Technische Universität Ilmenau
Pontificia Universidad Católica del Perú

Theoretical and practical approaches for novel composite volute springs

A thesis submitted in fulfillment of the requirements to obtain the degree of

Master of Science in Mechanical Engineering

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February, 2018

Technische Universität Ilmenau
Fakultät für Maschinenbau

Masterarbeit

für Herrn Jorge Enrique Llimpe Rojas

geboren am 11.05.1982 in Junin

Studiengang Maschinenbau

THEMA

„Theoretical and practical approaches for novel composite evolute springs“

verantw. Hochschullehrer: Prof. Dr.-Ing. Ulf Kletzin

Ausgabedatum: 30.03.2017 Abgabedatum: 02.10.2017

Ilmenau, den 11.05.2017

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TECHNISCHE UNIVERSITÄT
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Department of Mechanical Engineering

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Conceptual Formulation of the Master Thesis

of Mr. Jorge Enrique Llimpe-Rojas

Topic: Theoretical and practical approaches for novel composite evolute springs

Springs made of fiber composite materials are being investigated and used for over 50 years up to date. Nowadays, materials and production technologies provide excellent spring characteristics combined with the advantages of corrosion resistance, mass reduction (up to 50-75%), internal damping and good fatigue behavior.

Local layup adaptions offer a precise adjustment of the spring rate, allow predetermined breaking points or strengthen endangered areas respectively. These adjustments can be achieved by variation of the number of layers, usage of different fiber materials and modification of the fiber orientation.

However, the common helical spring design is complicated when it comes to composite manufacturing because it requires a complex segmented mould and the lamination has to be done manually. In addition, the resin needs some amount of time for curing. These facts slow down the production and increase the costs.

To solve the herein before mentioned problems, this master thesis deals with the evolute spring design as an alternative approach, which enables the usage of common flat fabrics. This novel application demands the following tasks:

- literature review, focused on evolute springs and material behavior of thin-walled composite beams
- preparation of theoretical approaches for flat composite beams under torsion loads, according to the relevant literature
- development of a spring-model, predicated on the beam descriptions constructed before and complemented by the factor of friction
- dimensioning and manufacturing of necessary composite test specimens and evolute springs by using different layups, fiber materials and fiber orientations
- measurements of typical spring characteristics (spring curve, fatigue loads, deformation)
- comparison and discussion of theoretical and practical considerations
- scientific documentation (including a data CD with all files, figures, pictures, literature,…)

Date of issue:	30.03.2017
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Declaration of Authorship

I, Jorge Llimpe, declare that this thesis titled, "Theoretical and Practical Approaches for Novel Composite Volute Springs" and the work presented in it is entirely my own. I also confirm that:

- This work was done wholly or mainly while running as a candidate for a research degree at this same University.
- None of its parts have been previously submitted for a degree or any other purposes at this or any other University or Institute.
- I have consulted the published work of others, all of them can be seen in the bibliography compendium.
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Abstract

Theoretical and Practical Approaches for Novel Composite Volute Springs

by Jorge Llimpe

A combined experimental/analytical approach for an efficient evaluation of stiffness and characteristic curves of fiber reinforced plastic volute springs is presented in this work.

Before performing the analysis mentioned in previous lines, in the early chapters, it can find the most common types of fibers, resins (matrices) and manufacturing processes used to produce composite laminates been briefly described. It also describes the analytical approaches that currently exist to determine the elastic constants of composites such as the longitudinal and transversal modulus, Poisson's ratios and shear moduli; it also describes the improved and semi-empirical formulas to calculate the effective shear moduli and the transversal modulus. At the end of the chapter, some manufacturing methods of fiber reinforced plastic springs are described.

Since fiber reinforced plastic volute springs are novel products, the fourth chapter presents and describes basic considerations that it must be taken into account when selecting material (fibers, resins, and additives) to manufacture these springs. At the end of the chapter, a method to produce volute springs is presented.

The fifth chapter presents the elastic constant calculations for laminates used to manufacture volute springs. An experimental/analytical method has also been performed to determine in-plane and out-of-plane shear moduli since these material constants are of greater importance in the rate spring calculation hence any cross-section of these springs shows the major load being torsional. On the one hand the analytical method to calculate these shear moduli is based on Sumsion's guidelines that use the theory developed by Lekhnitskii for anisotropic materials; on the other hand, it has been done torsion test of rectangular bars, which were manufactured using vacuum infusion method, to obtain shear moduli experimentally.

Finally, calculated values of shear moduli are used to determine stiffness and characteristic curves of volute springs in an analytical and experimental method. It is proposed to use the in-plane shear modulus in the classical calculation method for steel volute springs and to compare results obtained with compression test results carried out on fiber reinforced plastic volute springs.

Consistent results are achieved by performing this combined analytical and experimental method concluding that the best behavior of fiber reinforced plastic volute springs is when fibers have an orientation of $\pm 45°$ concerning the main axis of the laminate.

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Preface

This thesis was proposed in the Machine Elements Research Group "Wire and Spring" of the Mechanical Engineering Faculty at Technische Universität Ilmenau.

It arises with the goal of offering an alternative approach to manufacture and analysis of fiber reinforced plastic springs. In this sense, it is proposed to carry out a research on volute springs that can be produced using flat strips of unidirectional and biaxial fabrics or fiber flat braid strips which are more common and commercial compared with the production of fiber reinforced plastic helical springs whose design is complicated since they require complex methods to their manufacture and analysis.

After a few months of studies, I have concluded the present work as part of my studies in the mechanical engineering master program.

On the other hand, I would like to thank M. Sc. Martin Petrich for proposing this thesis topic, for his constant advice and support in the development of this work and for giving me the opportunity to develop thereof. Additionally, I would like to thank Ph. D. Fernando Torres for his support, from Peru, in the development of this work. Also, I would like to thank Univ.-Prof. Dr.-Ing. Ulf Kletzin for also giving me the opportunity to develop this topic and I am grateful to Prof. Dr.-Ing. René Theska, Dipl.-Ing. Jorge Rodriguez and Dipl.-Ing. Benjamin Barriga for giving me the opportunity to be accepted in the dual degree program in mechanical engineering master and the support provided during my stay in Germany.

Finally, thank you so much dear reader. If you are reading this line before the others, please continue your reading at least of one page of my thesis.

Jorge Llimpe Rojas
Ilmenau, February 10, 2018

Chapter 1

Introduction

Since times in which human beings began to build large buildings or use means of transport to move around (without the help of animals), they have always had the need to use materials that are strong and light at the same time, so many people have always experienced mixing two or more different materials to obtain a material with improved properties. in this sense, more than seventy years ago, fiber reinforced plastics arose as the result of mixing synthetic fibers with liquid resins. The mechanical properties of these fiber reinforced plastics turned out to be better than the properties of their constituent elements, as well as being lighter than steel and aluminum.

The influence of reinforced materials in our life has been so great that we humans have always used fibers with a binder or matrix to obtain stronger materials. For example, Egyptian, Inca and Mayan civilizations have used plant fibers to reinforce bricks and pottery against cracking. With the development of scientific knowledge and the coming of modern civilization, the demand for research and developing new materials for conventional and novel applications has increased.

In fact, with the significant technological advances in recent times, the research into reinforced materials has focused in materials that can withstand rigorous conditions such as high temperature and pressure, highly corrosive environments and high strains. Besides, the research has focused in the search for materials that have high strength and are lightweight.

What was mentioned in the previous paragraph was the reason why many engineers and scientists not only innovate in the development of materials with improved or novel properties, but also improve manufacturing techniques, the efficient use of energy in the production process and above all in considering the environmental impact that such materials would produce.

As mentioned earlier, fiber reinforced plastics have been widely used in designs of various mechanical elements for approximately the last seventy years and have therefore become the dominant emerging materials. In fact, the number of applications and production volumes with fiber reinforced plastics has grown constantly and competitively, penetrating and conquering markets implacably such as automotive, aerospace, transportation, marine equipment, and even markets like sports equipment, medicine, and infrastructure.

Besides, since a few years ago fiber reinforced plastics have started to challenge the materials most positioned, in the world markets, such as steel and its alloys and aluminum. To exemplify, it encounters them in everyday applications, as diverse as automobile bodies, military aircraft, airframes, hulls of boats and civil infrastructure, composite armoring designed to resist explosive impacts, fuel cylinders for natural gas vehicles, windmill blades [1]. Moreover, in products such as air intakes of formula race cars, industrial drive shafts, support beams of highway bridges, and recently in various spring types (leaf, Belleville, helical and wave springs). So that, it is correct to say that these days, fiber reinforced plastics will weaken the dominant role of metals in the world market, as it is currently happening with steel leaf and helical springs that they are being replaced with similar springs of composite materials in the vehicle suspension systems, although not in a fast way. In these applications, accurate design and dimensioning are necessary to guarantee the safety. Besides, all materials for these applications must have adequate mechanical properties which are significantly influenced by the fibers and resins used, geometries, processes, and processing conditions.

Although various products made of fiber reinforced plastics can easily replace similar ones made of steel, aluminum or other alloys, the same is not true for some products because their manufacture involves complex procedures that eventually raise the product cost. This is the case of helical cylindrical springs whose calculation and manufacturing processes are complicated to perform .

Currently, studies of fiber reinforced plastic leaf springs are widely developed, so that there is a broad range of researches regarding their design, calculation, evaluation, and production. This wide range can be easily verified because the researches began in the 80's and they are still being done until now with the desire to optimize the characteristics of these springs. The continuous study of leaf springs led to their commercial introduction several years ago being its main application in suspension and stabilization systems of cars, trucks, vans, pickup trucks, and trains [2].

In contrast, fiber reinforced plastic helical cylindrical springs are still under investigation. Although they have been already introduced commercially approximately five years ago, studies are still being carried out about optimization of the manufacturing process and the improvement of mechanical properties.

The production process of helical cylindrical springs requires a core that consists of long glass fibers twisted together and impregnated with epoxy resin. Then, resin-impregnated fibers are wrapped over this wet core in opposite directions of 45 degrees. The next step is to wind the "wire" obtained on a metal mold and finally proceed with the curing in an oven at a certain temperature.

Due to the complex process of producing helical springs, design alternatives have arisen, always with the aim of replacing springs in automobile suspension systems. This design option is the case for Belleville springs created by ABSSAC Ltd. [3] in the United Kingdom. They propose an assembled set of Belleville springs whose manufacture with carbon fiber layers is simpler than helical springs. Despite their advantage being more stable (in an assembly) than helical springs, these springs do not support large deflections making them somewhat inefficient for suspension systems.

In this sense, it arises the idea of producing an alternative that simplifies the manufacturing complexity of helical springs. Therefore, this work, proposes to analyze the behavior and develop a production process for fiber reinforced plastic volute springs starting from the premise that these springs require an analysis of their behavior and a manufacturing process that is simpler than helical cylindrical springs. It should be noted that, up to the date of issuance of this work, there is still no research about fiber reinforced plastic volute springs.

Therefore, this work aims to generate a simple manufacturing process using fiber fabric strips. Then, the behavior of the volute spring will be studied, to analyze its stiffness, performing analytical calculations and comparing these results with experimental results from tests carried out on springs with different orientations among their fibers. It is clear that, according to the theory of elasticity of composite materials, it is important to determine the laminate elastic constants of the springs, specifically shear moduli. In this sense, an experimental and theoretical analysis will be also carried out to determine these constants.

The purpose of the proposal presented here is not to use these springs in vehicle suspension systems, but rather to study them in a general way so that they can later be applied to any particular device.

Chapter 2

Basic considerations for fiber reinforced plastic springs

The following sections describe the components that are part of the fiber reinforced plastic springs and the manufacturing processes that allow obtaining composite materials called laminates. And at the end of the chapter is presented a brief description of the composite springs that currently exist.

2.1 Composite materials in general

2.1.1 A Brief introduction to composite materials

Fiber reinforced plastics have become increasingly important in a variety of engineering fields. The rapid growth in the use of composite materials in structures and mechanical elements has required the development of the theory for modeling the mechanical behavior and the analysis of structural elements made of composite materials as beams, sandwich beams, plates, shells, pipes, blades of wind turbines, bicycle frames, springs and so on.

But, the question is: Why do composite materials use? Composite materials (which are the result of combining two or more materials) are used because have better properties than the properties of their constituents acting separately. Another important reason for using fiber reinforced plastics is that these materials are lightweight, rigid, impact resistant, resist corrosion and wear well and allow complex shapes to be obtained with high precision. All these properties together are complicated to find in conventional materials (steel, aluminum, and other metal alloys). For these reasons, nowadays the use of composite materials is highly considered when designing new mechanical elements or structures. For example in the automotive, aeronautical, medical and civil construction sectors.

It is clear that fiber reinforced plastics have advantages over conventional materials, but their main disadvantage is price, i.e. the characteristics of materials and processes make the product very expensive. Another disadvantage is that, at present, calculation tools are not yet widely developed as in the case of metals. Also, the manufacturing processes of many elements are still in continuous improvement, so that in certain occasions it ceases to be an alternative material when designing mechanical elements.

According to the preceding paragraph, This work focuses on developing an approximate approach to analyzing the behavior of fiber reinforced plastic scroll springs, as well as developing a manufacturing method that is simple and fast.

2.1.2 A definition of composite materials

According to Mark E. Tuttle, a definition of "composite material", which includes a reference to a physical scale is as follows: a composite material is a material system consisting of two (or more) materials, which are distinct at a physical level greater than about 1 μm (As a reference, the diameter of human hair ranges from about 30 to 60 μm) and which are bonded together at the atomic and molecular levels [4].

In this general definition of composites is included modern composites that use metal, ceramic or polymer binders reinforced with a variety of fibers or particles. Also, an important group, of engineering materials, are the synthetic composites such as fiber or particle reinforced plastics where low weight in combination with high strength and stiffness are required in the structural design [4].

In general, one material has high strength, high stiffness and is called the reinforcement and is embedded into the another material that is mostly less stiff and weaker (that has a relatively low strength and low stiffness), it is continuous and is called the matrix (a mixture of resin and curing agent).

It must be taken into account that the composite material properties depend on:

- The properties of the constituents.
- The geometry of the reinforcements, their distribution, orientation and concentration usually measured by the fiber volume fraction or fiber volume ratio.
- The nature and quality of the matrix-reinforcement interface.

Therefore, ideally, the reinforcing and matrix materials interact to produce a composite whose properties are superior to either of the two constituent materials alone. The concentration of the reinforcement phase is a determining parameter of the properties of the new material; their distribution determines the homogeneity or heterogeneity on the macroscopic scale. The most important aspect of composite materials in which the reinforcement are fibers is the anisotropy caused by the fiber orientation [5].

2.2 Classification and manufacturing methods of composite materials

2.2.1 Classification

Composites can be classified by form (figure 2.1) and distribution of their components (figure 2.2).

The reinforcement constituent can be fibrous or particles. Besides, fibers can be continuous (long fibers) or discontinuous (short fibers). Long fibers are usually arranged in unidirectional or bidirectional, but also irregular reinforcements by long fibers are possible.

The arrangement and orientation of long or short fibers determine the mechanical properties of composites, and the behavior ranges between a general anisotropy to a quasi-isotropy [5].

Particulate reinforcements have different shapes (spherical, platelet or of any regular or irregular geometry). Their arrangement may be random or regular with preferred orientations. In the majority of practical applications, particulate reinforced composites are considered to be randomly oriented, and the mechanical properties are homogeneous and isotropic [5].

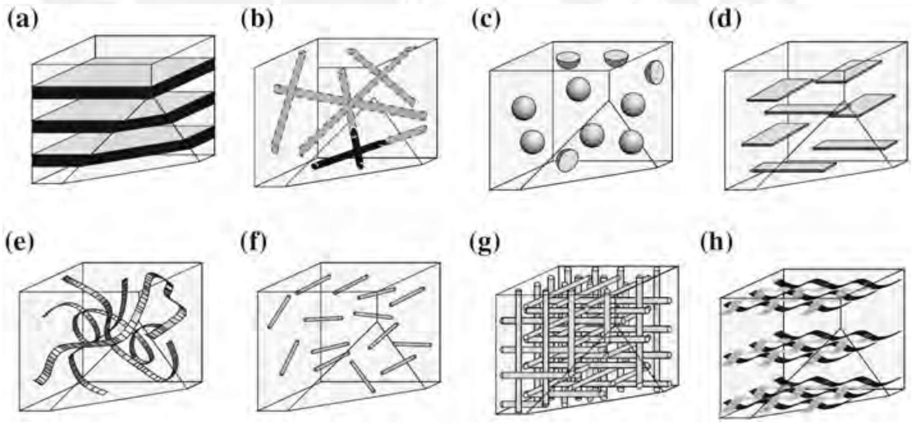


Figure 2.1: Examples of composite materials with different forms of constituents and distributions of the reinforcements. (a) Laminate with uni- or bidirectional layers, (b) irregular reinforcement with long fibers, (c) reinforcement with particles, (d) reinforcement with plate strapped particles, (e) random arrangement of continuous fibers, (f) irregular reinforcement with short fibers, (g) spatial reinforcement, (h) reinforcement with surface tissues as mats, woven fabrics, etc. [5].

In this work, the level of modeling and analysis do not differentiate between unidirectional continuous fibers or woven fiber composite layers, as long as material characteristics that define the layer response are used.

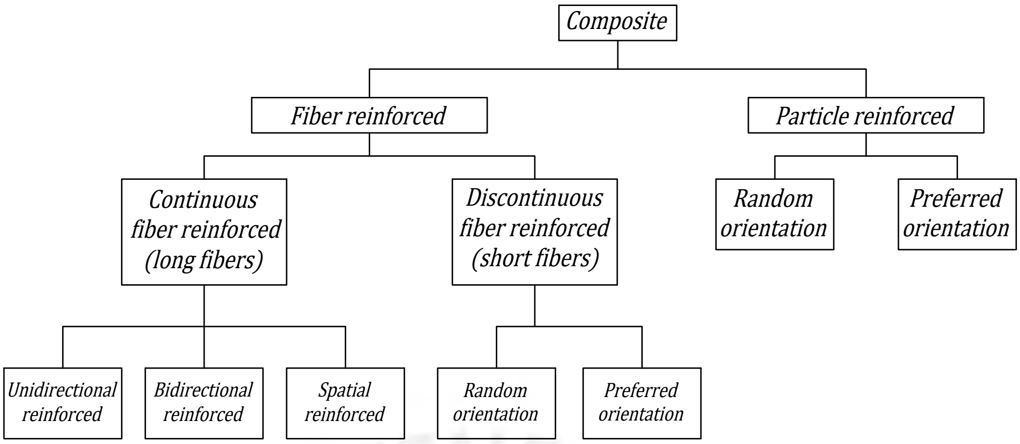


Figure 2.2: Classification of composites [5].

Composite materials can also be classified by the nature of their constituents. According to the nature of the matrix material, it classifies organic, mineral or metallic matrix composites [5].

- Organic matrix composites are polymer resins with fibers. The fibers can be mineral (e.g., glass), organic (e.g., Kevlar) or metallic (e.g., aluminum) [5].
- Mineral matrix composites are ceramics with metallic fibers or with metallic or mineral particles [5].
- Metallic matrix composites are metals with mineral or metallic fibers [5].

In the following, a composite material is constituted by a matrix (a mixture of resin and curing agent) and a fiber reinforcement.

2.2.2 Materials

The design of any element using composites involves simultaneously knowing the characteristics of the material and the design process. Unlike conventional materials, for example, steel, aluminum and its alloys, the properties of composite materials can be designed simultaneously with the structural aspects. Composite properties, for example, strength, stiffness, thermal expansion, etc., can be varied continuously over a broad range of values, under control of the designer [6].

This section describes the components used in the fabrication of composite materials. A brief review of the most common types of materials employed in the manufacture of composites is presented, with emphasis on their properties, advantages, disadvantages, and some cases the cost. It is not explained how fibers and polymers are produced because those subjects are extensive and their development is not part of this work.

Concerning the capabilities and limitations of various processing techniques used to fabricate composite materials these are presented in the next section.

2.2.2.1 Fiber reinforcements

Reinforcing fibers are the primary reinforcement element used in all composite materials. Fibers are more employed in composites because they are lightweight, stiff, and strong. Fibers are stronger than the bulk material from which they are made. This high strength is because of the preferential orientation of molecules along the fiber direction and because of the reduced number of defects present in fiber as opposed to the bulk material [4]. For example, whereas the tensile strength of bulk E-glass is small (about 1.5 GPa [7]), the same materials reaches 3.5 GPa in fiber form, mainly because of the reduction in the number and size of surface defects [4].

Fibers are used as continuous reinforcements in unidirectional composites by aligning a large number of them in a thin plate or shell, called "lamina" or "ply". A unidirectional lamina has maximum stiffness and strength along the fiber direction and minimum properties in a direction perpendicular to the fibers. If the same properties are desired in every direction on the plane of the lamina, then fibers should be randomly oriented [6].

The main reason for using continuous fibers for structural or machine elements applications is that composites reinforced with chopped fibers, whiskers (elongated single crystals), and particles may experience noticeable creep, even at room temperature, because they do not have continuous fibers to suppress it. This bad behavior is because the creep properties of the composite are dominated by the matrix, for this reason, if fibers with very low creep compliance are selected, for example, carbon or glass, then polymer matrix composites can be made as creep resistant as necessary [6].

A wide variety of fibers can be used as reinforcements in structural and machine element applications. Fibers can be classified by their length (short, long, or continuous fibers); according to with their strength and/or stiffness (low, medium, high and ultrahigh modulus); according to their chemical composition (organic and inorganic) [6]. Choosing a fiber type involves a compensation among mechanical and environmental properties and costs. Figure 2.3 shown tensile stress-strain diagrams obtained from single filament test of reinforcing fibers in use are almost linear up to the point of failure. Typical continuous fiber materials are:

- Glass
- Aramid
- Graphite or carbon
- Polyethylene
- Boron

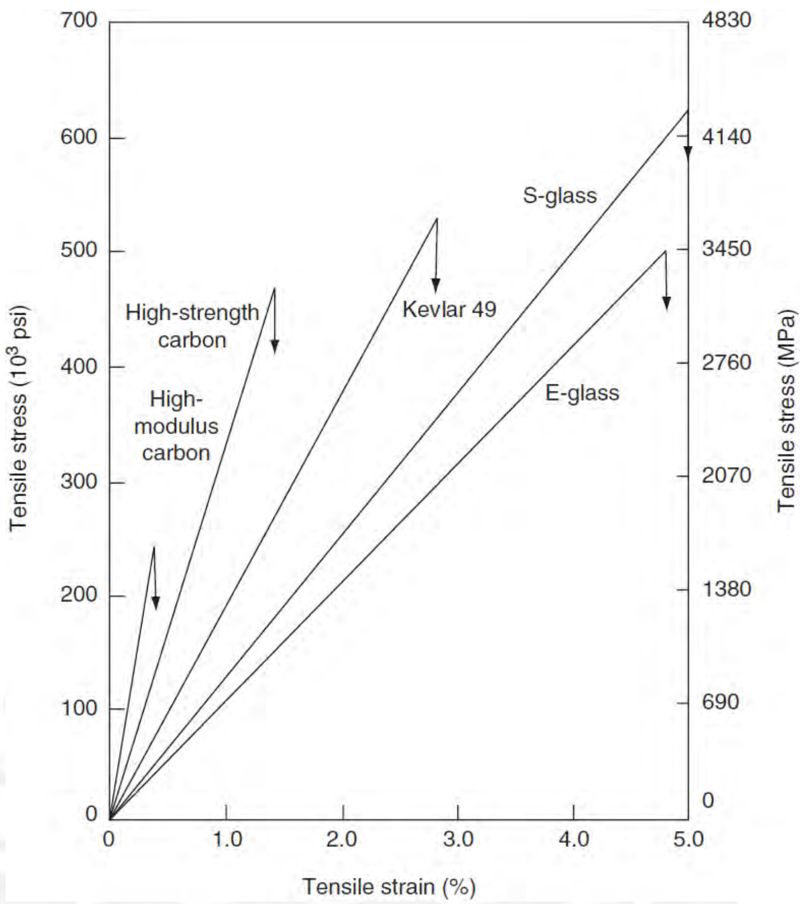


Figure 2.3: Tensile stress-strain diagram for various reinforcing fibers [8].

The most common inorganic fibers used in composites are glass, carbon, boron, ceramic, mineral, and metallic. The organic fibers used in composites are polymeric fibers. In all cases, the fiber diameters are quite small, ranging from about 5 to 12 μm for glass, aramid, or graphite fibers; from about 25 to 40 μm for polyethylene fibers; and from about 100 to 200 μm for boron and silicon carbide fibers [4].

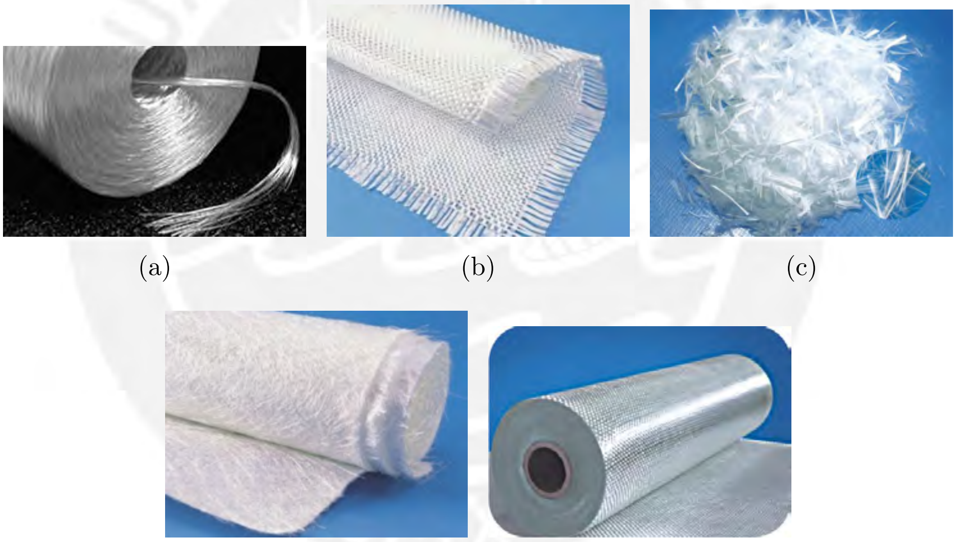
2.2.2.1.1 Glass fibers

Glass fibers are processed from bulk glass (at a temperature of about 1260°C), that is, an amorphous substance fabricated from a mixture of sand, limestone, and other oxidic compounds. Hence, the main chemical constituent of glass fibers is silica (SiO_2) about 46 to 75 percent. Glass fiber diameters range from 9.5 to 24.77 μm, and they are designed with a letter code [6].

The principal advantages of glass fibers are low cost, high tensile strength (the high strength of the glass fibers is attributed to the low number and size of defects on the surface of the fiber [6]), high chemical resistance, and excellent insulating properties. The disadvantages are relatively low tensile modulus and high density (among the commercial fibers), sensitivity to abrasion during handling (which frequently decreases its tensile strength), relatively low fatigue resistance, and high hardness (which causes wear on molding dies and cutting tools)[8].

Glass fiber strength is reduced by factors such as poor processing conditions (strength reduction can be up to 50%), residual stresses, shear and transverse loads to the fiber direction, high operating temperatures and chemical corrosion (glass fiber is susceptible to alkaline chemicals).

The corrosion resistance of glass fiber depends on the composition of the fiber, the corrosive solution, and the exposure time. Chemical corrosion and dissolution influence the growth and propagation of surface microcracks that are inherent to glass fibers [6]. Table 2.1 shows different types of glass fibers commonly used in the fiber reinforced materials. The basic commercial form of continuous glass fibers is a strand, which is a collection of parallel filaments. Other common forms of glass fibers are illustrated in Figure 2.4.



(a) (b) (c) (d) (e)

Figure 2.4: Common forms of glass fibers: (a) Continuous strand roving, (b) woven roving, (c) chopped strand, (d) Chopped strand mat, and (e) woven roving mat [8].

2.2.2.1.2 Organic fibers (Aramid fibers)

Among all the group of organic fibers, polymeric fibers are most commonly used in applications where high strength and stiffness are required, mainly because of their very low density, that results in very high values of the specific strength and stiffness values.

Table 2.1: Different types of glass fibers commonly used [6]

Type of fiber	Description
E-glass	(E for electrical) of alumino borosilicate, these fibers are used where high tensile strength (3.5 GPa), good modulus (70 GPa) and good chemical resistance is required. Also, these fibers are the preferred reinforcements because of the combination of mechanical performance, corrosion resistance, and low cost (about $1,60/kg[6]).
S-glass™ and S2-glass™[6]	(S for strength) of magnesium aluminosilicate. These fibers have the highest tensile strength (4.5 GPa) and modulus (87 GPa); Also, retain a greater percentage of its strength at elevated temperatures but they are of limited application because they cost three to four times more than E-glass. These fibers show a better stability in humid environments.
C-glass	(C for corrosion) this fiber is used in chemical applications requiring greater corrosion resistance to acids than provided by E-glass.
D-glass	(D for dielectric) is used for electrical applications such as the core reinforcement of high voltage ceramic insulators.
A-glass and AR-glass	these fibers are used where alkaline resistant is required. Also these fibers are used for lightweight surfacing veils or mats.
R-glass	This fiber is the European counterpart of the American high performance S-glass. Their high modulus and strength, as well as very good temperature, humidity, and fatigue stability makes them popular for filament winding and sheet molding compounds for high performance industrial applications [9]. This fiber has better strength retention at elevated temperature.

The manufacturing process used to make polymeric fibers comprises two main phases: the transformation of the solid bulk polymer to the liquid phase by either melting or solution, followed by extrusion and cooling. Liquid crystal polymer fibers refer to the manufacturing mentioned above process and the fact that some polymers feature anisotropic crystalline behavior in their liquid phase, forming stronger chemical connections along certain directions. These orientated strong connections are then preserved in the fiber fabrication process, resulting in strong fibers along their axis, with anisotropic behavior. In this way, liquid crystal polymer fibers can feature similar strength as carbon fibers [6].

The most known polymer fibers are those who have been processed from polyamide, called aramid fibers that are liquid crystal polymer fibers (these are highly crystalline aromatic polyamide fibers), produced by DuPont, Teijin, and Akzo Nobel under the trade names Kevlar™, Technora™, and Twaron™, respectively.

Some advantages and disadvantages of aramid fibers are [6] [4]:

- Aramid fibers have high energy absorption during failure, which makes them ideal for impact and ballistic protection
- Because of their low density, these fibers offer high tensile strength-to-weight ratio, and high modulus-to-weight ratio in the axial direction of the fiber, which makes them attractive for aircraft, body armor, and many marine and aerospace applications.
- These fibers have a relatively low tensile strength and stiffness in the transverse direction.
- Also, aramid fibers have low compressive strength since they are made of a polymer material that has similar characteristics to the polymer matrices.
- Aramid fibers creep, absorb moisture, and are sensitive to ultraviolet (UV) light.
- Their Mechanical properties vary with temperature, for example, the tensile strength at 177°C is reduced to 75-80% of their room temperature value.

The table 2.2 shows the commercially available aramid fibers with some of their characteristics [6] [4].

2.2.2.1.3 Graphite and carbon fibers

Tuttle [4] says that the terms graphite and carbon are often used interchangeably within the composites community. The elemental carbon content of either type of fiber is above 90%, and the stiffest and strongest fibers have carbon contents approaching 100%.

Furthermore, Tuttle [4] also says that attempts have been made to standardize definitions for carbon or graphite fibers. Therefore graphite fibers are defined as those that have:

- A carbon content above 95%.
- Been heat-treated at temperatures more than 1700°C.
- Been stretched during heat treatment to produce a high degree of preferred crystalline orientation.

Table 2.2: Commercial aramid fibers [6]

Fiber	Characteristics
Kevlar 49	A high performance, aerospace grade fiber with the highes strength of all Kevlar fibers.
Kevlar 149	A high performance, aerospace grade fiber with the highest modulus of all Kevlar fibers
Kevlar 129	A relatively inexpensive fiber with a lower strength and stiffness than Kevlar 149 and 49, but with a higher percent elongation.
Kevlar 29	A relatively inexpensive fiber with a strength and stiffness lower than Kevlar 129, but a higher percent elongation.
Technora™	Fibers that overcome some of the weaknesses of aramid fibers, having improved thermal stability; they can be used up to 200-250°C but loss of stiffness and with up to 50% loss of strength.
Zylon™	Fibers based in poly p-phenylene benzobisoxazole (PBO), which feature higher strength and stiffness than aramid and excellent tenacity.
Spectra™	The most known polyethylene fiber have lower moisture absorption, lower density, and stiffness-strengh properties comparable to aramid fibers, but they also have lower maximum operating temperature (about 120°C). These fibers are widely used for construction of structural, weatherproof enclosures that protects a microwave antennas (radomes) because they are highly transparent to electromagnetic waves.

If the fibers do not meet all conditions mentioned above, they are usually called carbon fibers (considering this small standard). However, in practice, this definition is not widely followed. So to the present, both terms are still used interchangeably equally.

According to Barbero [6] a motivation for using high modulus fibers is to maximize the stiffness-to-weight ratio in applications where both weight and deformations are critical.

Some advantages and disadvantages of carbon fibers are:

- The maximum operating temperature of carbon fibers varies from 315°C to 537°C, but it may be further limited by the operating temperature of the matrix as is the case with polymer matrix composites [6].

- Being stiffer than glass fibers, carbon fibers provide better fatigue characteristics to the composite by reducing the amount of strain in the polymer matrix for a given load [6]. This is the main reason for using a lower stress ration (safety factor) of 2.25 for carbon fiber, instead of 3.5 for fiberglass, for example, in the design of pressure vessels subject to permanent loading.
- Carbon fibers are good electrical conductors.
- The major limiting factor for the application of carbon fibers is the cost. The cost of carbon fibers can be justified when weight savings offer a large payoff, for example, in aerospace applications.

2.2.2.1.4 Boron fibers

Boron fibers are the oldest high-performance fibers available for use in composites. They are most notably used as reinforcement in aerospace and sporting goods.

These fibers are fabricated by deposition of boron on a heated core using the vapor deposition process. Both tungsten and carbon fiber cores are used. The strength values are controlled by the statistical distribution of defects during the manufacturing process. The diameter range of boron fibers are from 0.1 to 0.2 mm which is an order of magnitude larger than glass, aramid, or graphite fibers [4].

High stiffness, strength, and low density are common to boron fibers, for example, they can achieve values of elasticity modulus of about 410 GPa and tensile strength of about 3450 MPa.

These fibers have the advantage that their mechanical properties are preserved at high temperatures (typically, the tensile strength at 500°C is about 60% of the initial strength value at room temperature). Also, they have high toughness, high fatigue strength, and an excellent compressive behavior. However, these fibers are fragile and have low impact tenacity.

Because of slow production rate, boron fibers are among the most costly of all the fibers presently made.

2.2.2.2 Matrix

The functions of the matrix in the fiber reinforced plastics are:

- To keep the fibers fixed in certain position.
- To transfer stresses between the fibers. It must be kept in mind that the interaction between fibers and matrix is important in designing damage tolerant elements [6].
- To provide a barrier against hazardous or corrosive environments, such as chemical and moisture.

- To protect the surface of fibers from mechanical degradation, for example, by abrasion [6].

Furthermore, according to Barbero, the matrix is characterized because:

- It plays a secondary role in the tensile load-carrying capacity of a composite element. However, the selection of matrix has an important effect on the compressive, inter-laminar shear as well as in-plane shear properties of the composite material [6].
- Provides lateral support against the possibility of fiber buckling under compressive loading, thus influencing to a large extent the compressive strength of the composite material [6].
- The processing and defects of a composite material depend strongly on the matrix preparation characteristics. For example, for epoxy polymers used as matrix in many aerospace elements, the processing characteristics include the liquid viscosity, the curing temperature, and the curing time [6].

There are three categories of matrix materials, which are listed in table 2.3 according to Mallick [8], which shows various matrix materials that have been used either commercially or in research. Among these matrices, thermoset polymers (epoxies, polyesters, and vinyl esters) are most used as matrix materials with continuous or long fiber-reinforced composites, mainly because of the ease of processing due to their low viscosity. Thermoplastic polymers are most used with short fiber-reinforced composites that are injection molded. Metallic and ceramic matrices are principally considered for high-temperature applications [6].

