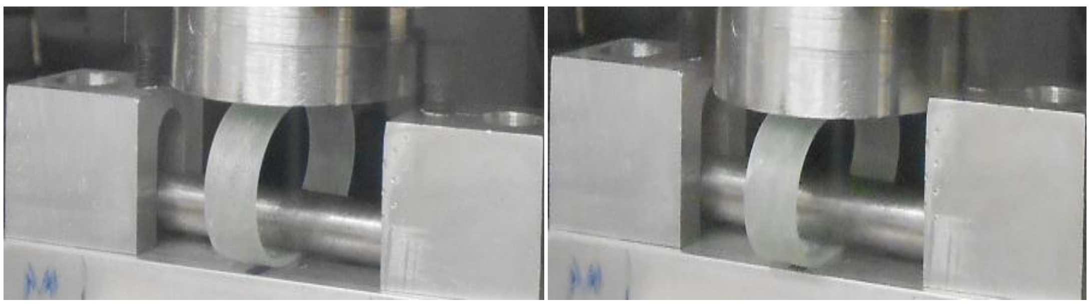


**Fig. 4.8** Pictures of 35 mm diameter O-shape glass fiber springs snapped at 5 mm displacement interval.

**4.3 Effect due to the fiber orientation**

The effect of fiber orientation on the response of glass fiber and carbon fiber reinforced springs were investigated. The load bearing capacity of carbon and glass spring wound at 88$^o$ was better than those wound at 70$^o$ and 80$^o$. If the fibers placed along longitudinal direction, they fully contribute for load bearing and they are fully tensioned. If they are placed with an angle other than 90$^o$, their load bearing capacity is divided into longitudinal and transverse components and reduced. Although placing fibers along 90$^o$ was best for load capacity. Spring would be very weak for bending loading in transverse direction. Therefore winding angle closest to 90$^o$ direction would be the best for spring performance, without jeopardizing bending capacity in transverse direction. The experimental results showed that the carbon fiber reinforced springs exhibited better performance in load carrying capacity as can be seen in Table 4.3.

For both the C-shape carbon fiber springs (Figure 4.9) and C-shape glass fiber springs (Figure 4.10), the 70$^o$ and 80$^o$ fiber orientation spring showed more linear behavior at the beginning than the 88° fiber orientation spring. A large variation between the $88^0$ fiber orientation graphs and the other 70° and 80° is observed from the graphs. This occurred because of the applied load direction almost coincide with the fiber orientation angle. Also, a little drop on the load displacement curve of spring with 88° fiber orientation was observed as the load reached to about 190 N. This drop represented matrix cracking observed on spring. Figure 4.11 shows optical pictures of O spring taken during compression test.

