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The Feasibility Study of Design and Manufacturing of Composite Coil Springs

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For With GOD Nothing Is Impossible.

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My unlimited gratitude goes to my most kind–most merciful GOD without whom nothing is possible.

I am unbelievably in debt to my parents for their supports. I could not have any success in my life without them.

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Declaration

I, hereby, certify that this thesis is my own work, the use of any external sources in the literature has been properly referenced.

Seyedalireza Razavi

Abstract

This thesis investigates the manufacture of a number of Carbon-Fibre Reinforced Plastics (CFRP) composite coil spring prototypes, and it is aimed to study the feasibility of their use as a helical spring for automotive suspension system. As the optimum mechanical properties and maximum strength of carbon fibres are along their axial direction, the best configuration to lay up the reinforcement material in a helical geometry was found to be in the ± 45 degree with respect to the helix axis. In addition, a comparison study was performed between the fabricated composite coil springs and their conventional steel spring counterparts.

Among seven fabricated composite coil springs, two were made from a 0/90 woven carbon fibre fabric, one from a braided carbon fibre sleeve, and the other four, from a prepreg unidirectional carbon fibre. The manufacturing methods used for the production of these specimens included autoclaving under a pressure (20 kN) at an elevated temperature (140°C), impregnation of dry CF-sleeve with a mixture of resin epoxy and hardener and curing the compound at room temperature for 24 hours, and finally, a wet-lay-up process which was followed by a curing process at 140°C for about one hour. The experimental results showed that the springs fabricated from unidirectional carbon fibre prepreg material were capable of providing the highest spring constant ($\approx$70% higher than other types), as well as having a comparably more uniform geometry (helix-shape) compared to the woven and braided specimens.

Interestingly, it was also found that the spring constant of the fabricated UD-type springs was about one order of magnitude higher than those of steel springs which were tested in this work. Furthermore, in terms of the manufacturing technique, it was shown that for low-scale production purposes, the use of hand lay-up manufacturing technique offers unique advantages, for example, providing the freedom and ease of changing the geometry and size of the part, providing a better control over fibre orientation and material choices, and being significantly less expensive compared to an automated fabrication method (e.g., using an robotic winding or a CNC machine to wrap the refinement around a helix mandrel).

However, a number of major drawbacks faced in this work were: inconsistencies in the geometry of springs and variations in the overall mechanical properties of the same specimens, requiring a time and labour-consuming procedure, and inevitable physical defects (e.g., bridges and wrinkles) during the hand lay-up process mainly associated with human error.

Contents

List of Figures

Chapter 1

Introduction

1.1 Project background

In this study, a new method for low-cost manufacturing of a series of composite coil springs for use in automotive suspension system was investigated. The use of composite materials in the automotive and aerospace industries provides unique advantages that cannot be achieved otherwise via monolithic materials, such as metals.

In this thesis, there will be antecedent discussion on the thus-far technological advances of composite materials manufacturing techniques and applications. Hence, the sequences of representing subjects in this study are as follows:

Chapter 1 briefly describes the overall aims and objective of the thesis.

Chapter 2 provides a background literature review on the topic. This chapter is presented in different sections. Section 2.1 begins with the composite materials, types of reinforcement and matrix materials, as well as the mechanical properties of composites; section 2.2 represents the design of a helical spring, and conducts a comparison study between steel and composite coil springs; section 2.3 discusses the current manufacturing methods and technologies in use for the production of composite springs. Sections 2.4 and 2.5 deal with the manufacturing technologies of composites and their failure modes.

In Chapter 3 the experimental investigations and practices including the design of a series of composite coil spring prototypes are discussed. In this chapter the fabrication process of other types of composite springs, such as leaf springs, has been provided. Furthermore, the use of other possible types of reinforcements (braided fibres or woven fabrics) and their performances and effects on the final properties of the spring (e.g., the spring rate) is covered.

Chapter 4 and Chapter 5 are allocated to the results and discussion, and conclusions of the project, respectively. Moreover, the latter chapter discusses to some extent about the accomplished aims and objectives of the project as well as the challenges and limitations of the study.

1.2 Project objectives

The main goal of this report is to investigate the feasibility of manufacturing composite coil springs by employing low-cost composite manufacturing technique, such as, hand lay-up method. Thus, in this project several aspects of composite materials, their characteristics, applications in automotive industry (as spring), and their manufacturing methods will be discussed. The sub-objectives of the project are as follows:

- investigating typical properties of carbon fibre reinforced plastic composites;
- comparing the physical properties of different types of reinforcements and matrices;
- comparing composite springs with the metallic ones; and
- identifying the most appropriate manufacturing method for the production of composite springs.

Chapter 2

Literature Review

Composite materials

The knowledge of building composite materials was latent to the mankind until the benefits of combining two or more different materials to improve the final mechanical properties of the combined material became obvious. Historical evidences show that such a discovery dates back to at least thousands of years ago when even in the Bible a quotation refers to the “difficulty of making bricks without straw” (Exodus, Chapter V, verses 6) [1]. This implies that composites have existed well before the human did, by manifesting within the nature in fruits, vegetables, leaf of the trees, rocks, etc. However, a combination of two substances creating a new material with modified/improved characteristics cannot easily be ascribed as “composite” if the behaviour/properties of each constituent part remains the same to its homogeneous state. Therefore, there must be defined a more engineering term to distinguish those materials which are simply combined from those which are in fact composed.

A composite material is a combination within which two or more materials are composed with some specific characteristics that make them distinct to other simply combined materials. For instance, a composite material needs to be microscopically identifiable, which means that not only the combination differs in molecular stage, but in terms of its overall properties as well [2]. In this context, a more technical term can be defined as: a combination of two or more reinforcement materials which are bonded homogeneously within a matrix (not as multi-component material) with their boundaries of combination not easily recognized by the naked eye. This combination is thus considered as a composite, since it has its own distinctive properties, such as, for example, being tougher than any of the constituent material, having negative thermal coefficient, or any other properties which were not clearly present in any of the constitutive component alone. The desire mechanical properties in a composite structure can be achieved with embedding one or more reinforcement fillers (short fibres, long fibres, or particles) within a polymeric, metallic, carbonous, or ceramic matrix. Fibre reinforced plastics (FRP), for instance, uses a polymer or plastic matrix with fibres as reinforcement, and if carbon fibres are used as fillers, the composite is called Carbon Fibre Reinforced Polymer Composite (CFRPC). Fibres then act as a reinforcement material since materials are at their strongest states when in fibre form. This is because of the special molecules' arrangement and their uniform direction in fibres, as well as the fact that fibre have less defections along their surface. For example, glass, boron, and graphite fibres have much more strength against breaking than when in bulk form. Such effect is very noticeable in the brittle materials where the existence of fibres restrains crack propagation in the material as they act as a bridge at the crack point [2] (Figure (2.1)).

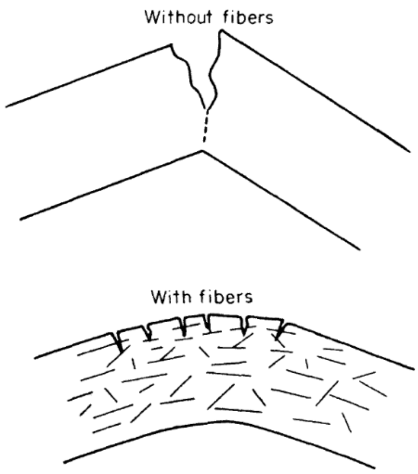

Figure 2.1: The influence of reinforcement fibres in preventing damage and delaying crack propagation in composite materials (Reproduced from [2]).

The creep resistance of fibres is another important criterion that has to be taken into account before manufacturing a composite part. Since in composites creep is mainly dominated in the matrix part (especially in polymer matrix composites), a very low creep compliance fibre (such as continuous carbon or glass fibres) can consequently decrease the strength of the whole structure. This is, particularly, evident in composites which are equipped with chopped fibres, whiskers, or particles which lack a high creep-resistance characteristic compared to continuous fibres.

Generally, composite materials can be divided into three categories based on their constituent materials and structures: particulate, fibrous, and laminated composites. In the case of particulate composites, a macro size particles of one material is embedded in the matrix of another one; in the case of fibrous composites, as briefly discussed earlier, fibres of one material are embedded within the matrix of another material. Finally, as for the laminated composites, a combined lamination of different materials is mixed together [3].

Fibre's orientation, content (continues or discontinues, unidirectional or stochastic distributed), and strength can all affect the overall mechanical properties of a composite material [4]. For example, fibres can reinforce the unidirectional composites when they are aligned in a thin plate (ply) to give the highest strength along the fibre direction. The strength in the transverse direction, however, is the lowest. Therefore, when a multi-directional load capability criterion is of interest, a composite material with 3D-woven fibre reinforcement architecture (three mutually perpendicular axes) is required to be designed [5, 6].

2.1 Introduction

2.1.1 Types of Composites

There are three main categories of composite materials (Figure (2.2)). Depending on which material is used as a matrix and which one as for the reinforcement part, the classification can fall further into: Polymer Matrix Composite (PMCs), Metal Matrix Composites (CMCs), Ceramic Matrix Composite (CMC), Carbon Matrix Composites (CAMCs), and Carbon/Carbon Composites (CCCs) [7].

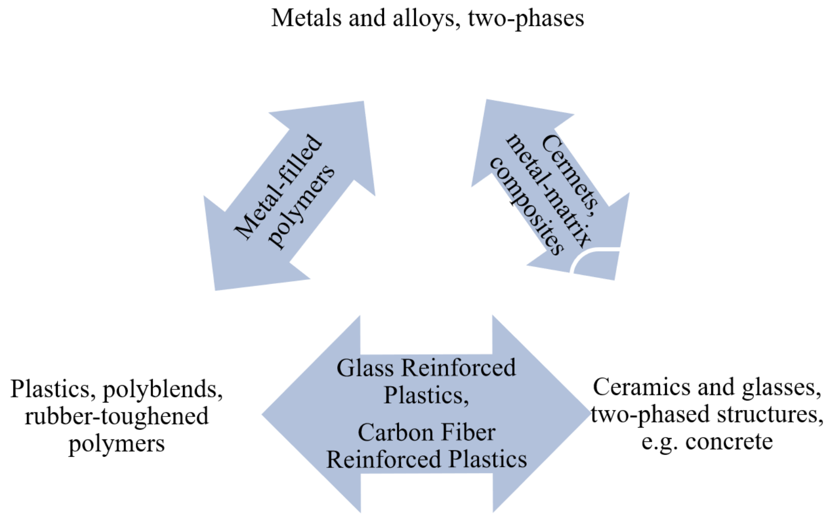

Figure 2.2: Schematic of three main composite classes (Reproduced from [7]).

The properties of materials in Figure (2.2) are depended on the macro-structure, quantity, and their distribution (reinforcing phase). Controlling these values can consequently modify the final properties of composites. Furthermore, the overall strength of each type is dependent on the materials' chemical bonds as well.

All materials have intermolecular defects in their microscopic structures, which this in turn results in the theoretical strength to be always higher than the actual experimental strength. This is more evident in the bulk form of materials where strength is not typically measured from their covalent or ionic bonds, but rather by the pores and intersectional cracks on the surfaces of the material. Hence, in Figure (2.2), the practical strength of the right-hand side group of materials (glass and ceramics) is usually about one thousandths of the predicted theoretical value; because, the strength in this group is mainly under the direct influence of the size of defects and cracks in the glass and ceramics. Similarly, in the case of metals, imperfect stacking of the crystalline arrays atoms results in the actual shear strength to be about a thousandth of the theoretical value [8]. In the 1920s an approximate relationship was derived by Griffith to express this behaviour:

$$\sigma_{max} = \sqrt{\frac{2E\gamma_{(F)}}{\pi\alpha}} \tag{2.1}$$

where: σ_{max} is the maximum stress before sample fails, E is the Young's modulus, $\gamma_{(F)}$ is the required work for the sample to fail, and α is the size of crack at the breaking point. It is worth noting that this equation (Eq. (2.1)) cannot exactly predict the exact point at which a material fails (maximum stress), and this is due to the fact that in reality, there are uneven and unequal distributions of flaws between two identical samples even if they are of a part of the same bulk material. Therefore, every sample can fail slightly at a different value of strength, i.e., at a different ultimate stress.