2.2.2.2.1 Polymer matrix

A collection of a large number of polymeric molecules of similar chemical structure but not of equal length is considered a polymeric matrix. Acording to Mallick: "In the solid state, these molecules are frozen in space, either in a random mode in amorphous polymers or a mixture of random and orderly mode (folded chains) in semi-crystalline polymers (Figure 2.6). However, on a submicroscopic scale, various segments in a polymer molecule may be in a state of random excitation. The frequency, intensity, and number of these segmental motions increase with increasing temperature, giving rise to the temperature-dependent properties of a polymeric solid" [8].

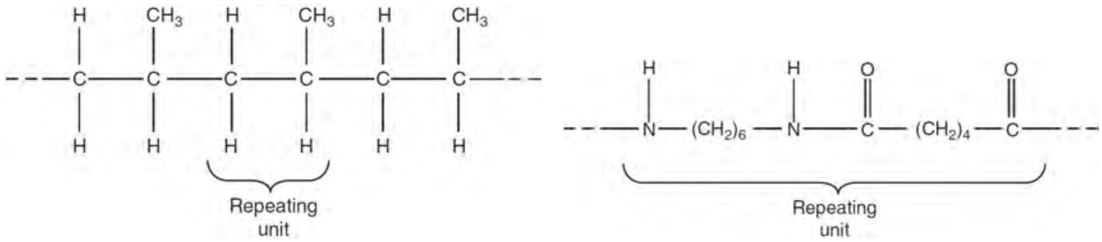
2.2.2.2.1.1 Thermoset matrices

A thermoset matrix is formed by the irreversible chemical transformation of a resin system into a cross-linked polymer matrix. In general, the polymer is called a

Table 2.3: Matrix materials according to Mallick [8]

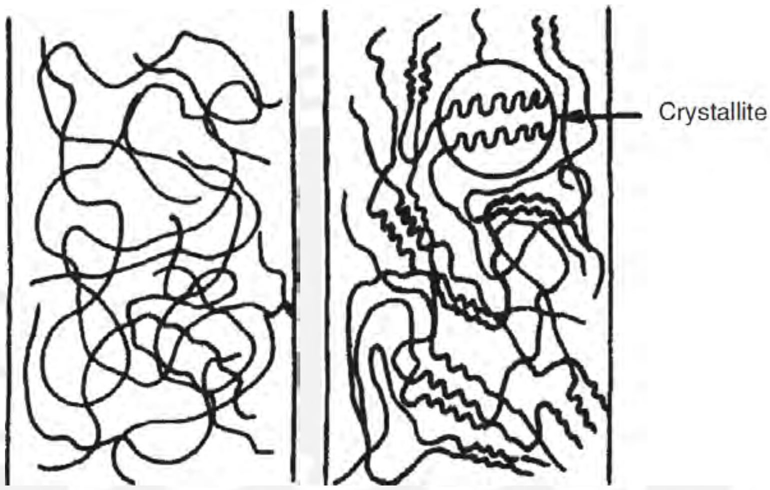
Matrix	Type	Name and characteristic
Polymeric	Thermoset polymers	Epoxies: Principally used in aerospace and aircraft applications. Polyesters, vinyl esters: Commonly used in automotive, marine, chemical, and electrical applications. Phenolics: Used in bulk molding compounds. Polymides, polybenzimidazoles (PBI), polyphenylquinoxaline (PPQ): for high-temperature aerospace applications (temperature range: 250°C-400°C). Cyanate ester.
	Thermoplastic polymers	Nylons (such as nylon 6, nylon 6,6), thermoplastic polyesters (such as PET, PBT), polycarbonate (PC), polyacetals: used with discontinuous fibers in injection-molded articles. Polyamide-imide (PAI), polyether ether ketone (PEEK), polysulfone (PSUL), polyphenylene sulfide (PPS), polyether-imide (PEI): suitable for moderately high temperature applications with continuous fibers.
Metallic		Aluminum and its alloys, titanium alloys, magnesium alloys, copper-based alloys, nickel-based superalloys, stainless steel: suitable for high-temperature applications (temperature range: 300°C-500°C).
Ceramic		Aluminum oxide (Al_2O_3), carbon, silicon carbide (SiC), silicon nitride (Si_3N_4): suitable for high-temperature applications.

"resin system" during processing and "matrix" after the polymer has cured. The low viscosity of thermoset matrices allow excellent impregnation of fiber reinforcement and high processing speeds. Thermoset resins are the most common resin systems used in composite systems because of their ease of processing and wide range of performance [6].



(a) (b)

Figure 2.5: (a) A polypropylene molecule. (b) A nylon 6,6 molecule. [8].



(a) (b)

Figure 2.6: Arrangement of molecules in (a) amorphous polymers and (b) semicrystalline polymers. [8].

Cure cycles can vary from minutes to hours depending on the choice of initiator or curing system, catalyst, and the reactivity of the resin. Also, cure cycles can take place at room temperature or elevated temperature. The curing reaction can be exothermic or endothermic depending on the resin.

All resins provide higher thermal insulation than most commonly used construction materials. The most common thermoset resins are:

- **Polyester resins:** These resins have a broad range of properties that can be matched to different applications and process requirements. They tend to have moderate physical properties but can be very cost-effective because of their low initial cost and low conversion cost. Polyester resins can be formulated to have excellent ultraviolet resistance to structural degradation and can be used in many outdoor applications. They can survive exposure to the elements or periods exceeding 30 years. In many applications, polyester resins are required to have some degree of resistance to burning, which can be accomplished by using either a filler or a specially formulated flame retardant polyester resin, depending on the level of resistance required. Sometimes, polyester resins are used in applications requiring resistance to chemical attack. Numerous applications like tanks, pipes, ducts, and liners can be found in chemical process and paper industries.

- **Vinyl ester resins:** Can have a higher elongation to failure, which allows more load to be transferred to the reinforcement and improved corrosion resistance. There is a great variety of vinyl ester resins available for applications up to 121°C. They are highly resistant to acids, alkalis, solvents, hypochlorites, and peroxides. Brominated versions have high flame retardancy. The cost of vinyl ester resins is between that of polyesters and epoxies [6].

- **Epoxy resins:** are considered high-performance resins in the sense that their elongation to failure and higher service temperature are superior to that of most other commonly used thermoset resins. They are most used because of their versatility, high mechanical properties, and high corrosion resistance. According to Barbero: "Epoxies shrink less than other materials (1,2-4% by volume), which helps explain their excellent bond characteristics when used as adhesives. Another advantage of epoxy resins is their simple cure process that can be achieved at any temperature between 5 to 150°C, depending on the type of curative and accelerators used. The application field of epoxy resins are the aircraft industry, the building and repair of plastic and metal boats and automobiles, building and highway construction, the fabrication of short-run and prototype molds, stamping dies, patterns, and tooling, and finally in the electrical industry because of their excellent electrical insulation. The cost of epoxy resins is proportional to the performance of the resin that varies over a broad range, but they are usually more expensive than vinyl esters. Epoxy matrices can be used at service temperatures up to 175°C. To increase the toughness of the resin and the composite the basic thermoset epoxy resins are toughened with additives, including the addition of thermoplastics" [6].

- **Phenolic resins:** are normally used in applications where smoke generation and longer-term flame spread is required by the customer or by code. These resins are more difficult to process than other common thermoset resins, so a functional reason normally drives their selection. Phenolic resins have low flammability and low smoke production, compared to other low-cost resins. Furthermore, they have good dimensional stability under temperature fluctuations and good adhesive properties. Phenolic resins are most commonly used for aircraft, mass transit vehicles, and as interior construction materials where outgassing due to fire must be extremely low. Processing of phenolic resins is quite different from other thermoset resins that they tend to substitute, especially polyester resins. Cost of phenolic resins is competitive with polyesters.

2.2.2.2.1.2 Thermoplastic matrices

Although for many years (since the decade of the 80s) much researches have been done in the development of thermoplastic compounds to replace thermoset compounds, however continuous fiber thermoplastic composites account for only a handful of production applications for commercial and military aircrafts for example.

According to Barbero: "A thermoplastic polymer does not undergo any chemical transformation during processing. Instead, the polymer is softened from the solid state to be processed, and it returns to a solid after processing is completed. The viscosities of thermoplastics during processing are orders of magnitude higher than those of thermosets (for example, $10^4 - 10^7$ poise for thermoplastics vs. ten poise for thermosets), which makes the process more difficult. Therefore the high shear stresses needed to make thermoplastics flow cause damage to the fibers resulting in a reduction of fiber length in the order of 10 to 100 times" [6].

Since thermoplastics do not crosslink during processing; they can be reprocessed. However, there is a limit to the number of times a thermoplastic can be reprocessed. Since the processing temperatures are close to the polymer degradation temperatures, multiple reprocessing will eventually degrade the resin. Furthermore, since thermoplastics are not crosslinked, they are inherently much tougher than thermosets.

Thermoplastics do not require refrigerated storage, and they have a virtually unlimited shelf life. Another advantage of thermoplastics involves health and safety. Since these resins are fully reacted, there is no danger to the worker. Another potential advantage of thermoplastics is their low moisture absorption.

As a disadvantage, some amorphous thermoplastics are very susceptible to solvents and may even dissolve in methylene chloride. Others thermoplastic matrices such as semi-crystalline thermoplastics are quite resistant to solvents and other fluids.

The thermoplastics mostly used in the industry, according to Barbero, are:

- **Polyether ether ketone (PEEK):** Is a common thermoplastic matrix for high-performance applications. It has very high fracture toughness, which is important for damage tolerance of composites. PEEK is a semi-crystalline thermoplastic with very low water absorption (about 0,5% by weight) at room temperature, much lower than for most epoxies. PEEK is normally used for continuous fiber-reinforced thermoplastic composites [6].

- **Polyphenylene sulfide (PPS):** Is a semicrystalline thermoplastic with an excellent chemical resistance. These thermoplastics have high glass transition temperature with good mechanical properties but are more costly. Like previous thermoplastic (PEEK) PPS is also used for continuous fiber-reinforced thermoplastic composites [6].

- **Polysulfone (PSUL):** Is an amorphous thermoplastic with a very high elongation to failure and excellent stability under hot and wet conditions [6].
- **Polyetherimide (PEI) and polyamide-imide (PAI):** Are amorphous thermoplastics with high glass transition temperature and are also used for continuous fiber-reinforced thermoplastic composites [6].

2.2.3 Manufacturing processes

The type of matrix and fibers, the temperature required to form the part and to cure the matrix, and the cost-effectiveness of the process will greatly influence the production method of fiber reinforced plastics (in this work a production method for volute springs). Often, the production method is the initial consideration in the design of a fiber reinforced plastic element. This consideration is because of cost, production volume, production rate, and adequacy of a production method to produce the type of element desired. Therefore it is necessary to understand the advantages, disadvantages, costs production rates and volumes, and typical uses of the most used manufacturing processes.

It should be kept in mind that when a fiber reinforced plastic element is designed, the material is designed simultaneously with the element. Because of this freedom, high-performance elements can be designed, provided the designer understands how the material is going to be produced.

Only fiber reinforced plastics are of interest for this work, and only the most common manufacturing techniques are described. Therefore, there are three categories of composite production methods: open and closed molding and cast polymer molding and there are a variety of processing methods within these molding categories, each with its benefits. Cast polymers are unique in the composites industry: they typically do not have fiber reinforcement so that they are not described in this section.

According to Barbero [6], the processing of fiber reinforced plastics involves the following individual operations:

1. Fiber placement along the required orientations.
2. Impregnation of fibers with resin.
3. Consolidation of the impregnated fibers to remove excess resin, air, and volatile substances.
4. Cure or solidification of the polymer.
5. Extraction from the mold.
6. Finishing operations, such as trimming.

In all production methods, the way in which these operations are carried out differs, however, no operation ceases to be carried out. Moreover, some of the operations may be combined into a simple step to save time or some operations may be carried out ahead of time such as the impregnation of a prepreg that is subsequently used in hand lay-up for example.

Barbero says that: “Variations in the way that material is processed have a significant impact on the cost, production rate, quality, and performance of the final product. Each processing method has inherent advantages and limitations that affect the structural and material design” [6].

2.2.3.1 Open molding

In open molding, resins and fiber reinforcements are exposed to air as they cure or harden. Open molding utilizes different methods, including hand lay-up, spray-up, prepreg lay-up, and filament winding.

2.2.3.1.1 Hand lay-up

The hand lay-up method is suitable for manufacturing a wide variety of both small and large size elements. With this method, the volume of production per mold is low, but it is possible to increase this volume by using more molds.

This manufacturing method is the most economical and simple one that exists within the open molding methods group because the investment in tools is low, however, it is required to invest in operators.

It should be pointed out that if the operators are quite skilled, the production rate increases and even products with good finishing quality can be obtained.

Also called wet lay-up, this method is the simplest and most widely used production method. It involves manual placement of the dry reinforcement in the mold and subsequent application of the resin (Figure 2.7) [6].

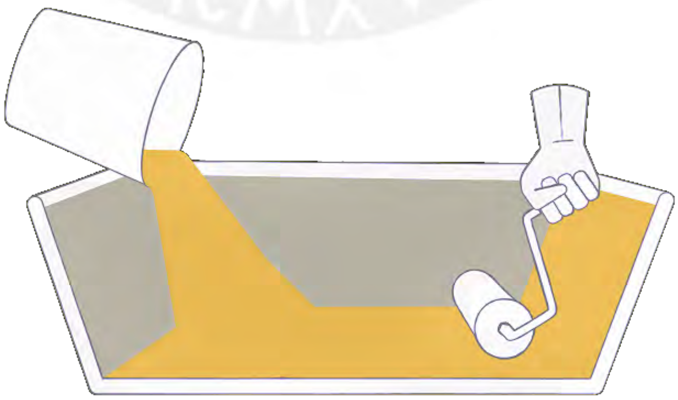


Figure 2.7: Hand lay-up method [6].

Then, the wet composite is rolled using hand rollers to facilitate uniform resin distribution and removal of air pockets. This process is repeated until the desired thickness is reached. Finally, the layered element is cured. Therefore the hand lay-up method may be divided into four basic steps: mold preparation, gel coating, lay-up, and curing [6].

The mold preparation is one of the most critical steps in the hand lay-up method. The mold may be made of wood, plaster, plastics, composites or metals depending on the number of parts, cure temperature, pressure, etc. The mold may be male or female type, depending on which surface needs to be smooth [6].

A coating or release agent is applied to the mold to facilitate the removal of the finished part. The most commonly release agents used are wax, polyvinyl alcohol, silicones, and release papers or films. The choice of the release agent depends on the type of material to be molded, and the degree of luster desired on the finished product [6].

After applying the release agent, a gel coat is applied after the mold preparation to produce a good surface appearance of the part being molded. The coating is normally a polyester, mineral-filled, pigmented, nonreinforced lamina. This resin lamina is applied to the mold before the reinforcements. Thus, the gel surface becomes the outer surface of the laminate when molding is complete. This surface forms a protective lamina through which the fibrous reinforcements do not penetrate, and the product may require no subsequent finishing operations [6].

The final steps involve material preparation, fiber placement, and curing. The fiber is applied in the form of chopped strand mat, fabric, or woven roving. After, resin and curing agent are mixed thoroughly. The mixture is then applied to the fibers. Serrated hand rollers are used to compact the material against the mold to ensure complete air removal. Curing is usually accomplished at room temperature, and the final molded part is removed by pulling it from the mold [6].

Some of the advantages and disadvantages of the hand lay-up process are listed in Table 2.4 and typical applications are shown in table 2.5.

2.2.3.1.2 Spray-up process

According to the American Composites Manufacturers Association: "the spray-up, or chopping, is an open mold method similar to hand lay-up in its suitability for making boats, tanks, transportation components, and tub/shower units in a large variety of shapes and sizes. A chopped laminate has good conformability and is sometimes faster to produce than a part made with hand lay-up when molding complex shapes.

In the spray-up process, the operator controls thickness and consistency; therefore the process is more operator dependent than hand lay-up. Although production volume per mold is low, it is feasible to produce substantial production quantities using multiple molds. This process uses simple, low-cost tooling and simple processing. Portable equipment permits on-site fabrication with virtually no part size

Table 2.4: Advantages and disadvantages of the hand lay-up process [6].

Advantages	Disadvantages
Large parts with complex geometries can be produced	Only one surface of the molded part is smooth
Minimal equipment investment	Quality depends on the skill of workers
Minimal tooling cost	Labor intensive
Void content under 1%	Low production rate
Sandwich construction is possible	High emission of volatiles
Inserts and structural reinforcements can be easily accommodated	Product uniformity is difficult to maintain
Parts requiring excellent finish can be easily manufactured	Long curing times at room temperature
curing ovens are not necessary	

Table 2.5: Some applications of hand lay-up [6].

Applications	Products
Marine	boats, boat hulls, ducts, pools, tanks, furniture.
Aircraft	rocket motor nozzles, and other aircraft parts.
Structural	Furnace filters, structural supports, flat and corrugated sheets, corrosion duct work, housings, pipe
Consumer	bicycle parts, truck parts

limitations. The process may be automated.

The process is as with hand lay-up (Figure 2.8), gel coat is first applied to the mold and allowed to cure. Continuous strand glass roving and initiated resin are then fed through a chopper gun, which deposits the resin-saturated “chop” on the mold. The laminate is then rolled to saturate the glass strands and compact the chop thoroughly. Additional layers of chop laminate are added as required for thickness. Roll stock reinforcements, such as woven roving or knitted fabrics, can be used in conjunction with the chopped laminates. Core materials of the same variety as used in hand lay-up are easily incorporated.

The molds are the same molds as hand lay-up: simple, single cavity molds of fiberglass composites construction. Molds can range from small to very large and are low cost in the spectrum of composites molds” [10].

Figure 2.8: Spray-up process [6].

2.2.3.1.3 Prepreg lay-up

The following paragraphs are according to the author Tuttle: “Prepreg is a pre-impregnated fiber-reinforced material where the fibers and matrix are combined resulting in an intermediate product. In this case, either single tow or a thin fabric of tow (which may be woven or braided) is embedded within a polymeric matrix and delivered to the user in this form. Because the fibers have already been embedded within a polymeric matrix when delivered, the fibers are said to have been "pre-impregnated" with resin, and products delivered in this condition are commonly known as "prepreg"

The method used to impregnate a large number of unidirectional tows with resin is illustrated in Figure 2.9. As indicated, tows delivered from a large number of roving spools are arranged in a relatively narrow band. The tows are passed through a resin bath and then wound onto a roll. An inert backing sheet (called a scrim cloth) is placed between layers on the roll to maintain a physical separation between layers and to aid during subsequent handling and processing. The pretreatments are intended to cause good wetting of the fiber by the resin, which ultimately helps ensure good adhesion between the fibers and polymer matrix in the cured composite. Products produced in this fashion are commonly known as "prepreg tape" (Figure 2.10).

Prepregs are widely used for making high-performance aerospace parts and complex geometries. Most prepregs are made from epoxy resin systems, and reinforcements usually include glass, carbon, and aramid fibers.

The prepregs are usually supplied in rolls of convenient widths (30-60 cm). They are normally cut to fit in the mold and laid up lamina by lamina until the desired thickness is reached.

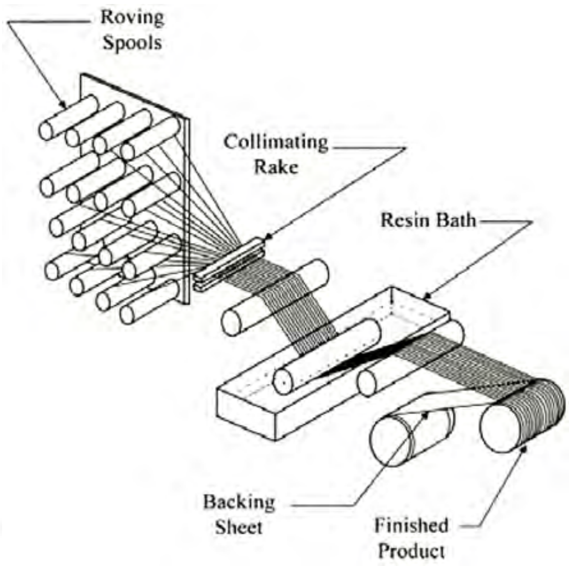


Figure 2.9: Method used to impregnate unidirectional tows with resin [4].

Figure 2.10: Boron-epoxy prepreg tape [4].

Since the resin is partially cured, prepregs have a limited shelf life, which is extended by storing them in freezers (-15°C or below). An autoclave or vacuum is usually required to assist in consolidating and curing parts laminated with prepregs. Some of the advantages and disadvantages of using prepreg are listed in table 2.6.

More recently, prepreg materials based on thermoplastic resins have become commercially available. In this case, the polymeric matrix is a fully cured thermoplastic polymer, and hence the prepreg does not require refrigeration during shipping or storage, which is a distinct advantage. These prepregs need to be heated to achieve tack (the ability of the prepreg to stick temporarily to the mold) and drape (the ability of the fabric to conform to a complex multi-curved surface) since they are usually stiff at room temperature. Unlike the processing of thermoset resins, the temperatures and pressures used for thermoplastics are usually higher because the viscosity of thermoplastics needs to be lowered by heat during processing. Then, curing is replaced by simply cooling down to room temperature" [4].

Table 2.6: Advantages and disadvantages of using prepregs [6].

Advantages	Disadvantages
High fiber volume fractions	Slow and labor intensive
Uniform fiber distribution	More expensive curing equipment
Simplified manufacturing	Added cost of making Prepreg

2.2.3.1.4 Filament winding

According to the American Composites Manufacturers Association: "Filament winding is an automated open molding process that uses a rotating mandrel as the mold. The male mold configuration produces a finished inner surface and a laminate surface on the outside diameter of the product.

Filament winding results in a high degree of fiber loading, which provides high tensile strength in the manufacture of hollow, generally cylindrical products such as chemical and fuel storage tanks, pipes, stacks, pressure vessels, and rocket motor cases. The process makes high strength-to-weight ratio laminates and provides a high degree of control over uniformity and fiber orientation. The filament winding process can be used to make structures that are highly engineered and meet strict tolerances. Because filament winding is computer-controlled and automated, the labor factor for filament winding is lower than other open molding processes.

In filament winding, continuous strand roving is fed through a resin bath and wound onto a rotating mandrel (Figure 2.11). The roving feed runs on a trolley that travels the length of the mandrel. The filament is laid down in a predetermined geometric pattern to provide maximum strength in the directions required. When sufficient layers have been applied, the laminate is cured on the mandrel. The molded part is then stripped from the mandrel. Equipment is available for filament winding on a continuous basis with to axis winding for pressure cylinders. Filament winding can be combined with the chopping process and is known as the hoop chop process.

Filament winding uses mandrels of suitable size and shape, made of steel or aluminum, to form the inner surface of the hollow part. Some mandrels are collapsible to facilitate part removal.

The significant limitations of filament winding are size restrictions, geometric

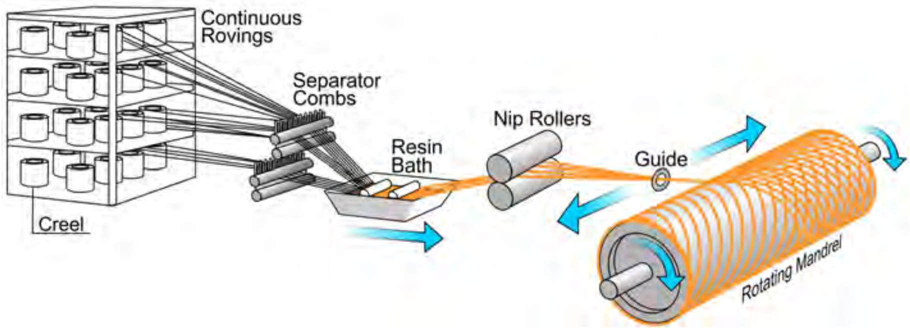


Figure 2.11: Filament winding [6].

possibilities, the orientation of the fibers, and the surface finish of the final product. Void content may be high since no vacuum or autoclave is used and the resin cures at low temperature.

Production rates for filament winding processes vary significantly because the size of the part and the mandrel type dictate the amount of time needed to setup and remove a part from the winding machine. If setup and removal time is not considered, the production rate is dictated by the feed rate at which fibers are wound onto the mandrel" [10].

2.2.3.2 Closed molding

In closed-molding, fibers and resin cure inside a two-sided mold or within a vacuum bag (shut off from the air). Closed-molding methods are usually automated and require specialized equipment, so they are mainly used in large plants that produce huge volumes of material up to 500,000 parts a year [10]. Closed molding utilizes different processes, including vacuum bag molding, vacuum infusion processing, resin transfer molding (RTM), pultrusion and autoclave processing.

2.2.3.2.1 Vacuum bag molding

According to the American Composites Manufacturers Association: "Vacuum bag molding improves the mechanical properties of open-mold laminates. This process can produce laminates with a uniform degree of consolidation, while at the same time removing entrapped air, thus reducing the finished void content.

By reducing the pressure inside the vacuum bag (Figure 2.12), external atmospheric pressure exerts a force on the bag. The pressure on the laminate removes entrapped air, excess resin, and compacts the laminate, resulting in a higher percentage of fiber reinforcement.

Vacuum bagging can be used with wet-lay laminates and advanced prepreg composites. In wet lay up bagging the reinforcement is saturated using hand lay-up, then the vacuum bag is mounted on the mold and used to compact the laminate

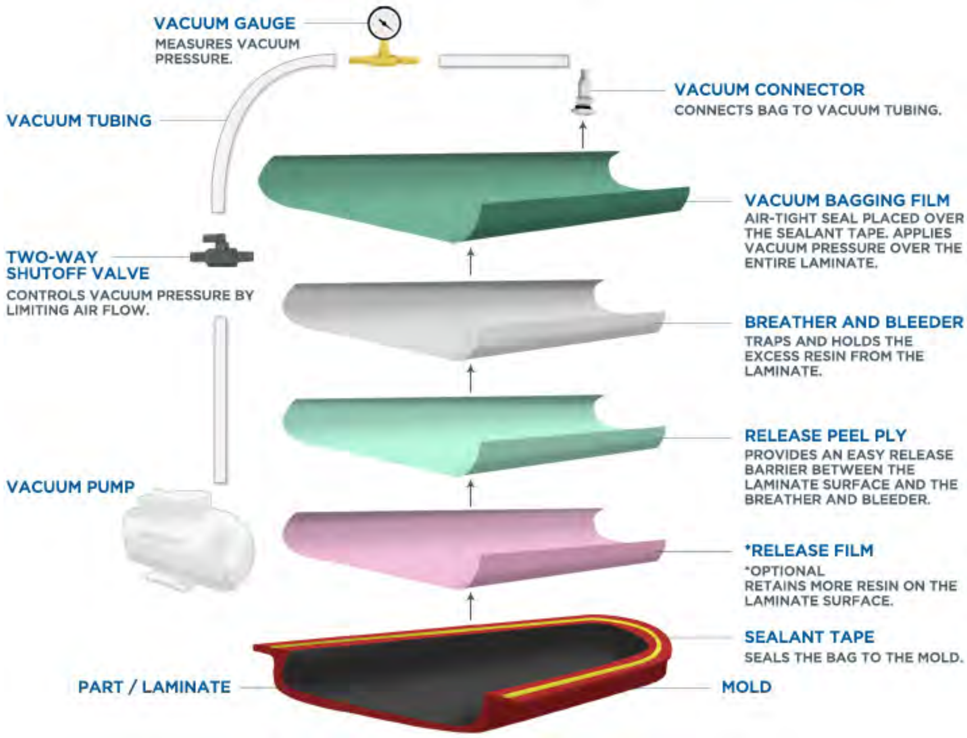


Figure 2.12: Vacuum bag molding scheme [11].

and remove air voids. In the case of pre-impregnated advanced composites molding, the prepreg material is laid up on the mold, the vacuum bag is mounted, and the mold is heated, or the mold is placed in an autoclave that applies both heat and external pressure, adding to the force of atmospheric pressure. The prepreg-vacuum bag-autoclave method is most often used to create In the simplest form of vacuum bagging, a flexible film (PVA, nylon, mylar, or polyethylene) is placed over the wet lay-up, the edges are sealed, and a vacuum is drawn. A more advanced form of vacuum bagging puts a release film over the laminate, followed by a bleeder ply of fiberglass cloth, non-woven nylon, polyester cloth, or other material that absorbs excess resin from the laminate. A breather ply of a non woven fabric is placed over the bleeder ply, and the vacuum bag is mounted over the entire assembly. Pulling a vacuum from within the bag uses atmospheric pressure to eliminate voids and force excess resin from the laminate. The addition of pressure further results in high fiber concentration and provides better adhesion between layers of sandwich construction. When laying non-contoured sheets of PVC foam of balsa into a female mold, vacuum bagging is the technique of choice to ensure proper secondary bonding of the core to the outer laminate. Molds are similar to those used for conventional open mold processes" [10].

2.2.3.2.2 Vacuum infusion processing

According to the American Composites Manufacturers Association: "Vacuum infusion processing is a variation of vacuum bagging in which the resin is introduced into the mold after the vacuum has pulled the bag down and compacted the laminate.

Vacuum infusion can produce laminates with a uniform degree of consolidation, producing high strength, lightweight structures. This process uses the same low-cost tooling as open molding and requires minimal equipment.

In this method the reinforcement and core materials are laid-up dry in the mold by hand, providing the opportunity to precise position the reinforcement. When the resin is pulled into the mold the laminate is already compacted; therefore, there is no room for excess resin. Vacuum infusion enables very high resin-to-glass ratios, and the mechanical properties of the laminate are superior. Vacuum infusion is suitable to mold large structures and is considered a low-volume molding process.

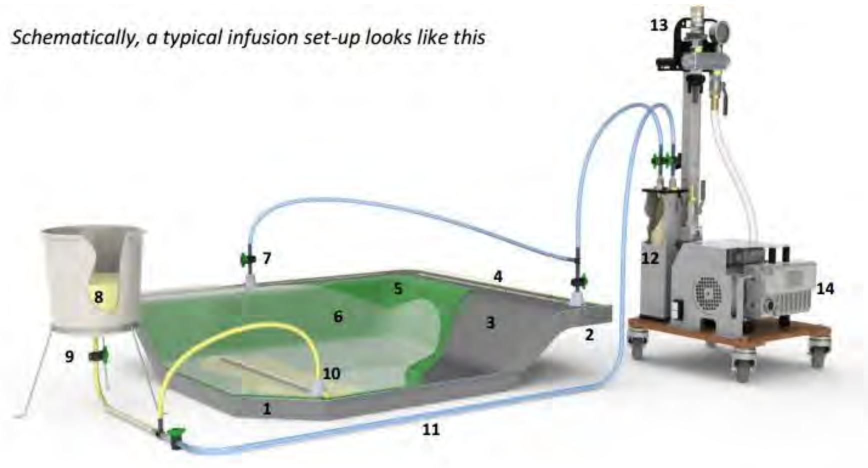
In the vacuum infusion processing, the mold may be gel coated in the traditional form. After the gel coat cures, the dry reinforcement is positioned in the mold. This operation includes all the plies of laminate and core material if required. A perforated release film is placed over the dry reinforcement. Next, a flow media consisting of a coarse mesh or a "crinkle" ply is positioned, and perforated tubing is positioned as a manifold to distribute resin across the laminate. The vacuum bag is then positioned and sealed at the mold perimeter. A tube is connected between the vacuum bag and the resin container. A vacuum is applied to consolidate the laminate and resin is pulled into the mold (Figure 2.13). Molds are similar to those used for conventional open-mold processes" [10].

2.2.3.2.3 Resin transfer molding

According to the American Composites Manufacturers Association: "Resin transfer molding (RTM) is an intermediate volume molding process for producing composites. In RTM, the resin is injected under pressure into a mold cavity. This process produces parts with two finished surfaces.

By laying up reinforcement material dry inside the mold, any combination of material and orientation can be used, including 3-D reinforcements. Part thickness is determined by the tool cavity. Fast cycle times can be achieved in temperature-controlled tooling, and the process can range from simple to highly automated. RTM can use a wide variety of tooling, ranging from low-cost composite molds to temperature controlled metal tooling. Vacuum assist can be used to enhance resin flow in the mold cavity.

In RTM process, the mold is gel coated conventionally, if required. The reinforcement (and core material) is positioned in the mold, and the mold is closed and clamped. The resin is injected under pressure, using mix/meter injection equipment, and the part is cured in the mold. The reinforcement can be either a preform or a pattern cut roll stock material. A preform is a reinforcement that is formed



Key

1	Mould, leak tight and pre-treated with mould release	7	Vacuum control valve(s). May be just a clamp on the vacuum tube
2	Sealing flange. Typically 75 mm (3") to 150 mm (6") wide	8	Resin (normally positioned below the part)
		9	Resin control valve. May be just a clamp on the resin feed tube
3	Laminate materials. Placed in mould in DRY state		
4	Permeable vacuum line under the bag	10	Resin entry point(s)
5	Disposable materials (typical). Peel ply above the laminate and flow medium above the peel ply	11	Optional vacuum line for pre-evacuation
		12	Resin trap with internal catchpot
6	Vacuum "bag". May be nylon (disposable) or a reusable film such as silicone rubber	13	Vacuum controls
		14	Vacuum pump

Figure 2.13: Vacuum infusion processing scheme [12].

to a particular shape in a separate process and can be quickly positioned in the mold. RTM can be done at room temperature; however, heated molds are required to achieve fast cycle times and product consistency. Clamping can be accomplished with perimeter clamping or press-clamping. Figure 2.14 shows the process cycle of resin transfer molding.

RTM can utilize either hard or soft tooling depending upon the expected duration of the run. Soft tooling would be either polyester or epoxy molds, while hard tooling may consist of cast machined aluminum, electroformed nickel shell, or machined steel molds. RTM can take advantage of the broadest range of tooling of any composites process. Tooling can range from very low-cost to high-cost, life-long molds" [10].

2.2.3.2.4 Pultrusion

According to the American Composites Manufacturers Association: "Pultrusion is a continuous process for the manufacture of products having a constant cross-section, such as rod stock, structural shapes, beams, channels, pipe, tubing, fishing rods, and golf club shafts.

Pultrusion produces profiles with extremely high fiber loading; thus, pultruded

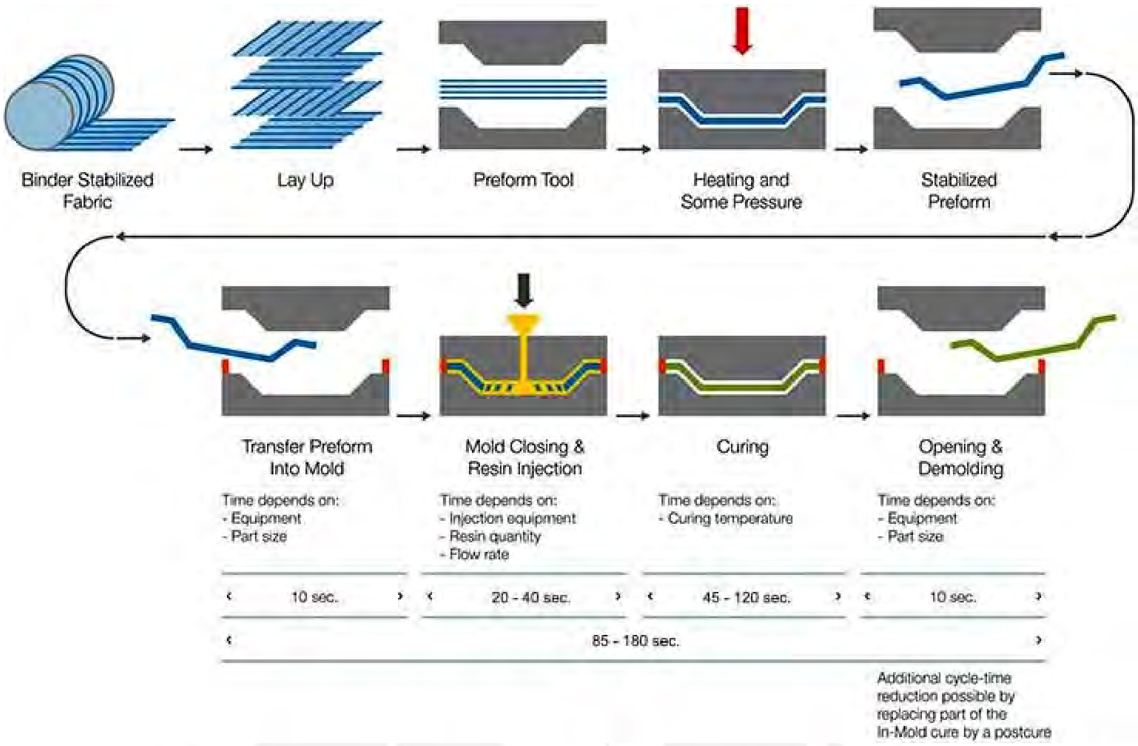


Figure 2.14: Resin transfer molding process cycle [13].

products have high structural properties. The process can be easily automated and is adaptable to both simple and complex cross-sectional shapes. Very high strengths are possible, and labor costs are low.