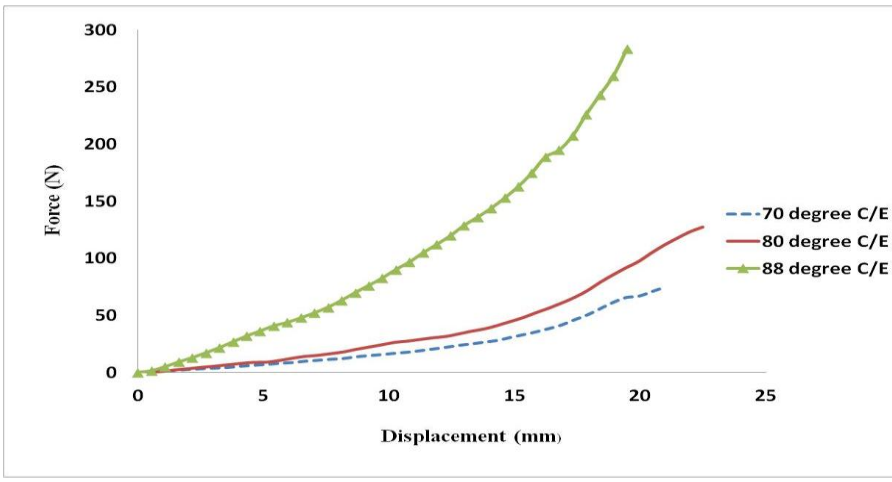



**Fig.4.9** Load-Displacement graph of three different fiber orientations for C-shape carbon fiber springs.

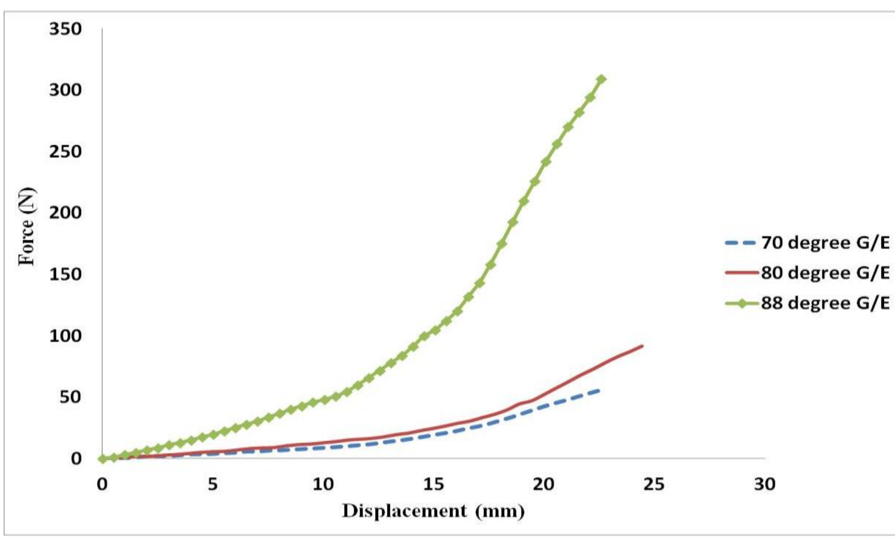



**Fig. 4.10** Load-Displacement graph of three different fiber orientations for C-shape glass fiber springs.

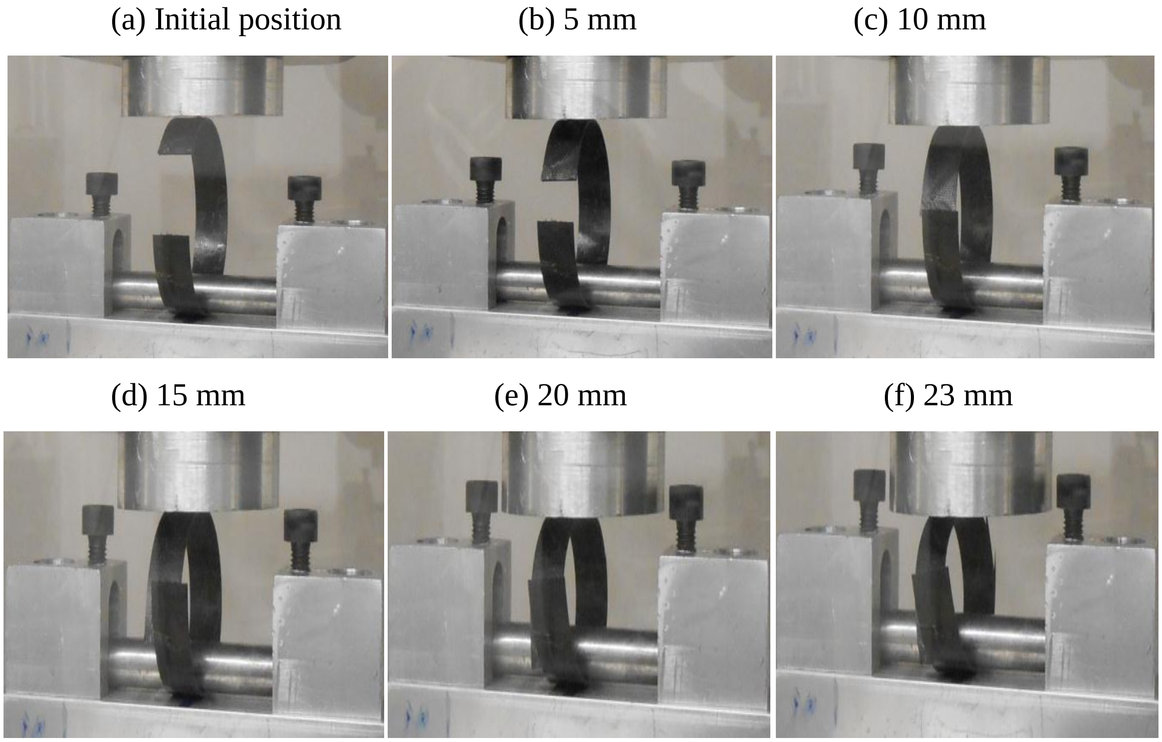



**Fig. 4.11** $88^0$ fiber orientation C-shape carbon fiber springs snapped at 5 mm displacement interval.

**Table 4.3** Load bearing capacity for different fiber winding angle of the springs.

Load (KN)

| Experiment | Spring shape | Fiber | 70º | 80º | 88º |
|---|---|---|---|---|---|
| Changing winding angle | C-shape | E-glass | 0.0597 | 0.0958 | 0.3237 |
| | | Carbon | 0.0798 | 0.1322 | 0.2986 |
| | O-shape | E-glass | 0.1039 | 0.2497 | 0.6675 |
| | | Carbon | 0.1377 | 0.1831 | 0.4343 |

The O-spring with 88º carbon fiber orientation exhibited almost a linear behavior compared to 88º glass fiber orientation but with less displacement, because of the toughness of the carbon fiber. Because of the high extensibility of the glass fiber, the $88^0$ glass fiber orientation spring deflected much. Moreover, a large variation can be seen between the $88^0$ and $80^0$ and $70^0$ fiber orientations, and this was also because of the load applied along the $88^0$ fiber orientations as shown in Figure 4.12 and Figure 4.13. Also, in Figure 4.14 optical pictures of O spring taken during compression test are shown.