2.1.2 Glass fibres reinforcement composites

Glass fibre is one of the most commonly used reinforcement material that has interesting properties in the bulk form, such as, being inexpensiveness, resistant to heat and chemical substances, transparency, and having a good chemical inertness. In addition, when in the fibre form, glass fibres offer interesting properties such as: strength, flexibility, and lightness. A basic process of producing glass fibres includes a melting and crystallisation of bulk glass, such as silicates with soda or with potash, lime, or various metallic oxides. The molten glass then is spun by centrifugal force and passed through a series of holes and rollers in order to be wound onto a spindle. The as-molten fibres are then cooled rapidly and crystallized. The final diameter of fibres can be in the range from 0.793 to 3.175 mm, and 3–20 µm.

After being formed into filaments, a sizing (coating) is required to prevent the filaments from robbing onto each other and, hence, to avoid their abrasion-degradation. This can be done through an oil emulsion stage before being heated and treated with resin coupling agent [9–11].

2.1.3 Organic fibres

In general, polymers can have better elastic modulus and strength when in the fibre form compared to their bulk state. This improvement is usually achieved as a result of the application of a cold drawing process which increases the strength of material by reorientating its molecular structures in the same direction as one another. According to Ward (1980) [12], the effect of cold drawing process on the polyolefin fibres causes both crystalline and non-crystalline sets of isotropic polymers to be stretched and hence, leading to a crystalline continuity within the material. Such drawing process results in the organic fibres' strength to reach the same order of magnitude as that of other reinforcement types, such as, glass and aluminium [13]. For example, Aramid, which is a type of Aromatic polyamide, known as Kevlar-49, has the oriented diamine acid mediocre which consists of ordered chain structures that can be oriented with actuate of shear forces. As a result, the strength and modulus of Kevlar fibres can reach up to 2.6 GPa to 130 GPa.

2.1.4 Carbon fibre reinforcement composites

Carbon fibres have been recognized as one of the best type of reinforcement materials for use in advanced composite structures in the automotive and aerospace industries. This is mainly because of the manufacturing techniques involved during the production of carbon fibres which has made these reinforcements to be more amenable for the large scale productions. Some of the most attractive mechanical properties of carbon fibres include: about five times stronger and yet lighter than steel 1020; about seven times the strength, two times the stiffness, and 1.5 times lighter than aluminium 6061; and when impregnated with a resin, exhibiting even better fatigue properties and corrosion resistance than other most common metals. Finally, in terms of the electrical conductivity, particularly pitch-based carbon fibres offer three times a better conductivity than its metallic counterpart, copper (Cu) – which is beneficial for manufacturing computers' internal parts [14].

2.1.5 The strength of fibres

Material scientists have always been interested in to eliminate the weakness of carbon fibres and improve their strength to the level as close to their expected theoretical value (Griffith formula) as possible. The main approach to achieving this has been by focusing on enhancing the manufacturing process and techniques that are used to fabricate carbon fibres. One method involves producing fibres with the diameters as small as possible since small size fibres have shown to have a significant positive effect on improving the strength of fibres, compared to when in bulk form. This is because fibres (typically very fine filaments with sizes in the order of 10 µm) have usually shown to have the least amount of defects and flaws on their surface which is advantageous in terms of their mechanical properties [15]. For example, poly-acry-lonitrile fibres have inherently a very weak molecular bond chain which; consequently, some additional post-processing steps are required to compensate for this weakness such as, stretching, oxidization and carbonation. As a result of such post-processing steps, the mechanical properties of the polymer can transform for better, reaching a perforamcne level even similar to that of carbon fibres. In this context, the two most common types of polymers are polyethylene and polyamides (Nylon) [13]. Other types of materials which exhibit improved mechanical properties after drawing process are presented in Table (2.3).

2.1.6 Reinforcements

Reinforcements are the essential constituent part of any composite material, as they support the structure mechanically. The reinforcement materials in composite structures are typically in the forms of fibres, particles, whiskers (silicon carbide or aluminium oxide), or longer tungsten-boron filaments; the matrix part also palys a key role in keeping together the reinforcement materials and also transfer the load between them. The matrix materials can be a polymer (epoxy resin), high-temperature plastic, aluminium, metals or ceramics. Particles have no specific predefined orientation and the whiskers can be considered as elongated particles. They both however, have a relatively shorter length and smaller diameter when compared to the fibres. Application of particles is generally in non-reinforced thermoplastics and thermoset resins (glass beads, wood floor, asbestos, etc.) where a huge modification is not required to form the final material; therefore, the cost of manufacturing is not usually

Material	Trade name	Density, 10^3 kg.m^{-3}	Fibre diameter, μm	Young's Modulus, GPa	Tensile Strength, GPa
High-carbon steel wire	*eg*. piano wire	7.8	250	210	2.8
Short fibres:					
α-Al_2O_3 (whisker crystals)		3.96	1-10	450	20
δ-Al_2O_3 + SiO_2 (discontinuous)	Saffil (UK)	2.1	3	280	1.5
Continuous fibres:(inorganic)					
α-Al_2O_3	FP (US)	3.9	20	385	1.8
Al_2O_3 + SiO_2 + B_2O_3 (Mullite)	Nextel480 (US)	3.05	11	224	2.3
Al_2O_3 + SiO_2	Altex (Japan)	3.3	10-15	210	2.0
Boron (CVD on tungsten)	VMC (Japan)	2.6	140	410	4.0
Carbon (PAN precursor)	T300(Japan)	1.8	7	230	3.5
Carbon (PAN precursor)	T800(Japan)	1.8	5.5	295	5.6
Carbon (pitch precursor)	Thornel P755(US)	2.06	10	517	2.1
SiC (+O)	Nicalon(Japan)	2.6	15	190	2.5-3.3
SiC (low O)	Hi-Nicalon(Japan)	2.74	14	270	2.8
SiC (+O+Ti)	Tyranno(Japan)	2.4	9	200	2.8
SiC (monofilament)	Sigma	3.1	100	400	3.5
Silica (E glass)		2.5	10	70	1.5-2.0
Silica (S or R glass)		2.6	10	90	4.6
Silica (Quartz)		2.2	3-15	80	3.5
Continuous fibres (organic)					
Aromatic polyamide	Kevlar 49 (US)	1.5	12	130	3.6
Polyethylene (UHMW)	Spectra 1000 (US)	0.97	38	175	3.0

Figure 2.3: Typical properties of some familiar reinforcing fibres (Reproduced from [13]).

so high [2]. Whiskers are single crystal (length/width >1) and are usually grown from the inorganic materials (Fe, Cu, Cr, Sn, Zn, Al_2O_3, Si, SiC, Si_3N_4, NaCl). Some types have desirable characteristics like strength up to 1000 ksi and high temperature capability up to 4000 F which makes them suitable to be used as an alternative reinforcement to fibres wherever their use is not possible. Fibres can have different diameters, lengths, and orientations; in addition to being available in either a continuous or short form (discontinuous), making them very versatile in applications. For example, the continuous form of fibres provides a maximum load capability in the fibre direction which results in an increase in the stiffness of the material (Fig1.1); although, the specific methods of using continuous fibres as well as the types of manufacturing (such as hand lay-up, prepreg lay-up, vacuum bagging, resin transfer moulding, etc.) have led to the process to be time consuming and costly. On the other hand, the short fibres form represents to be as an alternative option due to their lower manufacturing method (injection mould) and consequently their costs [5].

The first realisation of using fibres as the most suitable form of reinforcement material (due to their advantages such as lightness, stiffness, and strength) goes back to Thomas Edison during the development of his early electric lightbulbs. Although the effort to improve fibres' mechanical properties did not start until after 1950s. Well-used types of fibres are Carbon (graphite), Glass, Aramid, and Boron. Glass fibres are consisted of about 46–75 % silica (SiO2) which has a main contribution to the chemical characteristics; as well as being flexibility, lightness and inexpensiveness for industries use. The strength achieved form the glass fibres are not, at least, less than the other types, though, the modulus is the least among others [16].

Carbon fibres also have similar characteristics of lightness and strength as glass fibres. They are considered as the choice of the "advanced" composites because of the good fatigue resistance and not being subjected to the stress rupture as much as the Glass or Aramid [17]. Carbon fibres are not however, easily adhered to the matrix if not being treated beforehand. The main constituent of the carbon is the graphite which has the hexagonal rings arranged in an ABAB... order (Figure (2.4)) [18]. Graphite fibres are those carbon fibres where were subjected to the heat treatment (3000 F) with the 99 % carbon contents. In addition, actual graphite fibres have much similarity in characteristics with the carbon fibres. Therefore, these terms are usually used interchangeably [19, 20]. The thermal coefficient of the carbon fibres at the room temperature is negative along the fibre axes and positives above the temperature of 700°C. Typical physical properties of three common types of carbon fibres are summarised in Table (2.1.6).

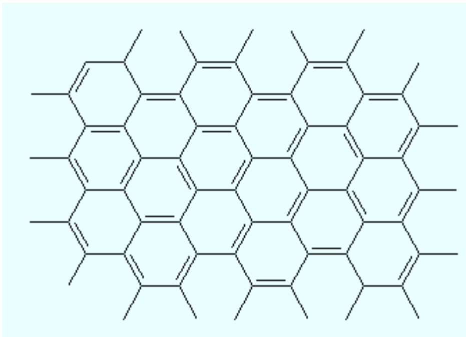

Figure 2.4: Schematic view of the arrangement of carbon fibre atoms (Reproduced from [18]).

Table 2.1: Typical carbon fibre properties (Reproduced from [21–23]).

Properties	Standard	Intermediate	High
Tensile Strength	3.45 – 4.83	3.45 – 6.2	3.45 – 5.52
Young's Modulus	220 – 241	290 – 297	345 – 448
Elongation at break	1.5 – 2.2%	1.3 – 2. %	0.7 – 1. %

Typical fibres mentioned above (Table (2.1.6)) have diameters between 2.54 µm to 30.4 µm, and a length-over-diameter ratio greater than 1 µm. Carbon fibre reinforcements are typically 5 to 8 microns in diameter and grouped into tows or yarns of 2,000 to 12,000 fibres [24]; in addition to having a strong covalent connection (Young's modulus ranging from 207 to 960 GN m^{-2}), and the space of 0.335 nm between the layers, making their crystal units anisotropic, as in Figure (2.5).

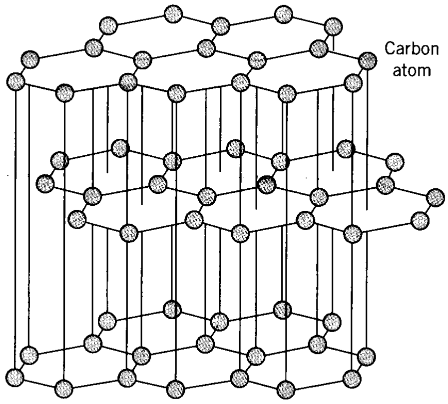

Figure 2.5: In-plane interconnections between carbon atoms and layer on layer connections on the normal plane due to the van der Waal forces (Reproduced from [18]).