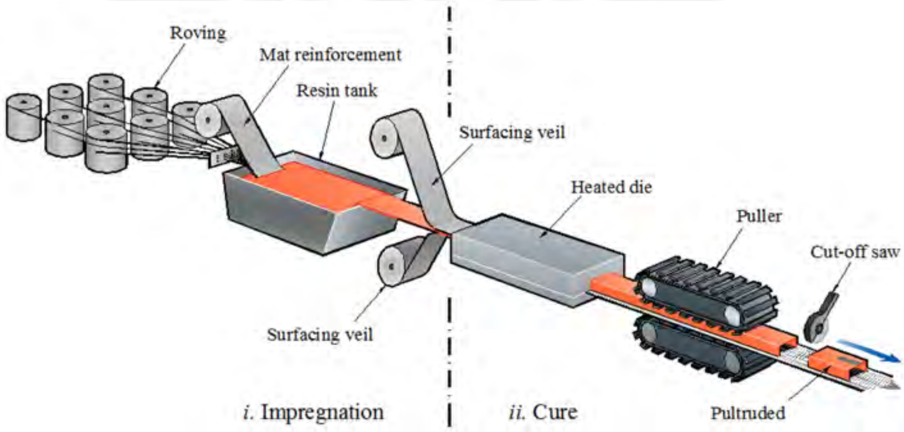


Figure 2.15: Standard version of horizontal pultrusion [14].

In pultrusion process, continuous strand glass fiber, carbon fiber or basalt fiber roving, mat, cloth, or surfacing veil is impregnated in a resin bath and then pulled (therefore the term pultrusion) through a steel die by a powerful tractor mechanism. The steel die consolidates the saturated reinforcement, sets the shape of the stock, and controls the fiber/resin ratio. The die is heated to cure the resin rapidly. Many creels (balls) of roving are positioned on a rack, and a complex series of tensioning devices and roving guides direct the roving into the die. Figure 2.15 shows the two-step pultrusion process: (i) impregnation and (ii) cured " [10].

2.2.3.2.5 Autoclave processing [6]

Autoclaves are pressure vessels that contain compressed gas during the processing of the composite. They are used for the production of high-quality, complex parts. This method is good for large parts and moderate production quantities.

Autoclave processing of composites is an extension of the vacuum bag technique, providing higher pressure than available with a vacuum and giving greater compression and void elimination. Figure 2.16 shows the principle of autoclave processing.

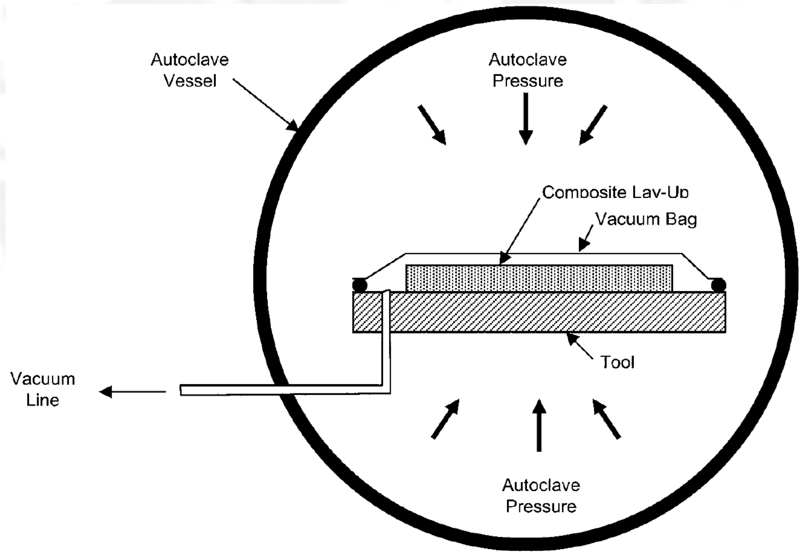


Figure 2.16: Principle of autoclave process [15].

The composite part is laid up and enclosed in a vacuum bag. Full or partial vacuum is drawn within the bag, and gas pressure greater than atmospheric is applied on the exterior of the bag. Then, the element temperature is raised to initiate cure of the polymer. Higher temperatures reduce the viscosity of the polymer, helping to wet of the reinforcement and consolidation of the composite.

The high pressure inside the autoclave exerts forces on the unconsolidated composite, increases the efficiency of transport of volatiles to the vacuum ports, and therefore causes increased wetting and flow of the resin. This effect causes that porosity and voids are minimized.

Autoclave operations consume large amounts of energy and materials, including industrial gases (nitrogen is used for pressurization as an alternative to high-pressure compressors) and bagging materials. Autoclave operations are also labor-intensive and time-consuming. The curing cycle and consolidation of a part in an autoclave is long and intensive. In the case of very thick parts, the curing cycle may have to be repeated several times to complete curing. Autoclave processing is the only choice for large parts, e.g., for products of the aerospace industry.

The production rate depends on many factors including the tools used, the size of the part, and the number of laminae. Also, the production rate is determined by the cure profile that includes heat up, curing, and cooling time. The tool size used also affects the production rate because the tool has to be heated too, for example, small parts can be cured in about three to five hours and large parts can take as long as twelve to sixteen hours to cure.

After describing the materials and production process for fiber reinforced plastics, it concludes that:

- To this work, glass and carbon fibers will be used in the form of braided sleeves, unidirectional and bidiagonal fabrics due to the mechanical properties and because they are the most economical and most used in the industry.
- Moreover, epoxy resin (with a curing agent) will be used given its comparative advantages over other resin types and the properties that it provides to laminates.
- Because there is still no standardized process for manufacturing fiber reinforced plastic volute springs, in the present work a method of manufacturing volute springs will be established but considering that only springs will be produced for a research stage, i.e., as a small-scale production. It will try to use the processes described in this chapter giving priority to open molding processes.

2.3 Fundamentals of calculation of composite material properties

This section describes the basic considerations and rules for calculating the elementary properties of fiber reinforced plastics. On the other hand, this section is based entirely on chapter 3 of Altenbach's book [5] and in the present work is presented in each subsection brief summaries of that chapter including the formulas used by this author.

As fiber reinforced plastics have at least two different material components which are bonded, the material response of a fiber reinforced plastic is determined by:

- The material moduli of all constituents.

- The volume or mass fractions of the single constituents in the composite material.
- The quality of their bonding, i.e., of the behavior of the interfaces.
- The arrangement and distribution of the fiber reinforcement, i.e., the fiber architecture.

The basic assumptions made in material science approach models of fiber reinforced composites are:

- The bond between fibers and matrix is perfect.
- The fibers are continuous and parallel aligned in each ply; they are regularly packed, i.e., the space between fibers is uniform.
- Fiber and matrix materials are linear elastic; they follow approximately Hooke's law and each elastic modulus is constant.
- The composite is free of voids.

Composites materials are heterogeneous, but in simplifying the analysis of composite structural elements in engineering applications, the heterogeneity of the material is neglected and approximately overlayed to a homogeneous material.

It should be noted that each single layer of laminates in general a fiber reinforced lamina. Thus, it has two different scales of modeling, according to Altenbach [5]:

- The modeling of the mechanical behavior of a lamina is called the micromechanical or microscopic approach of a composite. The micromechanical modeling leads to a correlation between constituent properties and average effective composite properties. Most simple mixture rules are used in engineering applications. Whenever possible, the average properties of a lamina should be verified experimentally by the tests [5].
- The modeling of the global behavior of a laminate constituted of several quasi-homogeneous laminae is called the macroscopic approach of a composite[5].

Fiber reinforced material is in practice neither monolithic (one-piece, seamless.) nor homogeneous, so that it is impossible to incorporate the real material structure into design and analysis of composite. Therefore the concept of replacing the heterogeneous material behavior with an effective material which is both homogeneous and monolithic, thus characterized by the generalized Hooke's law, will be used in engineering applications. In the following, it is assumed that the local variations in stress and strain state are tiny in comparison to microscopic measurements of material behavior.

2.3.1 Elementary mixture rules for fiber reinforced laminates

In this section, some simple approaches to the lamina properties are given with the help of the mixture rules and simple semi-empirical considerations.

One of the most important factors which determines the mechanical behavior of a composite material is the proportion of the matrix and the fibers expressed by their volume or their weight fraction. These fractions can be established for a two-phase composite in the following way:

The volume V of the composite is made from a matrix volume V_m and a fiber volume V_f.

Then

$$V = V_f + V_m \tag{2.1}$$

And

$$v_f = \frac{V_f}{V} \quad \text{and} \quad v_m = \frac{V_m}{V} \tag{2.2}$$

With

$$v_f + v_m = 1 \quad \text{or} \quad v_m = 1 - v_f$$

Equations (2.2) are the fiber and the matrix volume fractions. In a similar way the weight or mass fractions of fibers and matrices can be defined. The mass M of the composite is made from M_f and M_m.

$$M = M_f + M_m \tag{2.3}$$

And

$$m_f = \frac{M_f}{M} \quad \text{and} \quad m_m = \frac{M_m}{M} \tag{2.4}$$

With

$$m_f + m_m = 1 \quad \text{or} \quad m_m = 1 - m_f$$

Equations (2.4) are the mass fractions of fibers and matrices. With the relation between volume mass and density ($\rho = \frac{M}{V}$), it can link the volume fraction

$$\rho = \frac{M}{V} = \frac{M_f + M_m}{V} = \frac{\rho_f V_f + \rho_m V_m}{V} = \rho_f v_f + \rho_m v_m = \rho_f v_f + \rho_m (1 - v_f) \tag{2.5}$$

The density can also be linked with the mass fraction starting from the total volume of the composite, i.e. with:

$$V = V_f + V_m$$

It obtains

$$\frac{M}{\rho} = \frac{M_f}{\rho_f} + \frac{M_m}{\rho_m}$$

$$\frac{1}{\rho} = \frac{M_f}{\rho_f M} + \frac{M_m}{\rho_m M}$$

$$\frac{1}{\rho} = \frac{m_f}{\rho_f} + \frac{m_m}{\rho_m}$$

And finally

$$\rho = \frac{1}{\dfrac{m_f}{\rho_f} + \dfrac{m_m}{\rho_m}} \tag{2.6}$$

Furthermore, it knows that:

$$m_f = \frac{M_f}{M} = \frac{\rho_f V_f}{\rho V} = \frac{\rho_f}{\rho} v_f$$

$$m_m = \frac{M_m}{M} = \frac{\rho_m V_m}{\rho V} = \frac{\rho_m}{\rho} v_m$$

The inverse of these relations determine the volume fractions for the fiber and the matrix, then it obtains equation (2.7)

$$v_f = \frac{\rho}{\rho_f} m_f \quad \text{and} \quad v_m = \frac{\rho}{\rho_m} m_m \tag{2.7}$$

Then, the equations (2.2), (2.4), (2.5) and (2.6) give volume fraction, mass fraction and density, respectively, for fiber reinforced composites. Hence, with this values, the composite properties can be predicted using the rule of mixtures.

The rule of mixtures is based on the statement that the composite property is the sum of the properties of each constituent multiplied by its volume fraction. Then, in the following subsections, the application of the rule of mixtures to determine the density, longitudinal modulus, transverse modulus, Poisson's ratio, in-plane shear modulus and out-of-plane shear modulus will be described. But, before continuing, in table 2.7, it be described the notation used

2.3.1.1 Effective density

The derivation of the effective density of fiber-reinforced composites in terms of volume fraction is given for the equation (2.5) as follows:

$$\rho = \rho_f v_f + \rho_m v_m = \rho_f v_f + \rho_m (1 - v_f)$$

In diverse literature it can be found that $v_f \equiv \phi$ for the fiber volume fraction and it has the equation (2.8).

$$\rho = \rho_f \phi + \rho_m (1 - \phi) \tag{2.8}$$

It must be taken into account that in an actual lamina the fibers are randomly distributed over the lamina cross-section and for that reason the fiber packing is not known and can hardly be predicted, thus exactly typical idealized regular fiber arrangements are assumed for modelling and analysis (a layer-wise, square or a

Table 2.7: Notation used for properties and different variables

Properties and Variables	Description
E	Young's modulus.
G	Shear modulus
V	Volume.
M	Mass.
A	Cross-section area
v	Volume fraction.
m	Mass fraction.
ν	Poisson's ratio.
σ	Stress.
ϵ	Strain.
ρ	Density.
f , m	Subscripts that refer to fiber and matrix respectively.
L ≡ 1	Subscript that refers to the principal direction (fiber direction).
T ≡ 2	Subscript that indicates that is transverse to the fiber direction.

hexagonal packing), and also the fiber cross-sections are assumed to have circular form.

Therefore, according to the arrangement assumed there exist ultimate fiber volume fraction $v_{f_{max}}$, which can be:

- Square or layer-wise fiber packing $v_{f_{max}} = 0.785$.
- Hexagonal fiber packing $v_{f_{max}} = 0.907$.

Now, according to the autor H. Altenbach [5], for a real unidirectional laminate it has $v_{f_{max}}$ about $0.50 - 0.65$.

2.3.1.2 Effective longitudinal modulus of elasticity

According to the theory described by the author Altenbach [5], when an unidirectional lamina is acted upon by either a tensile or compression load parallel to the fibers, it can be assumed that the strains of the fibers, matrix, and composite in the loading direction are the same (see figure 2.17).

The mechanical model (model of Woldemar Voigt [16]) has a parallel arrangement

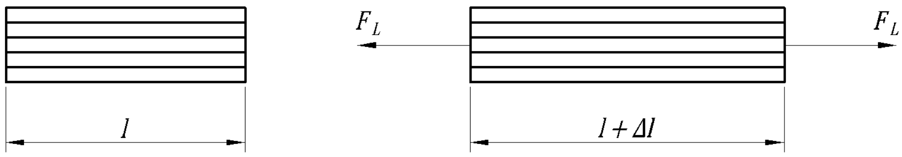


Figure 2.17: Mechanical model to calculate the effective Young's modulus E_L [5].

of fibers and matrix and the resultant axial force F_L of the composite is shared by both fiber and matrix. Then, according to this assumption, the effective modulus E_L can be written as equation (2.9). It can be read in the book of Altenbach [5] a complete development for obtainment of this equation.

$$E_L = E_f v_f + E_m v_m = E_f v_f + E_m(1 - v_f) = E_f \phi + E_m(1 - \phi) \qquad (2.9)$$

The predicted values of E_L are in good agreement with experimental results. According to the equation (2.9) it can be concluded that the stiffness of laminae in fiber direction is dominated by the fiber modulus.

2.3.1.3 Effective transverse modulus of elasticity

According to the theory described by the author Altenbach [5], the mechanical model (see figure 2.18) has an arrangement in a series of fiber and matrix (model of A. Reuss [17]). The stress resultant F_T is equal for all phases (iso-stress condition). Then, according to this assumption, the effective transverse modulus E_T can be written as equation (2.10). It can be read in the book of Altenbach [5] a complete development for obtainment of this equation.

$$E_T = \frac{E_f E_m}{(1 - v_f)E_f + v_f E_m} = \frac{E_f E_m}{(1 - \phi)E_f + \phi E_m} \qquad (2.10)$$

The predicted values of E_T are seldom in good agreement with experimental results [5], for this reason, there are improved formulas to predict the value of transverse modulus.

2.3.1.4 Effective Poisson's ratio

Again, according to the theory described by the author Altenbach [5], it is assumed a composite loaded in the on-axis direction (parallel to the fibers) as shown in figure 2.19. The major Poisson's ratio is defined as the negative of the ratio of

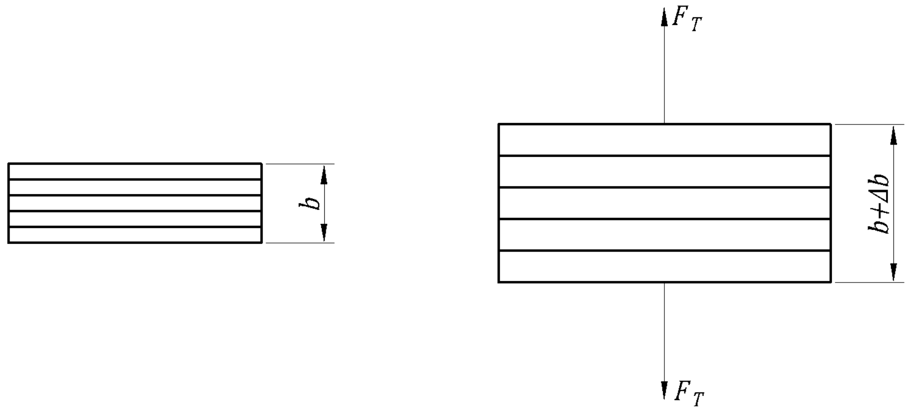


Figure 2.18: Mechanical model to calculate the effective transverse modulus E_T [5].

the normal strain in the transverse direction to the normal strain in the longitudinal direction. Then, according with this premise and with the Voigt model of parallel connection the equation for the major Poisson's ratio is shown in equation (2.11).

$$\nu_{LT} = v_f \nu_f + (1 - v_f)\nu_m = v_f \nu_f + v_m \nu_m = \phi \nu_f + (1 - \phi)\nu_m \tag{2.11}$$

The major Poisson's ratio obeys the rule of mixture. On the other hand, the minor Poisson's ratio ν_{LT} can be derived with the symmetry condition or reciprocal relationship [5]

$$\frac{\nu_{TL}}{E_T} = \frac{\nu_{LT}}{E_L}$$

Therefore, substituting the values of ν_{LT}, E_L and E_T in this expression, the equation (2.12) will be the minor Poisson's ratio.

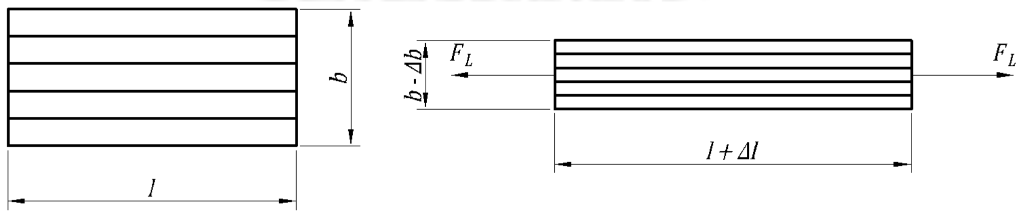


Figure 2.19: Mechanical model to calculate the major Poisson's ratio ν_{LT} [5].

$$\nu_{TL} = (v_f \nu_f + v_m \nu_m) \frac{E_f E_m}{(v_f E_m + v_m E_f)(v_f E_f + v_m E_m)} \tag{2.12}$$

2.3.1.5 Effective in-plane shear modulus

To determine the in-plane shear modulus G_{LT} Altenbach [5] considers a lamina that is subjected to pure shear stress and he makes the assumption that the stresses on the fiber and the matrix are the same, but the shear strains are different as can be seen in figure 2.20. Thus, the equation (2.13) is used to predict the value of the effective in-plane shear modulus.

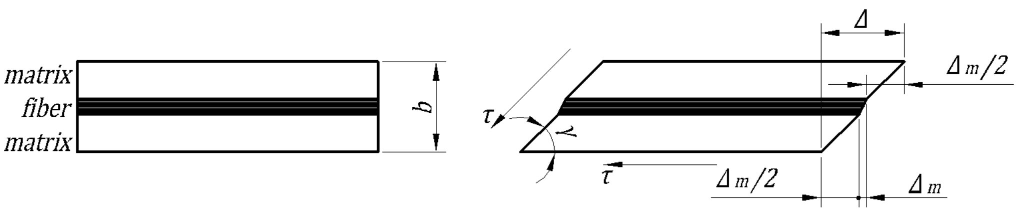


Figure 2.20: Mechanical model to calculate the effective in-plane shear modulus G_{LT} [5].

$$G_{LT} = \frac{G_m G_f}{(1 - v_f)G_f + v_f G_m} = \frac{G_m G_f}{(1 - \phi)G_f + \phi G_m} \tag{2.13}$$

Note that assuming isotropic fibers and matrix material it has the following expresions

$$G_f = \frac{E_f}{2(1 + \nu_f)} \quad and \quad G_m = \frac{E_m}{2(1 + \nu_m)}$$

2.3.2 Improved formulas for effective moduli of composites

Effective elastic moduli related to loading in the fiber direction, such as E_L or ν_{LT}, are dominated by the fibers. All estimations in this case and experimental results are very close to the rule of mixtures estimation. However, the values obtained for transverse Young's modulus, the in-plane shear modulus and the transverse/transverse Poisson's ratio with the rule of mixtures which can be reduced to the two model connections of Voigt and Reuss, do not agree well with experimental results [5].

Therefore a need arises for better modeling techniques based on elasticity solutions and variational principle models that include analytical and numerical solution methods. Unfortunately, the theoretical models are only available in the form of complicated mathematical equations, with solutions that are very limited and comprehend a huge effort. Due to this reason, semi-empirical relationships have been developed to overcome the difficulties with purely theoretical approaches [5].

2.3.2.1 Improved formula for transverse Young's modulus

Several researchers, such as Ekvall [18], Halpin [5], Tsai [5], Hashin (based on Hill's work) [19], [20], [21], [22], Förster and Knappe [23], Schneider [24], Chamis [25] and Puck [26], have proposed formulas for determining the transverse modulus E_T. All these authors have compared their theoretical results with experimental results of tests performed with different types of fibers and matrices.

In this work it considers the semi empirical equation of Alfred Puck [26] (see equation (2.14)), since his experimental results agree very well with his theoretical results as it is demonstrated in the book of Helmut Schürmann [27].

$$E_T = \frac{E_m}{1-\nu_m^2} \cdot \frac{1 + 0.85 \cdot \phi^2}{(1-\phi)^{1.25} + \dfrac{E_m}{(1-\nu_m^2)\cdot E_f} \cdot \phi} \tag{2.14}$$

2.3.2.2 Improved formula for in-plane shear modulus

As with the transverse modulus, the estimated calculations of the in-plane shear modulus according to equation (2.13) is too low. Again, as with the transverse modulus, many approaches to the in-plane shear modulus were developed by several authors in a manner analogous to that the transverse modulus was derived. In the literature there are many different approaches for the analytical determination of G_{LT}; An overview can be found in the book of Kuno K. U. Stellbrink [28].

According to the book of Helmut Schürmann [27] and the book of Kuno K. U. Stellbrink [28], in this work it considers the semi-empirical formula of Förster and Knappe [23] (see equation (2.15)).

$$G_{LT} = G_m \cdot \frac{1 + 0.4 \cdot \phi^{0.5}}{(1-\phi)^{1.45} + \dfrac{G_m}{G_f} \cdot \phi} \tag{2.15}$$

2.3.2.3 improved formula for tranverse/tranverse Poisson's ratio

The micro-mechanically derived basic elasticity values E_L, E_T, G_{LT} and ν_{LT} are sufficient to determine the elasticity law for the plane stress state. In the case of thick-walled components, helical or volute springs it is necessary to extend the stress and deformation analysis to a 3D stress condition. Since the transverse/transverse Poisson's ratio (here ν_{TT} or ν_{23}) represent a strain ratio in the transversal isotropic plane, it is possible to calculate it via the mixture rule using the cross-contraction numbers of fibers and matrix. However, the mixing rule does not take into account the constraints that the matrix undergoes in the fiber direction when stretched normal to the fibers. To solve this inconvenience Foye [29] obtains an effective

Poisson's ratio of the matrix material as it is shown in equation (2.16).

$$\nu_{m,eff} = -\frac{\varepsilon_3}{\varepsilon_2} = \nu_m \cdot \frac{\left(1 + \nu_m - \nu_{LT} \cdot \dfrac{E_m}{E_L}\right)}{\left(1 - \nu_m^2 + \nu_m \cdot \nu_{LT} \cdot \dfrac{E_m}{E_L}\right)} \tag{2.16}$$

Substituting this effective Poisson's ratio in place of the conventional one in the mixture rule gives the estimate for the transverse Poisson's ratio of the actual composite (see equation (2.17)).

$$\nu_{23} = \phi \cdot \nu_f + (1-\phi) \cdot \nu_{m,eff} = \phi \cdot \nu_f + (1-\phi) \cdot \nu_m \cdot \frac{\left(1 + \nu_m - \nu_{LT} \cdot \dfrac{E_m}{E_L}\right)}{\left(1 - \nu_m^2 + \nu_m \cdot \nu_{LT} \cdot \dfrac{E_m}{E_L}\right)} \tag{2.17}$$

Once the transverse/transverse Poisson's ratio has been calculated, the out-of-plane shear modulus $G_{TT} = G_{23}$ can now be determined, which is used to establish the law of elasticity by shear for the perpendicular plane to the direction of fibers. Since there is isotropy within this plane (transverse isotropy of the UD-lamina), the known relation between Young's modulus, the transverse/transverse Poisson's ratio, and the out-of-plane shear modulus is valid. Therefore, the equation (2.18) to calculate the out-of-plane shear modulus is derived from the law of elasticity for the plane state and the geometric considerations.

$$G_{TT} = G_{23} = \frac{E_L}{2 \cdot (1 + \nu_{TT})} = \frac{E_L}{2 \cdot (1 + \nu_{23})} \tag{2.18}$$

As can be seen, $G_{TT} = G_{23}$ is a dependent variable and therefore does not belong to the basic elasticity variables.

2.4 Fiber reinforced plastic springs

Currently, the most common composite springs that exist commercially are leaf springs, anti-roll bars, helical cylindrical springs, and Belleville springs. These springs are the most commercial because they arose as an alternative to their metal counterparts, mainly in the automotive industry to be used in suspension and stabilization systems of vehicles.

The oldest springs are fiber reinforced plastic leaf springs since they began to be researched and developed in the early 80's so that they are now widely used in the automotive industry as suspension springs and anti-roll bars and in the railway sector as suspension springs. There is a great list of researches that have been carried out in the design, manufacture, and optimization of this spring type. Mentioning such a list would be unnecessary because it is not the subject of this work. However, the main manufacturing methods that are of interest to this work will be described below. It is worth noting that studies on leaf springs are still being carried out at present to improve manufacturing processes, the weight strength ratio, fatigue life and fatigue damage characteristics, among other aspects.

Another type of spring being investigated is the fiber reinforced plastic helical cylindrical spring. Studies on these springs began at the end of the 80's, with some patents, referring to the manufacturing process, which are the first documents produced about these springs. Research on the behavior, strength, and optimization of this type of springs are beginning to be more proportionate at the first decade of the 2000's. Fiber reinforced plastic helical springs were commercially introduced a few years ago (Sogefi S.p.A. [30]) at the automotive industry to replace the steel springs of automobile suspension systems. As is the case with leaf springs, several types of research are currently being carried out on resistance, fatigue and the manufacturing methods of helical springs.

There are also the Belleville disc springs (commercially named Carbon Composite Bellows™Spring - CCBS [3]) which arose to replace conventional coil springs or metallic Belleville disc springs in applications such as weight-conscious projects, motorsports, aerospace, satellites, outdoor recreation, high-performance activities, general industry, steady camera, and prosthetics.

Finally, other fiber reinforced plastic spring types such as wave spring, elliptical spring, and multihelical spring. These springs were developed to replace the conventional helical springs (of steel or composite materials) in a variety of applications by providing the same force and deflection characteristics and using only half the space but thy are still under investigation.

Just as different ideas of fiber reinforced plastic springs arose with the aim of replacing the helical springs, it arises a proposal to elaborate fiber reinforced plastic volute springs to replace the helical springs in different fields since, currently, the manufacturing process of the classic helical springs is complex and expensive.

2.4.1 Different fiber reinforced plastic springs

Fiber reinforced plastic (FRP) is the most popular type of composite material for springs. There are a variety of examples like glass fiber reinforced plastic spring (GFRP), carbon fiber reinforced plastic spring (CFRP), hybrid spring (a combination of GFRP and CFRP), and hybrid form of metal an plastic [31].

Speaking of spring shape, there are leaf springs, helical springs, wave springs, volute springs, bellows™ springs [3] (like a Belleville springs), and anti-roll bars. Figures 2.21 and 2.22 show different forms of springs made of composite materials and some applications of them.

Since the 1980's the glass fiber reinforced plastic spring has been used for automobiles. After the 1990's glass fiber reinforced plastic springs became much popular

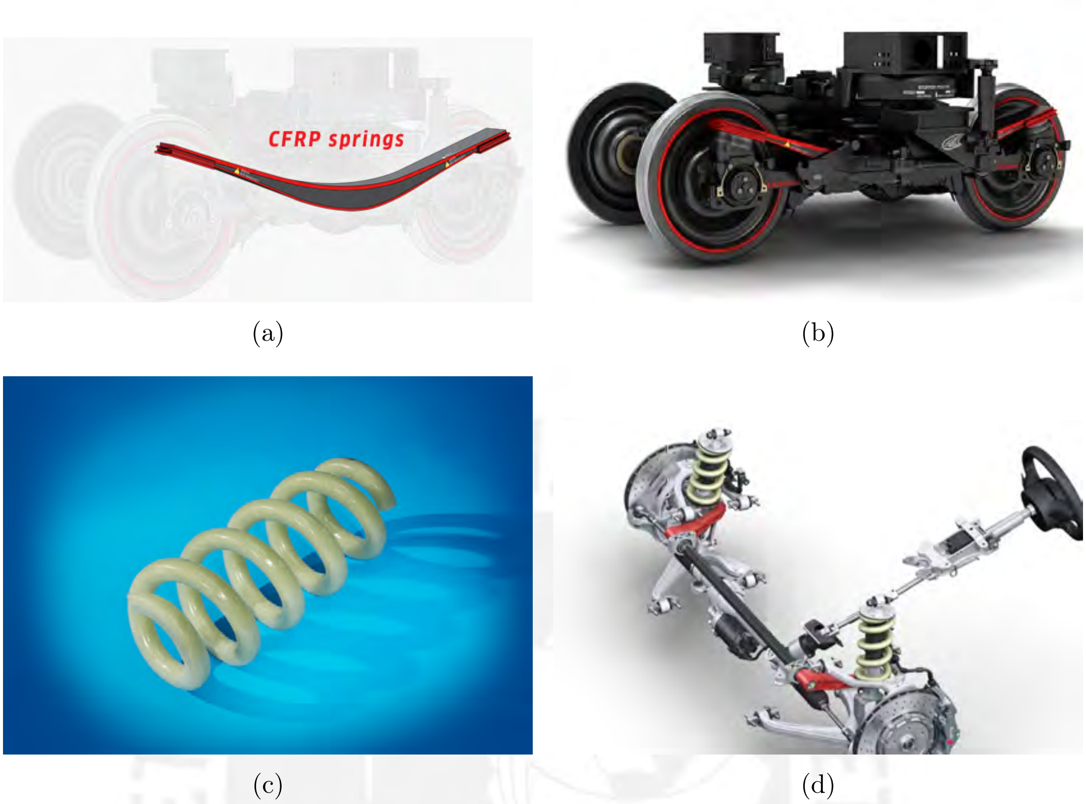


Figure 2.21: Different forms and their applications of springs made of composite materials: (a) Carbon fiber reinforced plastic leaf spring [2], (b) efWING® bogies equipped with CFRP leaf springs [2], (c) Fiberglass/Epoxy composite coil spring [32] and (d) Fiberglass/Epoxy coil spring of Audi R8 e-tron [33].

because of significant weight reduction, low spring rate, space allocation freedom, and comfortable riding quality were recognized to be superior to metals.

E-glass fiber (13 to 23 μm) and high-strength, high modulus continuous polyacrylonitrile-based carbon fiber (5 to 10 μm) are widely used for reinforcement. On the other hand, Epoxy resin, excellent in strength and weather resistance, is mainly used as the matrix resin for fiber reinforced plastic springs. Unsaturated polyester could be used when strength is not a demanding factor.

Leaf springs composed of carbon fiber and epoxy resin is the typical product as for carbon fiber reinforced plastic spring. By high-specific strength, high-specific modulus, and excellent fatigue resistance, the carbon fiber reinforced plastic spring has a remarkable feature of lightweight, compactness, and long service life. This merit could also be advantageous for the other high standard application like a volute spring which needs dimensional accuracy, compact or complex shape, chemical resistance, and weather resistance.

(a) (b)

(c)

Figure 2.22: Different forms and their applications of springs made of composite materials: (a) Carbon Composite Bellows™ Spring (CCBS) [3], (b) Carbon fiber springs on an SCCA D-Sport Racer (Belleville washers) [34] and (c) Manufactured CFRP wave springs, post-cure trim and polished wave spring [35].

Some typical applications of fiber reinforced plastic springs are feeder transportation machine springs, vibrator springs, engine valve springs and automotive suspension springs.

This next subsection describes the manufacturing processes most commonly used to produce fiber reinforced plastic springs and the evaluation of springs made with these materials.

2.4.2 Existing spring production methods

Filament winding, prepreg hand lay-up, resin transfer molding (RTM), vacuum bag molding, and pultrusion methods are put in place for fiber reinforced plastic spring manufacturing process (all these processes were described in section 2.2.3).

Currently the most widely manufactured and marketed spring is leaf spring type, which is manufactured using this five methods mentioned above. It should be noted that the use of one or another manufacturing method will depend on the quantity required, the type of application and the manufacturing costs.

The manufacturing process of carbon fiber reinforced plastic springs are identical with the glass fiber reinforced plastic. The hand lay-up method is preferred (prepregs are piled up to necessary thickness, and then cured under high pressure and specified temperature) for manufacturing springs of carbon fiber reinforced plastic when it has small batches of production where high-performance springs are required.

The manufacturing processes of fiber reinforced plastic coil springs are not yet well developed since they were commercially introduced a few years ago [30], however, the patent holder Sogefi S.p.A., an Italian designer and manufacturer of automotive components and the Audi project engineer Joachim Schmidt have jointly developed the fiber reinforced plastic springs (for the suspension system of Audi A4 auto). Their production method is explained by Barry Copping in his article of the magazine Plastic News Europe as follows: first "as compared with a conventional steel spring, the fiber reinforced plastic spring's ˝wire˝ is thicker, the spring's overall diameter is greater, and the number of turns is fewer" furthermore "the core of the spring consists of long glass fibers twisted together and impregnated with epoxy resin. A machine wraps additional fibers around the core, which is only a few millimeters in diameter, at alternating angles of plus and minus 45° to the longitudinal axis. The alternating layers support each other and act in either compression or tension. Torsional loads across the component are thus converted into the fibers into tensile and compression loads. The next production stage is for the ˝wire˝, while it is still wet and soft, to be wound onto a metal alloy core with a low melting point. The fiber reinforced plastic materials are then hardened in an oven at more than 100°Cso that the core melts [36]." This process is currently used to manufacture the prototypes, but the company Audi expects it to become very much faster and more efficient in volume production.

Other manufacturing processes of fiber reinforced plastic coil springs are still considered as experimental because they have only been used in researches to determine their stiffness. For example, Bok-Lok Choi and Byoung-Ho Choi [37] in their research they manufactured fiber reinforced plastic coil springs using the resin transfer molding process, as shown in Figure 2.23. During the resin transfer molding process, carbon fiber free-form is filled with epoxy resin and hardened by cross-linking under vacuum conditions.

Also, Bakhshesh M. and Bakhshesh M. [38] used the resin transfer molding process for manufacturing springs of composite materials. They worked on three different fiber reinforced plastic coil springs which are made of E-glass/Epoxy, Carbon/Epoxy, and Kevlar/Epoxy.