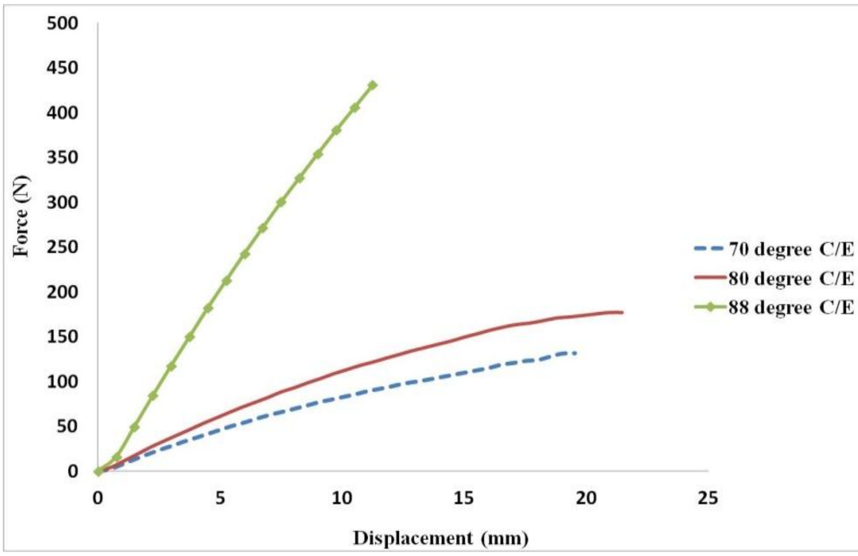



**Fig. 4.12** Load-Displacement graph of three different fiber orientation O-shape carbon fiber springs.

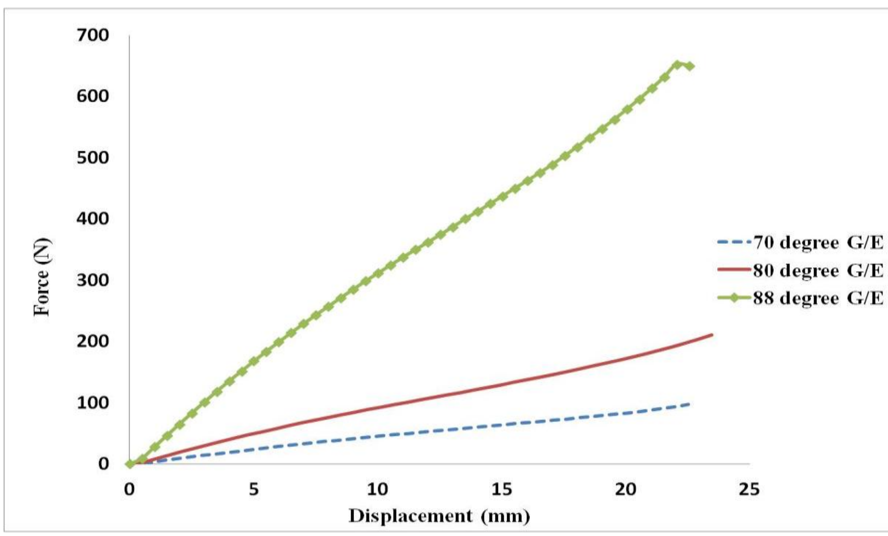



**Fig. 4.13** Load-Displacement graph of three different fiber orientation for O-shape glass fiber springs.

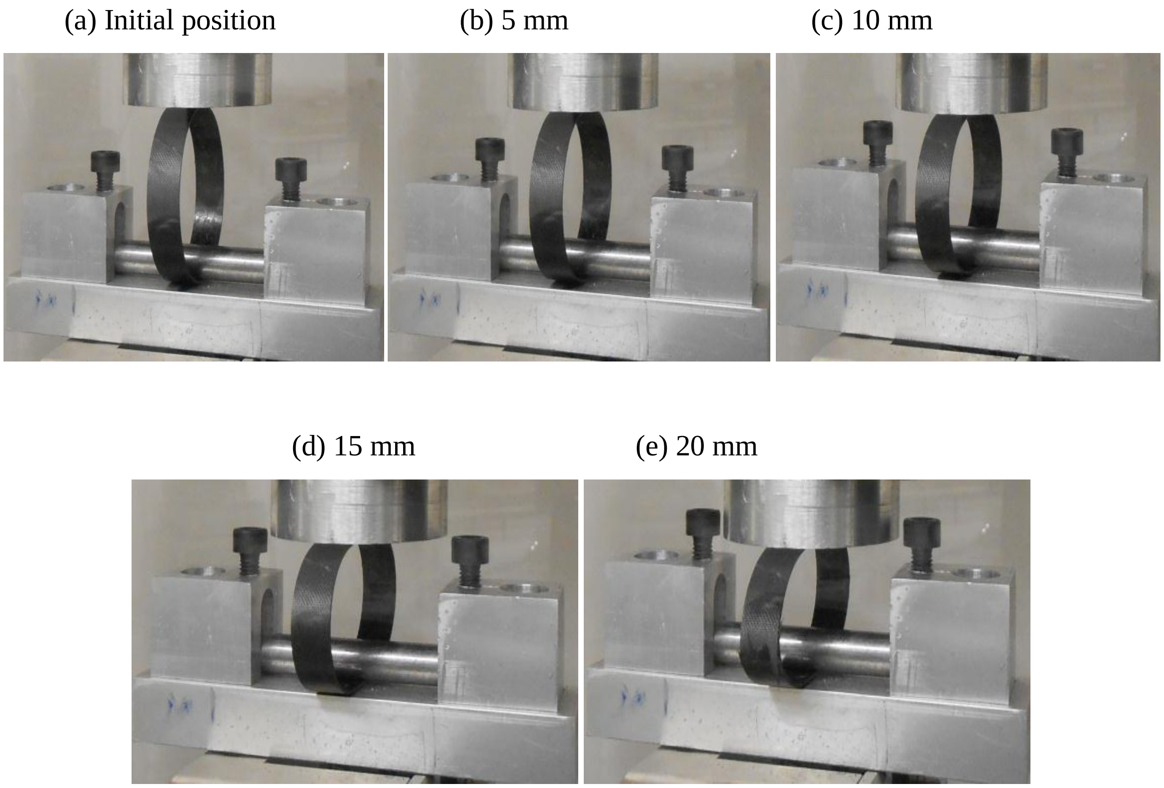



**Fig. 4.14** Pictures of the $70^0$ fiber orientation O-shape carbon fiber springs snapped at 5 mm displacement interval.

# CHAPTER FIVE

# FINITE ELEMENT ANALYSIS

The mechanical behavior of laminated composites can be evaluated using Classical Lamination Theory (CLT). Finite Element Analysis (FEA) is also commonly used approximate solution method. In this research work, FEA was employed to simulate behavior of composite springs

## 5.1 Classical lamination theory

A composite laminate is form by stacking together the lamina to the desired thickness. Their mechanical properties can be enriched by altering the orientation of the lamina in the lay-up. Compared with homogeneous isotropic materials, lamina is more complicated to study because they are not homogeneous and not isotropic. But they are often assumed to be homogeneous for macro-mechanical analysis. Fibers and matrix made up lamina and both are homogeneous, but their properties differ from point to point which relied on whether the point is in fiber, matrix or fiber matrix interface [3].

Although, lamina are assumed to be homogeneous their mechanical behavior still differ from a homogeneous isotropic material. The general form of Hook's law for isotropic material is given by the equation below:

$$\varepsilon_x = \frac{1}{E}\left[\sigma_x - v\left(\sigma_y + \sigma_z\right)\right]$$

$$\varepsilon_y = \frac{1}{E}\left[\sigma_y - v(\sigma_x + \sigma_z)\right] \qquad (5.1)$$

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - v\left(\sigma_x + \sigma_y\right)\right]$$

Also, Hooke's law governed the elastic response of the individual lamina in an orthotropic form as written below;

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} 1/E_1 & -\upsilon_{21}/E_2 & -\upsilon_{31}/E_3 & 0 & 0 & 0 \\ -\upsilon_{21}/E_1 & 1/E_2 & \upsilon_{32}/E_3 & 0 & 0 & 0 \\ -\upsilon_{13}/E_1 & -\upsilon_{12}/E_2 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix} \times \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{bmatrix} \qquad (5.2)$$

Where $E_1$, $E_2$, and $E_3$ are the modulus of elasticity in the 1-, 2-, and 3-directions, $v$ is the poison's ratio and G is the shear modulus. Also G is related to:

$$G = \frac{E}{2(1+v)} \qquad (5.3)$$

There are six components of stress and six corresponding components of the strain for three dimensional cases $(\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx})$as shown in Figure 5.1.

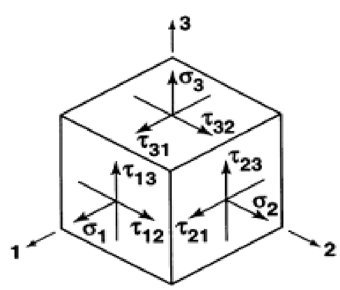



**Fig. 5.1** Stress of an element [4].

The general Hooke's law for anisotropic given with six equations is shown below and it is known as compliance matrix.

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{bmatrix} \qquad (5.4)$$

Where $S_{11}=1/E_1$. Now in stress form the equation is given below by inverting equation (5.4).

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} \tag{5.5}$$

This matrix (Equation 5.5) is called stiffness matrix. Also this equation can further be simplified to represent plane stress orthotropic behavior, because of symmetrical and thin sheet of the lamina. Also, all stresses that are not in x and y plane of the lamina sheet are normally small, thus $\sigma_3 = \tau_{23} = \tau_{13}$. Therefore,

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & 0 \\ 0 & 0 & 1/G_{12} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \tag{5.6}$$

In terms of strain, the lamina stresses are:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon 1 \\ \varepsilon 2 \\ \gamma_{12}/2 \end{bmatrix} \tag{5.7}$$

Where Q's are components of simplified stiffness matrix and, they are correlated to the engineering constants as:

$$\begin{aligned} Q_{11} &= \frac{S_{22}}{S_{11}S_{22} - S_{12}^2} = \frac{E_1}{1-\nu_{12}\nu_{21}} \\ Q_{12} = Q_{21} &= \frac{S_{12}}{S_{11}S_{22} - S_{12}^2} = \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} \\ Q_{22} &= \frac{S_{11}}{S_{11}S_{22} - S_{12}^2} = \frac{E_2}{1-\nu_{12}\nu_{21}} \\ Q_{66} = G_{12} &= \frac{1}{S_{66}} = \end{aligned} \tag{5.8}$$

Laminate may have a high strength in one direction and weak strength in other direction if placed in the same orientation. Generally, lamina is used to be orientated at an angle to assist balancing the properties in different directions. The coordinate system normally used for angled lamina is shown in Figure 4.7 below.

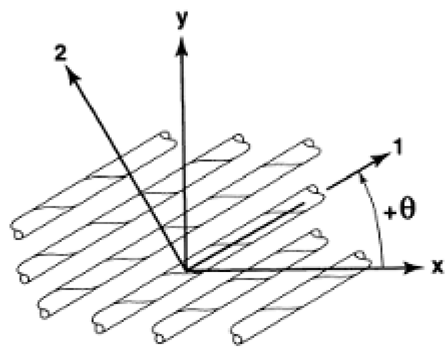



**Fig.5.2** Angle of an axes x-y lamina [4].

1-2 coordinate are the local axes in which 1-direction is parallel to fibers and 2-direction perpendicular to the fibers. The global axes of the laminate are the x-y coordinate system. Using matrix transformation, the stresses in 1-2 coordinate can be converted into x-y coordinate.