2.1.7 Matrix

Matrix serves two fundamental roles in a composite material. It helps to transfer and distribute evenly the applied mechanical loads to the fibre reinforcements' surfaces, while keeping them together; secondly, it protects the reinforcements from environmental degradation such as, physical damage, oxidization, corrosion, or thermal instability. In other words, matrix will act as a bonding (adhesive) to integrate fibres together and assign structural strength to provide a unified firmness to the structure [25]. In addition, service conditions for composites such as attrition resistance, chemical resistance, permissible temperature operation, and weathering capability all depend on the properties and matrix type used within the system.

In general, matrix can be made out of polymers, metals, or ceramics among which the polymers (either thermoset or thermoplastic) are the most commonly in used materials because of their unique advantages such as, low tooling costs and manufacturability characteristics (low processing temperature required for fabrication) [5, 25]. Thermoset and thermoplastics have molecular chains where, in the former, the molecules have chemical interconnections (cross-linked) in contrast to the latter. Such chemical differences have given thermosets better rigidity and a higher operating temperature capabilities; however, this means that a longer processing time is usually required for procrssing thermoset polymers in order to shape their molecules and help them taking a cross-link configuration.

In contrast, thermoplastics need only to be molten and cooled again to solidify into a desire shape. Moreover, thermoplastics do not require a reactive cure cycle, except only heat and pressure in order to be formed into a desire form; hence, their processing is generally much more time and cost effective than the thermoset polymer (especially where the thermoset resin does not immediately coat the reinforcements within a short time). These processes, however, are different for various applications. For example, in the automotive industry the most commonly used polymeric matrix, polyesters, require a relatively shorter time than that of thermoplastics, whereas in the aerospace industry a multi-curing process is required which will obviously causes the time and cost of processing to be higher [1].

As for the advantages of thermoset polymers, they can retain their shape and strength while being heated; also, their strength will not degrade by heat exposure when in operation. These can facilitate their use in high volume solid permanent components [26]. Nevertheless, in order for a polymer matrix to effectively transfer and integrate the reinforcement materials within a composite structure, there should be some general criteria satisfied, for example:

- Low moisture absorption;
- low shrinkage;
- having relatively low thermal expansion ratio;
- good flow characteristics to avoid the voids formation in curing process;
- rather good strength, modulus and elongation (which should be greater than fibre);
- having good elasticity where does not fail before the fibres do.

2.1.8 Matrix function

As discussed earlier, the main function of a matrix is to transfer and distribute the mechanical loads and stresses within composite structures; this is in addition to providing a binding between them. The applied loads can be compression, bending forces, shear forces, and tensile forces. Furthermore, matrix reduces the brittle nature of composite as the majority of high strength reinforcement materials used in the modern composite structures are inevitably brittle. However, what matrix essentially does in this process is to separate the reinforcing fibres form one another, which this in turn results in an increase in the maximum failure threshold of composite (because each fibres acts as a separate entity and if some of the fibres failed it does not result in the entire failure of all fibre batches together) [27].

However, ideally, the strength of composites can be maximized if matrix could keep all the constituent fibres perfectly separated from each other during the application of a load. Since this is not the case in real-life situations, a crack can potentially propagate easily through one fibre to the next. Nevertheless, depending on the stiffness of matrix, this phenomenon can be controlled or stopped if there is a lack of energy at the tip of the crack, or even by the effect of the presence of a higher fibre volume fraction at some random parts of composite which can help diverting the crack propagation path. In either case, if a matrix is to be responsible for retaining the crack propagation, it should preferably be of a ductile-type material; alternatively, the reinforcements should be chosen from high-strength fibres [13].

Another contribution of the matrix is to bring mechanical toughness into the composites. This is important since the reinforcements on their own cannot provide both a high strength and a high toughness. A schematic illustration of these properties are shown in Figure (2.6) and (2.7). At the same time, high-performance composite materials need to have a good elastic strain energy capability when under compression or tensile loads. This is an important characteristic of composites because it prevent a plastic deformation, which may as well lead to a brittle catastrophic failure of the whole structure. This capability can be seen from Figure (2.7) by measuring the area underneath the stress-strain curve within the elastic region of the curve [28]. The larger this area is, the higher the strain energy.

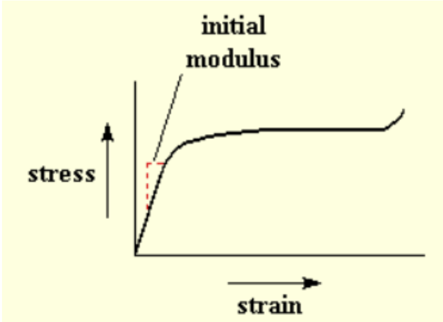

Figure 2.6: Young's modulus on a typical stress-strain curve graph (Reproduced from [28]).

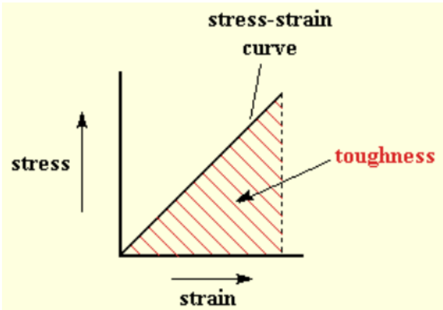

Figure 2.7: Toughness on a typical stress-strain curve graph (Reproduced from [28]).

2.1.9 Resin type

Today, several types of polymers have been developed as matrix systems. The most common types include, namely: polyester, epoxy, and polyether ether ketone (PEEK).

- Polyester is a common type of resin used especially with glass fibre reinforcements, and is usually used along with a type of silane as an agent to help to improve its adhesion to the reinforcement part. Usually, an accelerator agent is also used (such as organic peroxide with the temperature between 100°C to 160°C) to increase the solidification (polymerisation) of composite. Usually, the elevated temperature used for curing the matrix can cause shrinkage issue unless a thermoplastic additive is used.
- Epoxy is the most common type of resin which is in the form of liquid. Similarly, epoxy also requires a curing agent to enable curing at low temperature ranges (e.g., at room temperature). However, some of epoxy resins have a temperature resistance of up to 250°C. Epoxy has a comparably lower shrinkage rate as well as volatility levels; in addition to having a good adhesion to most of the reinforcement types, and having a good solvent resistance than that of the polyester.
- Polyether ether ketone (PEEK) is an increasingly used resin for producing continuous carbon fibre-reinforced composites. PEEK has a relatively good impact, temperature, and water resistances. Moreover, the fracture toughness of PEEK is typically about 100 times more than that of the epoxy resin. PEEK, however, has a relatively high melting temperature which can make its recycling process challenging (about 400°C).

2.1.10 Mechanical properties of composites

Steel and aluminium in the industry have a relatively long history as compared to composites, which their extensive use dates back to only about five decades. Early composites were mainly produced from glass and polyester resin and were used mostly in non-structural applications due to the fact that composite database and material properties used to be limited, unknown, and untested. However, common conventional materials such as aluminium also exhibited low corrosion resistance to salt water and harsh environments; in addition to being heavier than polymers by comparison.

Thus, as the overall behaviour and mechanical peripheries of resin and most fibres were known better over time, more industries began to explore the possibility of employing and even replacing the conventional metallic structures with lighter and stronger composite structures. The overall highlighting features which have made composites to be this much versatile and common in most industrial applications are their high strength-to-weight, high stiffness-to-weight, low density, environmental durability, and low cost of manufacturing [1, 22, 29].

The main difference between metals and composites is that metals are homogeneous whereas composites are not. If metals are cut at any point, they will still have the same material properties (e.g., density, internal structure, and micro properties throughout the material). On the other hand, composites are inhomogeneous as they are comprised of two or more different constituent materials from which different properties will be achieved at every point to point cuts. Moreover, composite materials are anisotropic which means that the mechanical properties (such as stiffness and strength) are different based on the direction of the applied load.

However, in composites the direction and distribution of fibres during fabrication process can be freely selected to be in such a way that ensures the highest available strength and stiffness of material is always being provided along the direction of loading. Hence, to identify the optimum mechanical properties of fibres, the mechanical properties of composites are usually evaluated through tensile testing samples along their fibres direction. Axial stress is expressed as $\sigma=\frac{P}{A}$ and it has relation with the strain and Young's modulus of material via $\sigma=E\epsilon$. The strain is defined as length added due to the deformation over the initial length of the bar as $\epsilon=\frac{\Delta}{L_0}$. So by substituting the stress and strain in the Hook's Law relationship, the deformation of a prismatic bar under axial load will be as:

$$\delta = \frac{PA}{AE}, \qquad M = \rho AL, \qquad M = \frac{PL^2}{\frac{4\delta E}{\rho}} \tag{2.2}$$

where, M is the mass of the bar in (lb. or Kg), P is the pressure (N/m^2 or kg·m^{-1}·s^{-2}), L is the length of the bar (ft. or mm), A is the cross section of the sample (ft^2 or mm^2), δ is the actual deflection in the length of the bar (ft. or mm), E is the Young's modulus of the material (Pa or N/m^2 or m^{-1}·kg·s^{-2}), and ρ is the density of the material (lb./ft^3 or kg/m^3).

E/ρ is the *specific* modulus ratio for a material. Since, the strength is referred to the maximum stress at which the material will fail, so, the relation of stress over the density of the material can also result in another ratio called specific strength which is expressed as σ/ρ for various types of materials. As it can be seen from Figure (2.8), composites and carbon fibre unidirectional laminate materials have an specific strength approximately four to six times higher than that of conventional aluminium and steel materials. However, the points to be taken into account are that, firstly, composites are comprised of at least two constituent materials, a reinforcement and a matrix, where their strength values are significantly different from each other; secondly, the anisotropic nature of composites causes these materials to exhibit different mechanical behaviours based on the direction of the applied load. For example, the specific strength in the transverse direction of a CFRP composite can be as low as even one-tenth of its longitudinal value [30].

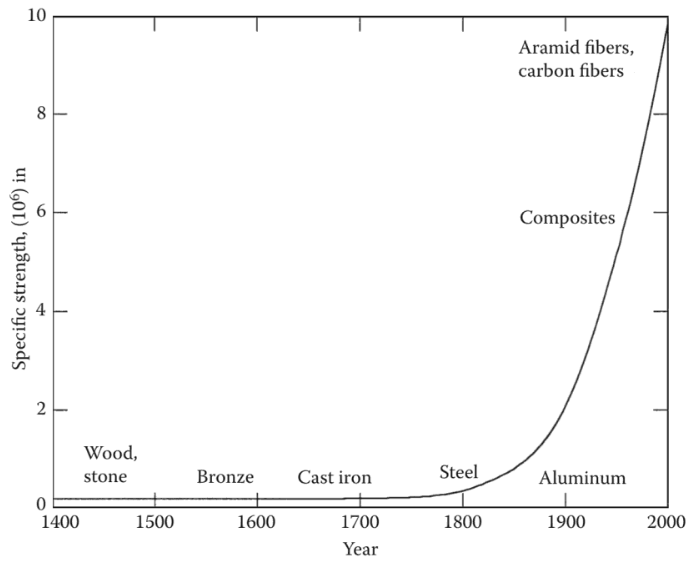

Figure 2.8: Comparison of the specific strength of different materials *versus* composites (Reproduced from [30]).

Moreover, composite materials are usually very brittle and can fail above only a few percent of elongations (often more than 2%). Metals, on the other hand, are more ductile and can elongate to strains of up to 10 % to 20 %. Another major difference between the mechanical properties of composites and metals is the way the strength value of each material can be improved; for instance, in metals it is simply done by performing a heat treatment, whereas, in the composites, several factors can influence their final mechanical properties, such as, the resin-to-fibre ratio, fibre type, resin type, orientation of fibres, and the lay-up stages [30, 31].