In their research, T. S. Manjunatha, and D. Abdul Budan [39] have experimented on the resistance of fiber reinforced plastic helical springs with materials such as glass fiber, carbon fiber and a combination of carbon/glass fiber (the orientation of fibers was +45°). In this research, filament winding technique has used to manufacture

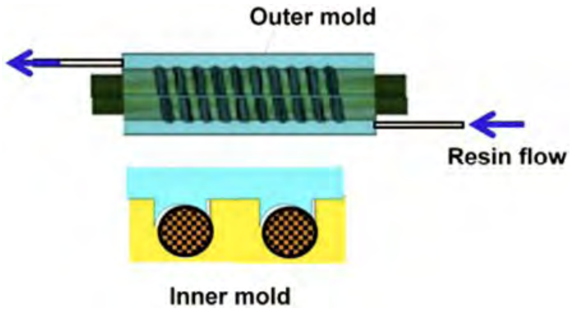
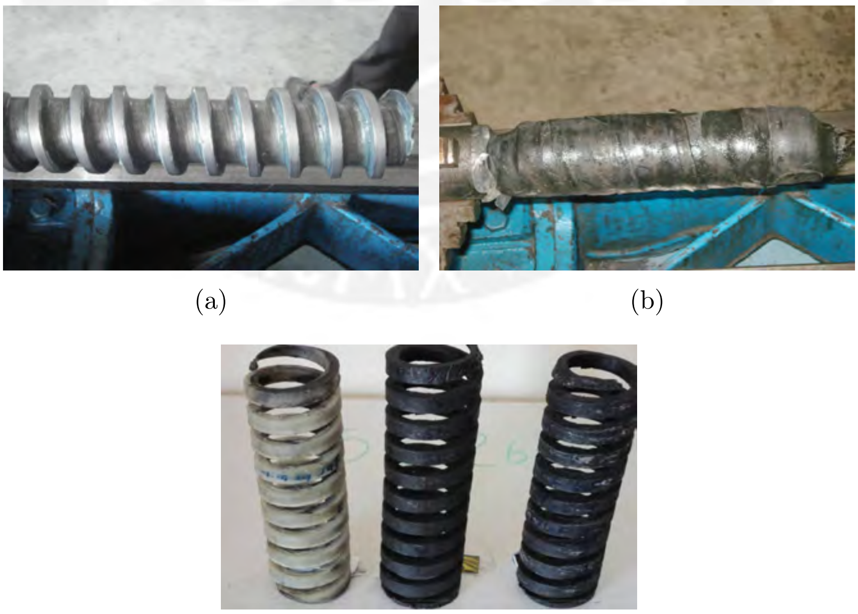


Figure 2.23: Fiber reinforced plastic coil spring manufacturing by resin transfer molding [37].

composite helical springs. The process consisted of a mold (cast iron or any other metal), which has the shape of the spring profile is prepared for the winding process. This mold is fixed between the centers of the lathe. A release agent silicone gel has been applied to the mandrel. The fibers have been cut in 45°orientation because the acting load on the compression spring is shear. After that, the fiber tape dipping in the epoxy resin has been wound on the mold. The winding process continued until the desired thickness was obtained on the mandrel. The curing process was carried out at room temperature for 24 hours in an environment determined by the researchers (see figure 2.24).



(a) (b)

(c)

Figure 2.24: (a) Metal mold, (b) Shrink tape wound on mandrel and (c) The springs after curing [39].

Chapter 3

Specification and objective of the topic

3.1 Conceptual formulation of the topic

As mentioned earlier, fiber reinforced plastic springs have been studied and used since the early 80's. Because production processes of composites and materials have been refined over time, it is now possible to manufacture various types of springs with excellent mechanical and physical properties. Moreover, the strength-to-weight ratio has been greatly improved.

Obtaining excellent properties and above all being a very light material has led to suggest the bold idea that composite materials can replace metals (steel, aluminum, and other alloys) in their dominant role in various industrial sectors.

The composite material properties can be controlled through the properties of the constituents, the geometry of the reinforcements, their distribution, orientation, and concentration usually measured by the volume fraction of fiber volume ratio and the nature and quality of the matrix-reinforcement interface. Also, the properties are controlled by the number of layers and their type of stacking sequence (symmetry or asymmetry to the neutral axis).

However, in the case of fiber reinforced plastic helical springs, it is difficult to control the material properties, since the spring wire is not manufactured following a conventional stacking sequence. Therefore, it requires a particular manufacturing process in which a core with twisted fibers must first be generated, and then additional fibers must be wrapped, with a certain inclination, over this core.

For this reason, the idea arose of analyzing the behavior of volute springs whose manufacture is simple and involves the use of commercial fiber fabrics and the conventional stacking of layers of composite material, apart from considering the best orientation of the fibers to support the predominant load in its cross section.

3.2 Objective and aims

In this work, two main objectives are proposed, namely:

- Development of a manufacturing method to produce fiber reinforced plastic volute springs.
- Development of an analytical/experimental approach of fiber reinforced plastic volute springs.

The following tasks must be carried out to achieve these objectives.

- Review of literature focused on volute springs and the behavior of material of thin-walled composite beams.
- Theoretical calculation of the elastic constants of the materials to be used in the present work.
- Determine the most important elastic constants that are involved in spring calculation (shear moduli) using analytical/experimental approaches that consider torsional load as the main load in the cross-section.
- Comparison of the elastic constants calculated both theoretically and experimentally.
- Establish a simple and fast method of manufacturing volute springs using fiber fabric strips.
- Dimensioning and manufacturing of test specimens and volute springs necessary to carry out tests, using different stacking sequences, fiber orientation and different fiber types.
- Development of a theoretical model to calculate the spring rate and determine the spring characteristic curve. This model should consider the constructive forms of the specimens manufactured.
- Carry out compression tests on volute springs manufactured to compare theoretical and experimental results.
- Comparison and discussion of theoretical and practical results.

Chapter 4

Novel fiber reinforced plastic volute springs.

This chapter presents a brief selection guide for spring material, a concise description of the materials (fibers and resins) used in the production of springs according to the guidelines established by Yoshiro Yamada [31]. Moreover, various manufacturing processes of composite material springs are described, and a manufacturing process of fiber reinforced plastic volute springs is proposed. At the end of this chapter, a theoretical approach is presented to determine the characteristic curve of the volute spring which describes its behavior.

4.1 Initial considerations

The quality of the spring materials can be taken into consideration or highlighted in cases such as (according to Yamada [31]):

- A spring installed in a mechanical device failed either by fracture or by significant deformation in use; this case can be divided into two situations:
  - Quality requirements set up in the initial quality design stage were not reflected in the actual products.
  - Although the quality requirements set up at the design stage were satisfying, the springs were used in very arduous conditions than initially expected or some important quality requirements failed to be included among the initial quality requirements during the design stage.
- A recently designed or improved mechanical product, where a new design of spring is needed, the same requiring a high degree of quality.
- A cost reduction requested for the spring been used without varying the quality.

Considering the availability, quality level, price, and the concordance with working processes (conventional or new process), the most suitable material can be chosen. Moreover, it can be said that the work process of such material plays an important role in quality increase and cost reduction.

The following subsection describes some functions and qualities required for springs and the selection of the material thereof.

4.1.1 Basic considerations in spring material selection [31]

In the spring material selection and the working process designing, the following considerations are taken into account according to Yamada [31].

- Selected material and manufacturing process are such that the quality of finished springs satisfies the customer's quality requirements.
- Availability of selected material.
- Economical feasibility of material and spring working processes (cost).
- The manufacturing processes, where the material quality should not be deteriorated.
- Recycling.
- No pollution, safety, and regulations observance through spring manufacturing to disposal or recycling.
- The roles or functions of springs (within the mechanical systems) which can be classified into the following:
  - Springs return to the original position or to the original shape when these are unloaded.
  - Absorption or utilization of vibration.
  - Relaxation or absorption of impact force.
  - Storage and/or release of energy.
  - Measurement of force.

In addition Yamada says that: "In any primary function that the springs perform, springs loaded under repeated or varying stresses can sometimes fracture due to fatigue. In general, permanent set (an unloaded spring often does not recover to its original shape, and this kind of shape change is called a permanent set of spring) and fatigue fracture can be said to be the most important quality factors of springs to be paid attention to. Moreover, failure of springs due to wear and/or corrosion is to be taken into consideration according to the application or the environments in use, for example, table 4.1 shows typical failures of springs, which occur in use [31].

Depending upon the load pattern of springs in use, quality requirements for spring material vary, for this reason in table 4.2 are shown relations between types of spring load pattern and the essential quality required for spring material are summarized. The quality requirements for spring materials changes with conditions such as temperature and environment where the springs are used" [31].

Table 4.1: Principal types of spring failures [31]

Type of failure	Description
Fracture	Fracture with repeated stresses: • Fatigue with no corrosion. • Corrosion fatigue. • Fatigue from fretting corrosion or wear. Fracture with impact stress: • Brittle fracture (low temperature brittle fracture). • Ductile fracture. Fracture with static stress: • Stress corrosion cracking. • Delayed fracture (Hydrogen embrittlement fracture).
Deformation (permanent set)	• Yielding, plastic deformation (due to over stressing). • Static creep. • Dynamic creep. • Stress relaxation.
Decrease of cross-sectional dimensions	• Wear. • Fretting. • General corrosion. • Local corrosion. • Erosion.

4.1.2 Spring material selection method

4.1.2.1 Procedures of spring material selection

In this subsection, more precise material selection procedures and special remarks are discussed, since in the above section basic factors were described that are considered in the selection of spring material. These procedures, according to Yamada [31], are:

- The condition where the spring is used, such as volume, dimensions, temperature and environmental atmosphere must be made clear.
- The quality requirements (load, deflection, fatigue life, etc.) must be made clear.
- The material type, section size, elastic modulus, design stress, spring shape and its dimensions must be determined. Since in conventional usages, kinds of material used are normally known it can be possible to make the material selection based on these criteria of information.

Table 4.2: Types of load [31].

Types of load		Variable to consider	Properties required for material
Static load	A constant and invariable load (permitted insignificant variation of load).	Load. Deflection.	High elastic limit.
Repetitive load	Constant loads repeatedly applied.	Mean load. Load amplitude. Deflection. Number of cycles.	High fatigue strength.
Impact load	A load applied abruptly at high speed.	Impact force. Deflection. Number of cycles.	High elastic limit. High impact value
Load for measuring load	Accurate load being ensured for a wide range of deflection, like a spring balance.	Spring constant. Maximum load.	High elastic limit. High dimensional accuracy.

- The testing methods and evaluation standards shall be determined in preparing material specifications.
- In the selection of spring material, the relevant international standards indicating and recommending design requirements, allowable stress for different types of springs used under static load, must be considered. Moreover, as reference should be used standards in which are established fatigue life estimations methods based on the fatigue strength.
- Material selection has to be made according to the temperature in use. However, sometimes the selection of final material can be difficult since the material's maximum temperature of use varies depending on stress condition of the spring.
- Since there are such cases where the strength of a spring deteriorates because its exposure to a hazardous environment, therefore the selection of spring

material should consider the environment in which the spring will perform or make measures to isolate the spring from the environment.

- In the selection of material it must be considered if the spring will have electrical conductivity capacity or not.

4.1.2.2 Information sources on spring materials

Information sources on spring materials are classified into documents sources (data books) and databases searchable in computers, being the most substantial document source books, magazines, reports, etc.

In this work different bibliography referring to the theory of springs (books of Gross [40], Meissner [41] and Wahl [42]) has been reviewed. All these books, although some of them old, present requirements, classification and selection of materials for springs, and also describe the corrosion effects on the spring materials.

Although the information presented in these books regarding the selection of material for springs is oriented to ferrous (steel in its different qualities) and non-ferrous materials (copper and its alloys for example). They do not present detailed information on the composite materials, however, the recommendations made for the selection of materials, provided in this bibliography, can be taken into account in the composite materials selection, also considering the information an literature provided in the chapter 1 of the present work.

Another type of information source, which may be taken into account, for the selection of spring materials are journals, magazines, books or standards published by institutes or associations specialized in the spring issue, for example, the Spring Manufacture Institute (SMI) or the European Spring Federation (ESF).

Finally nowadays, the information sources on spring materials provided in databases or web pages that in many cases are freely accessible can be used. For example, the database "Spring Materials Selector CD-ROM" [43] published by the Spring Manufacturers Institute in collaboration with the European Spring Federation.

4.2 Composite materials for springs

In chapter 2 of the present work the classification, characteristics, advantages and disadvantages of the fibers and matrices (resins) that are constituents of the composite materials are described, as well as a description of the composite materials production processes most used in the industry. This section gives a brief description of the most composite materials used for manufacturing springs.

4.2.1 Material composition of fiber reinforced plastic springs

According to the section 2.1.2 it is known that a composite material is formed of fibers and matrices (resins); therefore the fiber reinforced plastic springs have the same components. The properties of the springs are mostly controlled by the mechanical properties of fibers, and the matrix resin has the secondary properties such as environmental resistance and durability of springs (section 2.2.2). Also, it should be kept in mind that the bonding quality of fiber and resin has a crucial role of spring characteristics.

The high tensile strength and the high modulus of elasticity are the most popular characteristics of fiber reinforced plastic springs; therefore, glass and carbon fiber have been selected as a suitable fiber materials to the spring applications. On the other hand, Yamada says that "the Kevlar (high-modulus aramid fiber) was studied in spring applications, but the problem of creep and hygroscopic property remains to be solved" [31].

From a cost and productivity standpoint, glass fiber has a great advantage over carbon fiber, however, traditionally carbon fiber is mainly used in high-performance applications such as aerospace industries because of this fiber is lighter, but currently carbon fiber is also used in leaf and Belleville springs (see figures 2.21 and 2.22).

Although the matrix (resin) plays a secondary role for the mechanical properties of springs, the matrix controls hardness, heat resistance, moisture resistance, oil resistance and fatigue resistance. Of all types of resins described in section 2.2.2, the most widely used is the epoxy resin. However, it is also possible to use other resin types such as unsaturated polyester, phenolic or thermoplastic resins, but everything will depend on the type of application being treated.

4.3 Development of a production method for fiber reinforced plastic volute springs.

In this section, a manufacturing method for producing fiber reinforced plastic volute springs is presented. This method was developed taking into consideration the manufacturing processes described in section 2.2.3.

4.3.1 A method for manufacturing fiber reinforced plastic volute springs

Regarding the volute spring manufacturing process, in this work, a process like a manual filament winding process has been used because this is an experimental work. This process can be described as follows:

- First, because of its geometric shape, this spring requires a special mold for each one, i.e., if for some requirement of either load, strength, rigidity and/or space some geometric dimension must be changed then the mold must also be changed. Therefore a mold as shown in Figure 4.1 is prepared with polymer or cardboard sheets which, having the proper geometry, are wound in a steel bar (or tube) of certain diameter according to the required geometry. Before being wound on the bar, the polymer or cardboard sheets are stacked up to the required thickness of the spring. The mold can also be made of steel or any other metal but as discussed above it requires a specific mold for each spring so that it would increase the production cost, however in case of series production a metal mold is most appropriate.

- Second, the mold, having the shape of the spring profile, is fixed between the centers of a lathe. Then a film release agent silicone gel is applied to the mold (see figure 4.2) with a small soft brush sparingly and stripe-free, while the mold rotates slowly in the lathe, once applied the release agent is allowed to dry for 30 or 40 minutes, it is possible to apply further layers of the release agent after drying.

Figure 4.1: Top view of the mold to manufacturing volute springs.

Figure 4.2: Release agent for epoxy and polyester resins with maximum curing temperatures of 100°C [44].

- Third, while the release agent is drying, it is proceeded to cut carbon or glass fiber fabric strips. In this work, the different fiber fabrics or sleeves, shown in Table 4.3, were used. The dimensions of fiber laminae are according to the spring geometry, see figure 4.3, the length of each lamina is the developed spring length which is a function of the total number of coils that the spring will have. The total thickness of the fiber strip (laminate) depends on the number of layers that it has been determined or proposed for a particular purpose, for example in this work, strips of four and eight layers were used forming a symmetrical laminate to the mid-plane ($x_3 = 0$). Since the coils, in a volute spring, do not stack, the solid height of the spring is the width of the strip which is determined according to the application required. It should be taken into account that when it uses braided sleeves, the strip width is limited to the range of widths that can be obtained with the sleeve, this range depends on the orientation of fibers that is required. It should also be noted that, in some cases, since the acting load on the compression volute spring is shear, the fibers are cut in +⁄- 45 degree orientation. After cutting the fiber laminae, a pair of peel ply strips (see figure 4.4) are cut which will serve to avoid that the coils stick to each other.

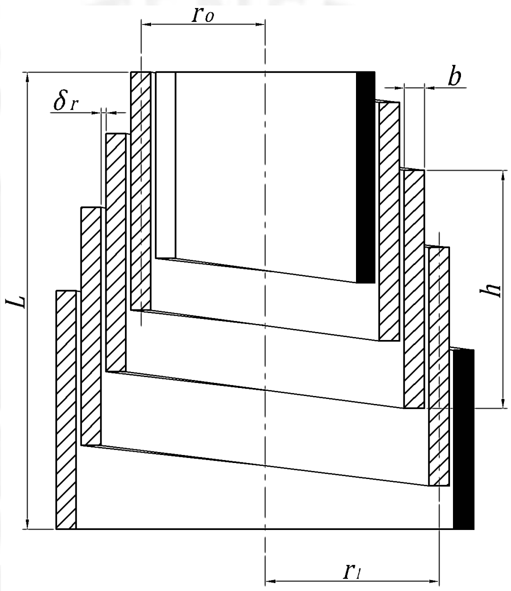


Figure 4.3: Section of volute spring. L = Spring length, h = Long side of the rectangular cross-section, b = Short side, r = Mean coil radius and δ_r = Radial coil distance [40].

- Fourth, after cutting the fiber strips, the resin and hardener mixture is prepared (in this work resin EPIKOTE RIMR 426[1] and hardener RIMH 434[2] [46] have been used). The quantity of resin required to impregnate it in the fiber strips can be calculated theoretically by making use of the equations described in section 2.3.1 as follows:

[1] Injection resin EPIKOTE RIMR 426 is a very low-viscosity injection resin systems for processing of glass, carbon and aramide fibers; clear, colorless and watery liquid with rapid curing at room temperature.

[2] When the hardener RIMH 434 is used the laminates can be demolded and processed at room temperature within a few hours.

Table 4.3: Different reinforcement fabrics [45] [46].

Type	Description
Multiaxial glass fabric EBX300 [46]	Weight: 325 g/m^2. Structure: biaxial +/– 45°. Product attributes: rolls of 1.27m wide.
Unidirectional glass fabric HP-U600E [45]	Weight: 600 g/m^2. Structure: Unidirectional 0°+ Stabilizing filaments in 90°. Product attributes: rolls of 1.27m wide.
Unidirectional glass fabric HP-U400E [45]	Weight: 400 g/m^2. Structure: Unidirectional 0°+ Stabilizing filaments in 90°. Product attributes: rolls of 1.27m wide.
Multiaxial carbon fabric SP BX 150 [46]	Weight: 150 g/m^2. Structure: biaxial +/– 45°. Product attributes: rolls of 1.27m wide.
Unidirectional carbon fabric HS 15/130 DLN2 [46]	Weight: 130 g/m^2. Structure: Unidirectional 0°. Product attributes: rolls of 1.00m wide.
Glass fiber braided sleeves 962111 [46]	Weight: 820 g/m^2 approximately. Structure: biaxial +/– 45°. Width flat: min. 10mm - max. 55mm (at 45° - 39mm). Diameter: min. 8mm - max. 35mm (at 45° - 25mm).
Carbon fiber braided sleeves 642100 [46]	Weight: 369.50 g/m^2 approximately. Structure: biaxial +/– 45°. Width flat: min. 10mm - max. 47mm (at 45° - 34mm). Diameter: min. 6mm - max. 30mm (at 45° - 22mm).

– Assume a value for the fiber volume fraction (see subsection 2.3.1.1), $v_f \equiv \phi$, in order to obtain the resin volume fraction value (matrix) with the following equation: $v_f + v_m = 1$.

– With the value of v_m and using equation (2.8), the theoretical laminate density ρ is calculated.

– With the value of the density ρ and using equation (2.7) it calculates the matrix mass fraction (resin mass fraction), then the value of the fiber mass fraction is obtained with the following equation: $m_f + m_m = 1$.

Figure 4.4: The peel ply fabric produced using washed polyamide 6.6 (nylon) is applied as a final layer to the epoxy or polyester resin laminate [44].

- With the known geometry of fiber strips which will be used to produce the volute spring, the mass thereof is calculated M_f. Then using equation (2.4) the total laminate mass is calculated M.
- Finally using equation (2.3) it can determines the theoretical resin mass required M_m.

Due to losses that may occur in the resin impregnation process, the calculated value of required resin mass should be increased, for example, one could consider increasing the M_m value by 25 or 50%. Finally, the mixture of resin and hardener is prepared, as the products EPIKOTE RIMR 426 and RIMH 434 are being used the ratio to be considered for the mixture is 100:26, i.e., for 100 parts of resin, 26 parts of hardener should be added. For a better understand this relationship the company R&G Faserverbundwerkstoffe GmbH offers a mixing chart in which it can read the amount of hardener for different amounts of resin [47].

- Finally, the fiber strips are wound over the mold as follows: an end of the set of fibers and peel ply is fixed on the mold, then while the lathe slowly rotates the strips are wound and at the same time resin is impregnated slowly with a brush; after wetting the fibers, they are covered with the peel ply to void that the coils stick to each other. The mold with fibers kept for curing in atmospheric temperature for 24 hours. After curing the spring is removed from the mold and for a better curing process is placed in an oven (preheated at 80°C) for at least 10 hours. The same procedure is followed for glass fiber and carbon fiber springs. It should be noted that random or total inspection of height, thickness of the laminate, diameters, and length of the narrow side in volute springs shall be checked according to the standards.

Summarizing the present chapter it can be said that the product characteristics of the fiber reinforced plastic springs are practically determined at the selection material stage and at the configuration stage. Furthermore, basic characteristics such as tensile strength, modulus of elasticity or coefficient of linear thermal expansion and specific characteristics such as specific gravity, specific tensile strength or specific modulus for each product should be checked out by lot inspection or random inspection. In view of the above, it should be kept in mind that due to the spring rate of the product varies with dimensional accuracy, the dimensional inspection becomes an important process.

Other general comments about behavior on fiber reinforced plastic materials are, for example, that resin is susceptible to the environmental condition, so the environment in which the material will be located must be carefully evaluated. As for temperature condition, the properties of fiber reinforced plastic spring changes along with the resin properties when used at high temperature. Moreover, resin deteriorates under wet condition, strong acid or a strongly alkaline environment. Avoiding these influences is absolutely recommended.

It should also be noted that the manufacturing method for volute springs may change in the future as more studies are carried out on this particular element.

Chapter 5

Theoretical/experimental analysis of the volute spring.

In this chapter, the theoretical and practical analysis of the volute spring manufactured from composite laminates (epoxy resin, glass fiber, and carbon fiber) is developed. First, the calculation of mechanical properties of composite laminates is presented (properties such as elasticity and shear moduli, effective density, fiber volume fraction and Poisson´s ratio). Second, an analytical method is established to determine the spring stiffness behavior. Finally, a comparison is made between analytical results and test results; these tests were performed with volute springs manufactured under the same considerations that were used to analyze the analytical calculations.

5.1 Basic considerations about laminate geometry

To continue with the present chapter, it is necessary to establish certain geometrical parameters that the fibers and laminate must have of which the spring will be composed, parameters such as the orientation of fibers and the number of layers. In this sense, in the present work, it is considered that fibers have 0° and 45° of orientation according to considerations made (regarding the way in which the twisting load acts in fibers) in the research carried out by D. Jang and S. Jang [48]. The choice of this orientation is also justified since the volute spring is classified as a torsion spring because its cross section is predominantly subject to torsion loading as stipulated by Dipl.-Ing. Siegfried Gross [40].

As regards the number of layers of laminate forming the volute spring, this depends on the specific application and stiffness desired for such purpose, however, it can also be considered that the number of layers may depend on the commercial presentation of fibers, for example unidirectional (0°) or biaxial (45°) fiber fabrics, or braided fiber sleeves (with which an orientation of +⁄- 45°can be obtained) are used. These products mentioned have an even number of layers, or in the case of braided sleeves, it can be assumed that they have four layers. So, if layer number is not available initially, then it can set the number of layers and then check its strength. In this current work, it is used laminates having eight layers. This choice is according to established by Altenbach [5]. He says that the stacking of laminates has a great influence on the global mechanical laminate response. However, there are some rules to guarantee an optimal global laminate behavior:

- Symmetric laminate stacking yields an uncoupled modeling and analysis of in-plane and bending/torsion stress-strain relations and avoids distortions in the processing.
- Laminates should be made up of at least three UD-laminae with different fiber angle orientation.
- The differences of the mechanical properties and the fiber orientations between two laminae following in the stacking sequence should not be so large that the so-called interlaminar stresses are small.
- Although it is possible to determine an optimum orientation sequence of laminates for any given load condition, it is more practical from a fabrication standpoint and from effective experimental lamina testing to limit the number of fiber orientations to a few specific laminae types, e.g. fiber orientations of 0°, +⁄- 45°and 90°, etc.

Considering these rules an angle-ply laminate (which has ply orientations of θ and $-\theta$ with 0°$\leq \theta \leq$90° and at least one lamina has an orientation other than 0°or 90°) or a symmetric balanced laminate (which consists of pairs of layers of the same thickness and material where the angles of plies are $+\theta$ and $-\theta$) are sought. These types of laminates are of particular importance in the engineering design of laminated structures [5].

It should be mentioned that dimensions of cross section all springs that have been tested in the present work have a width to thickness ratio of 18 to 20 approximately (thin laminates) according to the constructive configuration of volute spring (see figure 4.3).

5.2 Calculation of mechanical properties

5.2.1 Theoretical calculation of mechanical properties of laminates

In chapter 2 necessary equations were established to calculate approximately the mechanical properties with help of the rule of mixtures and empirical equations proposed by several authors, so that in this section it can proceed to calculate these properties according to the geometric configurations and composition of laminates that have been established to develop the theoretical model of volute springs. Of particular importance for the topic developed in the present document is to determine the in-plane and out-of-plane shear moduli, this latter is not of primary importance because, in the present work, it is working with thin laminates so it will assume a plane stress state, i.e., this assumption is made taking into account that, three of the six components of stress state are generally much smaller than the other three [5].

To perform the calculations, the properties of laminate components must be previously collected (fibers and epoxy resin), they are shown in table 5.1 and table 5.2 respectively. As can be seen, carbon and glass fibers are used to compare the stiffness of the produced springs.

Table 5.1: Material properties of fiber materials

Material	Density ρ_f ($^g/_{cm^3}$)	Young's modulus E_f (GPa)	Poisson's ratio ν_f	Shear modulus [a] G_f (GPa)	Weight ($^g/_{m^2}$)
Multiaxial glass fabric EBX 300 [46]	2.55 - 2.58	69 - 72	0.21 - 0.23	28.89	300
Unidirectional glass fabric HP-U400E [45]	2.59 - 2.62	73	0.21 - 0.23	29.92	440
Multiaxial carbon fabric SP BX 150 [46]	1.78	240	0.26 - 0.28	94.49	150
Unidirectional carbon fabric HS 15/130 DLN2 [46]	1.78	240	0.26 - 0.28	94.49	130
Glass fiber braided sleeves 962111 [46]	1.78	240	0.26 - 0.28	94.49	830.77 [b]
Carbon fiber braided sleeves 642100 [46]	1.78	240	0.26 - 0.28	94.49	479.30 [c]

[a] This value was calculated with the equation $G = \dfrac{E}{2(1+\nu)}$.

[b] This weight was calculated from a strip with dimensions 39mm x 250mm and a weight of 8.1g.

[c] This weight was calculated from a strip with dimensions 34mm x 270mm and a weight of 4.4g.

Since a general laminate has layers in which the orientation angle of fibers should be in the region of -90° to +90° [5] in the present work it has been considered

Table 5.2: Material properties of resin and curing agent mixture [49].

Properties	Mixture of resin EPIKOTE RIMR 426 and curing agent RIMH 434 [46]
Density ρ_m ($^{g}/_{cm^3}$)	1.108 [a]
Young's modulus E_m (GPa)	3.4
Poisson's ratio ν_f	0.3
Shear modulus G_f (GPa)	1.31 [b]

[a] This value was calculated using the mixture rule and considering a proportion of 26g of curing agent per 100g of resin.

[b] This value was calculated with the equation $G = \dfrac{E}{2(1+\nu)}$.

laminates whose orientation of fibers of layers are $[0°/+45°/-45°/0°]_s$ and $[+45°/-45°/+45°/-45°]_s$. It should be noted that the fiber orientation of braided sleeves is approximately equal to the second arrangement. It should also be taken into account that the choice of such fiber orientations are based on the rules mentioned above guaranteeing optimum behavior of laminates [5].

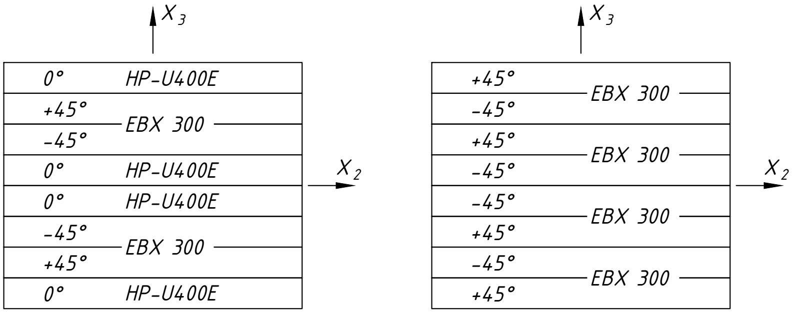
As mentioned above, it is of primary importance for the torsional analysis to determine the shear modulus, so that torsion tests were carried out with flat strip laminates to be able to compare the approximate calculation with actual values obtained from tests.

The composition of plates and strips that were made to obtain test specimens are shown in table 5.3, figure 5.1. This table shows the orientation of fibers of these laminates, which were made using the vacuum infusion method (see chapter 2 subsection 2.2.3.2.2). Moreover, tables A.1 to A.8, in appendix A, show the dimensions of test specimens obtained by cutting the plates and which were tested under torsion load.

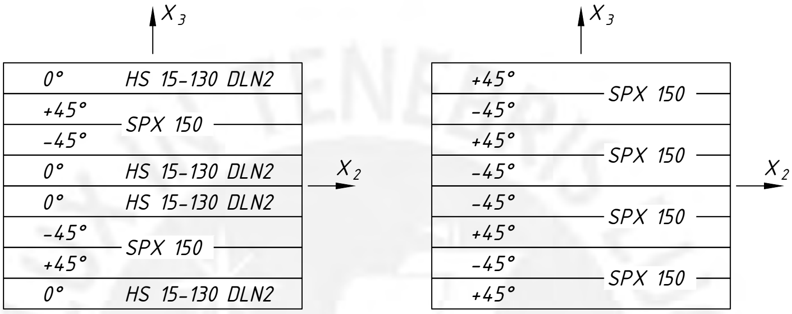
Continuing with calculations of mechanical properties, the most important data required to calculate this values is the fiber volume fraction (v_f or ϕ) according to equation 2.2, therefore, it proceeds as follows:

- The individual area of each piece of fiber fabric is determined with equation 5.1.

$$area_{individual} = length \cdot width \tag{5.1}$$



(a)



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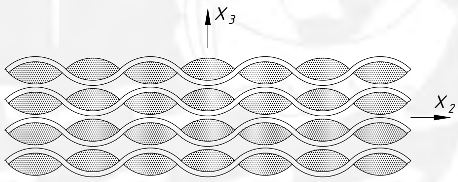


(c)

Figure 5.1: (a) Composition of glass fiber laminates, (b) Composition of carbon fiber laminates and (c) Cross section of fiber braided sleeves.

- Then, the individual area is multiplied by the number of pieces to obtain the total area (equation 5.2).

$$area_{total} = \#pieces \cdot area_{individual} \tag{5.2}$$

- The total area is multiplied by the weight to obtain the fiber mass (equation 5.3).

$$m_f = weight \cdot area_{total} \tag{5.3}$$

- Then, the mass value is divided by the density of fiber to obtain the fiber volume (equation 5.4).

$$V_f = \frac{m_f}{\rho_f} \tag{5.4}$$

Table 5.3: Composition of laminates plates (number of layers)

Material	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set7	Set8
Unidirectional glass fabric HP-U400E [45]	4	4	-	-	-	-	-	-
Multiaxial glass fabric EBX 300 [46]	2	2	-	-	-	-	-	4
Unidirectional carbon fabric HS 15/130 DLN2 [46]	-	-	4	4	-	-	-	-
Multiaxial carbon fabric SP BX 150 [46]	-	-	2	2	-	-	4	-
Glass fiber braided sleeves 962111 [46]	-	-	-	-	2	2	-	-
Carbon fiber braided sleeves 642100 [46]	-	-	-	-	2	2	-	-

- Finally, the total fiber volume is divided by the total laminate volume (fiber volume plus resin volume) to obtain the fiber volume fraction (equation 2.2).

Table 5.4 shows the dimensions of each fiber fabric piece, table 5.5 shows the calculation of individual area, the total area, the fiber mass, the fiber and resin volumes and finally the fiber volume fraction.

Table 5.4: Dimension of fiber reinforced plastic plate samples

		Length (mm)	Width (mm)
Glass and carbon fiber $[0°/+45°/-45°/0°]_s$	Sample 1	230	230
	Sample 2	230	290
Glass and carbon fiber braided sleeves	Sample 1	250	39
	Sample 2	250	24
Glass and carbon fiber $[+45°/-45°/+45°/-45°]_s$	Sample 1	300	300

Table 5.5: Calculation of fiber volume fraction

Material	Number of layers or strips		Individual area (mm^2)		Total Area (mm^2)		Fiber mass (g)		Fiber volume (cm^3)		Total volume of fibers (cm^3)	Resin mass (g)	Resin volume (cm^3)	Fiber volume fraction
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2				
Unidirectional glass fabric HP-U400E [45]	4	4	52900	66700	211600	266800	93.10	117.39	35.74	45.06				
Multiaxial glass fabric EBX 300 [46]	2	2	52900	66700	105800	133400	31.74	40.02	12.37	15.60		163.80	147.84	0.42
Total							124.84	157.41	48.11	60.67	108.78			
Unidirectional carbon fabric HS 15/130 DLN2 [46]	4	4	52900	66700	211600	266800	27.51	34.68	15.45	19.49				
Multiaxial carbon fabric SP BX 150 [46]	2	2	52900	66700	105800	133400	15.87	20.01	8.92	11.24		75.60	68.23	0.45
Total							43.38	54.69	24.37	30.73	55.10			
Multiaxial carbon fabric SP BX 150 [46]	4	-	90000	-	360000	-	54.00	-	30.34	-	30.34	50.40	45.49	0.40
Multiaxial glass fabric EBX 300 [46]	4	-	90000	-	360000	-	108.00	-	42.11	-	42.11	63.00	56.86	0.43
Glass fiber braided sleeves 962111 [46]	10	10	9750	6000	97500	60000	81.00	49.85	31.58	19.43	51.01	81.90	73.92	0.41
Carbon fiber braided sleeves 642100 [46]	10	10	9750	6000	97500	60000	46.73	28.76	26.25	16.16	42.41	69.30	62.55	0.40

With the value of fiber volume fraction, it proceeds to calculate the effective density (equation 2.8), the longitudinal modulus of elasticity (equation 2.9), the transverse modulus of elasticity (equation 2.14), the major Poisson's ratio (equation 2.11), the in-plane shear modulus (equation 2.15) and the out-of-plane shear modulus. Equation 5.5 (proposed by Tsai [50]) is used to calculate the out-of-plane shear modulus.

$$G_{TT} = G_{23} = \frac{\phi + \delta \cdot (1 - \phi)}{\dfrac{\phi}{G_f} + \delta \cdot \dfrac{1-\phi}{G_m}} \tag{5.5}$$

Where

$$\delta = \frac{3 - 4 \cdot \nu_m + \dfrac{G_m}{G_f}}{4 \cdot (1 - \nu_m)} \tag{5.6}$$

To calculate the longitudinal modulus of elasticity, the transverse modulus of elasticity, the major Poisson's ratio and the in-plane shear modulus of braided sleeves it is used the equations proposed by the Crimp model [51] (equations 5.7, 5.8, 5.9 and 5.10).

$$\frac{1}{E_x} = \frac{\cos^4(\theta)}{E_1} + \left(\frac{1}{G_{12}} - \frac{2\nu_{21}}{E_2}\right)\cos^2(\theta)\sin^2(\theta) + \frac{\sin^4(\theta)}{E_2} \tag{5.7}$$

$$E_y = E_2 = E_3 \tag{5.8}$$

$$\frac{1}{G_{xy}} = \frac{\cos^2(\theta)}{G_{12}} + \frac{\sin^2(\theta)}{G_{23}} \tag{5.9}$$

$$\nu_{yx} = \nu_{21}\cos^2(\theta) + \nu_{32}\sin^2(\theta) \tag{5.10}$$

Here, the angle between the 1 and x axes is θ (see figure 5.2), for the case of braided sleeves the theta angle is 45°.