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [T]^{-1} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \tag{5.9}$$

Where [T] is transformation matrix and it is equivalent to:

$$[T]^{-1} = \begin{bmatrix} \cos^2\theta & \sin^2\theta & -2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & 2\sin\theta\cos\theta \\ \sin\theta\cos\theta & -\sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \tag{5.10}$$

For strain components, the transformation can be:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \dfrac{\gamma_{xy}}{2} \end{bmatrix} = [T] \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \dfrac{\gamma_{12}}{2} \end{bmatrix} \tag{5.11}$$

Now, stress-strain relation can be determined as:

$$(\sigma_x) = [\overline{Q}](\varepsilon_x)$$

$$\text{Here, } [\overline{Q}] = [T]^{-1}[Q][T]$$

Also, the $[\overline{Q}]$ terms called transformed lamina stiffness and are defined as:

$$[\overline{Q}] = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix} \tag{5.12}$$

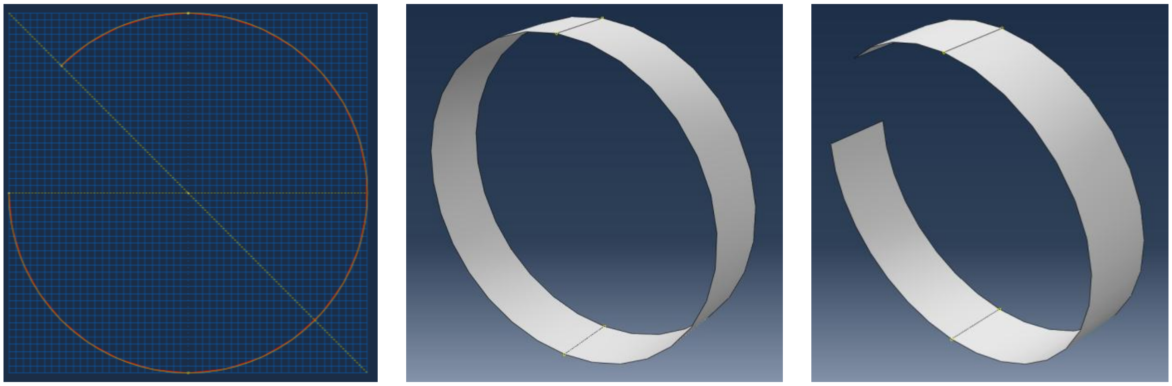
Where,

$$\begin{aligned}
\overline{Q}_{11} &= Q_{11}\cos^4\theta + Q_{22}\sin^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta \\
\overline{Q}_{12} &= (Q_{11} + Q_{22} - 4Q_{66})\sin^2\theta\cos^2\theta + Q_{12}(\cos^4\theta + \sin^4\theta) \\
\overline{Q}_{22} &= Q_{11}\sin^4\theta + Q_{22}\cos^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta \\
\overline{Q}_{16} &= (Q_{11} - Q_{12} - 2Q_{66})\cos^3\theta\sin\theta - (Q_{22} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta \\
\overline{Q}_{26} &= (Q_{11} - Q_{12} - 2Q_{66})\cos\theta\sin^3\theta - (Q_{22} - Q_{12} - 2Q_{66})\cos^3\theta\sin\theta \\
\overline{Q}_{66} &= (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\theta\cos^2\theta + Q_{66}(\sin^4\theta + \cos^4\theta)
\end{aligned} \tag{5.13}$$

**Modeling**

In the finite element analysis, ABAQUS/CAE was used for modeling and simulating the behavior of composite springs. For every complete finite element analysis there are three stages, those are: Pre-processing, Processing, and Post-processing.

**Creating the geometry;** 3-D shell with deformable and extrusion type was used in creating the geometry. A $45^0$ part was cut for the C-shapes similar to the experimental one.

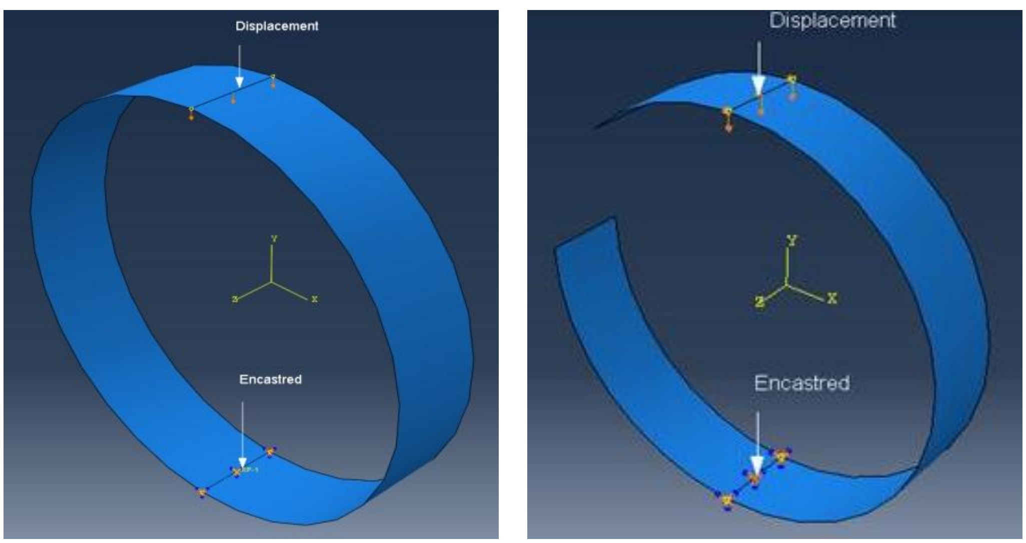


(a) (b) (c)

**Fig. 5.3** parts created (a) $45^0$ part cut (b) O-shape (c) C-shape.

**Boundary conditions;**

An encastred boundary (which implies that no motion along or rotation along all the coordinate axes) condition was used at the bottom side for all the C and O-shapes. That is $U_1 = U_2 = U_3 = UR_1 = UR_2 = UR_3 = 0$. Also, a displacement was applied along the negative y-axis.

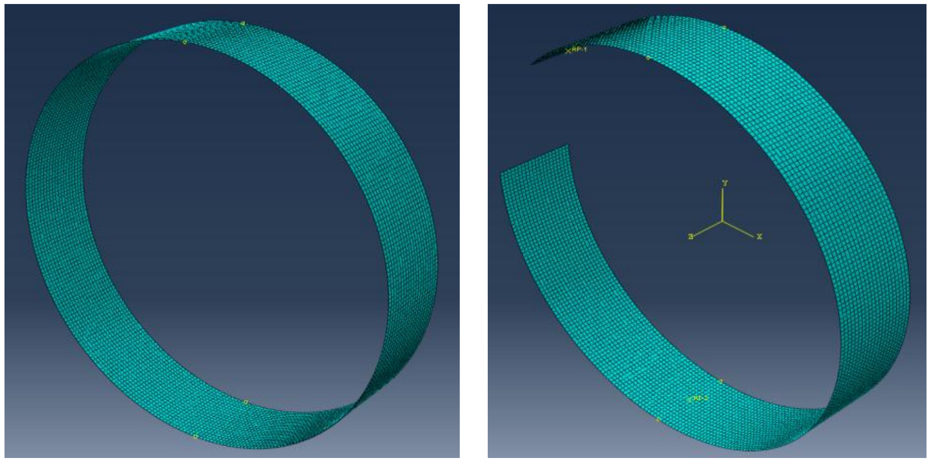



(a) (b)

**Fig. 5.4** Boundary conditions applied to the parts (a) O-shape spring (b) C-shape spring.

**Parts meshing;**

The sizing controls of the mesh used were 0.5 approximate global sizes, and the curvature control was 0.1 maximum deviation factors with 8 approximate number of circle.