2.2 Design of Spring

The most common spring shape which are in use in most wheeled vehicles suspension systems is the helical spring. Helical springs in automotive suspension reduce the road seismic and vibrations by absorbing impacts abruptly, and then releasing the energy slowly during a physical deformation and dissipating the energy as heat. Therefore, springs performance optimization plays an important role in improving the dynamic and comfort of ride within vehicles. In recent years, the automotive industry has shown an increasing tendency to improve the comfort and cost of manufacturing of the steel springs. This has been by moving towards high strength-to-weight materials such as carbon fibre composite coil springs. carbon fibre coil springs offer a better dynamic performance and help reducing the fuel consumption by as much as 40% due to being lighter (by 70 %) compared to the steel springs [32].

In this chapter, there will be an overview on the mechanism and design of a typical steel spring and the aspects contributing to their functionality. Next, the design of carbon fibre spring and the necessary criterion which has to be satisfied for the design of such springs will be discussed.

2.2.1 Steel springs

Basically, the fabrication of a wire spring initiates from winding the wire around a helical shape mandrel. This rather simple process, however, can result in four different types of springs with different applications and designs: a) compression springs, b) extension springs, c) torsion springs, and d) wire forms. Moreover, the physical design of the springs can vary from cylindrical, conical, barrel, to hourglass shaped. However, since the purpose of this report is mainly to focus on the automotive suspension system spring, the cylindrical flat ends springs (which are the typical form of springs) will be hence discussed and other categories will not be covered in this report [33].

2.2.2 Parameters in the design of helical springs

The very first factor to be considered when designing coil springs is to consider for the elasticity; this means that how good a spring can absorb the mechanical energy and dissipate it by converting it to other forms of energies (deformation, heat, etc.) whilst remaining within its elastic region. Therefore, the design of a spring should be based on the Hook's Law. In the round springs the basic parameters upon which a typical helical spring can be designed are the coil diameter (D) and the wire diameter (d) (Figure (2.9)) [34].

Where: D is the mean diameter of the helix (D_{out} +D_{in})/2, d is the diameter of the wire, L_0 is the length of an unloaded spring, L_s is the minimum length in fully loaded and close gaps between the coils, p is the distance of two consecutive cycles of the wire in adjacent active coils, N is the number of coils in a loaded spring which have actively deformed, P is the angle between the coil and the base of the spring and is calculated as follows:

$$\alpha = tan^{-1} \frac{p}{\pi d} \tag{2.3}$$

2.2.3 Stress in helical springs

Constant pitch helical springs are one of the most widely and commonly in use type of springs used in most light and heavyweight vehicles. Their operating principal can be simply illustrated as in Figure (2.10), where when two directionally different axial forces act upon the spring, tensile or compressive loads are created within the wires as reaction forces. Such

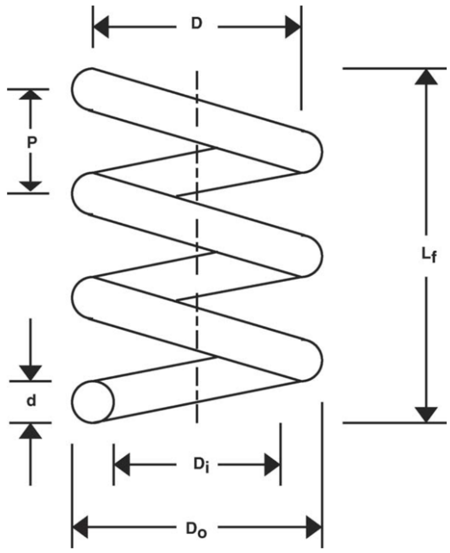

Figure 2.9: Dimensional parameters for a helical compression spring (Reproduced from [34]).

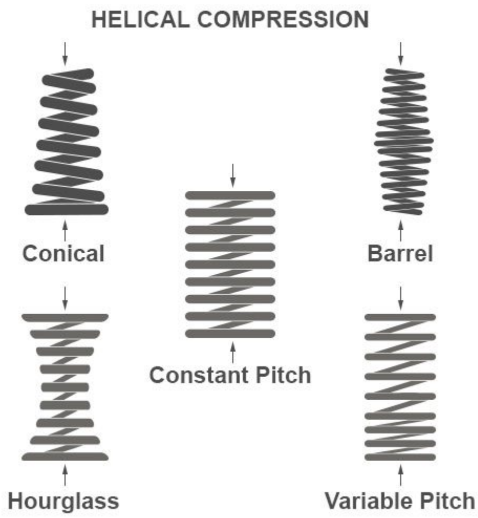

Figure 2.10: Common types of helical springs (Reproduced from [35]).

reaction forces will be manifested along the cross section of spring as shown in Figure (2.11). Equations (2.4) can be used to quantify such forces.

$$T = F \times \frac{D}{2}$$
$$\tau_T = \frac{T_r}{I_p} = \frac{F\frac{Dd}{4}}{\frac{\pi d^4}{32}}$$
$$\tau = \frac{F}{\frac{\pi d^2}{4}} = \frac{4F}{\pi d^2}$$

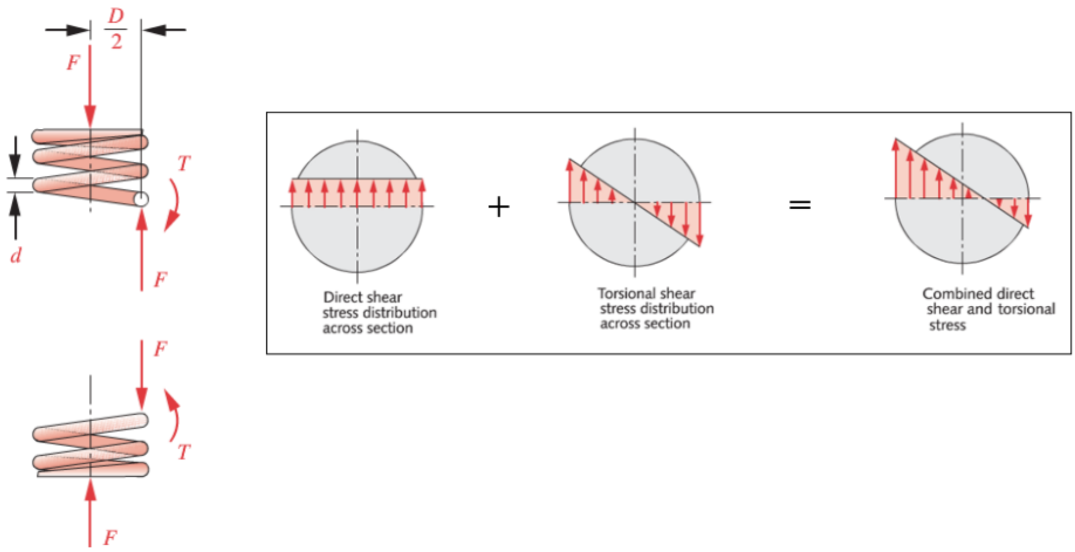

Figure 2.11: The cut section of a helical spring under tensile and compression forces (Reproduced from [36]).

Therefore, the shear stress can be written:

$$\tau_T + \tau_F = \frac{8FD}{\pi d^3} + \frac{4F}{\pi d^2}$$
$$\tau_{max} = \frac{8FD}{\pi d^3}(1 + \frac{1}{\frac{2D}{d}})$$

Where $C = \frac{D}{d}$ is known as the spring index; therefore, the maximum shear stress in the spring can be rewritten as:

$$\tau = \frac{8FD}{\pi d^3}(1 + \frac{1}{2C})$$
$$\tau_{max} = K_s \frac{8FD}{\pi d^3} \tag{2.4}$$

From the above equation, the most important spring factor can be said to be the spring index (C), as it can affect stress distribution along the cross-section of spring. The higher the C, the lower the stresses within the spring wire, and vice versa. Normally,constant pitch springs under compression will have a higher amount of stress concentration at the inner diameter of the spring. Therefore, it is always aimed to design springs with a high D/d ratio as possible in order to decrease the negative effect of this phenomenon called, which is called the curvature effect (Figure (2.12)). Formula-wise, to compensate for this effect, the stress correction factor in the maximum shear stress formula should be modified as K_{wahl}, which can be rewritten as below:

$$\tau_{max} = K_{Wahl} = \frac{8FD}{\pi d^3}$$

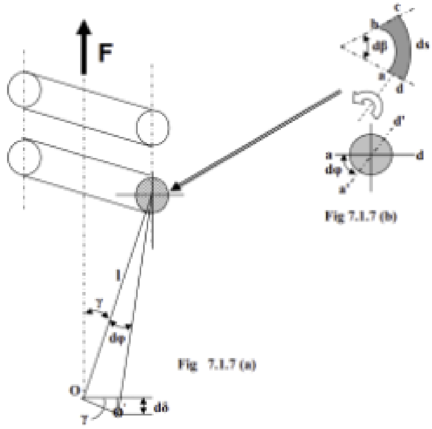

Figure 2.12: A schematic view of a helical spring under compression (Reproduced from [37]).

where,

$$K_{Wahl} = (\frac{4C-1}{4C-4} + \frac{0.615}{c})$$

For high values of (C), the correction factor (K_s) can be reasonably ignored. However, another factor which is the Wood's factor should be considered for the deflection of spring, as defined below:

$$K_{wood's} = \frac{2C^2 + C - 1}{2C^2}$$

It is important to note that the curvature effect can cause the spring elements to deflect which this is an important design factor in terms of defining the strain energy of the spring. This deflection can be written as: Deflection:

$$\delta = (K_{wood's} \frac{8FD^3N}{GD^4}) \tag{2.5}$$

where, N is the number of active coils and G is the shear modulus of elasticity. The factors affecting the performance of most springs are the outer diameter (D) and the wire diameter (d), as deflection is proportional to (D) by a factor of 4 and to (d) by a factor of 3. Therefore, the value of spring index (C = D/d) should be chosen carefully.

For example, as mentioned before, for C>154 there would be manufacturing problems to form the spring wire curvature; for C>15, because of the curvature effect, the torsional stress will be predominant; hence, the optimum value of C is usually between 5 to 10 in order to provide the least distortion during the manufacturing and assembly process.

2.2.4 Composites in automotive industry

Composite materials are increasingly used within the automotive industry due to their unique mechanical and physical properties which cannot be achieved by conventional metallic materials. The attempts to substitute metals with composites in vehicles have been already made for almost half a century when McLaren used CFRP composites for the first time in their formula 1 cars [38]. Factors attributing to the rapid deployment of composites can be said to be: high strength (fracture deformation), high modulus (stiffness which describes elastic deformation), low density (light weight), thermal resistance (thermal cycling), high ductility and high vibration damping (flexure at various loading), improved corrosion resistance, and excellent fatigue life [1], which have made composites being so versatile for applications ranging from aerospace, sport goods, to leisure cases such as car's interior panel, seat belt, and lifts compartments etc.

For automotive the main structural application of composites include the chassis, body, and suspension system. To make these parts out of composites at least two important requirements should be satisfied: (1) mechanical durability and strength; (2) manufacturing cost worthiness when compared to other alternatives. As for the suspension system and its incorporated spring mechanism, some indirect (lower consumption due to lower weight of the spring) and direct factors (more convenience due to the ability to sustain all road impacts) make composites to be considered as a better option compared to the traditional metallic springs. A Composite spring has to satisfy the design requirements while providing an acceptable level of vehicle dynamic requirement such the ride comfort. These requirements must be satisfied through both the design and material selection of composites in order to meet the manufacturer's efficiency criteria.

2.2.5 Carbon fibre composite coil spring

Carbon fibre reinforced composite coil springs offer unique mechanical properties such as: a high strength-to-weight ratio and excellent corrosion resistance. Other common parts where composites have found extensive uses in the automotive industry include the drive shaft or propeller shaft [39–41], the bumper of vehicles [42], side door beam [43], bearings, breaks [44], and of course the springs [45] (Figure (2.13)).