According to the Crimp model, it is also understood from the assumption of transverse isotropy of the filling yarn that

$$\nu_{12} = \nu_{13}$$

$$\frac{E_1}{\nu_{12}} = \frac{E_2}{\nu_{21}}$$

$$\nu_{23} = \nu_{32}$$

$$G_{23} = \frac{E_2}{2(1+\nu_{23})}$$

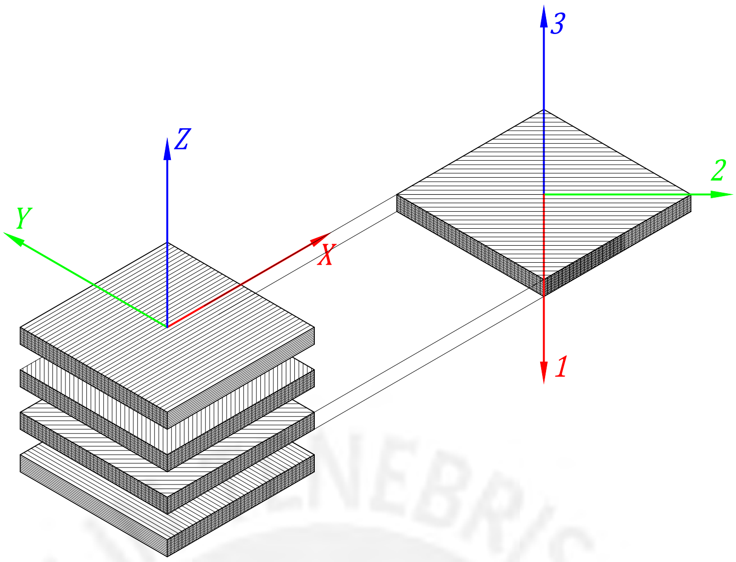


Figure 5.2: Coordinate systems applied in laminate and lamina [28].

The complete properties of laminates (composites of 8 layers) have been calculated taking into consideration the theory proposed in the books of Helmut Schürmann "Konstruieren mit Faser-Kunststoff-Verbunden", chapters 7, 8 and 9 [27], and Holm Altenbach "Mechanics of Composite Structural Elements", chapters 2, 3 and 4 [5]. To simplify the calculation effort of stiffness and compliance matrices and therefore the laminate properties it has been made use of the software "Advanced layerwise failure analysis of Laminates (AlfaLam)" of Thorsten Weber.

Finally, in table 5.6 values of calculated properties, for individual layers, are presented as specified in the preceding paragraphs, and table 5.7 shows the complete properties of laminates produced by torsion tests.

5.2.2 Experimental determination of shear moduli.

5.2.2.1 Review of the specialized literature.

As previously mentioned, the in-plane shear modulus is of primary importance because the analysis of volute springs mainly involves torsion loading which produces shear stresses. For this reason and in order to compare with the previously calculated theoretical values of shear modulus a combined experimental/analytical approach for effective evaluation of in-plane and out-of-plane shear moduli of laminates from torsion is presented in this subsection (the geometry of sets 1, 2, 3, 4, 5, 6, 7 and 8 can be seen in the appendix A).

The calculation of the in-plane and out-of-plane shear moduli have been determined under the considerations made by H. T. Sumsion and D. S. Rajapakse [52]. It should be mentioned that there are other authors who propose different

Table 5.6: Engineering constant values calculated with models based on simplifying assumptions "rule of mixtures" and empirical expression.

Property			Set 1 and Set 2 [a]	Set 3 and Set 4 [b]	Set 5	Set 6 [c]	Set 7	Set 8 [d]
Effective density	ρ	(g/cm^3)	1.738	1.408	1.703	1.380	1.377	1.728
Effective longitudinal modulus of elasticity	E_L	(GPa)	32.282	109.870	9.178	13.392	98.040	32.253
Effective transverse modulus of elasticity	E_T	(GPa)	8.139	9.111	7.925	7.944	7.944	8.346
Effective major Poisson's ratio	ν_{LT}		0.266	0.287	0.267	0.288	0.288	0.266
Effective minor Poisson's ratio	ν_{TL}		0.067	0.024	0.202	0.193	0.023	0.069
Effective in-plane shear modulus	G_{LT}	(GPa)	3.485	3.889	3.167	3.138	3.397	3.572
Effective transversal-transversal Poisson's ratio	ν_{TT}		0.333	0.355	0.335	0.362	0.362	0.331
Effective out-of-plane shear modulus	G_{TT}	(GPa)	2.618	2.908	2.968	2.916	2.616	2.746

[a] Set 1 and Set 2 are glass fiber laminates with orientation $[0°/+45°/-45°/0°]_s$
[b] Set 3 and Set 4 are carbon fiber laminates with orientation $[0°/+45°/-45°/0°]_s$
[c] Set 5 and Set 6 are glass and carbon fiber strips respectively produced with braided sleeves with an orientation $[+45°/-45°/+45°/-45°]_s$
[d] Set 7 and Set 8 are carbon and glass fiber laminates respectively with orientation $[+45°/-45°/+45°/-45°]_s$

approaches to calculate such shear moduli, for example, G. Yaniv, I. M. Daniel, and C.-L. Tsai propose a closed-form solution for a general orthotropic laminate, based on the Mindlin-Reissner theory [53]. They propose an experimental procedure (torsion test of rectangular laminates), insensitive to end effects, which gives two shear moduli with one specimen only. However, their model requires a complex assembly of strain gages on the surface and edge of specimens in order to obtain the value of shear forces and twist angles that are involved in its equations. R. D. Kurtz and C. T. Sun propose a simple experimental procedure for determining shear moduli and strengths by using thick rectangular composite coupons (6.35 mm and 12.7 mm thick) in a torsion test and then making the data reduction with the Lekhnitskii theory [54], but their model requires the manufacture of pairs of specimens whose orientation of fibers of one specimen, in each layer, should be perpendicular to fibers of the other specimen. Furthermore, this model is only recommended to the unidirectional composite specimens, such as the [0], [90] and cross-plied laminates. Davalos et al. propose an approach in which the shear moduli are evaluated through

Table 5.7: Complete engineering constant values to laminates calculated with the software AlfaLam©

Property			Set 1 and Set 2 [a]	Set 3 and Set 4 [b]	Set 5	Set 6 [c]	Set 7	Set 8 [d]
Effective longitudinal modulus of elasticity	$E_{L,Zug}$	(GPa)	26.89	75.55	10.37	13.08	12.09	10.90
Effective longitudinal modulus of elasticity	$E_{L,Biegung}$	(GPa)	29.32	88.70	14.36	32.95	30.73	15.04
Effective transverse modulus of elasticity	$E_{T,Zug}$	(GPa)	9.50	15.88	10.37	13.08	12.09	10.90
Effective transverse modulus of elasticity	$E_{T,Biegung}$	(GPa)	9.59	15.24	14.36	32.95	30.73	15.04
Effective in-plane shear modulus	$G_{LT,Schub}$	(GPa)	4.95	12.87	8.81	27.20	25.37	9.21
Effective in-plane shear modulus	$G_{LT,Torsion}$	(GPa)	4.61	10.92	8.81	27.20	25.37	9.21

[a] Set 1 and Set 2 are glass fiber laminates with orientation $[0°/+45°/-45°/0°]_s$
[b] Set 3 and Set 4 are carbon fiber laminates with orientation $[0°/+45°/-45°/0°]_s$
[c] Set 5 and Set 6 are glass and carbon fiber strips respectively produced with braided sleeves with an orientation $[+45°/-45°/+45°/-45°]_s$
[d] Set 7 and Set 8 are carbon and glass fiber laminates respectively with orientation $[+45°/-45°/+45°/-45°]_s$

using paired samples with material orientations normal to each other and using the torsion solutions by Lekhnitskii [55] and Whitney [56] as data-reduction methods to obtain the shear moduli [57]. This method is similar to Kurtz's method but is exclusively oriented to thick laminates since its priority is to obtain the out-of-plane shear modulus so that for the present work is not of interest because it is working with thin laminates for which plane stress is often assumed and only in-plane elastic constants are needed.

There are other types of tests to determine shear moduli such as ultrasonic evaluation of lamina properties [58], torsion of cylindrical rods [59], a test technique that uses split rings [60], and a test that subjects a circular ring to torsion [61]. These methods give good results but involve the production of complex specimens. Furthermore, they also require a complex assembly to perform the tests.

Therefore, the Sumsion's method is a good shear test method that is easy to run, requires no complex specimens preparation, gives reproducible results, and provides all shear properties. To that effect, the method suggested by this author allows the determination of two shear moduli of a homogeneous, orthotropic material in the shape of a rectangular parallelepiped and from torsion tests performed on specimens of the same material having a minimum of two different cross sections (flat sheet of different widths), the effective in-plane and out-of-plane shear moduli can be determined.

5.2.2.2 Tests, measurements, and calculation of shear moduli.

Torsion tests were performed under controlled deflection (twist angle) using a TIRA model 2810 machine equipped with devices to hold one end of the specimen and produce twist at the other end (see figure 5.3). The output of both the torque and twist angle were recorded using electronic sensors connected through an interface to a computer in which, employing its respective software, the torque versus twist angle graph was automatically obtained.

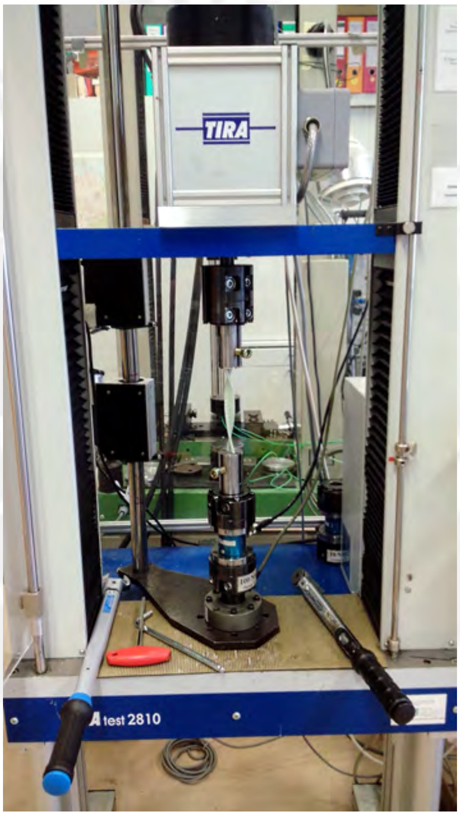


Figure 5.3: Torsion machine with TIRA model 2810 for testing specimens with rectangular cross sections.

For each specimen tested until breaking, the torque and twist angle were recorded and stored in an excel format file. With these data a representative torque versus twist angle graph was made for each specimen, figures B.1 to B.8, in appendix B, show these graphs.

About shear moduli calculation, Sumsion and Rajapakse suggest that, in the case of torsion of laminated rectangular specimens, it is more appropriate to use the formulas for torsion of an orthotropic rectangular bar (see figure 5.4) [55]. Therefore, for a linearly elastic orthotropic rectangular parallelepiped, the relationship between the applied torque and twist angle is that shown in equation 5.11.

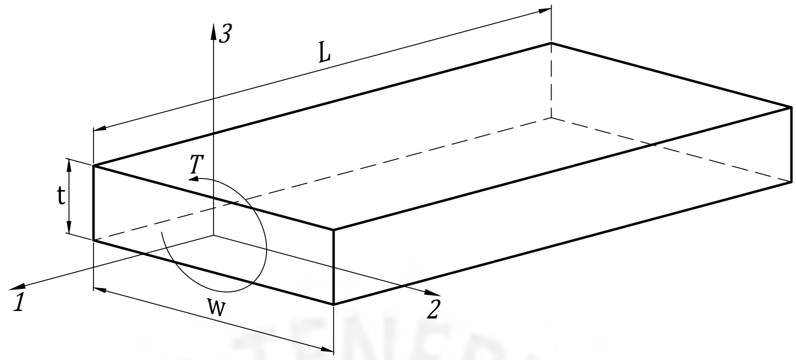


Figure 5.4: Test specimen (schematic).

$$T = G_{12} \cdot \beta \cdot w \cdot t^3 \cdot \frac{\theta}{L} \qquad \text{or} \qquad G_{12} = \frac{T \cdot L}{\theta \cdot \beta \cdot w \cdot t^3} \tag{5.11}$$

Where

$$\beta = \frac{32}{\pi^4} \cdot \left(\frac{w}{t} \sqrt{\frac{G_{13}}{G_{12}}} \right)^2 \cdot \sum_{n=1,3,\ldots}^{\infty} \frac{1}{n^4} \cdot \left[1 - \frac{2}{n\pi} \cdot \left(\frac{w}{t} \sqrt{\frac{G_{13}}{G_{12}}} \right) \cdot \tanh\left(\frac{n\pi}{2} \cdot \frac{t}{w} \sqrt{\frac{G_{12}}{G_{13}}} \right) \right]$$

Here G_{12} is the in-plane shear modulus and G_{13} the out-of-plane modulus. Since β depends on the two ratios (w/t) and (G_{12}/G_{13}), equation 5.11 involves both shear moduli G_{12} and G_{13}.

To obtain shear moduli from torsion solution by Lekhnitskii (equation 5.11), it should be determined the (T/θ) values for at least two specimens with distinct dimensions of the cross section. In this work, specimens with these geometric characteristics and the same material orientations were paired (see tables A.1 to A.8).

Therefore, equation 5.11 is rewritten for each specimen as it shows in equations 5.12a and 5.12b.

$$\beta_1 = \frac{T_1 \cdot L_1}{G_{13} \cdot w_1 \cdot t_1^3 \cdot \theta_1} \tag{5.12a}$$

$$\beta_2 = \frac{T_2 \cdot L_2}{G_{13} \cdot w_2 \cdot t_2^3 \cdot \theta_2} \tag{5.12b}$$

and β_1 and β_2 are expressed in equations 5.12c and 5.12d.

$$\beta_1 = \frac{32}{\pi^4} \left(\frac{w_1}{t_1} \sqrt{\frac{G_{13}}{G_{12}}} \right)^2 \sum_{n=1,3,\ldots}^{\infty} \frac{1}{n^4} \left[1 - \frac{2w_1}{n\pi t_1} \sqrt{\frac{G_{13}}{G_{12}}} \tanh\left(\frac{n\pi t_1}{2w_1} \sqrt{\frac{G_{12}}{G_{13}}} \right) \right] \tag{5.12c}$$

$$\beta_2 = \frac{32}{\pi^4}\left(\frac{w_2}{t_2}\sqrt{\frac{G_{13}}{G_{12}}}\right)^2 \sum_{n=1,3,\ldots}^{\infty} \frac{1}{n^4}\left[1 - \frac{2w_2}{n\pi t_2}\sqrt{\frac{G_{13}}{G_{12}}}\tanh\left(\frac{n\pi t_2}{2w_2}\sqrt{\frac{G_{12}}{G_{13}}}\right)\right] \tag{5.12d}$$

Both equations 5.12a and 5.12b need to be solved simultaneously, and to simplify the computational effort it divides equation 5.12c by equation 5.12d, resulting in equation 5.13.

$$\frac{T_1\, L_1\, t_2\, w_2^3\, \theta_2}{T_2\, L_2\, t_1\, w_1^3\, \theta_1} = \frac{\sum_{n=1,3,\ldots}^{\infty} \frac{1}{n^4}\left[1 - \frac{2w_1}{n\pi t_1}\sqrt{\chi}\tanh\left(\frac{n\pi t_1}{2w_1}\sqrt{\frac{1}{\chi}}\right)\right]}{\sum_{n=1,3,\ldots}^{\infty} \frac{1}{n^4}\left[1 - \frac{2w_2}{n\pi t_2}\sqrt{\chi}\tanh\left(\frac{n\pi t_2}{2w_2}\sqrt{\frac{1}{\chi}}\right)\right]} \tag{5.13}$$

where

$$\chi = \frac{G_{13}}{G_{12}}$$

Now, there is only one unknown, χ, in equation 5.13, and by solving for χ using a program made in Matlab software, it can obtain the in-plane (G_{12}) and out-of-plane (G_{13}) shear moduli as it shows in equations 5.14a and 5.14b.

$$G_{13} = \frac{\pi^4}{32}\cdot\frac{T_1\, L_1}{w_1^3\, t_1\, \theta}\cdot\frac{1}{\sum_{n=1,3,\ldots}^{\infty} \frac{1}{n^4}\left[1 - \frac{2w_1}{n\pi t_1}\sqrt{\chi}\tanh\left(\frac{n\pi t_1}{2w_1}\sqrt{\frac{1}{\chi}}\right)\right]} \tag{5.14a}$$

$$G_{12} = \frac{G_{13}}{\chi} \tag{5.14b}$$

Finally, tables C.1 to C.8, in appendix C, presents the results for the paired specimens with different cross section dimensions according to data shown in tables A.1 to A.8. To calculate the shear moduli, three twist angles have been taken (12.5°, 25° and 50°) with their respective torques of data recorded for each pair of specimens. These values are chosen because they are in an approximately linear zone as can be seen in figures B.1 to B.8.

5.2.3 Comparison between theoretical and experimental results.

Table 5.8 shows the comparison between shear modulus averages experimentally obtained and theoretical shear moduli calculated according the theory of authors Altenbach [5] and Schürmann [27].

Table 5.8: Comparison between experimental and theoretical results of the in-plane and out-of-plane shear moduli using Lekhnitskii's solution.

		Experimental average values						Theoretical values
		Pair 1	Pair 2	Pair 3	Pair 4	Pair 5	Pair 6	
Set 1	G_{12}	4.38	4.54	4.74	3.82	4.40	3.72	4.61
	G_{13}	0.686	0.530	0.396	1.51	0.933	1.78	2.618
Set 2	G_{12}	6.66	6.22	7.42	5.94	6.73	6.38	4.61
	G_{13}	0.190	0.245	0.129	0.299	0.193	0.241	2.618
Set 3	G_{12}	10.10	10.62	9.94	12.25	10.84	13.12	10.92
	G_{13}	0.244	0.030	0.085	0.042	0.076	0.050	2.908
Set 4	G_{12}	13.00	13.59	12.42	13.42	13.24	13.35	10.92
	G_{13}	0.062	0.045	0.046	0.058	0.049	0.052	2.908
Set 5	G_{12}	6.83	6.79	7.30	6.65	5.48	–	8.81
	G_{13}	0.192	0.111	0.276	0.347	0.244	–	2.968
Set 6	G_{12}	14.01	17.65	15.24	22.63	25.48	–	27.20
	G_{13}	0.375	0.183	0.198	0.098	0.085	–	2.916
Set 7	G_{12}	20.98	25.15	24.82	22.30	17.52	–	25.37
	G_{13}	0.014	0.011	0.017	0.023	0.024	–	2.616
Set 8	G_{12}	6.73	7.30	7.06	6.42	6.69	7.08	9.21
	G_{13}	1.05	0.132	1.80	0.176	0.148	0.141	2.746

As can be seen in table 5.8, the in-plane shear modulus experimentally obtained is much greater than the out-of-plane shear modulus, therefore, it can be concluded that the Sumsion's method to calculate both shear moduli widely underestimates out-of-plane shear moduli. However, since thin laminates are used in this work, values of out-of-plane shear moduli are not of primary interest because, as it mentioned above, it is often assumed plane stress state so that it is of greater interest to determine only the elastic constants in the plane.

5.3 Analysis of volute spring behavior

In this section, the theoretical calculation of volute spring stiffness is performed first. Secondly, compression tests are conducted to obtain practical results on spring stiffness. Finally, the theoretical and practical results are contrasted to demonstrate whether the approach presented is correct or not.

5.3.1 Geometry of volute springs

Over time, several authors (M. Meissner, H. Schorcht and U. Kletzin [41], S. Gross [40], A. M. Wahl [42], N. P. Chironis [62] and C. Reynal [63]) have studied steel volute springs, establishing relationships that allow the calculation of spring geometry. Therefore, if the idea of studying and producing volute springs made of composite materials is to replace, to some extent, steel springs for lighter weight in equipment or devices where they are included then the same relations, developed by the aforementioned authors, will be used to calculate the geometry of fiber reinforced plastic volute springs.

Since fiber reinforced plastic volute springs consist essentially of a relatively wide and relatively thin laminate, which is wound to form the shape shown in cross-section in figure 4.3, it is necessary to know the width, length and thickness of said strips which will form the spring.

5.3.1.1 Width of the fiber strips.

The width of strips is determined according to width to be achieved with braided sleeves in such a way that the fibers have an orientation of +⁄- 45°, then, according to catalog product of Lange Ritter company the suggested width, for such braided sleeves, is shown in table 5.9 [46]. The widths of unidirectional fiber fabric strips shall be equal to widths of braided sleeves.

Table 5.9: Widths of glass and carbon fiber braided sleeves [46].

Product	Yarn count (Tex)	Width (mm)			Diameter (mm)		
		min.	45°	max.	min.	45°	max.
962111	EC-272	10	39	55	8	25	35
642100	CF-200	10	34	47	6	22	30

5.3.1.2 Length of fiber strips.

To calculate the length of fiber strips, it will describe some concepts related to the determination of the equation to calculate the strip length.

Therefore, the “directrix surface” is defined as the revolution surface which has as generatrix a line that would join the centroids of cross sections located in the same axial plane, as indicated in figure 5.5. It should be taken into account that results of length calculation of these springs are difficult to predict accurately since there is an important difference between the practical realization thereof and hypotheses that serve as the basis for establishing theoretical formulas.

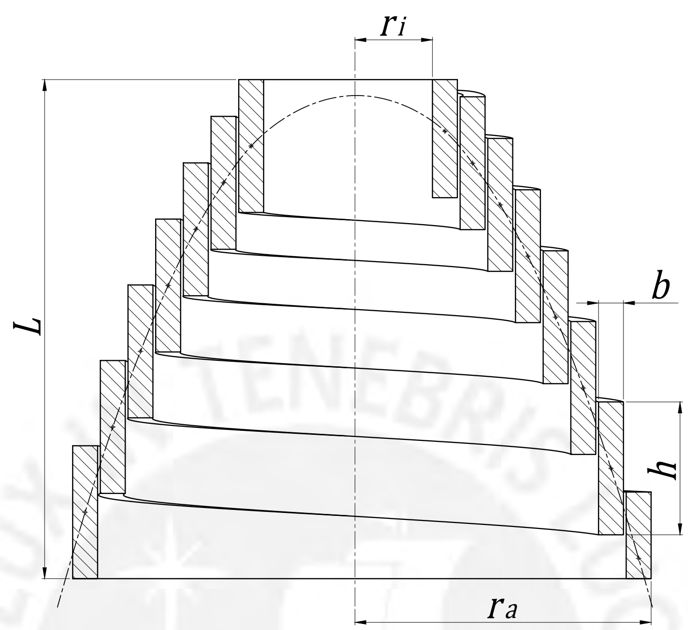


Figure 5.5: Section of volute spring with its generatrix (schematic) [63].

Figure 5.5 shows a section view of volute spring, which has a constant helix angle relative to a perpendicular plane to the axis of spring. This results in a pitch that varies (along the entire length of the spring) with the value of coil radius of each centroid. Moreover, to reduce the total apparent volume of volute spring, maintaining certain conditions of load and flexibility, a uniform gap is often established between the turns. Under these conditions, the winding surface of the neutral fiber is a revolution surface that at any point the coil radius is proportional to the angle described up to this point from the vertex of cone considered as the origin of winding. It will result in a surface whose equation is easy to establish.

Therefore, since the gap between coils is constant, the neutral fiber projection on a perpendicular plane to the spring axis will be a curve in which equation 5.15 is verified (see figure 5.6).

$$\frac{r-r'}{\omega-\omega'} = constant = m = \frac{r}{\omega} = \frac{r'}{\omega'} \tag{5.15}$$

Where

$$r = m \cdot \omega \tag{5.16}$$

Equation 5.16 is the equation of an Archimedean spiral.

In order to calculate the length of the Archimedean spiral it must be taken into account that, if the function is defined by polar coordinates where the radial coordinates and polar angle are related by $r = f(\theta)$, the arc length in the range

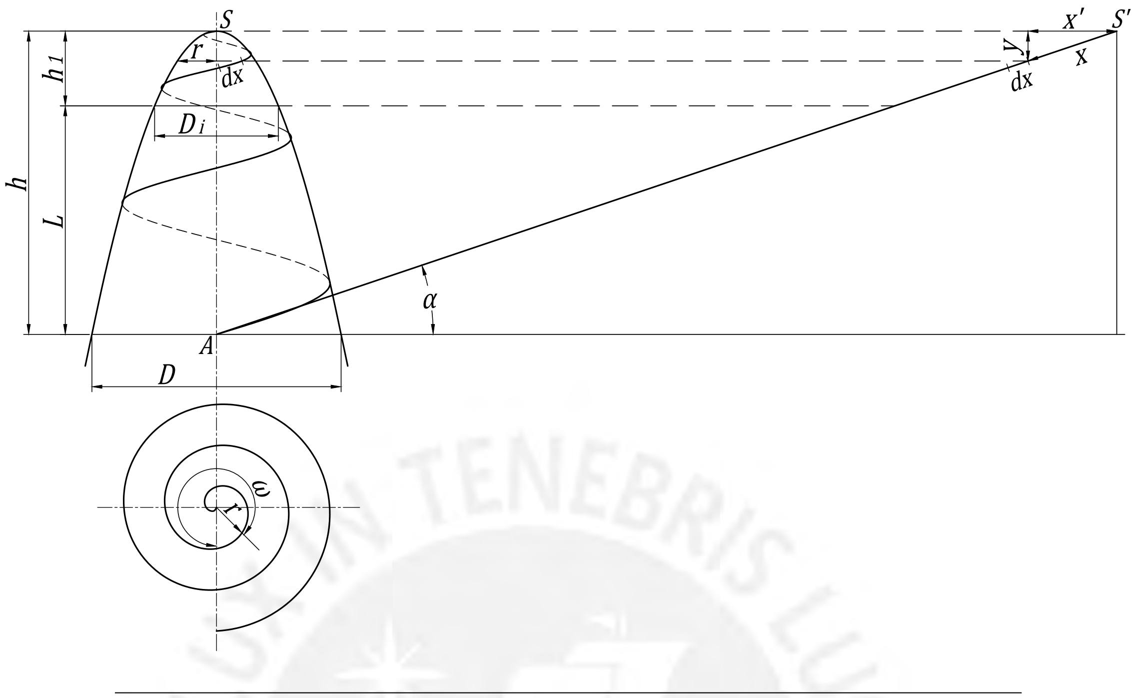


Figure 5.6: Parabolic spring drawing with constant helix angle [63].

$[\alpha, \beta]$, takes the form of equation

$$s = \int_{\alpha}^{\beta} \sqrt{|f(\theta)|^2 + |f'(\theta)|^2}\, d\theta \tag{5.17}$$

If $f(\theta) = r = m \cdot \omega$ and $f'(\theta) = \dfrac{dr}{d\omega} = m$ and replacing these values in equation 5.17 it gives equation 5.18.

$$s = \int_{\alpha}^{\beta} \sqrt{(m \cdot \omega)^2 + m^2}\, d\omega \tag{5.18}$$

Thus, solving this latter equation and taking as integral limits $\alpha = 0$ and $\beta = \omega$, it obtains the developed length of Archimedean spiral from center to any point (see equation 5.19).

$$x' = \frac{m}{2} \cdot [\omega\sqrt{1+\omega^2} + \ln(\omega + \sqrt{1+\omega^2})] \tag{5.19}$$

To calculate the length of strips to manufacture fiber reinforced plastic volute springs it is necessary to know the general equation of Archimedean spiral (equation

5.20) for the particular case of these springs.

$$r = a + m \cdot \omega \tag{5.20}$$

Equation 5.20 is different from equation 5.16 because the spiral does not start from the origin but from inner radius of springs. Therefore, r is the distance from the origin to any point of spiral, a is the start point of the spiral and m affects the distance between each arm (the total angle turned by the spiral in radians is given by $2\pi m$, so the distance between each arm is $2\pi m$ divide by the number of turns).

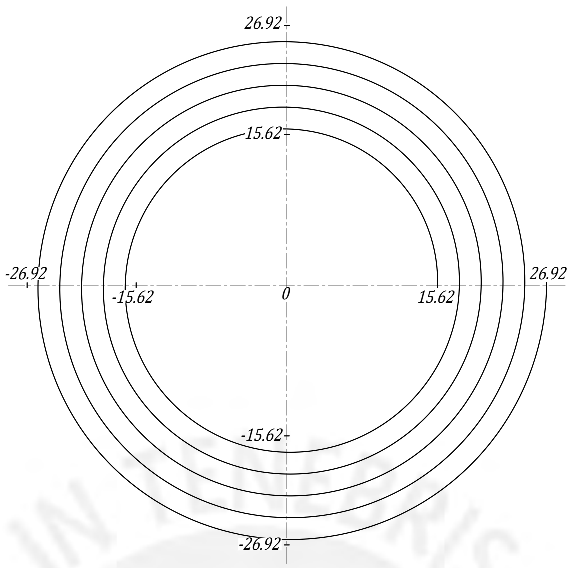
In this work, a is equal to the smaller radius of molds (figures 5.7) used to produce springs and $2\pi m$ is equal to the increase in radius per turn according to the spiral projected in a perpendicular plane to the mold axis (figure 5.8). In table 5.10 values for a and m can be seen and in the last column it can be seen the general Archimedean spiral equation for each mold.

(a)

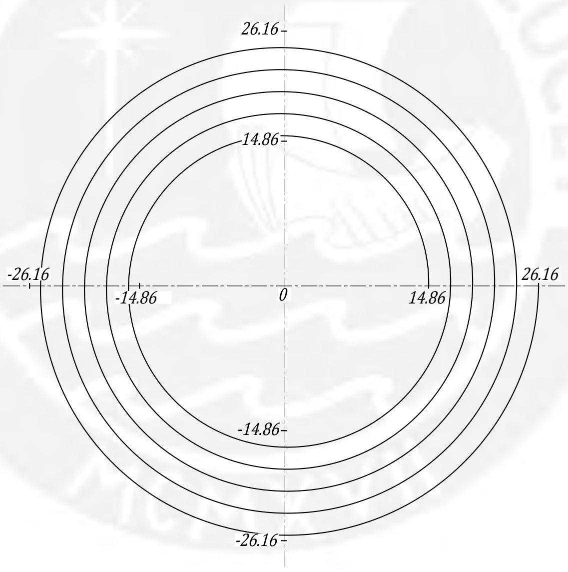
(b)

Figure 5.7: Molds used to produce volute springs: (a) with smaller diameter of $31.24mm$ and (b) with smaller diameter of $29.72mm$.

Equations of table 5.10 and their respective derivatives are replaced into equation 5.17 to obtain the necessary length of fiber fabric strips (Table 5.11). For practical purposes fiber fabric strips of length of $700\,mm.$ are used.



(a)



(b)

Figure 5.8: Archimedean spirals: (a) Inner radius of 15.62 mm, outer radius of 26.92 mm and distance between each arm of 2.26 mm, (b) Inner radius of 14.86 mm, outer radius of 26.16 mm and distance between each arm of 2.26 mm

5.3.1.3 Thickness of fiber strips.

The thickness of laminates can be calculated in a predictive way considering the total number of layers (fiber fabric strips) and the quantity of resin that is used to produce each spring from either glass or carbon fibers. Thus, it proceeds as follows:

Table 5.10: Characteristics of molds used to produce volute springs.

	Inner radius (*mm.*)	Outer radius (*mm.*)	increase in radius per turn (*mm.*)	a -	m -	spiral equation -
Mold 1	15.62	26.92	2.26	15.62	0.3596902	$r = 15.62 + 0.36\,\omega$
Mold 2	14.86	26.16	2.26	14.86	0.3596902	$r = 14.86 + 0.36\,\omega$

Table 5.11: Integral and length of fiber fabric strips

	α (*rad.*)	β (*rad.*)	Integral -	Length (*mm.*)
Mold 1	0	10π	$\int_0^{10\pi} \sqrt{(15.62 + 0.36\,\omega)^2 + (0.36)^2}\ d\omega$	668.5
Mold 2	0	10π	$\int_0^{10\pi} \sqrt{(14.86 + 0.36\,\omega)^2 + (0.36)^2}\ d\omega$	644.6

- First, the area of each fiber strip is calculated and then this value is multiplied by the total number of strips that will make up the laminate.
- Second, it calculates the total fiber and resin volumes (approximate value) used in the manufacturing process.
- Third, the fiber volume fraction according to equation 2.2 is calculated.
- Fourth, the thickness is calculated according to equation 5.21.

$$t_{lam} = n \cdot \frac{Weight_{fiber}}{\phi_{fiber} \cdot density_{fiber}} \tag{5.21}$$

In the present work, six volute springs have been produced according to the configurations (number of layers and type of fiber orientations) of the flat laminates that were produced for torsion tests which have been described and analyzed in the previous subsection. Then, table 5.12 shows the calculation of fiber volume fraction and table 5.13 shows the thickness calculation. Nevertheless, It should be pointed out that these results are approximate values because the quantity of mixture mass (resin and curing agent) is approximate due to in practice a greater quantity of this mixture is prepared.

5.3.1.4 Useful equations for spring geometry.

Some useful equations are presented below , related to the spring geometry, which will then allow the calculation of stiffness and deflection of volute spring [41]. All variables of those equations are based on the geometry established in figure 5.9.