(a) (b)

**Fig.5.5** View of the meshing structure (a) O-shape spring, (b) C-shape spring.

**Analysis;**

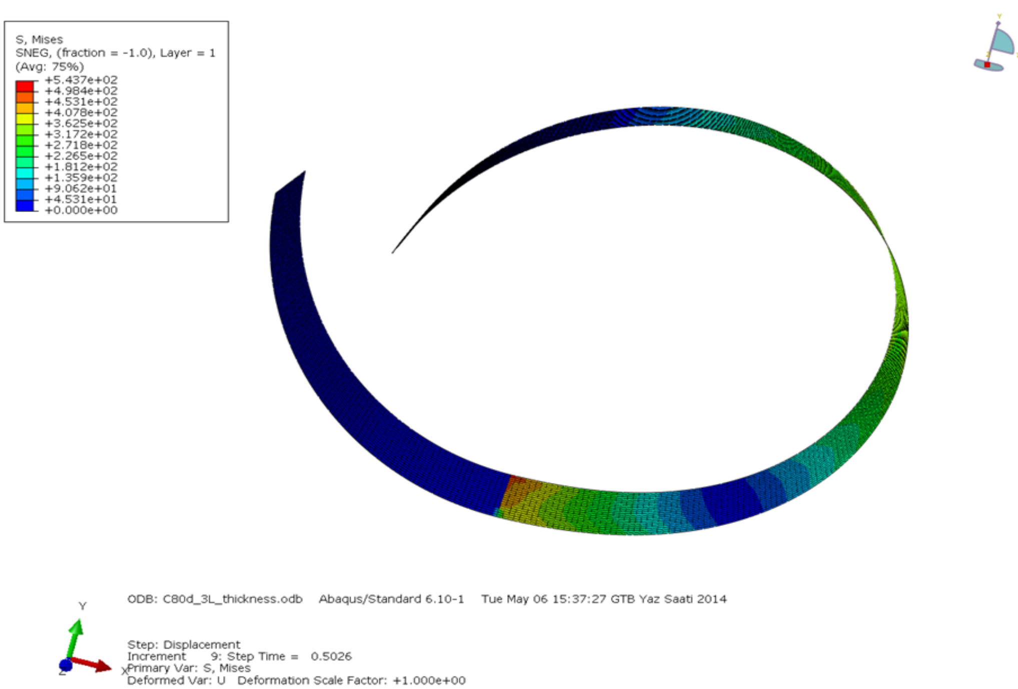



**Fig. 5.6** Von Mises equivalent stress for C-shape spring.

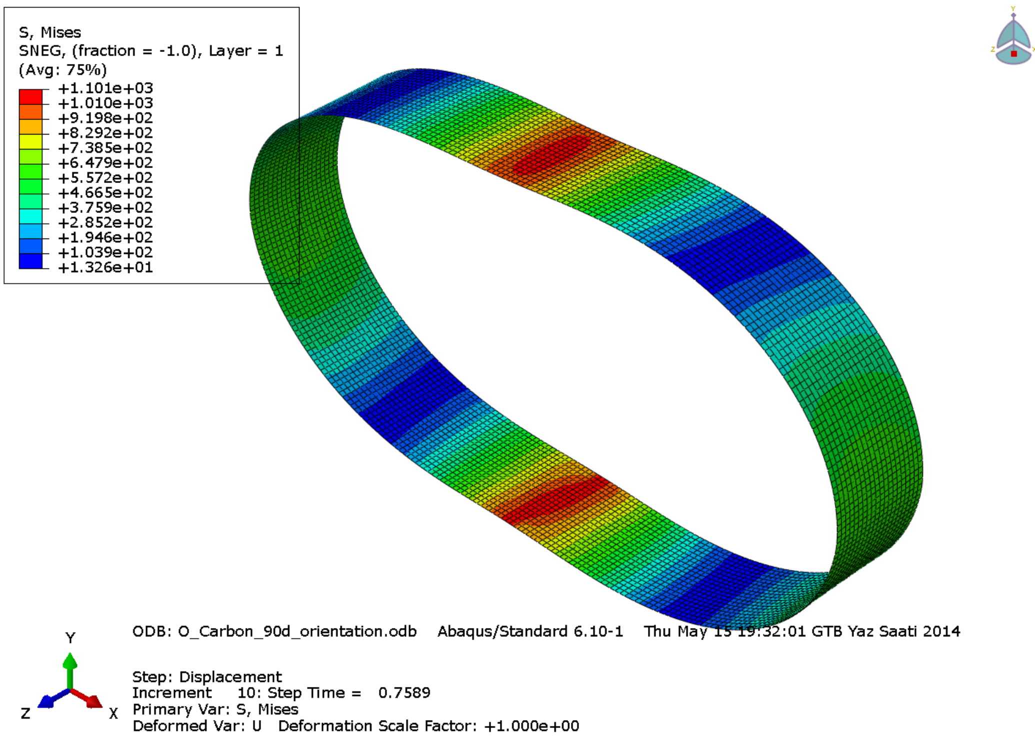



**Fig. 5.7** Von Mises equivalent stress for O-shape spring.

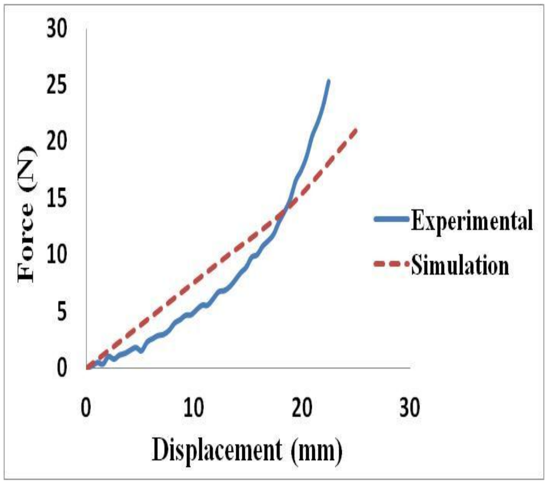
# CHAPTER SIX

# RESULTS AND DISCUSSIONS

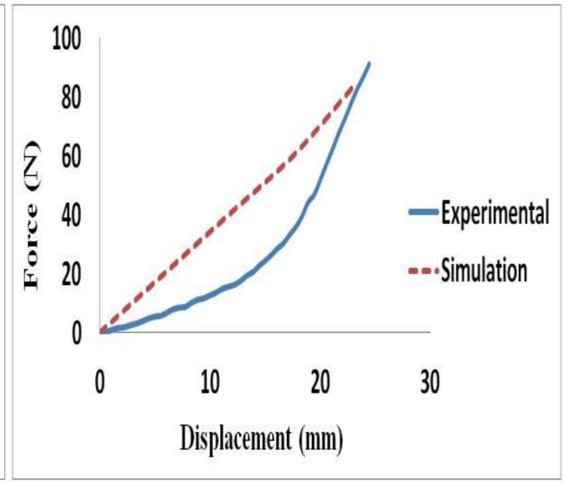
The experimental results were compared with the FEA results and the analyses are as follows:

**Thickness effect**

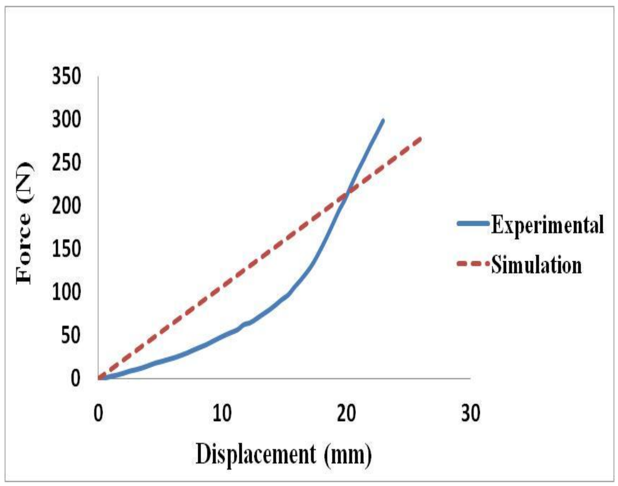
The combine experimental and simulation individual graphs for one, two, and three layers are shown in Figure 6.1 for C-shape and Figure 6.2 for O-shape springs. The numerical results and experimental results showed an agreement for both the C and O- shape springs. For C-shape springs, the experimental graphs showed a non linear behavior while the simulated one showed a linear behavior. This is because, the linear elasticity in an orthotropic material defined by the engineering constants: $E_{1,}$ $E_{2;}$ Poison's ratio $\upsilon_{12;}$ and shear moduli $G_{12}$, $G_{13}$, and $G_{23}$ associated with the material's principal direction. These moduli defined the elastic compliance according to Equation 5.2. This linear elasticity is defined using ELASTIC option in the Abaqus/CAE [33]. The experimental graphs for the O-shape springs exhibited more correlated behavior with the simulated graphs. And this is because, the geometry of the O-shape spring gave it rigidity to carried enough load along with the displacement during the experimental test that made it behaved almost linearly.