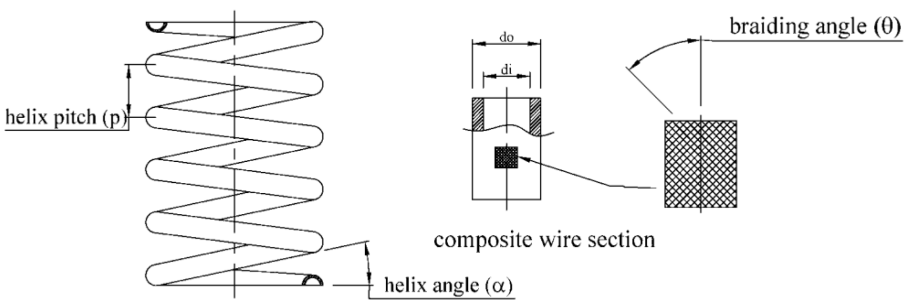

Figure 2.13: A schematic view of a composite coil spring (Reproduced from [46]).

Strain energy (σ_y) is an important factor to be considered for the design of a composite spring. This is proportional to the square of the applied stress and is inversely proportional to the density of the material and it's Young;s modulus (Eq. (2.6)).

$$U = \frac{\sigma^2}{\rho E} \tag{2.6}$$

Other parameters also include: the weight and spring constant (k). Accordingly, the weight of a carbon fibre composite spring, having a square cross section, are expressed in Eq. (2.7) and (2.8) [45].

$$W = \frac{\pi^2 D_m n(d_0^2 - d_i^2)}{4\cos\alpha} \tag{2.7}$$

$$K = \frac{G_{12} d_0^4}{8 D_m^3 n}[1 + f_n(C, \alpha, \zeta, n, \theta)] \tag{2.8}$$

where, W is the specific weight-to-density ratio; D_m is the mean coil spring diameter, n is the active number of coil in the spring, d_0 and d_i are the outer and inner diameters of the spring wire, respectively, α is the helix angle of the spring, p is the helix pitch; (G_{12}) is the shear module of the composite material consisting of both fibre and matrix, K is the spring constant, C is the spring index as D_m/d_0, ζ is the ratio of d_i/d_0, and θ is the braiding angle of the fibre. K should be corrected for different materials because of the anisotropic nature of composites. This difference results in approximately 4% difference between the composite and actual stiffness formulae. Hence, we have in Eq. (2.9) and (2.10):

$$K = 1.04\frac{G_{12} d_0^4}{8 D_m^3 n}$$

$$\frac{1}{G_{12}} = \frac{\nu_f}{G_f} + \frac{\nu_m}{G_m}$$

where,
G_f is the shear modulus of fibre;
ν_f is the fibre volume fraction;
G_m is the shear modulus of matrix; and
ν_m is the matrix volume fraction.

Other design parameters to be satisfied are the maximum displacement and maximum shear stress within a helical spring, as follows:

$$\delta = \frac{8 F D_m^3 n}{1.04 G_{12} d0^4} < \Delta \tag{2.9}$$

$$\tau = c\frac{8 F D_m}{\pi d_0^3} < S_{SD} \tag{2.10}$$

where: δ is the axial deflection of the spring, Δ is the allowable deflection of the spring as n(p-d_0), C is the shear stress multiplication factor, and S_{SD} is the design shear stress of spring ($\frac{S_{UltimateShear}}{FS}$).

2.2.6 Design of composite coil spring

The coil spring needs to satisfy some of the key parameters in order to be designed and manufactured. These parameters are the pitch, number of coils, length, and the outer and inner diameters [47]. The information, upon which a spring is designed here, represents common specifications required for a typical spring in a light vehicle Figure (2.14). Therefore, it is first required to start with sketch and realizing that such specifications are feasible for this application.

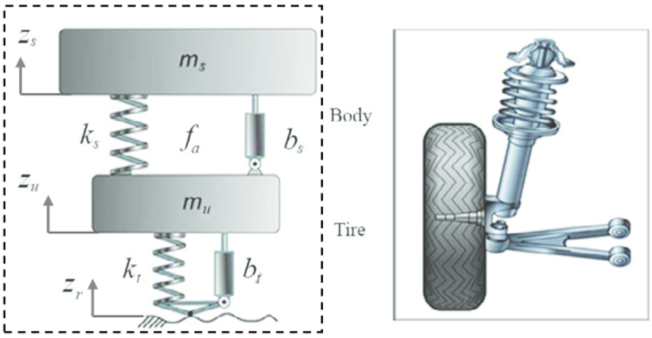

Figure 2.14: Schematic of coil spring in vehicles' suspension system (Reproduced from [47]).

An important factor, apart from the physical and dimensional aspects in the design of a spring, is the performance and damping characteristics of spring. The energy dissipation (in springs known as damping) is a conversion process of energy from one phase (e.g., mechanical) to another form (e.g., heat) over a period of time. This energy dissipation is significantly important to the stability of dynamic systems such as automotive and aircraft, wind turbines, and trains, as well as static structures, such as, bridges, platforms, and buildings. Active damping systems incorporate sensors and actuators to actively stabilise vibration and mechanical disturbances; thus, such systems are typically expensive and complex. On the other hand, in the passive damping system, which is the focus of this work, a conversion of the mechanical energy into heat is done via utilising the physical characteristics of helical spring, which is absorbing the applied mechanical strain energy and releasing it slowly as heat and deformation.

2.2.7 The CAD-design of a coil spring

A constant pitch coil spring was modelled using pro-Engineering Creo software (Figure (2.15)).

2.3 Manufacturing Method

Before manufacturing an actual coil spring, it is essential to understand whether the final part is feasible and cost-effective to be manufactured. Thus, it is important to identify and study the manufacturing techniques that are currently in used for the production of

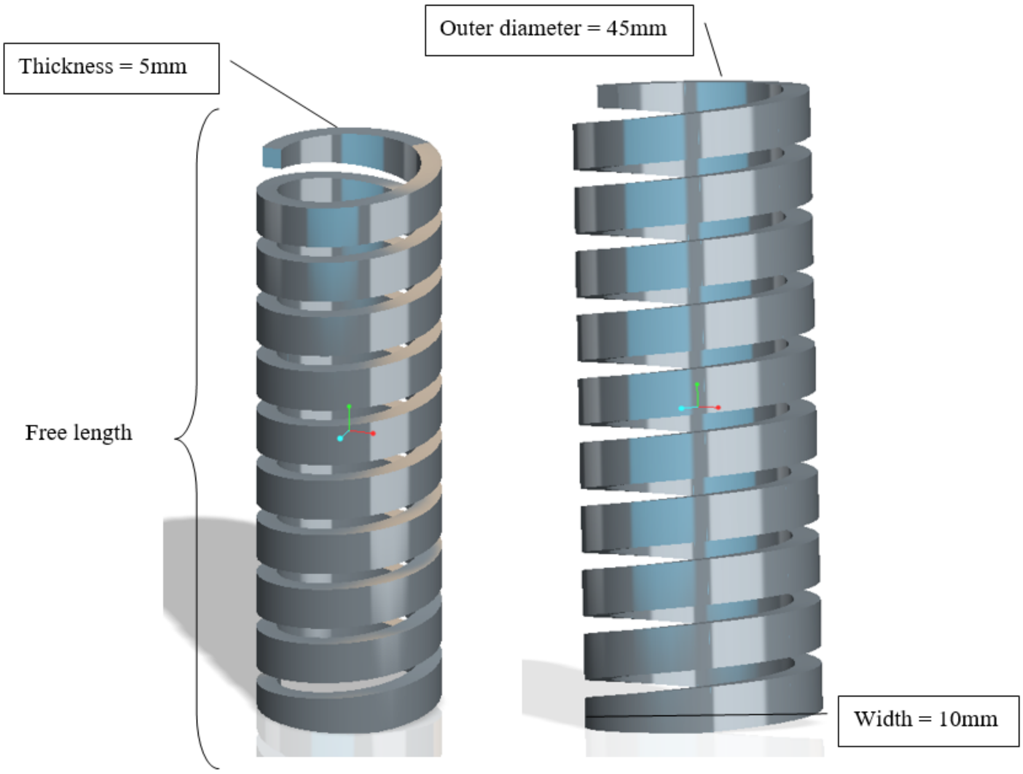

Figure 2.15: The CAD-model of a helical coil spring in Creo.

such springs–in order to avoid "reinventing the wheel". In this context, many researches have previous investigated the manufacturing methods of composite coil, leaf, and C-shape springs. However, there still exists many ambiguities, difficulties, and cost-related challenges associated with these methods which are addressed in the literature [33]. In particular, explicit advantages of using composites springs within the today's modern vehicles can be named as: reducing the fuel consumption and weight of vehicle, being stronger and more durable than steel springs, providing a better ride comfort, and requiring less maintenance. As a result, every intention has been to improve the current or conventional fabrication methods to produce novel composite springs that can actually be used in the today's high-performance vehicles.

2.3.1 Current manufacturing techniques

Different methods are available for manufacturing composite materials. Generally, these can be classified as: wet layup [48], cold press moulding [49], resin transfer and injection moulding [50], autoclave vacuum bag [51], hot press moulding [52], pultrusion [53], and filament winding [54], etc. Each of these techniques has its own advantages and applications depending on the type of reinforcement, matrix, cost, and complexity of the shape of the final parts. Below presents an overall comparison of these manufacturing technologies.

- Wet layup: this technique is usually used with complex shape moulds. The reinforcement fibres are laid by hand. The resin is then poured over the fibres and left within the room temperature to be cured (if a hot curing process is not used, some catalyses can be used to accelerate the curing process at room temperature). A post curing process can also be used to improve the result (e.g., 2 hours at 80°C or 16 hours at 40°C). A gel-coat can then be applied to provide a smooth protective surface on the mould. This method is commonly used due to its simplicity and the ease of creating high strength parts by simply modifying the fibre contents during the stack-up process.

- Cold press moulding: in this method, the reinforcement fibres are first placed within a mould and resin is poured over. A pressure is used to infuse the resin to penetrate through the centre of the mould to all corners and edges. This pressure also help expelling any excess air bubble within the mould. In this method, usually a portion of the edge of fibre mat should be placed in such way that overlaps the pinch-off areas around the mould in order to not let the resin to replace with air. This pressure will cause additional increase in the temperature which reduces the need of applying external heat (the reason why it is called the cold press moulding). To reduce the curing time (up to 15 minutes), catalyses and accelerator may be used.
- Resin transfer and injection moulding: in these methods the reinforcement materials are pressed into the shape of a desire mould before being placed into a half of the mould; the other mould half will be closed and clamped afterwards during the process. The resin can be either injected into the mould with pressure (about 5 bars), or drawn in by a negative pressure caused by vacuum. After completion of the resin injection, the laminates are left to be cured. The resin injection moulding has several types such as:
  - Structural Reaction Injection Moulding (SRIM): this uses high pressure rapid distribution of low viscous Polyurethanes.
  - Vacuum Assisted Resin Injection (VARI): a part of the mould is vented through which the vacuum force is applied.
  - Vacuum Infusion (VI): this technique is an extension of the VARI technique and is used when a high quality flexible tooling is required (e.g., for aerospace parts).
  - Resin Film Infusion (RFI): in this method a single mould plus a vacuum bagging process is used–it is therefore not a complex method. The mould in the vacuum bag will receive heat and pressure to travel along the entire parts.
- Resin Infusion Moulding (RTM): the produced laminates by this method have a high fibre contents and with good surface finish. However, the realisation of whether or not all the reinforcement fibres have been covered properly by the resin is not possible until the curing process is completed and the part can be taken out for inspection. Therefore, manufacturing large-scale, high precision, and expensive parts using RTM is to some extent very challenging and can be costly. In addition, the mould used in the RTM processing should be capable of resisting high pressure and high temperature conditions which will again result in adding to the overall cost of manufacturing. Therefore, RTM can be more suitable for low-volume manufacturing purposes or prototype productions [55].
- Autoclave vacuum bag: in this method, before the reinforcement fibres are located

within a mould, they are impregnated with resin. After that fibres are located within autoclave and carefully sealed and vacuumed. The autoclaved part can then be put into an oven to be pressurized and subjected to heat for curing. A breathing cloth is also located between the mould and the laminates to allow the expel of an excess air bubbles and resin. This method provides a good quality and excellent properties of the part. However, for large scale parts due to the significant weight of the autoclave, an extensive capital cost of transferring equipment and labour is required.