- Mean coil radius at the beginning of the active portion of the spring.

$$r_{Kn} = r_i + 0.5 \cdot (n_g - n_f) \cdot (t + \Delta a) + 0.5 \cdot t \tag{5.22}$$

- Mean coil radius at the end of the active portion of the spring.

$$r_{K1} = r_{Kn} + n_f \cdot (t + \Delta a) \tag{5.23}$$

- Coil outer radius

$$r_a = r_i + n_g \cdot (t + \Delta a) \tag{5.24}$$

- Free length of volute spring (generally $s_c = s_n$)

$$L_0 = s_c + b \tag{5.25}$$

- Block or solid length and spring deflection until the blocking state is reached.

$$L_c = L_0 - s_c = b \tag{5.26}$$

$$s_c = s_n = L_0 - L_c \tag{5.27}$$

Table 5.12: Calculation of fiber volume fraction of fabric strips

Name, material and configuration	Strip dimensions $(mm\,x\,mm)$	Individual area (mm^2)	Number of layers -	Total area (mm^2)	Weight (g/m^2)	Fiber mass (g)	Fiber density (g/cm^3)	Fiber volume (cm^3)	Resin mass (g)	Resin density (g/cm^3)	Resin volume (cm^3)	Fiber volume fraction -
Spring 1, carbon fiber, $[0°/+45°/-45°/0°]_s$	34×700	23 800	0° ⟶ 4 45° ⟶ 2	95 200 47 600	130 150	12.38 7.14	1.78 1.78	6.95 4.01	18.90	1.108	17.05	0.40
Spring 2, carbon fiber, $[+45°/-45°/+45°/-45°]_s$	34×700	23 800	4	95 200	150	14.28	1.78	8.02	12.60	1.108	11.37	0.41
Spring 3, carbon fiber, braided sleeve laminate	34×700	23 800	2	47 600	479.30	22.82	1.78	12.83	18.90	1.108	17.06	0.43
Spring 4, glass fiber, braided sleeve laminate	39×700	27 300	2	54 600	830.77	45.36	2.57	17.68	25.20	1.108	22.74	0.44
Spring 5, glass fiber, $[0°/+45°/-45°/0°]_s$	39×700	27 300	0° ⟶ 4 45° ⟶ 2	109 200 54 600	440 300	48.05 16.38	2.61 2.57	18.45 6.39	31.50	1.108	28.43	0.47
Spring 6, glass fiber, $[+45°/-45°/+45°/-45°]_s$	39×700	27 300	4	109 200	300	32.76	2.57	12.77	18.90	1.108	17.06	0.43

Table 5.13: Calculation of laminate thicknesses to produce springs

	Number of layers	Weight	Fiber volume fraction	Fiber density	Individual thickness	Total thickness
	-	$^{g}/_{m^2}$	-	$^{g}/_{cm^3}$	(mm)	(mm)
Spring 1	0° ⟶ 4 45° ⟶ 2	130 150	0.40	1.78	0.73 0.42	1.15
Spring 2	4	150	0.41	1.78	-	0.85
Spring 3	2	479.30	0.43	1.78	-	1.25
Spring 4	2	830.77	0.44	2.57	-	1.47
Spring 5	0° ⟶ 4 45° ⟶ 2	440 300	0.47	2.61 2.57	1.44 0.50	1.94
Spring 6	4	300	0.43	2.51	-	1.10

5.3.2 Calculation and analysis of volute spring stiffness

In this subsection, a theoretical and practical procedure is presented to determine and analyze the behavior of volute spring stiffness.

5.3.2.1 Considerations about laminates.

It is necessary to consider the following aspects, according to Altenbach [5] and Schürmann [27], referring to the fiber reinforced laminates, to perform the calculation and analysis of stiffness.

- At a macro-mechanical level laminates are considered as an equivalent single layer element with a quasi-homogeneous, orthotropic material behavior. This behavior is typical for unidirectional laminae with on-axis loading [5].
- For this application (volute springs) the laminates are simplified models by reducing the three-dimensional state of stress approximately to a two-dimensional plane stress state. Therefore, in a plane stress state, all components in the out-of-plane direction are approximately zero [5], [27].
- There is a uniform bonding of all laminae, in other words, there is no slip between laminae at their interface, and no special interface layers are arranged between the angle plies [5].
- And finally, the strains and displacements are continuous throughout the laminate. The in-plane displacements and strains vary linearly through the laminate thickness [27].

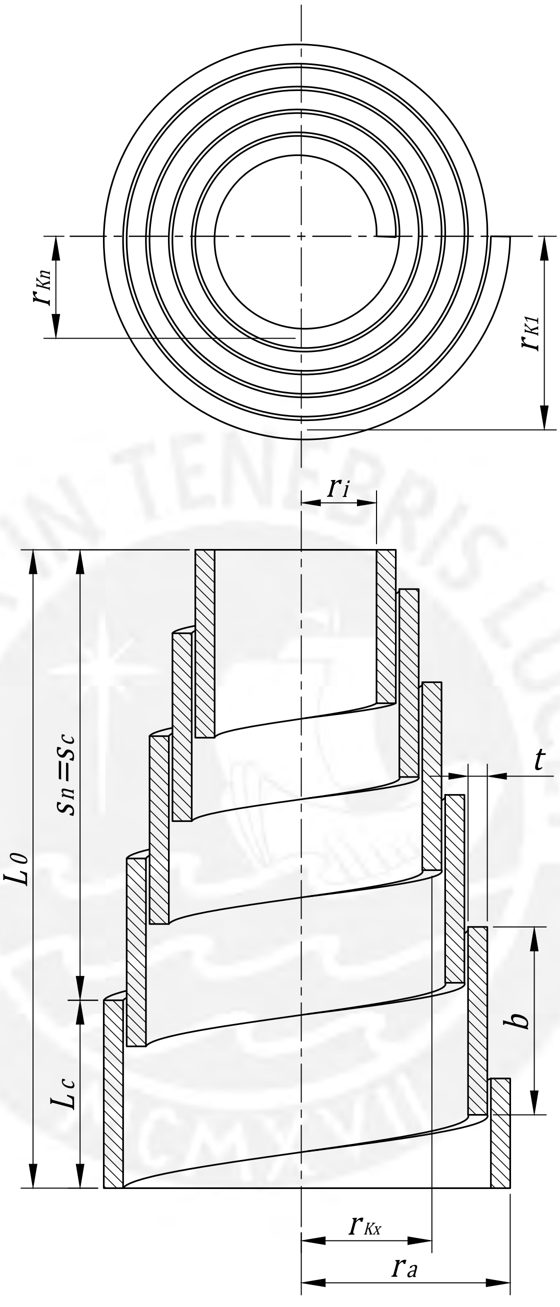
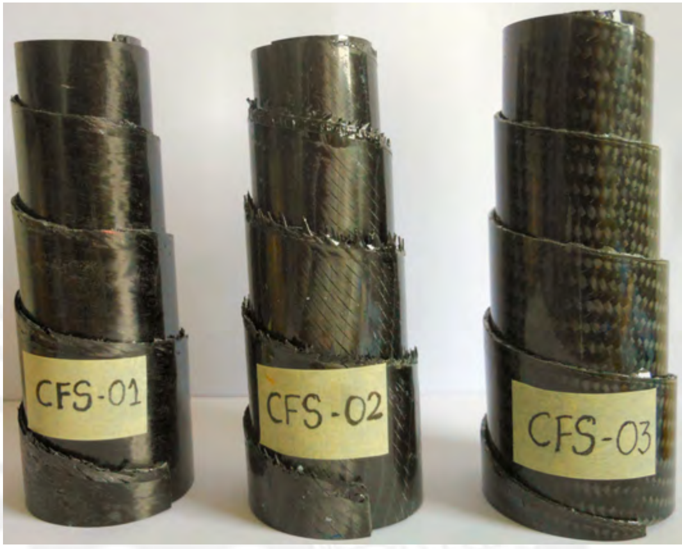


Figure 5.9: Section and top view with descriptions of volute spring [41].

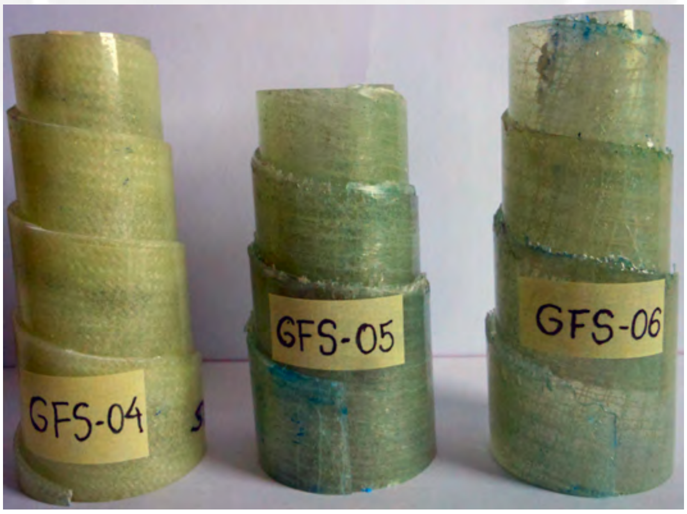
5.3.2.2 Theoretical/experimental analysis of the volute springs.

A goal of producing glass and carbon fiber reinforced plastic volute springs is to provide an alternative to fiber reinforced plastic helical springs because these springs require a complicated manufacturing process and the calculation of them is arduous. Moreover, a secondary goal is to replace volute steel springs to reduce the weight and at the same time perhaps obtain similarly or the same spring properties.

Therefore, it is proposed, in the present work, to carry out the analysis of fiber reinforced plastic volute springs using the same analytical calculations used for steel springs but considering the effect of fiber orientation on the shear modulus and finally on the spring rate. It should be mentioned that, to compare theoretical analytical results, six glass and carbon fiber volute springs have been manufactured and tested under compressive load (figures 5.10(a) and 5.10(b)).



(a)



(b)

Figure 5.10: Carbon (a) and glass (b) fiber reinforced plastic volute springs.

5.3.2.2.1 Theoretical procedure.

The Theoretical procedure that can be used to calculate a spring that already exists is as follows [41]:

- Basic geometric variables such as the coil inner radius r_i, the total coils n_g, the number of active coils n_f (here it is considered that, the springs have plain ends and ground so that $n_g = n_f + 1$), the gap between turns Δa, the free length (which can be calculated with $L_0 = L_{strip} \cdot \sin(\alpha)$ considering the geometry of figure 5.6) and the spring deflection until reaching the block state s_c are determined.

- Spring behavior evaluation: Since in the load-displacement diagram of volute springs the characteristic line is of the progressive type then the calculation of the displacement of volute springs can be divided into two zones, the first zone being linear and covers from the free length until the spring displacement (s_{x1}) is approximately $0.6s_c$, and the second zone being non-linear and covers from this last position until the spring displacement reaches the blocked state. Therefore, the linear part of the characteristic line can be represented by the load-deflection relationship 5.28, where F_{x1} and s_{x1} are force and displacement variables within the linear range of this characteristic line [41].

$$F_{x1} = q_3 \cdot \frac{2\, G_{12}\, b\, t^3}{\pi\, n_f\, (r_{K1} + r_{Kn})\, (r_{K1}^2 + r_{Kn}^2)} \cdot s_{x1} \tag{5.28}$$

  Where the factor q_3 can be approximated according to equation 5.29, for a width to thickness ratio of strips of $\beta_t = \dfrac{b}{t} > 3$.

$$q_3 = \frac{\beta_t - 0.63}{3\, \beta_t} \tag{5.29}$$

- The non-linear part of the characteristic line of volute spring can be represented as follows:

  - The mean coil radius r_K of elastic coils is calculated (in the range $r_{K1} \geq r_{Kx} \geq r_{Kn}$) with

$$r_{Kx} = r_{Kn} + m\, (r_{K1} - r_{Kn}) \tag{5.30}$$

    Where the factor m is divided into intervals Δm within the range $1 \geq m \geq 0$. For $m = 1$ then $r_{Kx} = r_{K1}$ and $F_x = F_1$ and for $m = 0$ then $r_{Kx} = r_{Kn}$ and $F_x = F_n$.

  - With r_{Kx}, the associated spring displacements s_x are calculated according to equation 5.31.

$$s_x = s_{ax} + s_{bx} \tag{5.31}$$

Where

$$s_{ax} = \frac{r_{K1}^2 - r_{Kx}^2}{r_{K1}^2 - r_{Kn}^2} \cdot s_n \tag{5.32}$$

and

$$s_{bx} = \frac{(r_{Kx}^2 + r_{Kn}^2)\,(r_{Kx}^2 - r_{Kn}^2)}{2\,r_{Kx}^2(r_{K1}^2 - r_{Kn}^2)} \cdot s_n = \frac{r_{Kx}^4 - r_{Kn}^4}{2\,r_{Kx}^2(r_{K1}^2 - r_{Kn}^2)} \cdot s_n \tag{5.33}$$

In this equation, the spring displacement s_a is produced in the range between r_{K1} and r_{Kx} by "closing" of coils and the spring displacement s_b from the remaining active coils between r_{Kx} and r_{Kn}.

- The spring force within the non-linear part of spring characteristic line is calculated according to equation 5.34.

$$Fx = q_3 \cdot \frac{G_{12}\,b\,t^3}{\pi\,r_{Kx}^2\,n_f\,(r_{K1} + r_{Kn})} \cdot s_n \tag{5.34}$$

- The maximum shear stress after all coils reached the blocking state is calculated wit equation 5.35.

$$\tau_{max} = \frac{F_n\,r_{Kn}}{q_2\,b\,t^2} \tag{5.35}$$

Where the factor $q_2 = q_3$

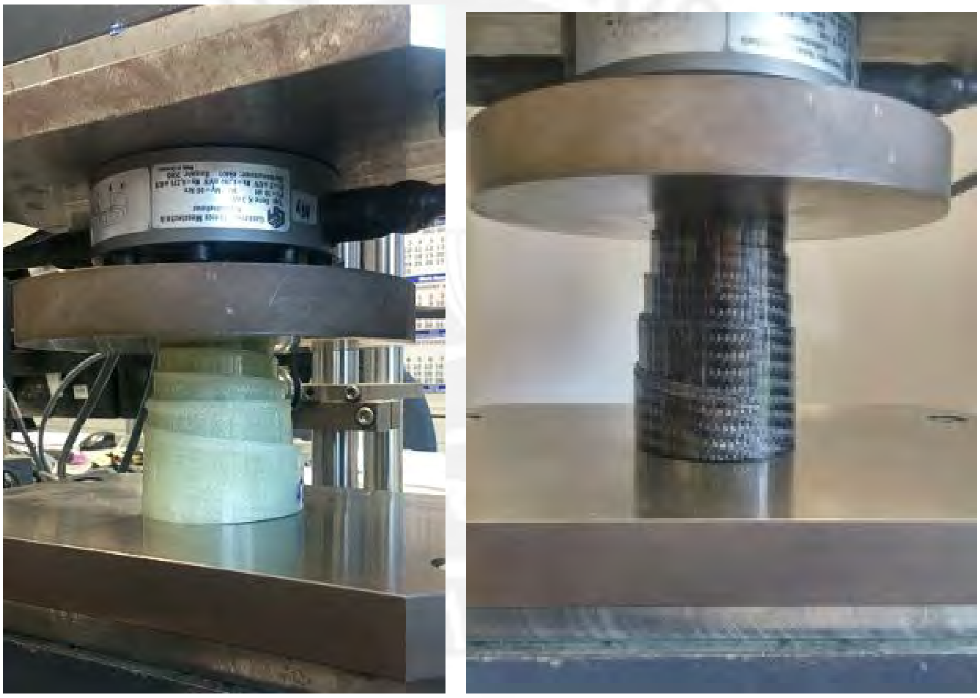
Tables D.1 and D.2, in appendix D, show the numeric values of variables that have been used to determine characteristic spring curves according to the procedure mentioned above.

5.3.2.2.2 Experimental procedure.

Before starting the experimental procedure, three carbon fiber volute springs and three glass fiber volute springs were manufactured (Figure 5.10). Strips of symmetrical laminates were used, the stacking sequence and fiber orientation are equal to the flat laminates used for the torsion tests (see section 5.2). The method used to manufacture the springs is described in the subsection 4.3.1.

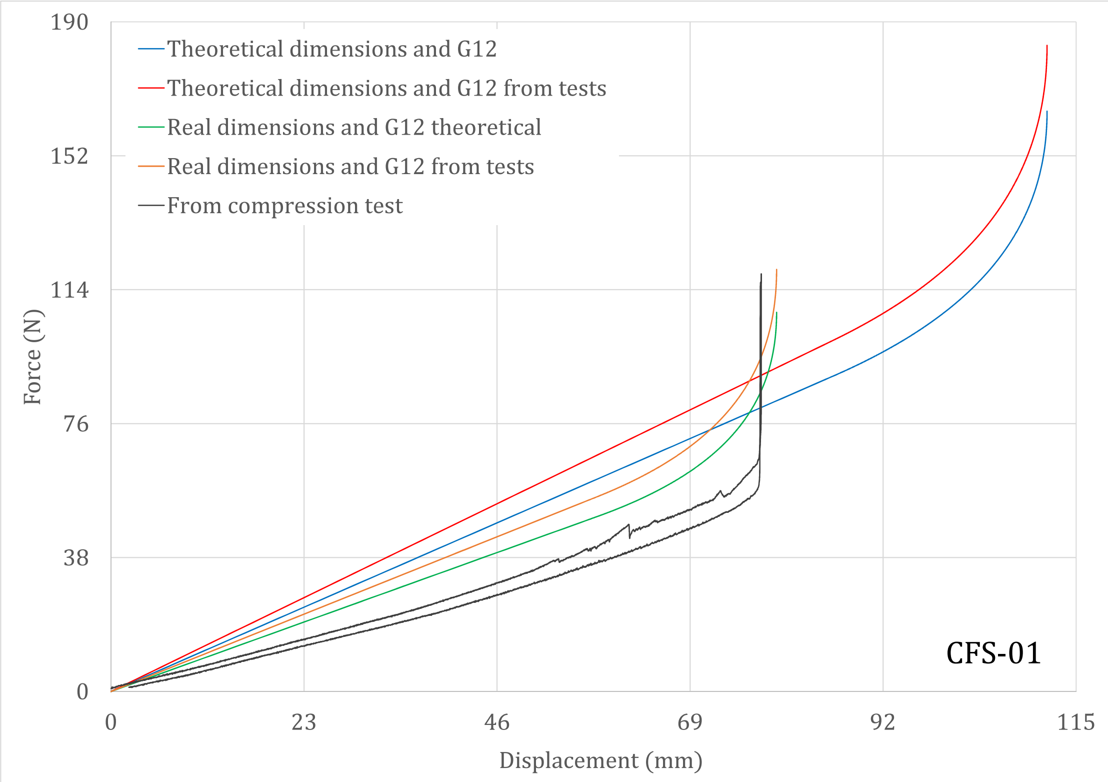
Compression tests were carried out by controlling the compression force on the springs using a universal testing machine model Zwick 1446. This machine is equipped with a fixed base on which the spring is placed and an upper platform that moves vertically, which exerts a compressive load on the spring (see figure 5.11). Each spring was tested until it reaches the blocking state.

The output of both the compression force and vertical displacement were recorded using electronic sensors connected through an interface to a computer in which, employing its respective software, the force versus displacement graph was automatically obtained. Figures 5.12 and 5.13 show the comparison of theoretical calculation with the results of compression tests made on springs.



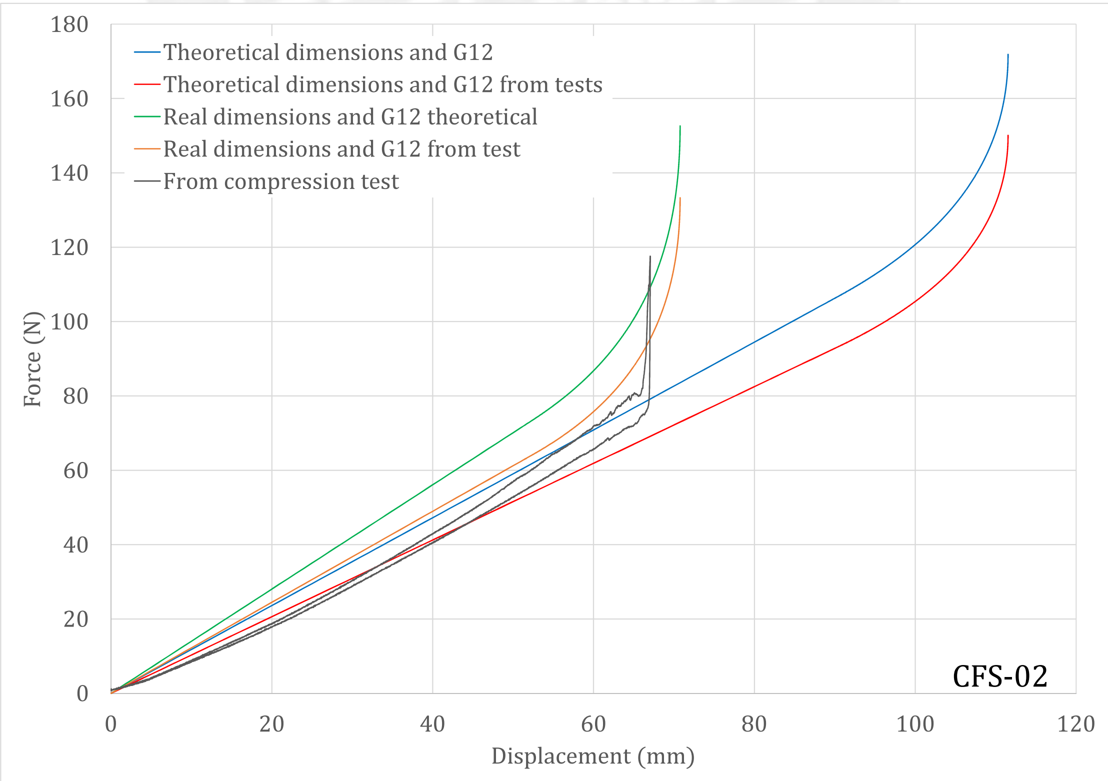
(a) (b)

Figure 5.11: Compression tests of glass (a) and carbon (b) fiber reinforced plastic volute springs.



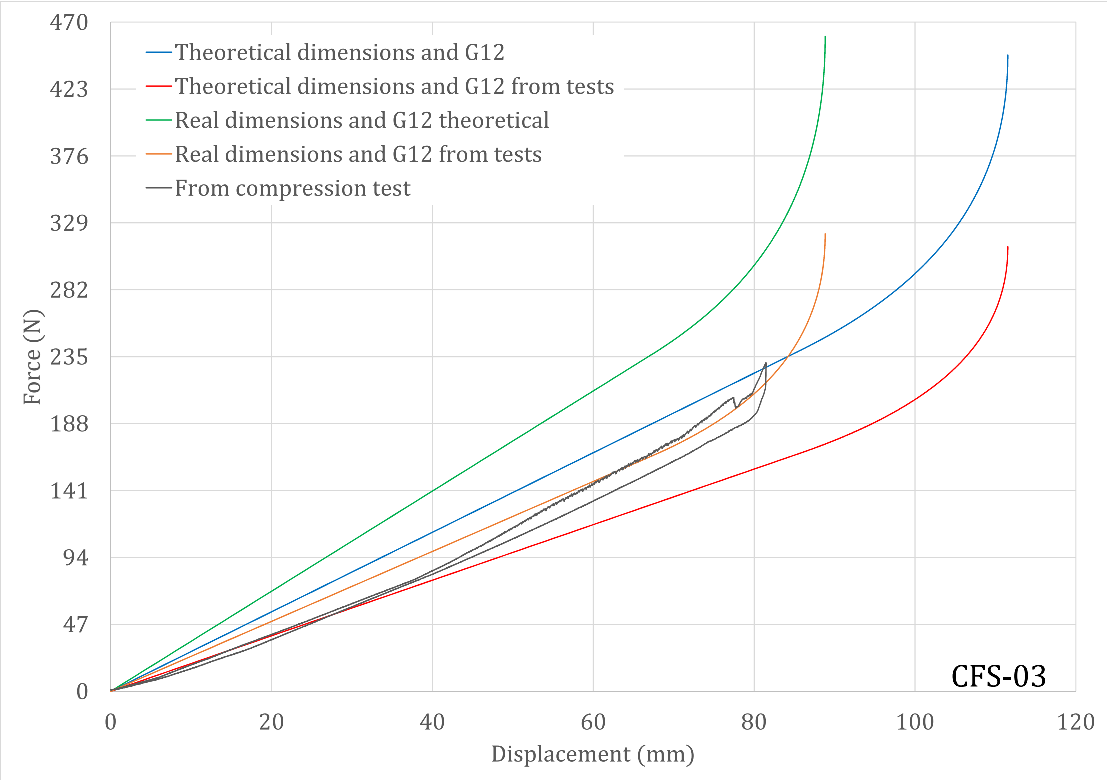
190
152
114
76
38
0
Force (N)
0
23
46
69
92
115
Displacement (mm)
Theoretical dimensions and G12
Theoretical dimensions and G12 from tests
Real dimensions and G12 theoretical
Real dimensions and G12 from tests
From compression test
CFS-01

(a)



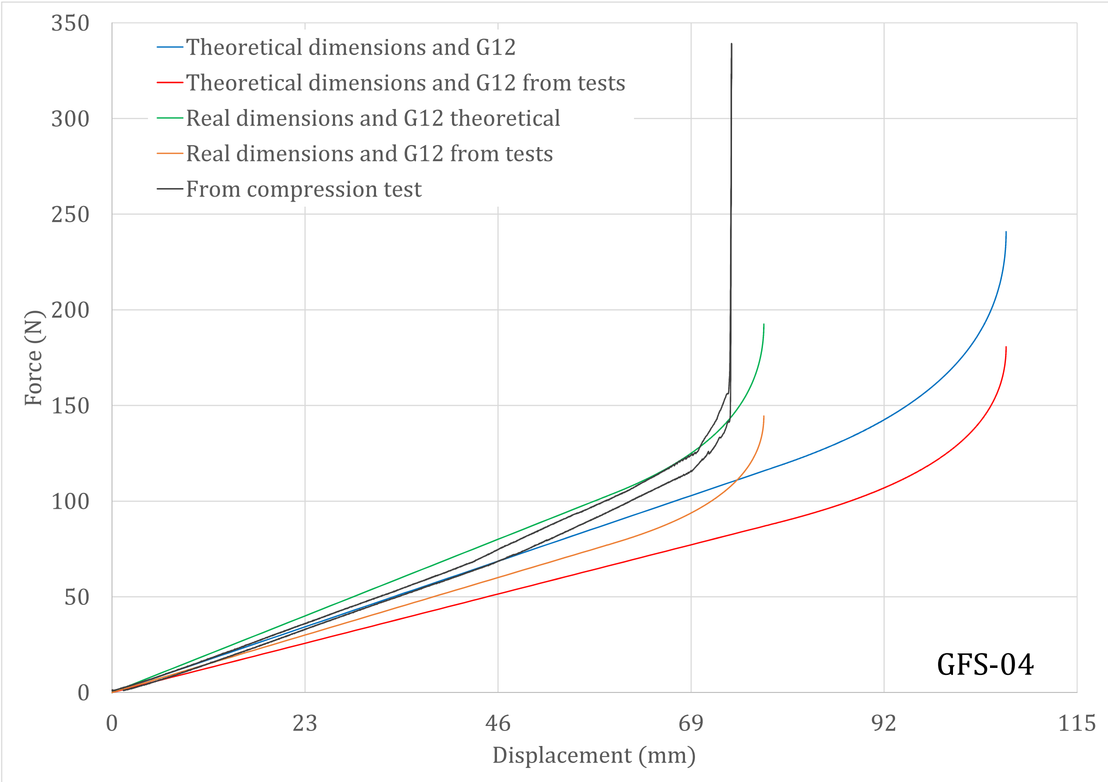
180
160
140
120
100
80
60
40
20
0
Force (N)
0
20
40
60
80
100
120
Displacement (mm)
Theoretical dimensions and G12
Theoretical dimensions and G12 from tests
Real dimensions and G12 theoretical
Real dimensions and G12 from test
From compression test
CFS-02

(b)



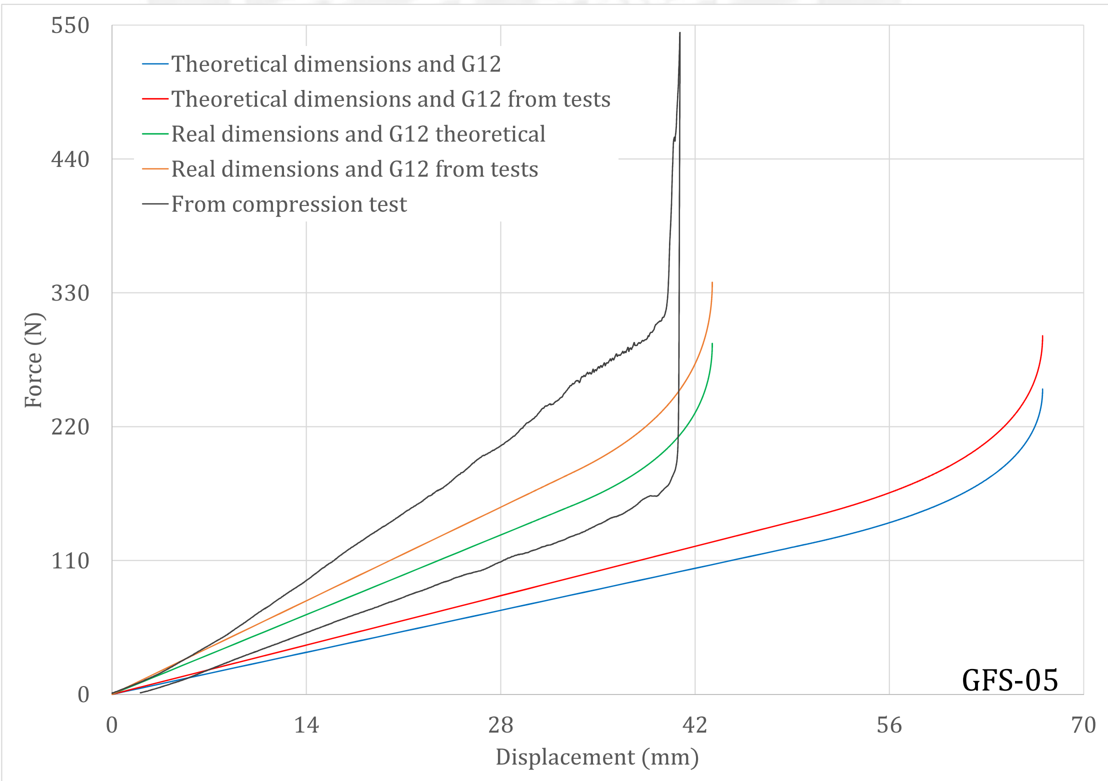
(c)

Figure 5.12: Characteristic curves of carbon fiber volute springs: (a) Spring 1 with orientation $[0°/+45°/-45°/0°]_s$, (b) Spring 2 with orientation $[+45°/-45°/+45°/-45°]_s$, and (c) Spring 3 made of braided sleeves.



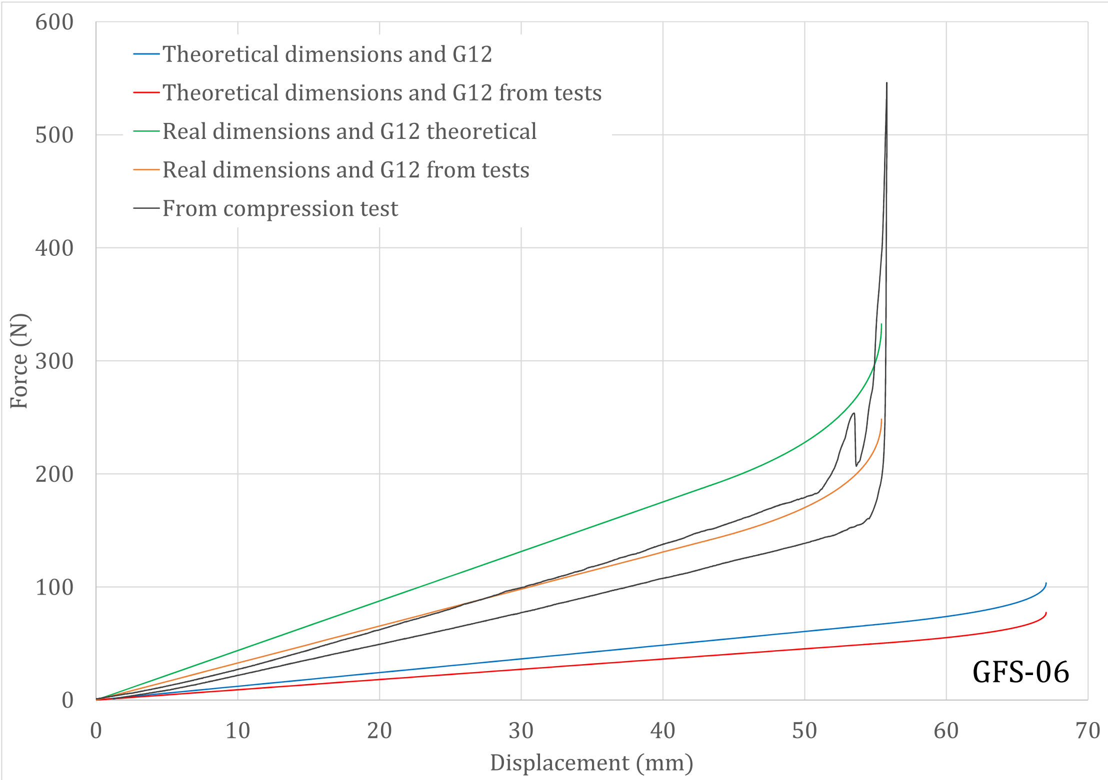
350
300
250
200
150
100
50
0
Force (N)
0
23
46
69
92
115
Displacement (mm)
Theoretical dimensions and G12
Theoretical dimensions and G12 from tests
Real dimensions and G12 theoretical
Real dimensions and G12 from tests
From compression test
GFS-04

(a)



550
440
330
220
110
0
Force (N)
0
14
28
42
56
70
Displacement (mm)
Theoretical dimensions and G12
Theoretical dimensions and G12 from tests
Real dimensions and G12 theoretical
Real dimensions and G12 from tests
From compression test
GFS-05

(b)



(c)

Figure 5.13: Characteristic curves of glass fiber volute springs: (a) Spring 4 made of braided sleeves, (b) Spring 5 with orientation $[0°/+45°/-45°/0°]_s$, and (c) Spring 6 with orientation $[+45°/-45°/+45°/-45°]_s$.

5.3.3 Discussion and evaluation of results.

Among the characteristic curves resulting from the theoretical calculation with the actual dimensions and the compression test results, it can be seen that there is a good agreement in the spring rate behavior. This good agreement occurs in a better way with results of glass fiber springs. With these results it is concluded that using the in-plane shear modulus in the conventional analytical calculations, for volute springs, is suitable to determine its behavior, provided that it is working in a plane stress state.

It should also be noted that the best behavior and agreement occurs with springs produced with braided sleeve strips whose fibers have the approximate configuration of $[+45°/-45°/+45°/-45°]_s$ and with springs produced with unidirectional strip laminates whose fibers also have the configuration of $[+45°/-45°/+45°/-45°]_s$. This good agreement demonstrates that the best response to torsion loads in the cross-section of springs is obtained with those fiber orientations (see figures 5.12(b), 5.12(c), 5.13(a) and 5.13(b)). Other fiber configurations (orientation and symmetry) could be considered. However, it should always be kept in mind that the orientation that has a better response to applied loads should be far from the neutral axis of the laminate cross-section and the orientation that does not have a good response to applied loads should be located in the central part of the cross-section [5].

It is also demonstrated that the greater the width and thickness of laminate strips the greater the stiffness of springs (spring rate) even if they have few coils (see figure 5.13(b)). Additionally, it has been analytically proven that a small variation in the thickness or width of the laminate strips produces a large variation in the characteristic curve of these springs. Therefore, optimizing the cutting and handling process of the fiber strips becomes a decisive step in the production of volute springs.

Finally, it can be said that the smaller the gap between coils, the greater the friction that occurs between their surfaces, which makes the spring useful to absorbing impact loads because it develops a good damping property. However, friction produced between coils surfaces causes that the spring useful life to be reduced.

The effect of friction can be seen in the internal area of the graphs resulting from the compression tests (black lines in figures 5.12 and 5.13). The top of these graphs correspond to the moment of spring loading (compression), and the bottom part corresponds to the moment of spring discharge. The larger the internal area of the graphs, the greater the friction between the active adjacent coils of the spring, which shows that the larger the internal area, the greater the damping capacity of the spring, i.e. the greater the conversion of the stored work into heat due to internal friction.

However, the fact that there is friction between adjacent active coils generates two situations. On the one hand, if springs are to be used as load carriers, friction should be avoided as much as possible by increasing the gap between adjacent coils; otherwise, fatigue endurance would be reduced. On the other hand, if springs are to be used as damping elements, the gap between adjacent coils must be reduced, which would increase friction. However, It should be kept in mind that when the spring is used as a damping element, this friction is lost as the material wears away.

In further research, studies can be carried out on the quality of the material and the construction of the spring in such a way that springs with good resistance to friction wear are produced.

Chapter 6

Conclusions and future work

In this chapter conclusions and possible future investigations that derive from this work are presented.

6.1 Conclusions

Regarding the materials that form part of laminates, it can be concluded that:

- In the first place, the braided sleeves whose fibers are oriented towards an angle of +/–45° (approximately) provide better surface finishes. This result is because these sleeves are easy to handle which greatly benefits the manufacturing process. In the second place, it has been demonstrated that unidirectional fiber fabrics are quite acceptable for volute springs because they also offer good mechanical properties, but with these fibers, a good surface finish cannot be obtained over the strip edges which would produce a rapid delamination of springs the moment they are used.