(a) 1 layer

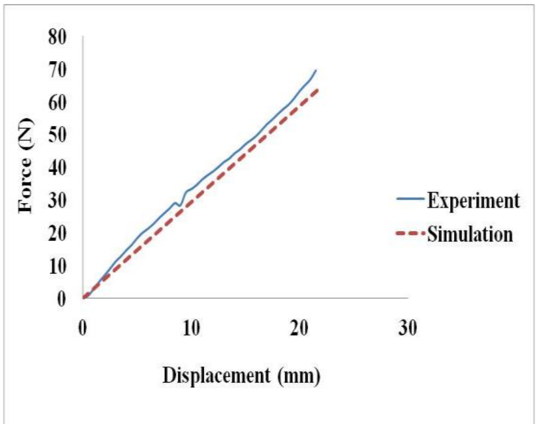



(b) 2 layers

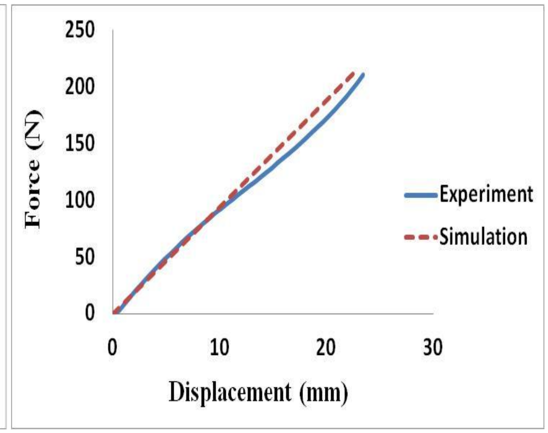



(c) 3 layers

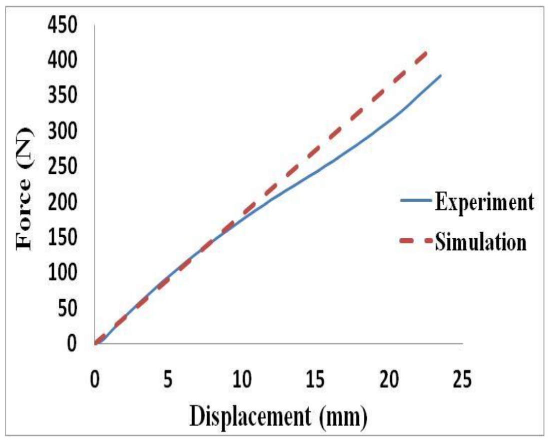
**Fig. 6.1** Load-displacement graphs for the combine experimental and FEA of C-shape spring for (a) one layer, (b) two layers and (c) three layers.




(a) 1 layer




(b) 2 layers

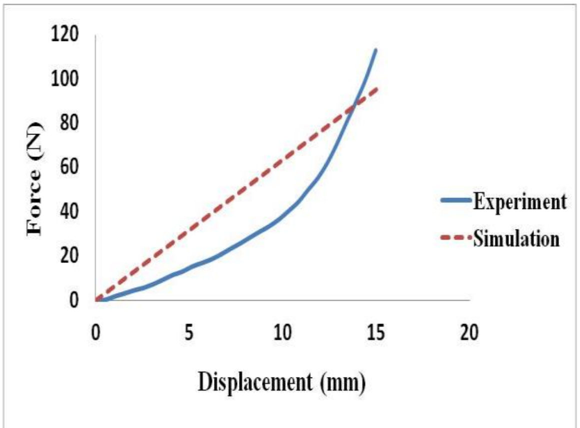



(c) 3 layers

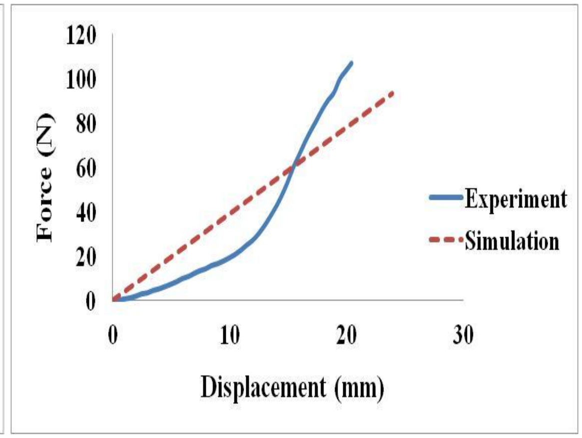
**Fig. 6.2** Load-displacement graphs for the combine experimental and FEA of O-shape spring for (a) one layer, (b) two layers and (c) three layers.

**Diameter effect;**

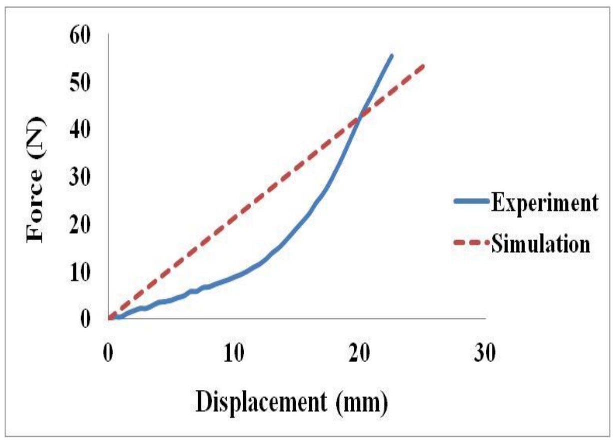
Figure 6.3 and Figure 6.4 showed the individual 35, 40, and 50 mm diameter of the combine experimental and simulated load versus displacement graphs for C and O-shape springs. The O-shape springs exhibited more related behavior between the experimental and simulation than the C-shape springs. This is because the geometry of the O-shape spring gave it rigidity to carry enough loads along with the displacement during the experimental test that made it behaved almost linearly.