- Hot press moulding: the reinforcements are located between a tool which has a cavity in the shape of the final desire part; next a hydraulic press applies a temperature of 130 to 170°C to cure and complete the lamination process (2 to 3 minutes). For an ease of removal, release agents are used into the resin mix or applied on the surface of the tool. Hot press moulding uses other combinations such as Sheet Moulding Compound (SMC), Dough Moulding Compound (DMC), and Bulk Moulding Compound (BMC), which use polyester resin, filler, catalyst and other additives. The fibres are in the form of a thermally deformed chopper strand mat which consists of a thermoplastics binder. This technique is much favoured by automotive industries.
- Pultrusion: in this technique the reinforcements are passed through a resin bath, and then introduced to a heated die (150°C) to take the final shape of the desire part. The reinforcements can be of either/both a glass or/and a carbon type; the resin can be made of polyester (most common), vinyl ester (corrosion resistance applications), and urethane meth-acrylate (good fire, toxicity, and smoke resistance applications). Pultrusion is currently a very common method used in industry because of offering a fast and economical process.
- Filament Winding: the reinforcement fibres in this method are impregnated through a resin bath before being wound onto a rotating mandrel and traverse the length of the mandrel. As in this method the laminates are not laid by hand, the angle of fibres is determined by the speed of the rotary mandrel. One way to cure the composite part in this method is to apply heat on the mandrel while it is rotating; alternatively, removing the fibres and locating them in an oven afterwards. The filament winding is a fast and cost-effective process. Pipes in the gas and oil industries are made usually by this method. For such applications the outer surface is not usually moulded (depends on the application). Therefore, the interior surface, which is going to be in contact with a medium, has a much better surface quality and finish.

2.3.2 Wet lay-up technique

In the wet lay-up technique the prepreg woven fabrics are usually used. Yet, the prepreg types do not generally contribute to high laminate stiffness and strength. This is because of the crimps in the fibre tows where the weft fibres cross the warps fibres when the two is bent fo example. The free space between fibre yarns is filled with resin which therefore the volume of fraction V_f of woven laminates can have values of about 50 % for heavy, 58 % near-unidirectional woven fabrics with 90-98 % of reinforcements in the weft direction.

The carbon volume of fraction in the unidirectional prepreg where there is multidirectional lay-up fabrication V_f varies between 58-63 %. This means that, the impregnated woven fibres are much heavier in weight as well as less stiff and string than the unidirectional laminates. However, the woven laminates are much better resistant to delamination and crack propagation [56]. The application of the prepreg hand lay-up method in the composite materials manufacturing has widely expanded in both dynamic applications (such as leaf spring) to static applications (such as sewage tanks). Other types of composites which can be used in high performance applications are such as aramid fibres which can be used in the laminates structures for low-velocity bullets defence systems. The advantage of the prepreg hand lay-up method is that almost all types of the reinforcements can be used by. A Wide range of the fibres with different stiffness form 280 GPa (E-glass fibres) to about double than that of the original value of the carbon fibre can be used by prepreg hand lay-up method. For instance, the stiffness achieved form the E-glass fibres can provide the laminates with the tensile moduli of about 42 GPa to almost ultra-high moduli carbon fibre laminates with tensile moduli of 490 GPa. The typical type of resin which can be used are the epoxies type because of the high strength, high adhesion characteristics with carbon, slow curing (which is beneficial in terms of the time it allows to be kept out of the freezer (consequently a longer lay-up period). The temperature limit is between 150°C to 200°C with the polyamides with 270°C [57].

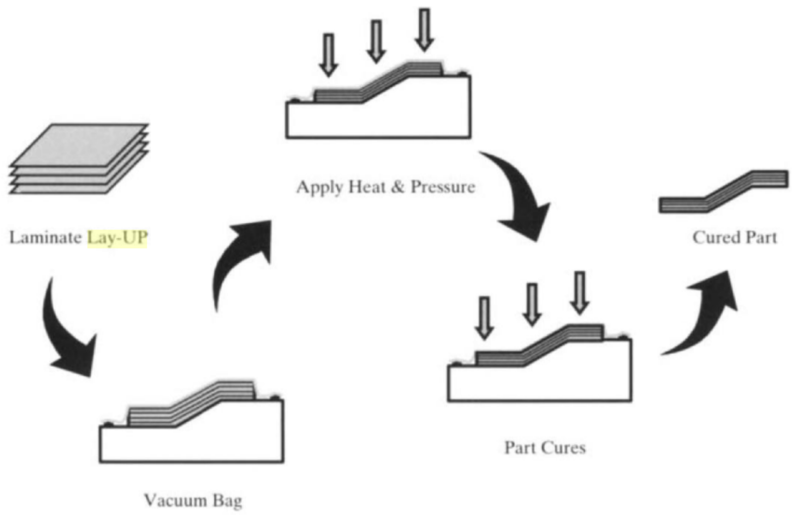

Figure 2.16: Hand lay-up manufacturing process (Reproduced from [57]).

2.3.3 Resin Transfer moulding (RTM)

The resin transfer moulding (RTM) technique basically involves the liquidized moulding form of composites, where a polymer liquid is injected into a stationary fibre bed (Figure (2.17)). The quality of the final part can vary by some elements like the pressure gradient of injection and the way it is applied. This simple process has given RTM the ability to be suitable and yet a cost-effective method for producing different composite parts for various applications

[58]. Some typical advantages of the RTM method compared to other common composite manufacturing techniques are summarised din Table (2.3.3).

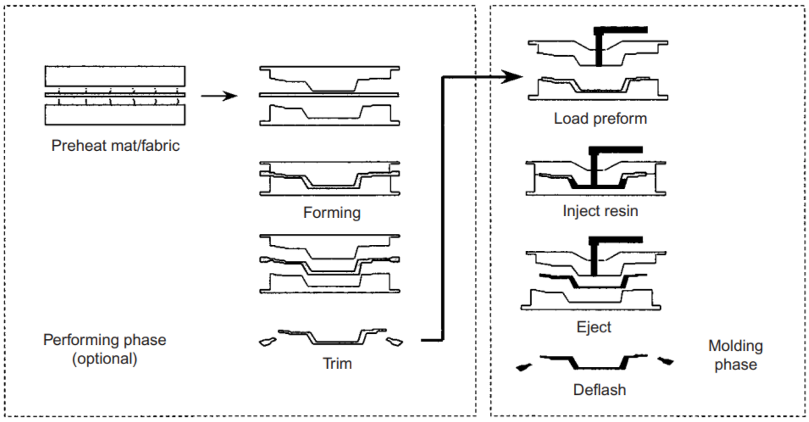

Figure 2.17: RTM process (Reproduced from [59]).

Table 2.2: Comparison of common composite manufacturing techniques (Reproduced from [58, 60])

Advantages	Disadvantages
RTM	
Reduction/elimination of VOC emissions	High costs of tooling and equipment
Improved uniformity, quality assurance	
Two cosmetic faces	
Reduced labor costs	
RTM compared to vacuum bag autoclave	
Reduced materials costs	Higher tooling costs
Reduced labour costs	In-house resin formulation
Thick sections possible and easier de-bulking	Greater quality assurance responsibility
Direct control of thickness and fibre volume fraction	
Flexible use of reinforcement, resins	
Fewer shelf life issues	
RTM compared to compression moulding	
Reduced tooling costs	Longer cycle times
Fewer shelf life issues	In-house resin formulation
Use of structural performs	Greater quality assurance responsibility
	Greater floor space requirement

The RTM process includes filling a mould cavity by the reinforcement material (up to a desire thickness) and enclosing the mould for injecting a liquid resin inside the cavity (Figure (2.18)). The injection of a liquid resin happens with combination of compression to exit any air bubble between the laminates. The mould cavity is divided into two parts where in operation are closed with a freedom degree, usually a fraction of the cavity height. This is the space that can directly affect the permeability and consequently the thickness. The point to be taken into account is that, the resin injection does not always travel to the far end portion of the part (due to either geometry of the part or injection pressure) which therefore the final impregnation occur by the compression applied by moulds as they are closing into the necessary thickness [61].

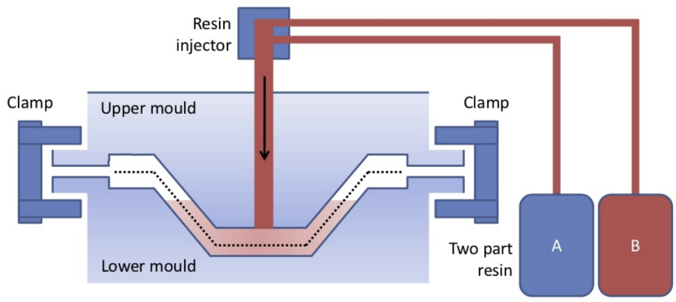

Figure 2.18: Schematic of RTM manufacturing process (Reproduced from [61]).

In terms of the economics and cost of the products fabricated with RTM, a schematic cycle break down in form of pie chart graph has been provided for a typical large part. The injection and curing times are the two important variables that can control the final quality of the produced part in this technique. The gravity or vacuum injection methods are specially incorporated with low-volume scale (or prototyping) operations. However, the overwhelmingly majority of industrial applications intend to use positive-pressure systems (where the operation pressure can vary between 2 to 10 bar), with the components filling rate of 1-3 l/min (these values, though, are affected by some other factors such as gating strategy, fibre fraction, and characteristics of the injection being used). The SRIM metering systems, because of providing a high pressure distribution, can increase or even double the aforementioned outputs. Generally, in a RTM process the heating and curing times can be changed depending on the thickness or the resin which is used during that process. For example, Urethane SRIM resins can roughly be solidified within about 40 seconds to be able to be separated from the mould, where in a more thicken sections of the part or incorporating the epoxy resins may need time to about hours before being released from the mould [60].

The freedom of choosing different resin materials in liquid moulding techniques has made the use of RTM very appealing to the aerospace and automotive industries. This is also the case in terms of the type of the reinforcement material that could be used in this technique (e.g., narrow strands which can be used in prepreg composites, or three-dimensional waves fabrics). Typically, an average fibre volume fraction that can be achieved using a RTM process is about 65 % for flat panels, and 35 % for continuous random reinforcements. Yet, reduced costs of production has been a motivating factor in the automotive sector to use RTM as a main technique for manufacturing their major vehicles' composite components (Figure (2.19)).