- Glass and carbon fibers are very well suited to manufacture volute springs which allow obtaining good properties, lightweight and low costs. So far, these fibers have been chosen because they are economical and more commercial in comparison with other fibers such as aramid and boron.

- Epoxy resin is very suitable to produce volute spring strips because it allows a simple curing process that can be achieved at any temperature and it has good properties in comparison with other thermoset resins, furthermore, this resin shrinks less than other materials. In this work, the curing process was performed at room temperature when the vacuum infusion was used and in an oven at 80℃ for 6 or 10 hours when the hand lay-up process was used.

- Since in the present work only prototypes of fiber reinforced plastic volute springs have been produced, the hand lay-up process has proved to be the most suitable since it allows the volute springs manufacture in a fast and simple way without the need of special equipment. Other manufacturing processes, such as vacuum infusion, pultrusion or RTM, are not suitable due to the complex spring shape.

Regarding calculation of effective moduli of composite materials:

- The calculation of transversal properties (for example the shear moduli) with empirical models do not always produce values according to the particular case being worked since these relationships are results of curve fitting so that it is necessary to contrast these results with specific tests for particular cases.

Regarding spring materials and their manufacturing process:

- The method and considerations mentioned through this thesis for selecting materials and producing fiber reinforced plastic volute springs will largely depend on the final application of the spring, i.e., the function that it will perform as part of some equipment, the required geometry and the load that it will support. It is worth noting that there are still no standards that establish an adequate orientation for the manufacture of these springs using fiber reinforced plastics.

- Initially, the manufacturing process of fiber reinforced plastic volute springs was described as a variant of filament winding process, however, with the progression of the present work and trying other manufacturing processes, certain variations of this process took place, for example, before winding the fiber strips in the mold, they should be completely impregnated with resin-hardener mixture and then covered with a very thin plastic foil. A better surface finish is obtained by performing this step before winding. Furthermore, it was decided to cure directly the spring in an oven preheated at 80℃ for a period from 6 to 10 hours. This way of curing gives better mechanical properties to springs.

- It should be emphasized that the manufacturing process should continue to be improved in order to obtain good surface finishes (to avoid friction between coils), good properties and better geometrical spring shape. For example, this can be achieved by optimizing the cutting of fiber strips or by establishing an application variant of resin in fiber strips.

Regarding development of a theoretical volute spring model:

- The method used to determine elastic constants of laminates has proved to be adequate, provided that thin laminates are used under the assumption of a plane stress state since only the in-plane properties of the material are taken into account. It should be emphasized that the torsion test of rectangular bars is the best method for determining the properties (specifically shear moduli) because it is easy to perform and produces a pure shear state.

- The method developed by Sumsion [52] underestimates the value of out-of-plane shear modulus so that another method should be chosen to determine both shear moduli, for example, the method proposed by Davalos [57] or Kurtz [54], these are specially adequate whenever it works with thick laminates.

- It is fully demonstrated that the best result and behavior of volute spring stiffness is obtained from fiber braided sleeves and when the fiber orientation is ±45° towards the principal axis of the laminate.
- The most important variables that define the behavior of spring stiffness are the thickness and width of strips that make up springs, therefore the larger the width and thickness the greater the stiffness of spring.
- It can be said that the smaller the gap between coils, the greater the friction that occurs on their surfaces, which makes the spring very suitable for absorbing impact loads because it develops a good damping property (see figure 5.13(b)). However, friction produced between coils surfaces causes that the spring useful life to be reduced.

6.2 Future work

Possible future researches that can be carried out later could be:

- Analysis of stresses and strains of volute springs subjected to static load and variables load over time, considering finite element analysis.
- Vibration analysis of volute springs and their performance as damping elements.
- A further study looking the optimization of the manufacturing process of volute springs for mass production and considering the manufacturing of springs made with strips of thick laminates.
- Analysis of volute springs made from thick laminates strips considering the out-of-plane shear modulus effect and a general stress state.
- Analysis of the friction between spring coils considering its effect on the volute spring property to absorb impact loads.

Appendix A

Dimensions of cut test specimens

Table A.1: Set 1 - Glass fiber laminates with orientation $[0°/+45°/-45°/0°]_s$

	w_1 [a]	t_1 [b]	L_1 [c]	L [d]	w_2	t_2	L_2	L
Pair 1	11.05	2.07	217.10	140	21.39	2.01	216.90	140
Pair 2	11.56	2.02	217.20		21.17	2.03	217.10	
Pair 3	11.66	2.07	217.20		21.18	2.05	217.20	
Pair 4	10.29	2.02	217.20		21.63	2.11	217.10	
Pair 5	11.27	2.05	217.10		21.71	2.01	217.30	
Pair 6	9.48	2.06	217.10		21.44	2.07	217.30	

[a] w:width of specimen cross section.
[b] t: specimen thickness.
[c] L_1,L_2: total length of specimens.
[d] L: gage length.

Table A.2: Set 2 - Glass fiber laminates with orientation $[0°/+45°/-45°/0°]_s$

	w_1	t_1	L_1	L	w_2	t_2	L_2	L
Pair 1	17.30	2.03	217.50	140	31.84	2.05	217.50	140
Pair 2	15.88	2.09	217.50		32.76	2.06	217.30	
Pair 3	17.96	2.09	217.50		31.62	2.04	217.40	
Pair 4	16.71	2.16	217.40		31.92	2.06	217.40	
Pair 5	17.38	2.10	217.70		32.02	2.06	217.50	
Pair 6	16.96	2.06	217.60		32.08	2.05	217.42	

Table A.3: Set 3 - Carbon fiber laminates with orientation $[0°/+45°/-45°/0°]_s$

	w_1	t_1	L_1	L	w_2	t_2	L_2	L
Pair 1	12.37	0.97	219.30	120	22.88	0.95	218.70	120
Pair 2	12.30	0.92	217.80		21.87	0.93	218.00	
Pair 3	12.86	0.94	218.90		21.73	0.93	217.90	
Pair 4	13.29	0.93	219.20		22.41	0.92	218.20	
Pair 5	12.10	0.92	219.50		21.98	0.93	218.40	
Pair 6	12.64	0.92	219.20		22.43	0.93	218.10	

Table A.4: Set 4 - Carbon fiber laminates with orientation $[0°/+45°/-45°/0°]_s$

	w_1	t_1	L_1	L	w_2	t_2	L_2	L
Pair 1	17.68	0.95	218.10	120	32.14	0.94	217.20	120
Pair 2	17.67	0.95	218.80		32.09	0.95	216.70	
Pair 3	18.18	0.93	218.90		32.54	0.95	216.20	
Pair 4	15.58	0.92	218.60		31.95	0.93	218.00	
Pair 5	18.56	0.93	218.40		32.39	0.92	215.20	
Pair 6	17.84	0.942	218.56		32.28	0.94	215.70	

Table A.5: Set 5 - Glass fiber strips produced with braided sleeves and an orientation of $[+45°/-45°/+45°/-45°]_s$ approximately

	w_1	t_1	L_1	L	w_2	t_2	L_2	L
Pair 1	24.03	2.18	252.10	160	38.77	1.91	252.80	160
Pair 2	25.23	2.31	249.70		38.49	1.95	248.50	
Pair 3	25.01	2.12	254.00		39.21	1.87	249.90	
Pair 4	24.83	2.14	252.10		38.94	1.93	254.70	
Pair 5	24.05	2.23	251.40		38.58	2.04	251.80	

Table A.6: Set 6 - Carbon fiber strips produced with braided sleeves and an orientation of $[+45°/-45°/+45°/-45°]_s$ approximately

	w_1	t_1	L_1	L	w_2	t_2	L_2	L
Pair 1	23.73	1.69	253.20	160	38.62	1.60	253.60	160
Pair 2	24.65	1.67	251.10		39.58	1.46	254.50	
Pair 3	24.20	1.73	254.60		39.20	1.59	253.60	
Pair 4	24.72	1.72	251.50		39.02	1.41	252.20	
Pair 5	24.92	1.72	251.70		38.86	1.42	252.60	

Table A.7: Set 7 - Carbon fiber laminates with orientation $[+45°/-45°/+45°/-45°]_s$

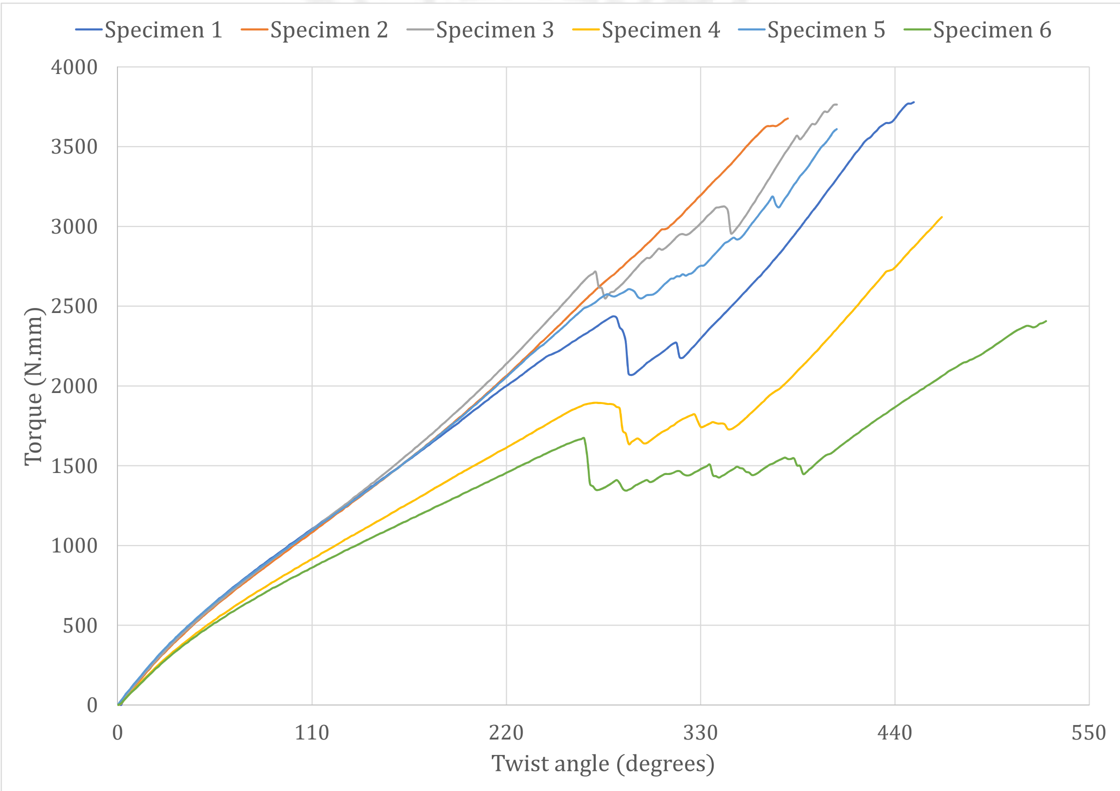
	w_1	t_1	L_1	L	w_2	t_2	L_2	L
Pair 1	22.54	0.81	333.00	240	33.56	0.78	335.00	240
Pair 2	19.49	0.93	334.00		36.19	0.80	335.00	
Pair 3	24.67	0.80	333.00		38.83	0.76	333.50	
Pair 4	24.23	0.77	334.00		38.50	0.76	333.00	
Pair 5	23.00	0.84	334.00		37.95	0.79	334.50	

Table A.8: Set 8 - Glass fiber laminates with orientation $[+45°/-45°/+45°/-45°]_s$

	w_1	t_1	L_1	L	w_2	t_2	L_2	L
Pair 1	17.39	1.30	289.5	200	36.22	1.31	290.00	200
Pair 2	13.90	1.36	289.00		36.60	1.27	290.00	
Pair 3	15.47	1.28	289.50		36.04	1.28	290.50	
Pair 4	19.60	1.31	289.50		35.75	1.33	290.50	
Pair 5	13.11	1.30	289.00		36.25	1.30	290.00	
Pair 6	13.85	1.31	289.50		36.28	1.29	290.20	

Appendix B

Representative torque versus twist angle graphs



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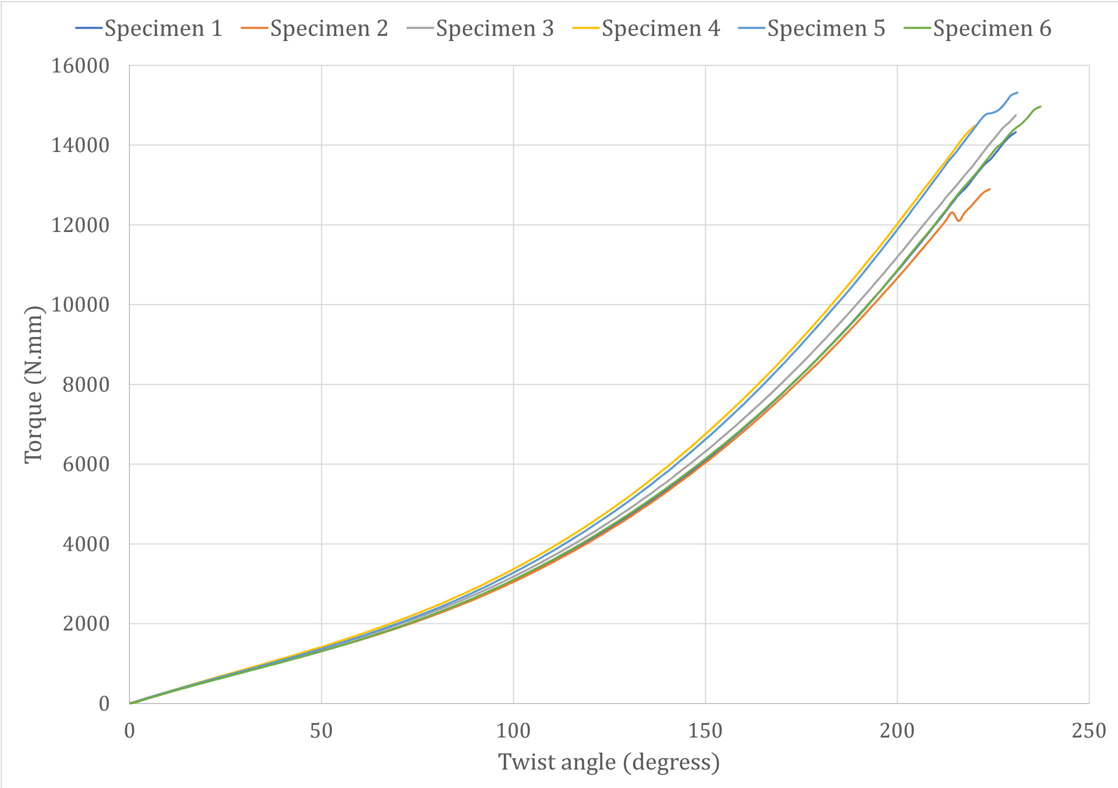
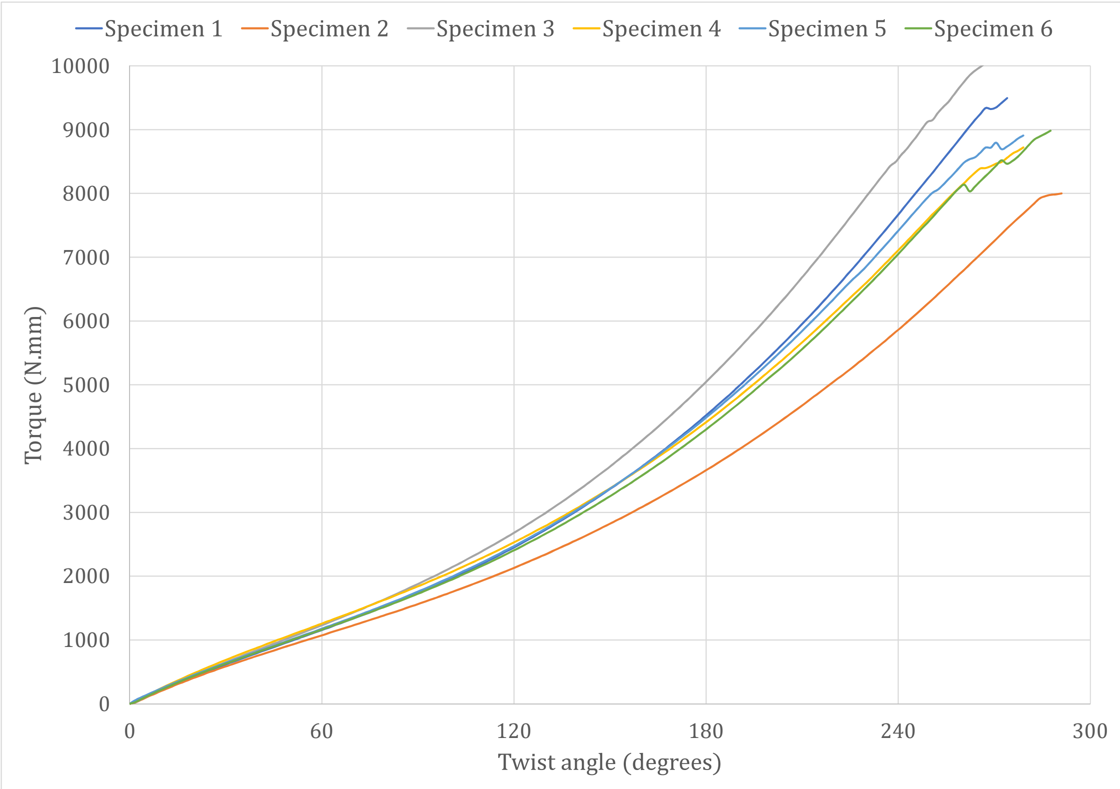


(b)

Figure B.1: Torque versus twist angle of set 1: (a) Small specimens and (b) Big specimens.



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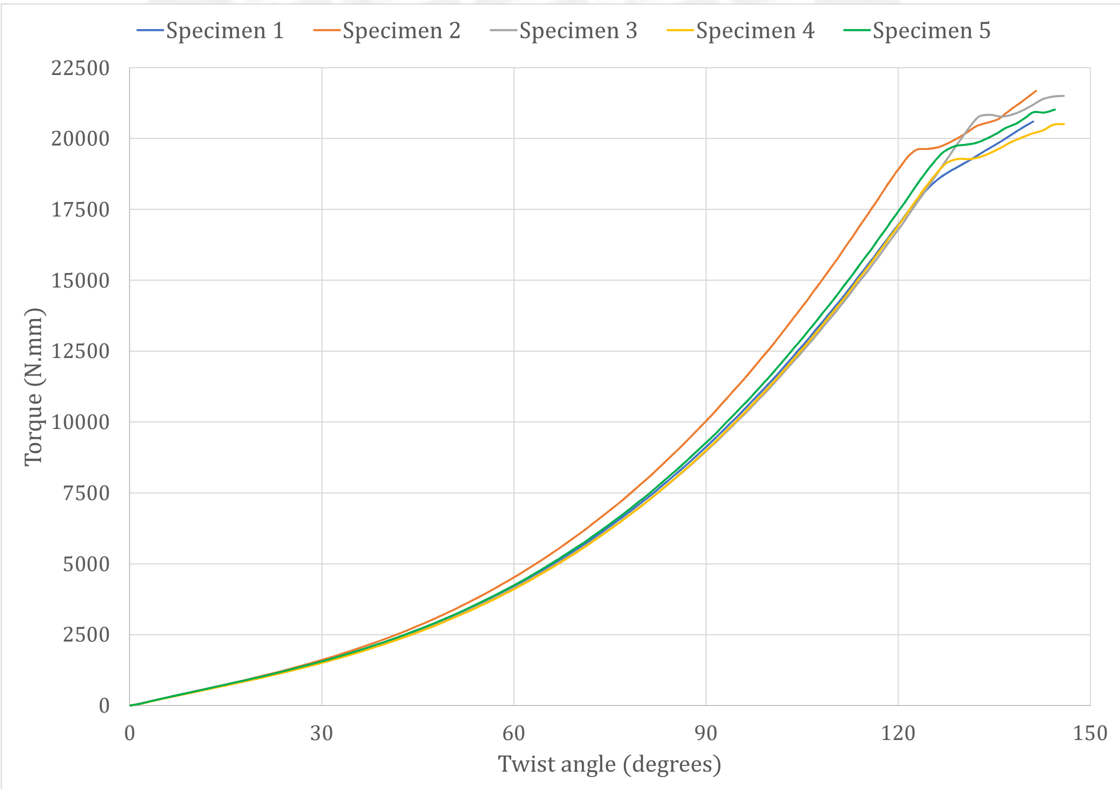
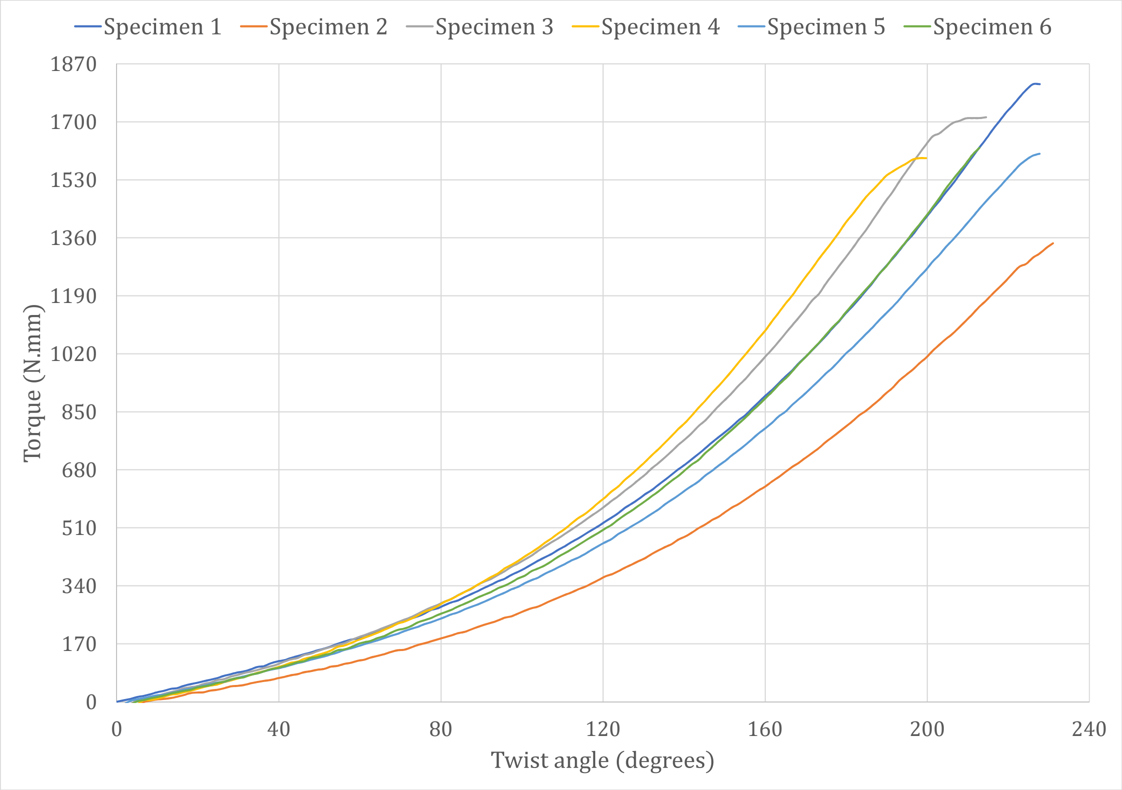
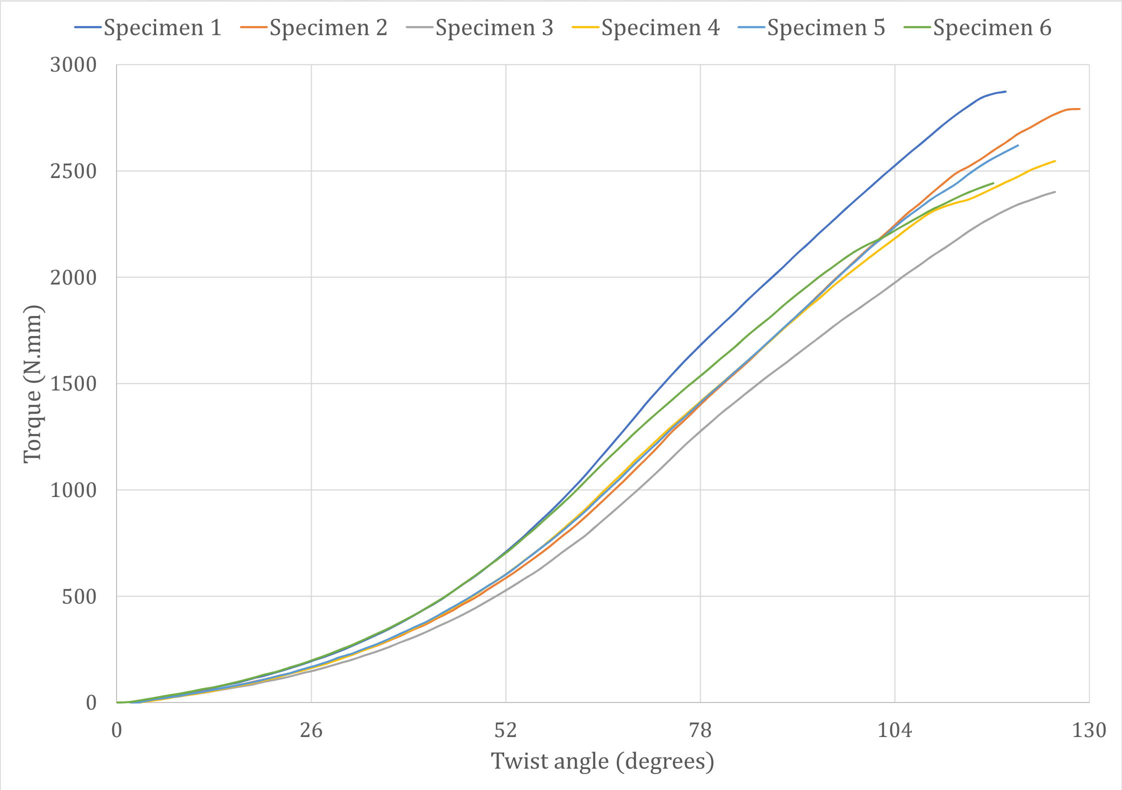


(b)

Figure B.2: Torque versus twist angle of set 2: (a) Small specimens and (b) Big specimens.

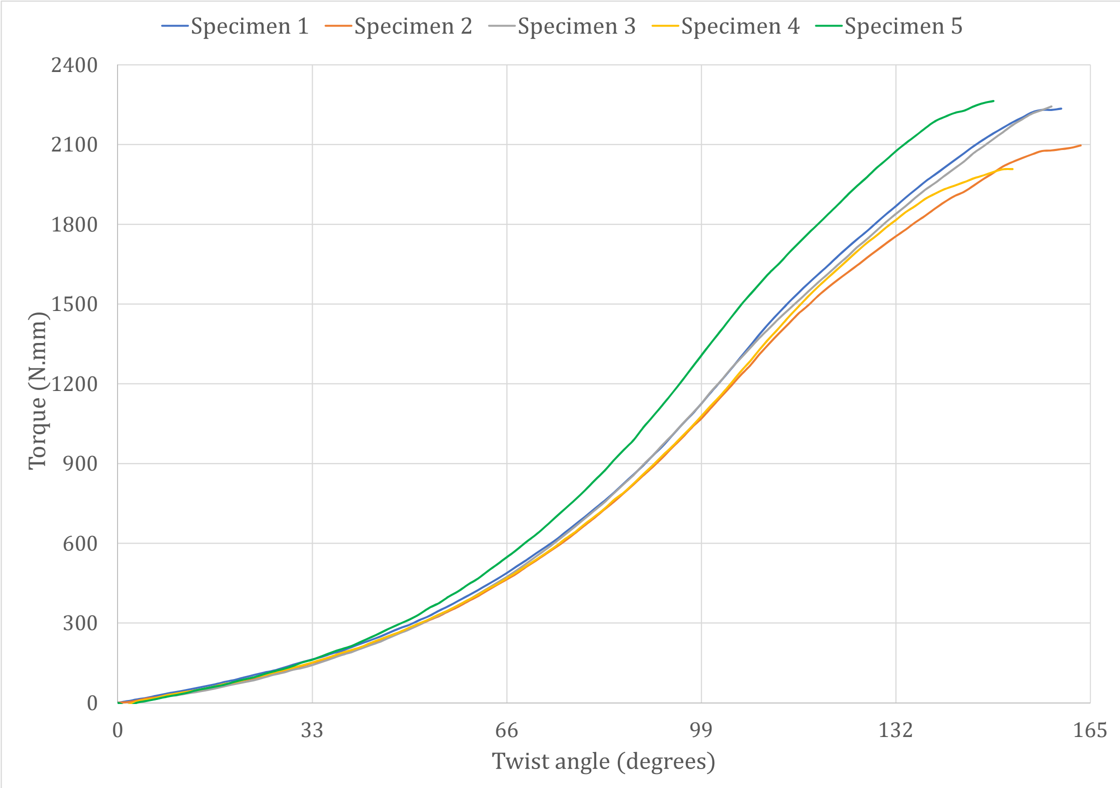


(a)

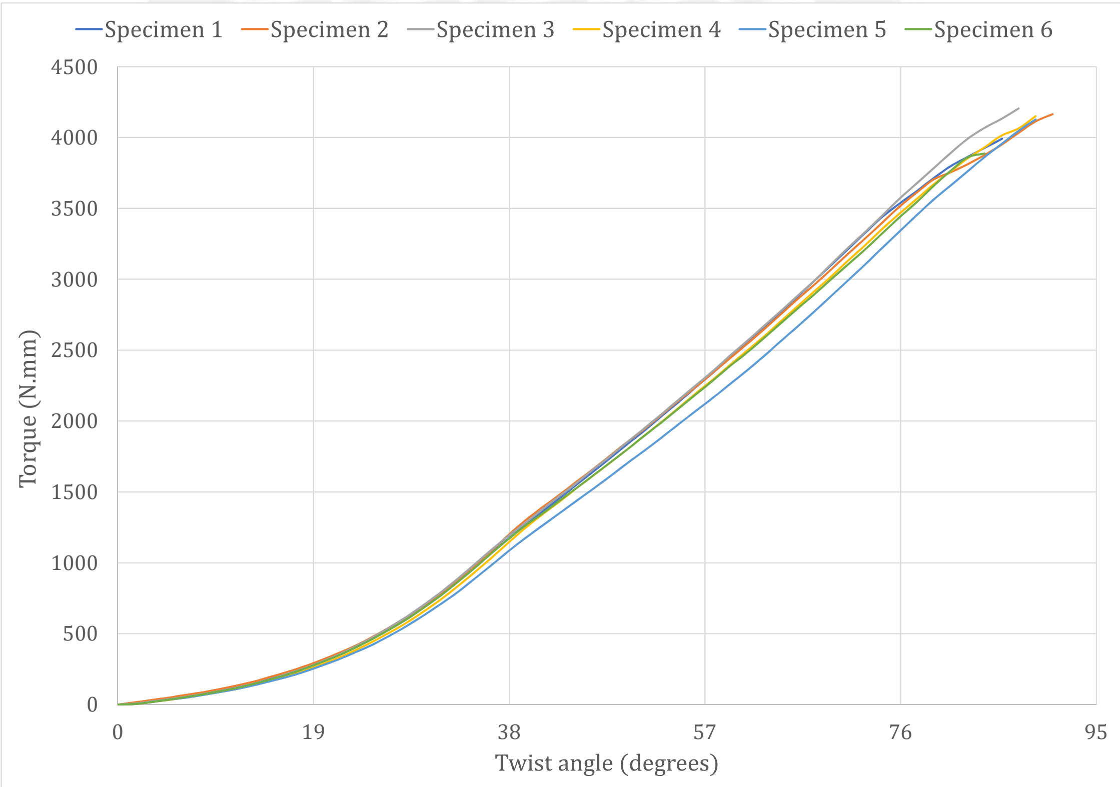


(b)

Figure B.3: Torque versus twist angle of set 3: (a) Small specimens and (b) Big specimens.

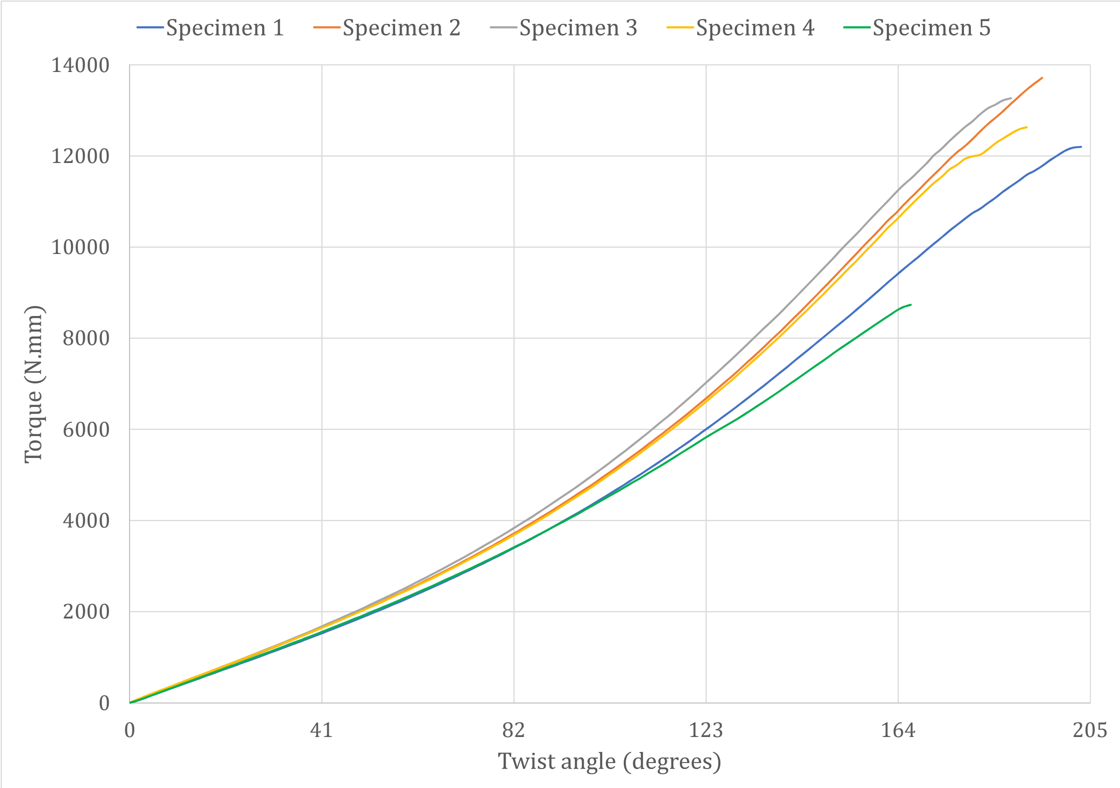


(a)

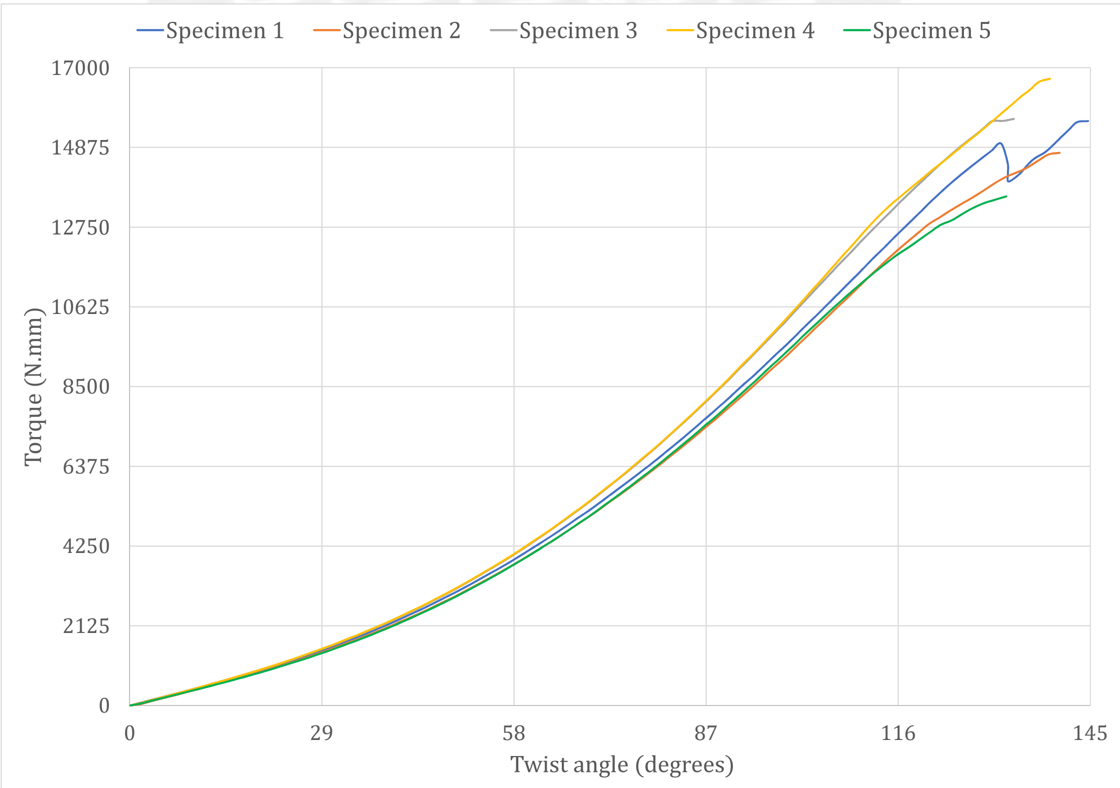


(b)

Figure B.4: Torque versus twist angle of set 4: (a) Small specimens and (b) Big specimens.