(a) 35 mm diameter

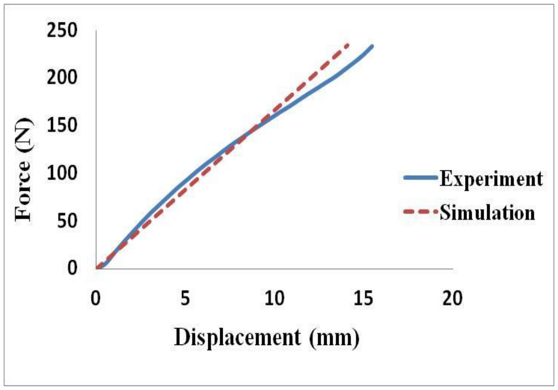



(b) 40 mm diameter

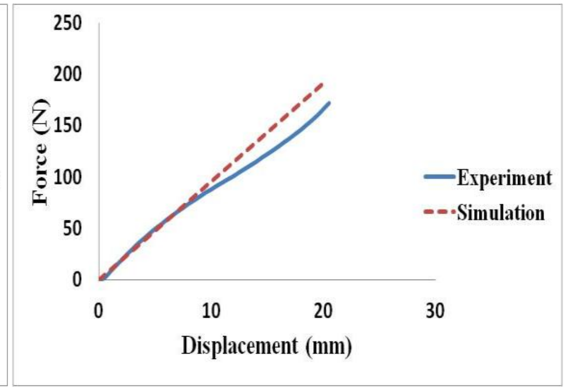



(c) 50 mm diameter

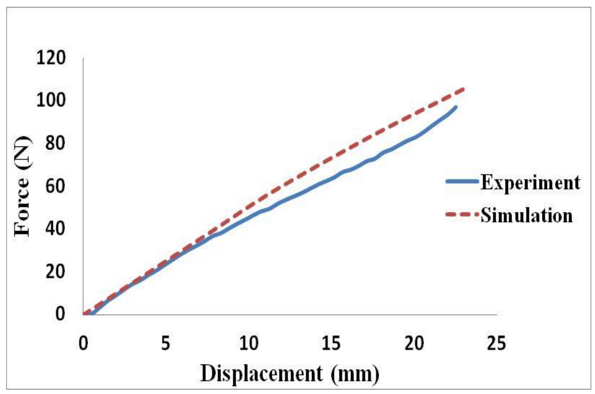
**Fig. 6.3** Combine load-displacement graphs of the experimental and FEA for glass fiber C-shape springs with (a) 35 mm diameter, (b) 40 mm diameter and (c) 50 mm diameter.




(a) 35 mm diameter




(b) 40 mm diameter

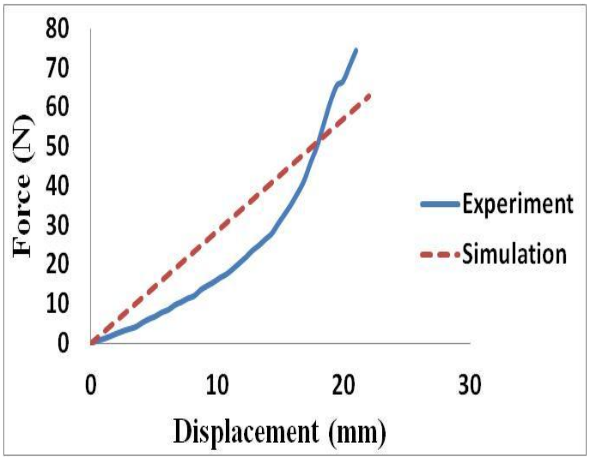



(c) 50 mm diameter

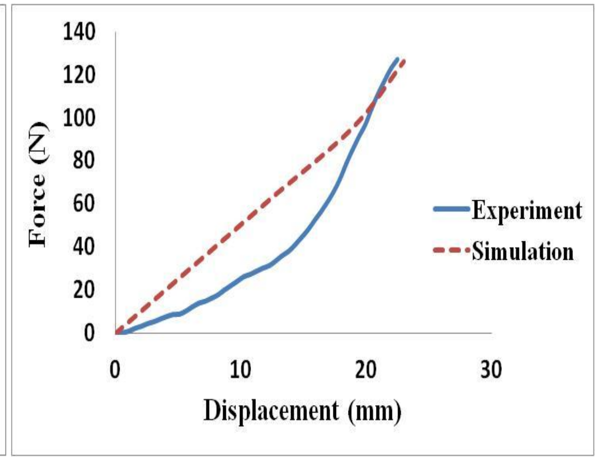
**Fig. 6.4** Combine load-displacement graphs of the experimental and FEA for glass fiber O-shape springs with (a) 35 mm diameter, (b) 40 mm diameter and (c) 50 mm diameter.

## Fiber orientation effect;

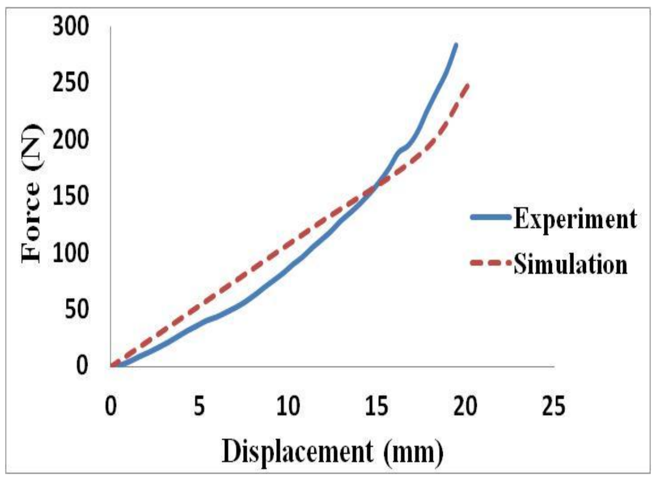
Figure 6.5 and Figure 6.6 showed the individual graphs of the combine experimental and simulation for the $70^0$, $80^0$, and $88^0$ fiber orientations for carbon and glass fiber composite C-shape springs respectively. For $70^0$ and $88^0$ carbon fiber orientation springs, a little drop of the curve is observed at about 68 N and 190 N respectively. This is caused by a crack observed from the matrix of the specimens. Figure 6.7 and Figure 6.8 also showed the graphs of the individual fiber orientation for O-shape carbon fiber and glass fiber springs respectively. The O-shape glass fiber springs showed more correlated behavior between the experimental and simulation results.




(a) $70^0$ fiber orientation

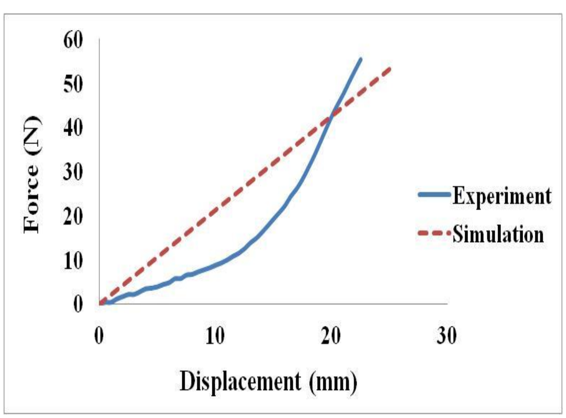



(b) $80^0$ fiber orientation

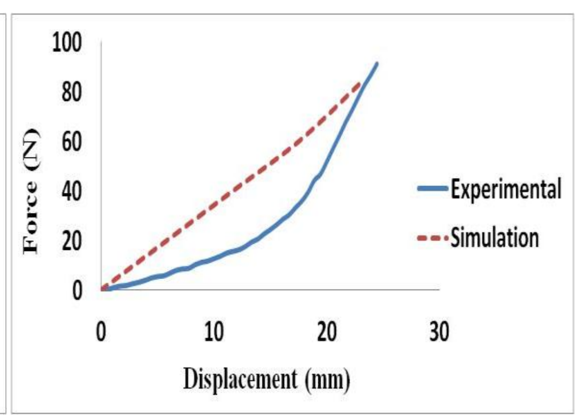



(c) $88^0$ fiber orientation

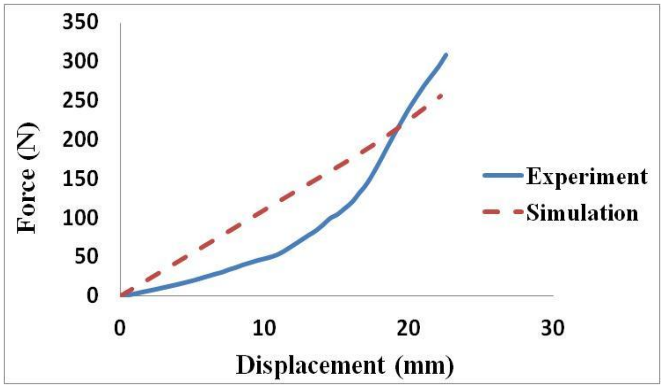
**Fig.6.5** Combine experimental and FEA load-displacement graphs for different orientation angle of the carbon fiber C-shape springs.