In the aerospace industry, RTM has been extensively used for the productions of monolithic or syntactic cored laminates by woven or knitted sock tubes. Particularly, the Royal Air Force (RAF) has implemented this technique in their Tornado fighter with the dimension of about 2 meters long and 1.6 meters diameter approximately. Moreover, a provocative factor

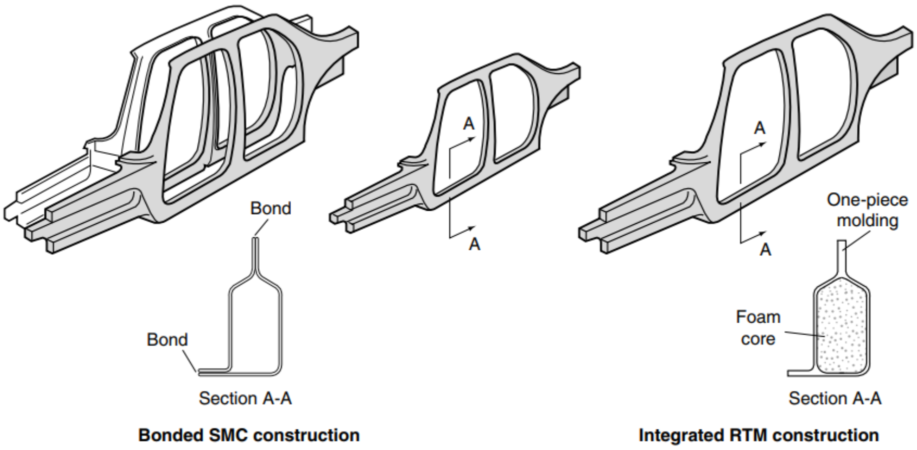

Figure 2.19: An application paradigm of the RTM technique; Curtsey of Ford Motor Company (Reproduced from [59]).

in using RTM was in propellers application for both hovercraft and aircraft by cleverly combining processes of fabrics, mat, foam injection, and braiding together for F-22 and F117-A fighters [62]. RTM in many of these applications is mainly considered as a replacement for the hand wet-layup process with a cost saving of about $25,000 per aircraft. Therefore, today, applications that rely on the RTM processing have extended to a variety of components such as engine inlet glands, fuselage, and Boeing's door blocker 40-piece aluminium with a 6-piece carbon/epoxy in match with metal mould.

2.3.4 Compression moulding (long fibre)

The long fibre granulator (LFG) has been well-known since 1990 in the market. The material comprises glass-fibre bundles cut into 12.5, 25, or 50 mm long strands, which are manufactured by a pultrusion process. The production process of these fibres, however, is considered to be lengthy and costly (since the rotational speed of the screw should be kept slow to preserve the fibre orientation) for automotive industry. As a result, a direct process (long fibre reinforced thermoplastics LFT) was developed in order to help double the heating process. This process involves the continuous fibres that are impregnated with thermoplastic matrix (such as polypropylene) extruded into the mould cavity [63, 64] (Figure (2.20)).

2.4 Composite Coil Spring Manufacturing

The manufacturing of composite coil springs is a relatively challenging process due to the geometrical complexities that are associated with a helix geometry. This is in addition to the anisotropic nature of e composite materials — making the prediction of the final properties of the spring very difficult. However, typical methods such as hand lay-up technique help to reduce some of these challenges as it is a repeatable and inexpensive method by reasonably good surface finish prototypes can be fabricated. For this aim, a predefined structure (man-

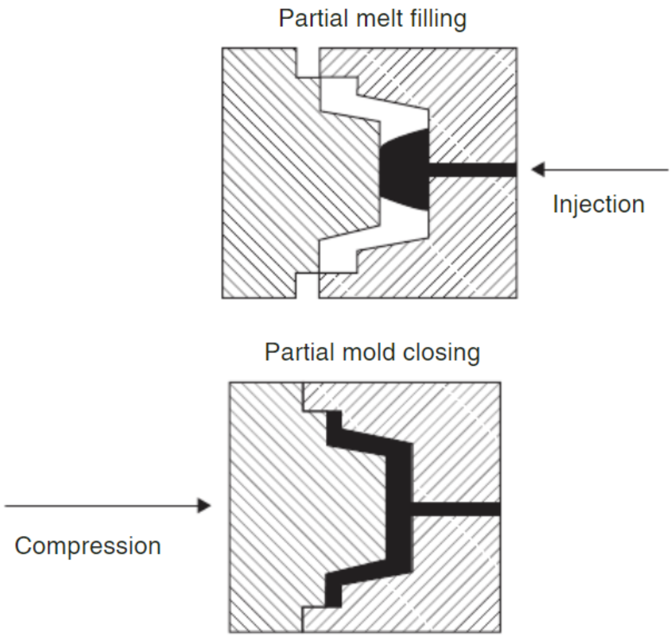

Figure 2.20: Schematic of injection–compression moulding process (Reproduced from [23]).

drel) with in the form of a helix is required. This is the most feasible and, by far, common method taht is currently in use for producing composite coil springs. Another alternatives is to use the injection moulding or compression moulding methods that are mainly suitable for low volume high quality parts, by incorporating the polymer materials (such as PEEK, Epoxy etc.).

As described in the US patent (No. 4,380,483) [65], in this work also a similar approach to manufacturing a series of composite coil springs has been adopted. The patent also suggests that a braid angle (α) between plus or minus 30 to plus or minus 60 with (respect to the helix axis A-A) can potentially be the most effective configuration to achieve optimum mechanical properties in a coil spring (Figure (2.21)). Hence, in this work, a braid angle of ± 45 has been chosen, as fibres at this angle exhibit the highest strength due to torsional forces that are usually applied on helical springs.

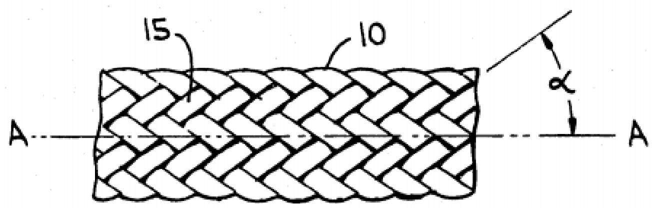

Figure 2.21: Braided carbon fibre rope (Reproduced from [65]).

Figure (2.22) illustrates an aluminium bar cylinder (mandrel) which was formed into the shape of a helix for the reinforcement materials to be embedded in. The outer diameter and overall length of mandrel is 45 mm and 140 mm, respectively. The mandrel was made with

the lathe machine on an aluminium bar. The reinforcement carbon fibres can then be wound onto the mandrel within its helix groove. The groove has a size of 10 mm by 5 mm, a pitch of 14 mm, and a thickness of 4 mm for each rim on the mandrel.
The carbon fibre braids are then impregnated with resin and wound around the mandrel

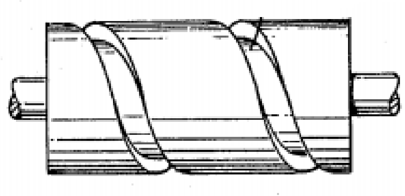

Figure 2.22: Schematic of a helical mandrel produced for fabricating a composite coil spring (Reproduced from [65]).

within the grooves as can be seen in Figure (2.23).

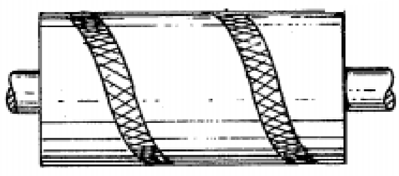

Figure 2.23: Resin impregnated carbon fibres are wound around the mandrel (Reproduced from [65]).

Carbon fibres can be impregnated with resin before being wounded onto the mandrel, or alternatively, get impregnated afterwards when dry fabrics are laid down within the grooves of the mandrel. The resin can be either applied continuously on the carbon fibres as they pass through a resin bath (immersion technique) beforehand, or being applied when the carbon fibre braids are wounded within the grooves. However, the former technique is more advantageous, because of providing sufficient impregnation on the fibres. In this report, the braided carbon fibre lamina, which are already pre-impregnated with resin, are stacked up on top of each other up to the thickness which is equal to the groove's depth. The types of resin systems that can be used for this propose are, for example, epoxy, phenol, polyester, polyamide, etc.; among which the epoxy and polyester are more favourable because of their high torsional modulus and temperature sensitivity.

Thermosetting resins can be cured by heat treatment or the use of curing agents. The former, for example, can yield to the development of a molecular chain in the epoxy resin that can grow and take up the form of a cross-linking structure. The latter (curing agent), includes different types of hardeners from co-reactant substances (such as aromatic amines, polyamides, tertiary amines, amine adducts, acid anhydride, acids, etc. In terms of the thermoplastic resins, polyethylene, polypropylene, and polyesters can be used as for the matrix material for the fabrication of a composite coil springs. Thermoset resins may be applied after or during the fabrication process. In addition, there is a possibility of adding one or more accelerating, diluents, or curing agents to the process. However, in terms of thermoplastic resins, they need to be kept in a liquid condition. Hence, the reinforcements fibres (carbon) can be immersed afterwards within the resin bath before being wounded onto the mandrel. The impregnated fibres will then need to be cooled down to solidify. Generally, the choice of a resin matrix is based on its ability to provide a solidified continuous matrix. For instance, thermoset polymers are suitable for applications where the operation temperature is between 100–1000 °C.

As for the reinforcements, different types of fibres can be used for the construction of a braided composite coil spring. These include, glass, carbon, aromatic polyamide, polyester, and natural fibres. Besides, it is possible to have a combination of two or more different reinforcements, whcih can be done by incorporating a longitudinal axial fibre within the braid preform (Figure (2.24)).

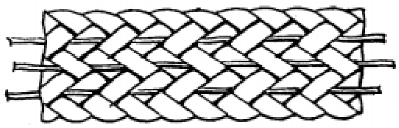

Figure 2.24: Reinforced braided carbon fibre with longitudinal fibre strands (Reproduced from [65]).

During the winding stage, application of an additional pressure on the surface of the braid is advantageous to eliminate voids and further to facilitate the solidification process. The mould release agent, which had been applied in the mandrel grooves already, will help the separation of the coil spring form the mandrel easier. The release agent can be tetrafluoroethylene which is also marketed as “Teflon” and polymeric silicon compound.

2.5 Failure of composites

Failure analysis of composites provides important information regarding the structure's effective life cycle that will help preventing their catastrophic failure during their service. This comes true especially in a high performance structural composite parts, in particular, when they are subjected to a cyclic (fatigue) loading conditions, such as in the case of springs. It is therefore essential to study the mechanical behaviour and potential flaws and fractures tat could lead a composite springs to failure. In this section, damage in composites and their fatigue analysis will be discussed. It is worth noting that in composites constituent materials can act differently and unexpectedly when a damage is incurred compared to the monolithic materials (e.g., metal springs). Thus, this section will continue with a brief review on the micro-mechanism damages (such as micro-cracking of the matrix, delaminating, ageing, etc.). Next, a review on some of the predicting models that identify changes in the composite materials' behaviour due to the presence of damage is discussed. Generally, plastic reinforced composite materials have incorporated glass or carbon fibres which are intrinsically brittle. The micro-scale damages as a result of deformation can remain within the structure before reaching the point that the load-ability of material is actually impaired. Hence, a damage progressing beyond the constituent materials' mechanical properties (elastic properties) can result in a further propagation of the crack within the system from micro to a macro-scale. Such kind of damage behaviour are even more complex in composites to be fixed than in metals (or homogeneous materials). In some cases, if the matrix has a reasonably high toughness, this can help restraining a crack propagation at the interfaces between the fibres and matrix; as well as in the multi-ply lamina, between every individual laminate. Therefore, the complexity which comes in the study of composites' fracture and, consequently, their crack propagation behaviour, lies in not only the fractures of the fibre and matrix parts, but also in the modes and characteristics of the crack itself within the laminates. This complexity is because of the heterogeneity and anisotropy natures of composites, which ironically, make them to have a higher toughness as compared to the homogenous, isotropic materials [31, 66–69].

2.5.1 The effects of reinforcement and matrix on composites failure

Composites achieve their mechanical properties (such as strength) from their reinforcement constituent, which is embedded within a matrix medium. Although, the matrix can also have some contributions to the improvement of the overall strength and mechanical properties of composites, but its main faction is to transfer mechanical stresses and loads to the reinforcements. Therefore, as the strength of composites mainly relies on the reinforcements, their fracture and failure modes, also, can be governed by the existence of a potential defect in the reinforcement material. The fibres physical configuration in the matrix with respect to the load direction is one of the main factors contributing to the defects in composites. Thus, in this chapter the importance of orientation of the reinforcements within composites, and its attribution to failure is discussed. Then, composite materials with multi-layer lamina will be discussed. It then follows to study the weakness of fibres under strain and specific loading conditions.