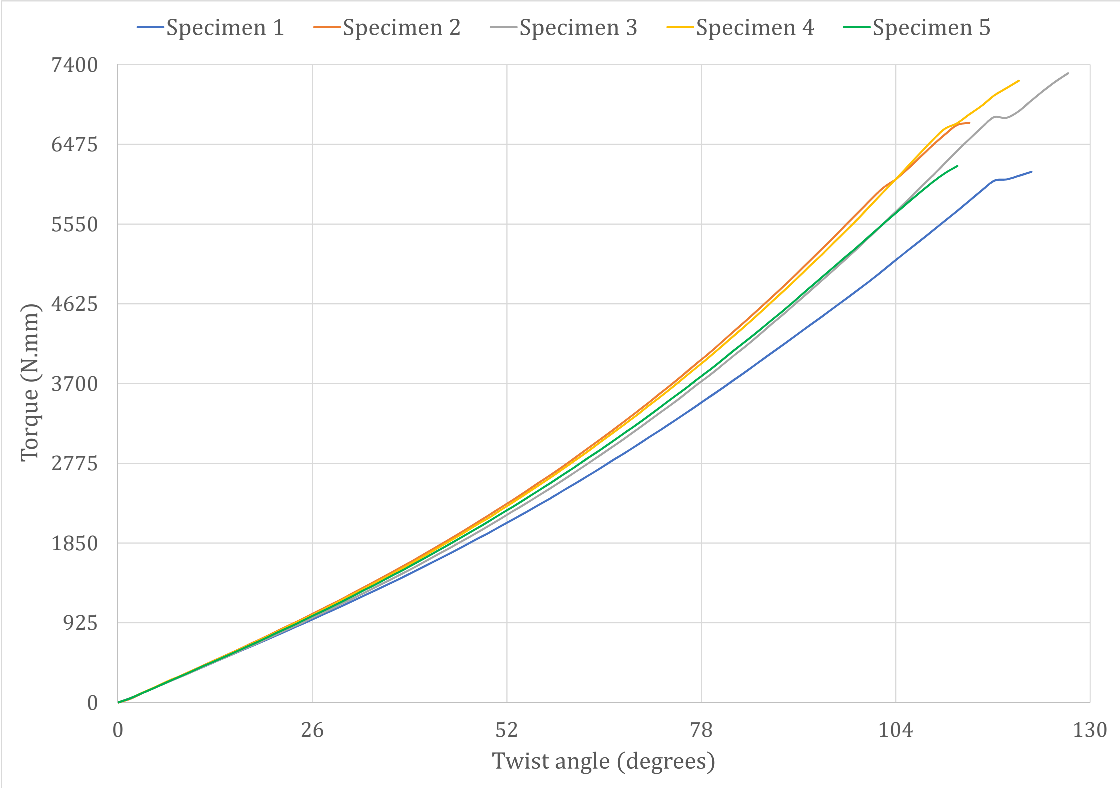


(a)

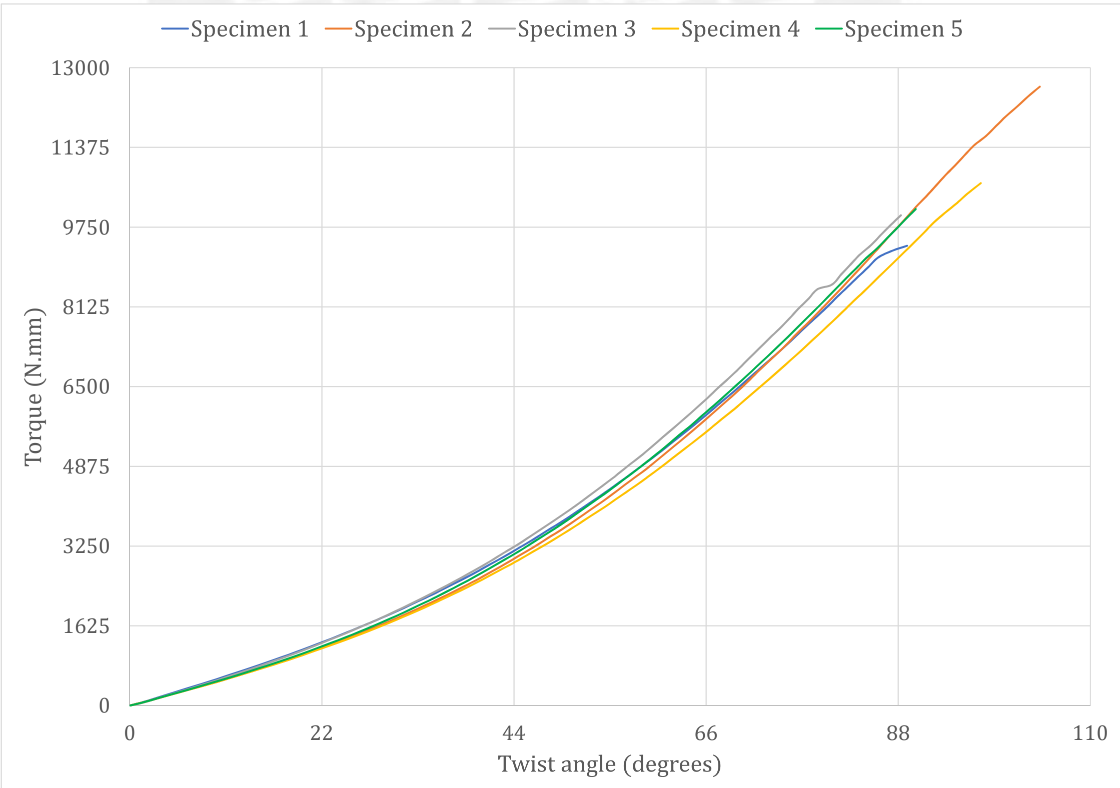


(b)

Figure B.5: Torque versus twist angle of set 5: (a) Small specimens and (b) Big specimens.

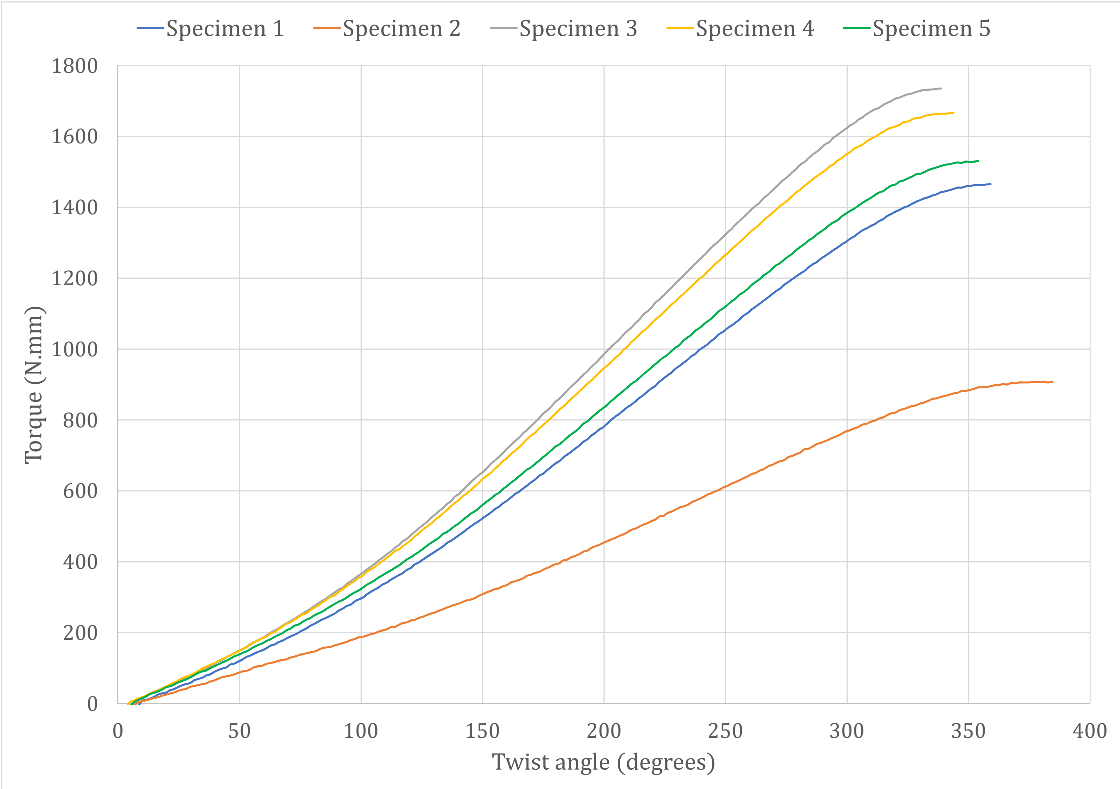


(a)



(b)

Figure B.6: Torque versus twist angle of set 6: (a) Small specimens and (b) Big specimens.



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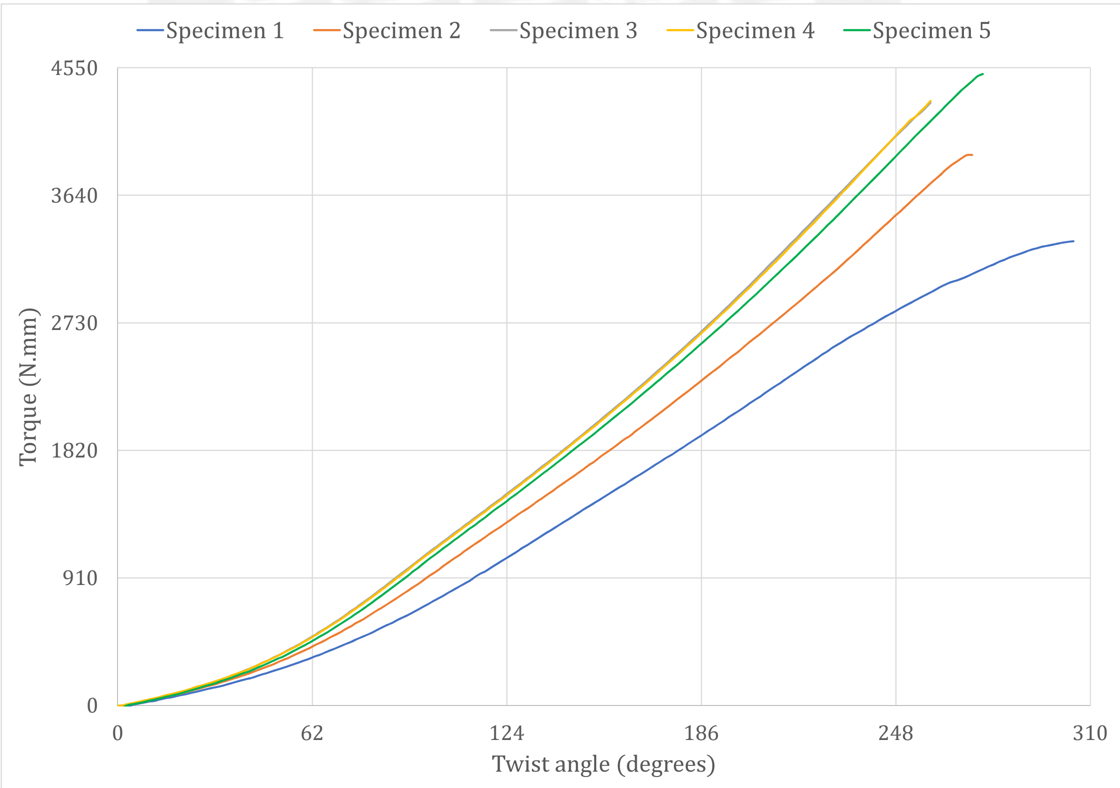
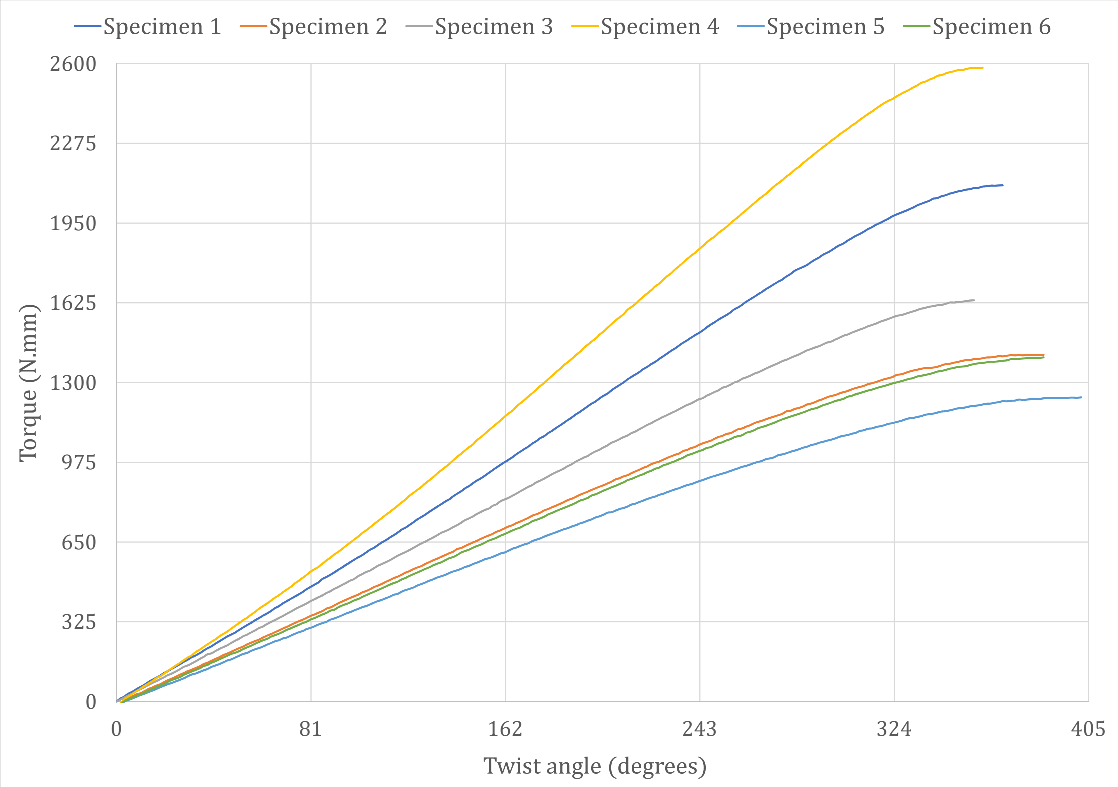
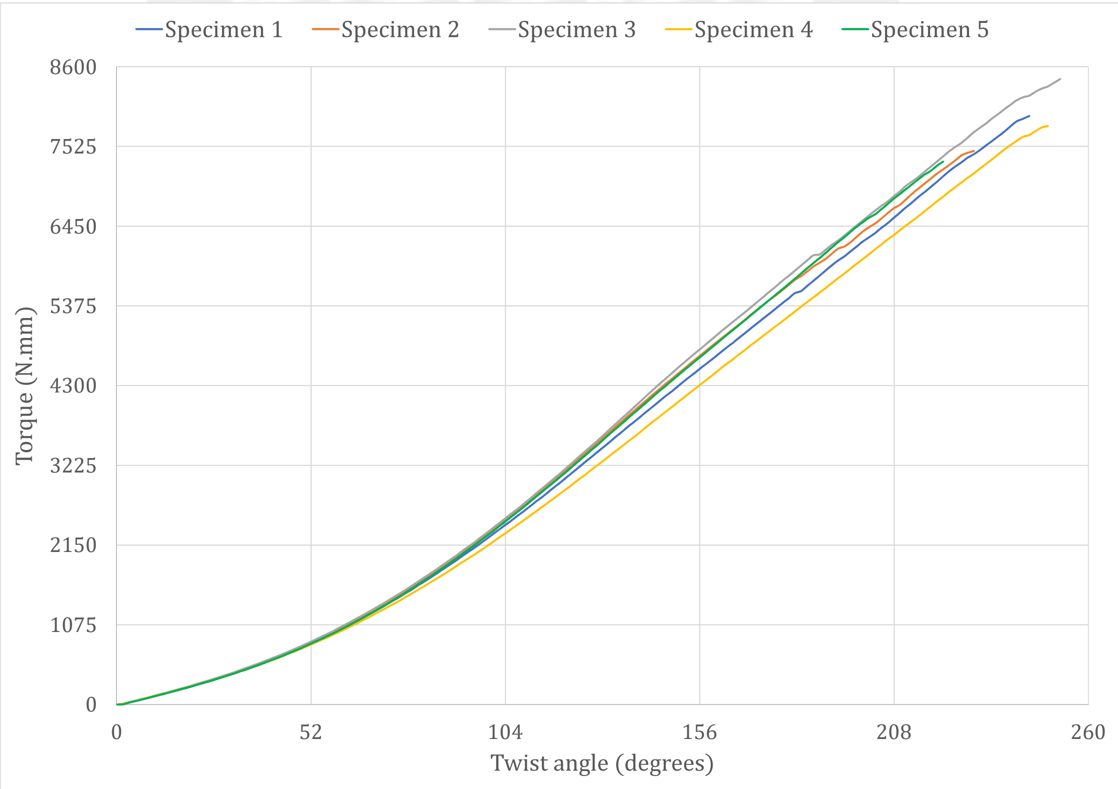


(b)

Figure B.7: Torque versus twist angle of set 7: (a) Small specimens and (b) Big specimens.



(a)



(b)

Figure B.8: Torque versus twist angle of set 8: (a) Small specimens and (b) Big specimens.

Appendix C

Results of shear moduli calculations

Table C.1: Set 1 - Experimental shear moduli G_{12} and G_{13} for glass fiber specimens with orientations $[0°/+45°/-45°/0°]_s$

	T_1 $(N \cdot mm)$	θ_1 $(\,°\,)$	T_2 $(N \cdot mm)$	θ_2 $(\,°\,)$	χ	G_{12} (GPa)	G_{13} (GPa)
Pair 1	159.26	12.5	346.79	12.5	0.1399	4.54	0.64
	321.55	25	669.85	25	0.2063	4.25	0.88
	593.37	50	1310.95	50	0.1257	4.34	0.55
Pair 2	155.65	12.5	361.77	12.5	0.0928	4.88	0.45
	312.96	25	681.36	25	0.1600	4.34	0.70
	572.43	50	1316.73	50	0.1000	4.40	0.44
Pair 3	164.78	12.5	367.96	12.5	0.0887	4.88	0.43
	318.97	25	702.54	25	0.0974	4.61	0.45
	580.53	50	1365.84	50	0.0649	4.74	0.31
Pair 4	136.72	12.5	366.63	12.5	0.4440	3.83	1.70
	272.12	25	720.48	25	0.5521	3.72	2.05
	495.47	50	1419.62	50	0.2006	3.90	0.78
Pair 5	174.35	12.5	359.23	12.5	0.2838	3.81	1.60
	334.76	25	695.97	25	0.2531	4.27	1.08
	596.57	50	1372.01	50	0.1037	4.55	0.47
Pair 6	129.46	12.5	342.01	12.5	0.4116	3.81	1.57
	262.65	25	664.72	25	0.7727	3.60	2.78
	475.71	50	1313.59	50	0.2615	3.76	0.98

Table C.2: Set 2 - Experimental shear moduli G_{12} and G_{13} for glass fiber specimens with orientations of $[0°/+45°/-45°/0°]_s$

	T_1 $(N \cdot mm)$	θ_1 $(\,°\,)$	T_2 $(N \cdot mm)$	θ_2 $(\,°\,)$	χ	G_{12} (GPa)	G_{13} (GPa)
Pair 1	268.21	12.5	609.72	12.5	0.05360	5.21	0.28
	522.02	25	1257.56	25	0.03547	5.65	0.20
	976.97	50	3106.80	50	0.01003	9.11	0.09
Pair 2	254.89	12.5	617.76	12.5	0.07706	4.82	0.37
	498.39	25	1294.28	25	0.04825	5.28	0.20
	915.80	50	3316.69	50	0.01263	8.54	0.11
Pair 3	284.31	12.5	608.18	12.5	0.03039	5.71	0.17
	552.38	25	1254.72	25	0.02203	6.22	0.14
	1037.17	50	3087.20	50	0.00728	10.3	0.08
Pair 4	307.97	12.5	587.92	12.5	0.11109	4.64	0.32
	584.33	25	1219.55	25	0.05289	5.13	0.27
	1070.30	50	3039.23	50	0.01364	8.04	0.12
Pair 5	296.49	12.5	616.79	12.5	0.06327	5.10	0.32
	545.78	25	1266.20	25	0.03053	5.69	0.17
	998.50	50	3139.43	50	0.00878	9.41	0.08
Pair 6	277.16	12.5	608.08	12.5	0.07757	4.96	0.38
	533.68	25	1258.46	25	0.04375	5.44	0.24
	987.40	50	3137.87	50	0.01131	8.75	0.10

Table C.3: Set 3 - Experimental shear moduli G_{12} and G_{13} for carbon fiber specimens with orientations of $[0°/+45°/-45°/0°]_s$

	T_1 $(N \cdot mm)$	θ_1 $(\,°\,)$	T_2 $(N \cdot mm)$	θ_2 $(\,°\,)$	χ	G_{12} (GPa)	G_{13} (GPa)
Pair 1	35.08	12.5	66.52	12.5	0.09406	6.06	0.570
	70.28	25	182.49	25	0.00784	10.79	0.084
	152.28	50	651.79	50	0.00583	13.47	0.079
Pair 2	9.58	12.5	57.72	12.5	0.00235	6.54	0.015
	35.72	25	155.09	25	0.00196	13.87	0.027
	94.56	50	541.22	50	0.00403	11.44	0.461
Pair 3	25.72	12.5	51.34	12.5	0.01603	6.22	0.010
	63.98	25	139.78	25	0.00911	9.28	0.085
	150.40	50	486.35	50	0.00496	14.32	0.071
Pair 4	17.64	12.5	52.94	12.5	0.00216	10.47	0.023
	51.50	25	152.57	25	0.00228	14.73	0.034
	138.73	50	556.96	50	0.00598	11.53	0.069
Pair 5	23.22	12.5	57.50	12.5	0.01167	7.12	0.083
	56.54	25	158.27	25	0.00652	10.99	0.072
	129.48	50	557.28	50	0.00499	14.41	0.072
Pair 6	21.28	12.5	69.24	12.5	0.00279	12.20	0.034
	55.31	25	185.78	25	0.00365	13.45	0.037
	133.03	50	651.35	50	0.00493	13.70	0.068

Table C.4: Set 4 - Experimental shear moduli G_{12} and G_{13} for carbon fiber specimens with orientations of $[0°/+45°/-45°/0°]_s$

	T_1 $(N \cdot mm)$	θ_1 $(\,°\,)$	T_2 $(N \cdot mm)$	θ_2 $(\,°\,)$	χ	G_{12} (GPa)	G_{13} (GPa)
Pair 1	51.50	12.5	136.53	12.5	0.00324	12.56	0.041
	114.42	25	476.50	25	0.00391	12.83	0.050
	298.70	50	1868.20	50	0.00688	13.59	0.094
Pair 2	43.74	12.5	150.55	12.5	0.00237	12.46	0.030
	102.43	25	488.16	25	0.00269	13.62	0.037
	282.20	50	1882.10	50	0.00460	14.71	0.068
Pair 3	37.48	12.5	135.97	12.5	0.00208	11.32	0.024
	96.21	25	485.34	25	0.00285	12.34	0.035
	281.60	50	1883.60	50	0.00578	13.61	0.079
Pair 4	44.08	12.5	126.85	12.5	0.00285	12.25	0.035
	104.41	25	454.16	25	0.00325	13.64	0.044
	287.70	50	1831.30	50	0.00653	14.36	0.094
Pair 5	42.05	12.5	124.57	12.5	0.00242	11.14	0.027
	108.88	25	432.84	25	0.00272	13.63	0.037
	319.20	50	1731.50	50	0.00561	14.93	0.084
Pair 6	43.77	12.5	133.47	12.5	0.00200	13.67	0.027
	105.27	25	474.12	25	0.00323	12.80	0.041
	293.90	50	1831.30	50	0.00651	13.59	0.089

Table C.5: Set 5 - Experimental shear moduli G_{12} and G_{13} for glass fiber braided sleeves specimens with an approximate orientation of $[+45°/-45°/+45°/-45°]_s$

	T_1 $(N \cdot mm)$	θ_1 $(\ ^\circ\ )$	T_2 $(N \cdot mm)$	θ_2 $(\ ^\circ\ )$	χ	G_{12} (GPa)	G_{13} (GPa)
Pair 1	449.58	12.5	557.84	12.5	0.06007	5.20	0.313
	912.02	25	1223.20	25	0.02833	6.11	0.173
	1892.16	50	3094.95	50	0.00970	9.19	0.089
Pair 2	490.56	12.5	541.75	12.5	0.03124	5.12	0.160
	983.62	25	1185.40	25	0.01751	6.05	0.106
	2046.84	50	2993.07	50	0.00729	9.20	0.067
Pair 3	501.62	12.5	585.39	12.5	0.08973	5.61	0.503
	1002.30	25	1253.80	25	0.03522	6.44	0.226
	2085.73	50	3187.23	50	0.00981	9.85	0.097
Pair 4	508.46	12.5	584.01	12.5	0.08950	5.62	0.502
	994.06	25	1261.20	25	0.07731	5.58	0.432
	2040.03	50	3201.03	50	0.01227	8.75	0.107
Pair 5	458.88	12.5	536.37	12.5	0.05717	5.03	0.287
	931.47	25	1165.40	25	0.05691	5.11	0.291
	1924.68	50	2974.03	50	0.02456	6.31	0.155

Table C.6: Set 6 - Experimental shear moduli G_{12} and G_{13} for carbon fiber braided sleeves specimens with an approximate orientation of $[+45°/-45°/+45°/-45°]_s$

	T_1 $(N \cdot mm)$	θ_1 $(\,^\circ\,)$	T_2 $(N \cdot mm)$	θ_2 $(\,^\circ\,)$	χ	G_{12} (GPa)	G_{13} (GPa)
Pair 1	453.99	12.5	687.67	12.5	0.06348	10.67	0.677
	924.80	25	1500.77	25	0.02415	12.54	0.303
	1988.49	50	3809.35	50	0.00770	18.84	0.145
Pair 2	472.64	12.5	617.75	12.5	0.01877	13.21	0.247
	984.66	25	1374.05	25	0.01168	15.54	0.182
	2195.21	50	3652.92	50	0.00492	24.20	0.119
Pair 3	454.90	12.5	664.28	12.5	0.02712	11.04	0.300
	940.64	25	1493.95	25	0.01351	13.45	0.181
	2071.67	50	3942.49	50	0.00532	21.22	0.113
Pair 4	470.36	12.5	616.36	12.5	0.00636	17.24	0.110
	975.14	25	1358.03	25	0.00499	20.02	0.100
	2166.08	50	3543.10	50	0.00280	30.64	0.086
Pair 5	463.44	12.5	629.45	12.5	0.00526	18.09	0.095
	961.60	25	1410.75	25	0.00392	21.82	0.086
	2124.04	50	3765.73	50	0.00201	36.52	0.073

Table C.7: Set 7 - Experimental shear moduli G_{12} and G_{13} for carbon fiber specimens with orientations of $[+45°/-45°/+45°/-45°]_s$

	T_1 $(N \cdot mm)$	θ_1 $(\,°\,)$	T_2 $(N \cdot mm)$	θ_2 $(\,°\,)$	χ	G_{12} (GPa)	G_{13} (GPa)
Pair 1	12.16	12.5	38.24	12.5	0.00043	15.69	0.007
	47.24	25	98.36	25	0.0076	20.71	0.016
	120.03	50	250.55	50	0.00075	26.53	0.020
Pair 2	10.80	12.5	49.06	12.5	0.00038	18.38	0.007
	36.30	25	115.46	25	0.00054	23.25	0.013
	87.64	50	298.71	50	0.00043	33.81	0.014
Pair 3	24.36	12.5	53.74	12.5	0.00067	19.29	0.013
	62.86	25	130.41	25	0.00088	21.33	0.019
	149.64	50	346.54	50	0.00055	33.83	0.018
Pair 4	25.38	12.5	56.58	12.5	0.00095	18.32	0.017
	65.61	25	133.46	25	0.00152	19.11	0.029
	149.04	50	344.48	50	0.00081	29.46	0.024
Pair 5	24.02	12.5	46.78	12.5	0.00185	11.86	0.022
	60.25	25	119.13	25	0.00172	25.34	0.026
	138.90	50	324.01	50	0.00086	25.36	0.022

Table C.8: Set 8 - Experimental shear moduli G_{12} and G_{13} for glass fiber specimens with orientations of $[+45°/-45°/+45°/-45°]_s$

	T_1 $(N \cdot mm)$	θ_1 $(°)$	T_2 $(N \cdot mm)$	θ_2 $(°)$	χ	G_{12} (GPa)	G_{13} (GPa)
Pair 1	74.12	12.5	144.82	12.65	0.05865	6.67	0.391
	144.34	25	316.35	25	0.46673	5.62	2.623
	284.83	50	778.03	50	0.01805	7.91	0.143
Pair 2	46.72	12.5	143.51	12.5	0.02341	6.10	0.143
	102.34	25	320.73	25	0.02143	6.87	0.147
	212.61	50	784.78	50	0.01192	8.94	0.106
Pair 3	63.29	12.5	151.25	12.5	0.86411	5.64	4.873
	123.94	25	331.72	25	0.05811	6.65	0.387
	250.60	50	803.26	50	0.01598	8.88	0.142
Pair 4	68.44	12.5	145.11	12.5	0.04443	5.30	0.235
	148.41	25	320.35	25	0.03414	5.96	0.203
	312.55	50	766.54	50	0.01106	8.01	0.089
Pair 5	35.54	12.5	142.25	12.5	0.02261	5.74	0.130
	83.26	25	318.63	25	0.02786	6.32	0.176
	181.64	50	775.71	50	0.01740	8.02	0.140
Pair 6	40.74	12.5	145.38	12.5	0.02067	6.11	0.126
	94.66	25	321.56	25	0.02621	6.62	0.173
	200.97	50	781.66	50	0.01461	8.51	0.124

Appendix D

Variables to determine the characteristic curves of springs

Table D.1: Numerical values of variables used to determine the characteristic curves of carbon fiber springs.

		Spring 1 $[0°/+45°/-45°/0°]_s$		Spring 2 $[+45°/-45°/+45°/-45°]_s$		Spring 3 Braided sleeves	
		Theoretical	Real values	Theoretical	Real values	Theoretical	Real values
r_i	(mm)	14.86	17.01	14.86	15.69	15.62	17.68
n_g	-	5	5	5	5	5	5
n_f		4	4	4	4	4	4
b	(mm)	34	50.8	34	55.78	34	42.02
t	(mm)	1.15	1.15	0.85	0.89	1.25	1.45
α	$(\,^\circ\,)$	12	12	12	12	12	12
Δa [a]	(mm)	0.29	1.06	0.21	0.99	0.31	0.46
L_{strip}	(mm)	700	-	700	-	700	-
L_0	(mm)	145.54 [b]	130.11	145.54 [b]	126.54	145.54 [b]	130.85
s_c	(mm)	111.54	79.31	111.54	70.76	111.54	88.83
L_c	(mm)	34	50.8	34	55.78	34	42.02
s_n [c]	(mm)	111.54	79.31	111.53	70.76	111.54	88.83
r_{Kn}	(mm)	16.15	18.69	15.82	17.07	17.03	19.36
r_{K1}	(mm)	21.90	27.50	20.07	24.60	23.28	27.00
r_a	(mm)	22.05	28.03	20.17	25.10	23.43	27.23
β_t	-	29.57	44.30	40.00	62.67	27.20	29.03
$q_3 = q_2$	-	0.326	0.329	0.328	0.330	0.326	0.326
G_{12}^{Theor}	(MPa)	10 920	10 920	25 370	25 370	27 200	27 200
G_{12}^{Test} [d]	(MPa)	12 157.5	12 157.5	22 154	22 154	19 002	19 002

[a] It has been assumed that Δa is equal to 1/4 of thickness.
[b] The theoretical value of L_0 is according to: $L_0 = L_{strip} \cdot \sin(\alpha)$ (see figure 5.6).
[c] It has been assumed that $s_c = s_n$ in order to simplify calculations.
[d] This value is the average of values shown in table 5.8.

Table D.2: Numerical values of variables used to determine the characteristic curves of glass fiber springs.

		Spring 4 Braided sleeves		Spring 5 $[0°/+45°/-45°/0°]_s$		Spring 6 $[+45°/-45°/+45°/-45°]_s$	
		Theoretical	Real values	Theoretical	Real values	Theoretical	Real values
r_i	(mm)	15.62	17.45	14.86	17.90	15.62	16.68
n_g	-	5	5	4	4	4	4
n_f		4	4	3	3	3	3
b	(mm)	39	40.74	39	60.13	39	62.70
t	(mm)	1.47	1.64	1.94	2.40	1.10	1.64
α	$(°)$	12	12	12	12	12	12
Δa [a]	(mm)	0.37	0.08	0.49	0.04	0.28	0.33
L_{strip}	(mm)	700	-	510 [b]	-	510 [b]	-
L_0	(mm)	145.54 [c]	118.41	106.03 [c]	103.37	106.03 [c]	118.12
s_c	(mm)	106.54	77.67	67.03	43.24	67.03	55.42
L_c	(mm)	39	40.74	39	60.13	39	62.70
s_n [d]	(mm)	106.54	77.67	67.03	43.24	67.03	55.42
r_{Kn}	(mm)	17.27	19.13	17.04	20.32	16.86	18.48
r_{K1}	(mm)	24.62	26.01	24.32	27.65	20.98	24.38
r_a	(mm)	24.81	26.05	24.56	27.67	21.12	24.55
β_t	-	26.53	24.84	20.10	25.05	35.45	38.35
$q_3 = q_2$	-	0.325	0.325	0.323	0.325	0.327	0.328
G_{12}^{Theor}	(MPa)	8 810	8 810	4 610	4 610	9 210	9 210
G_{12}^{Test} [e]	(MPa)	6 610	6 610	5 413	5 413	6 880	6 880

[a] It has been assumed that Δa is equal to 1/4 of thickness.
[b] This value (different to values in table 5.11) was recalculated considering the actual spring geometry.
[c] The theoretical value of L_0 is according to: $L_0 = L_{strip} \cdot \sin(\alpha)$ (see figure 5.6).
[d] It has been assumed that $s_c = s_n$ in order to simplify calculations.
[e] This value is the average of values shown in table 5.8.

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