(a) $70^0$ fiber orientation

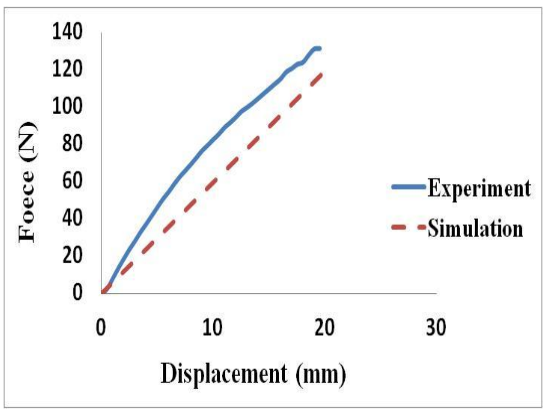



(b) $80^0$ fiber orientation

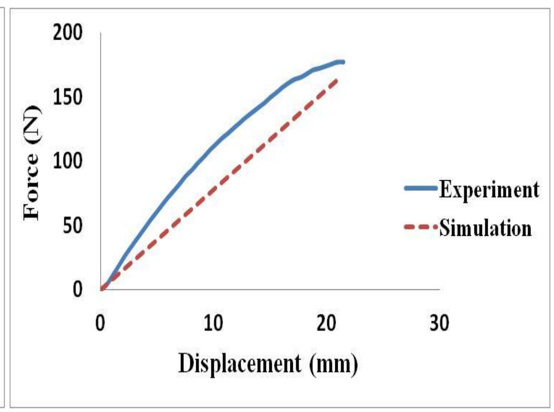



(c) $88^0$ fiber orientation

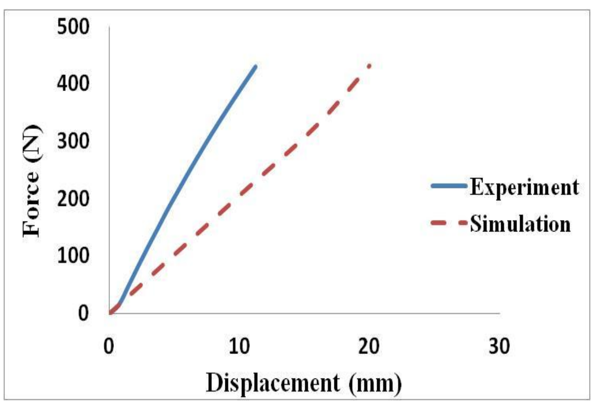
**Fig.6.6** Combine experimental and FEA load-displacement graphs for different orientation angle of the glass fiber C-shape springs.




(a) $70^0$ fiber orientation

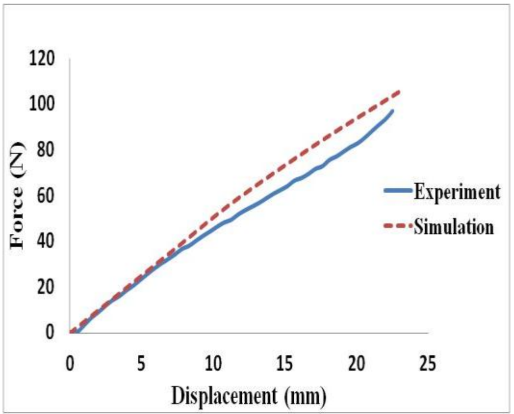



(b) $80^0$ fiber orientation

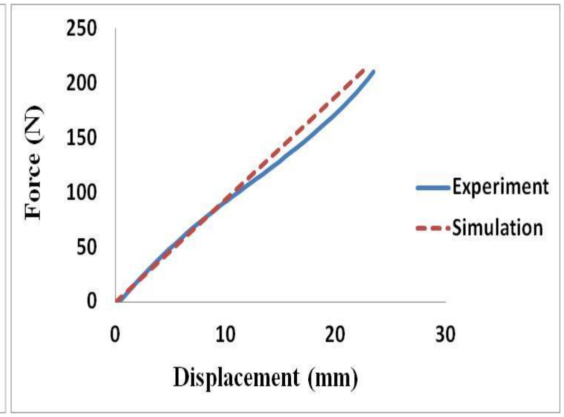



(c) $88^0$ fiber orientation

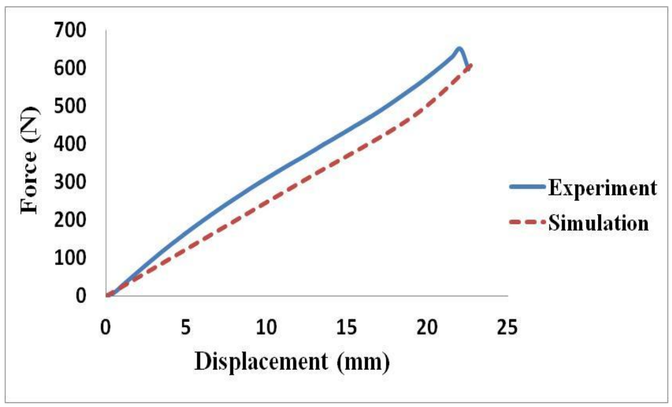
**Fig. 6.7** Combine experimental and FEA load-displacement graphs for different orientation angle of the carbon fiber O-shape springs.




(a) $70^0$ fiber orientation




(b) $80^0$ fiber orientation




(c) $88^0$ fiber orientation

**Fig. 6.8** Combine experimental and FEA load-displacement graphs for different orientation angle of the glass fiber O-shape springs.

# CHAPTER 7

# CONCLUSION

As observed from the experimental results the spring thickness, diameter, and orientation angle, play important role for stiffness and load carrying capability of the spring. The O-shape springs withstand much load and rigidity compared to the C-shape springs. Also, the carbon fiber springs 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;

The three layers spring bear more load and stiffness compared to the one layer and two layers springs. The load bearing capacity of three layers springs are 34% more than the two layers and 75% more than the one layer springs.

35mm diameter spring carried more load and showed higher stiffness than the 40mm and 50mm diameter springs for the same thickness and fiber orientation angle. Also, the load carrying capacity of 35mm diameter springs are 10% more than the 40mm and 31% more than the 50mm diameter springs.

The $88^0$ fiber orientation springs withstand more load and exhibited higher stiffness compared to the $80^0$ and $70^0$ fiber orientation springs. The load bearing capacity of $90^0$ fiber orientation springs are 47% more than the $80^0$ fiber orientation and 62% more than the $70^0$ fiber orientation springs.

The finite element analysis conducted using linear elastic orthotropic material model was very successful simulating the behavior of O-Spring. However nonlinear load displacement curves produced by C-Springs were not simulated sufficiently. This is due the linear elastic orthotropic material model used for simulations. However FE predicted results for C-Spring can still be used for estimating maximum load and general behavior of C-Springs.

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