In addition, a broader study has been performed on the micro and macro-mechanical level failures in composites. The micro-mechanical the properties related failures are investigated where the results can vary differently based on a variation in the loading conditions. These studies involve the effects of matrix, reinforcement and the interface-interphase sections on the failure modes in composites. However, according to DANIEL (2007), these failure analyses provide the failures at the initiation points with a rather approximation values; whereas, in the macro-mechanical failure investigation, the lamina and furthering to multi-laminate failures is analysed, which is more preferred in this report. Based on this approach, the classification of common theories includes: (a) limit or non-interactive theories; (b) interactive theories (Tsai-Hill, Tsai, Wu); and (c) partially interactive theory (Hashin-Rotem, Puck). The selection of a theory depends on the application as well as the suitability of the approach to match the experimental results. However, the difficulty to select the most suitable theory lies in the dearth of experimental data to verify the theory. Therefore, in order to simplify the selection of the analyse method, the failure type has been categorized into two classes: (a) single lamina failure, and (b) multi-laminates first-ply-failure prediction and the corresponding propagation behaviour.

SUN (2000) in DANIEL (2007) [70] provide a reviewed “six failure theories” governed by different loading configurations including normal and shear, non-centric loads, and biaxial loading. In their studies, it is shown that most diversity in the theories come from the combined transverse loadings under compression. The prediction of the Tsai-Wu interactive theory agrees better with the experimental results than others. Therefore, in this section there will be first a discussion over the single lamina failure by considering the theoretical behaviours of normal and shear stresses on the composites. Then, the factors influencing multi-directional laminates failure behaviours will be discussed.

2.5.2 Matrix share

The matrix related crack propagation issues are not as much catastrophic when using long fibre reinforcements as it is in the case of short fibres. Thus, in composites which are reinforced with short fibres there is a relatively more contribution of the matrix to the crack propagation. In addition, the crack in the matrix is depended on the fibre volume fraction by which the resistance of composite against a crack is directly determined. For example, in Dark Matter Composites it is about 10% while in the Carbon Fibre Reinforced Plastics Composites (CFRPC) it is approximately 70% [31, 33].

According to HARRIS (1980) [13], generally, in composites with low fibre volume fractions it is often the case that matrix-related fractures initiate a crack within composites. However, in composite with a low V_f (flexible materials), the minimum load or stress required to initiate a crack is usually high, which is advantageous. In addition, incorporation of fibres or particles in the matrix can improve toughness by slowing down the propagation speed in the vicinity of the crack. The crack propagation speed in a matrix examined by inspecting the surface roughness of crack; i.e., the rougher the surface of a crack is, the slower the speed of propagation must have been [71].

2.5.3 Fibre share

Composite failures at the fibre stage is mainly depended on the type of reinforcement fibres used in them. For instance, polyester textile fibres which are used in rubber tires or, aromatic polyamide fibres, are used high performance fibres because of providing the toughness and an excellent load-bearing capability during large deformations and the necking stage before failure. On the contrary, are the brittle materials such as glass and carbon fibres which will fail catastrophically even at very low strains due to having a very low intrinsic fracture energies. However, failure of brittle fibres is mainly associated with the distribution of the flaws within the material, which at the same time, this does not have a significant contribution to the fracture of composite as a whole [13]. In general, fibres may break several times at different points (multiple cracking), however, this does not necessarily mean that the composite is going to completely fail, because these broken fibres can still act as short reinforcement fibres, hence, distributing stresses over a wider area and delaying failure of composite (Figure (2.25)).

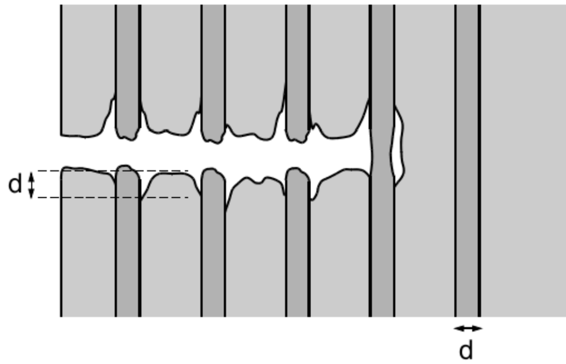

Figure 2.25: A schematic view of a crack propagation in a composite material where fibres constrain the plastic deformation of the matrix (Reproduced from [13]).

Failure in the reinforcement fibres can occur depending on the stiffness of the fibre (e.g., a highly stiff fibre such as carbon, or a less stiff one such as glass fibre), as well as on the shape of them, e.g., continuous, short, woven, or chopped. At the same time, matrix can play a significant role in initiating a crack within the composite. For instance, when a brittle resin is used with a highly stiff reinforcement (e.g. carbon fibres), matrix provides a low failure strain which consequently leads to weaker fibres to start to break prematurely before all of the load is distributed evenly to all the reinforcement fibres. Hence, a premature crack propagates at the weaker points throughout the composite.

The energy required to break fibres in a typical composite system can be expressed by $1/2\sigma\epsilon$ per unit volume; for example, for a V_f of $\approx$0.7 and a volume deformation in the order of d^3, the fracture energy of composite will be in the order of 1 J/m^2. This much of the fracture energy would therefore be enough to break the majority of fibres. However, this in the case of long continuous fibres, for example, >10 cm, can lead to the breakage of the smallest critical particles (0.5 mm for CFRP), and the fracture energy would still be only in the range of a few hundred J/m^2. A crack propagation phenomenon is illustrated in Figure (2.26)(a), where fibres in a matrix are resisting a crack initiation. As it can be seen in Figure (2.26)(b), the crack is first halted by the stiffness of matrix (b), which prevents its sudden propagation throughout the material. At the same time, fibre also prohibits further penetration of the crack. This is done, first, by some amount of strain energy that is available within the fibres itself (although this energy cannot provide as much elasticity as the matrix does, but it can help to prohibit the crack propagation force to some extents); then, by the strength of fibres that is a major contributing factor preventing a catastrophic failure of the composite as a whole (Figure (2.26)(c)). However, if the loading continues above this point, up to the point where the strength of fibres can no longer withstand the concentrated stresses at the crack tip, fibres will fail one after another within the composite (Figure (2.26)(d)). From this point onward, any slight increase in force (or a shear force) can lead to a complete failure of composite (Figure (2.26)(e)) [13].

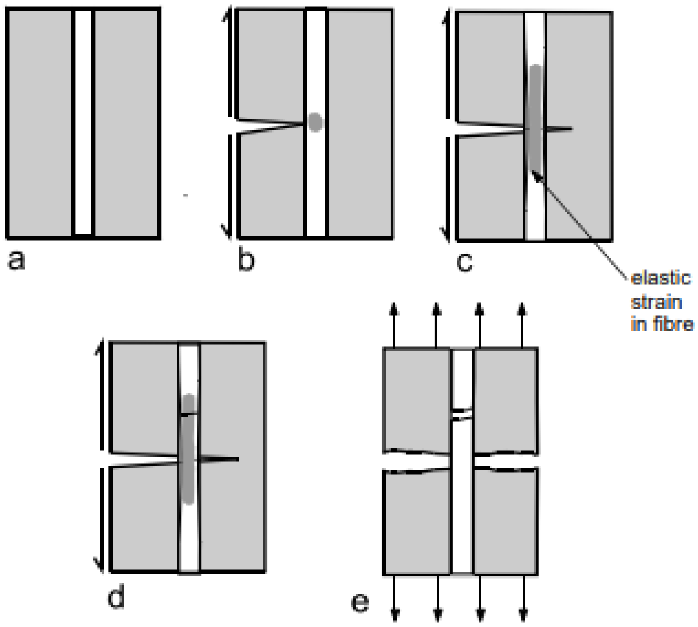

Figure 2.26: A schematic view of the crack propagation steps within a composite material (Reproduced from [13]).

Moreover, when the length of fibre embedded within the matrix has reached the "critical transfer length of fibre", any further increase of the applied load will appear as a shear force acting at the fibre– matrix interface; consequently, this will result in the initiation of laminate de-bonding (Figure (2.27)(a)). At this point, the load will immediately fall slightly as a result of a sudden increase in the speed of the crack growth. The energy required in order to initiate the crack in such way is represented by the surface area under a load-displacement graph (as shown in Figure (2.27)(b)).

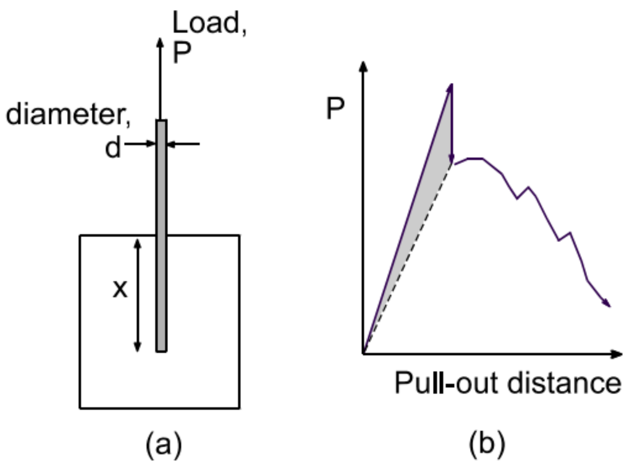

Figure 2.27: A schematic view of a fibre pull-out process during a crack propagation (Reproduced from [13]).

Accordingly, the stress required to de-bond the composite can be quantified using equation

Eq. (2.11) [72].

$$\sigma_{fu} = \frac{4\tau x}{d} + \sqrt{\frac{8E_f G_{II}}{d}} \tag{2.11}$$

Where the de-bonding process starts at $\tau = 0$.

2.5.4 Failure analysis

Generally, composite materials are subjected to four types of failures, or a combination of them; crack in the matrix, decomposition of fibres and matrix, plies delamination, and the breakage of the fibres. The overall failure of the composite, however, occurs with the cumulative effects of these types in forms of fibre misalignment, laminate stacking, and fibre-rich or matrix-rich. Therefore, in failure mode analyses of the material it is important to investigate the extent and complexity of the failure which could have been presented before the final failure. One of the important initial testing methods can be visual inspection which the acceptability of the result and extent of the damage can then be evaluated by non-destructive or destructive methods. NDT is usually divided into macro (bulk) or micro (details) techniques which the latter is provided in the laboratory to analyse the material failure mode [73]. This can accurately be performed in the laboratory through a series of processes in order to first understand if there had been any deviation of the part specifications with the actual one which may have contributed to the failure. The visual inspection process also is required to identify the place, type, numbers, and sensitivity of the failure, which can pretty much help in understanding the failure mode and sequences [74–76].

2.5.5 Visual inspection

Visual inspection of polymer matrices can provide details regarding various important failure causes, such as crack initiation, propagation direction, sequences, and modes of failure. By studying the crack pattern it will be useful to understand the failure mode. For instance, the transverse cracks in laminates, can represent a mode which is called crack branching where the more the number of cracks increase, the more direction the crack propagation will have (Figure (2.28)).

Another example indicating the failure mode by visualizing the crack propagation and direction is shown in Figure (2.29), where a graphite epoxy composite airfoil is exposed to the transverse fracture due to bending force. The examinations show that the upper surface of the airfoil has relatively lower percentages of fibre pull-out with compare to the lower section; representing the compression force and tensile force actin on the upper and lower surfaces of the wing respectively.

The fractures due to the tensile or shear forces can be identified by analysing the surface colour of the fracture. For instance, shear failure can be identified by rather a white appearance at the point; this in the case of a tensile force fracture can be identified with a rather shiny black appearance. In terms of the former fracture type, this will create a “hackle” shape, whereas a “ river” pattern is associated with the latter fracture mode. In addition,

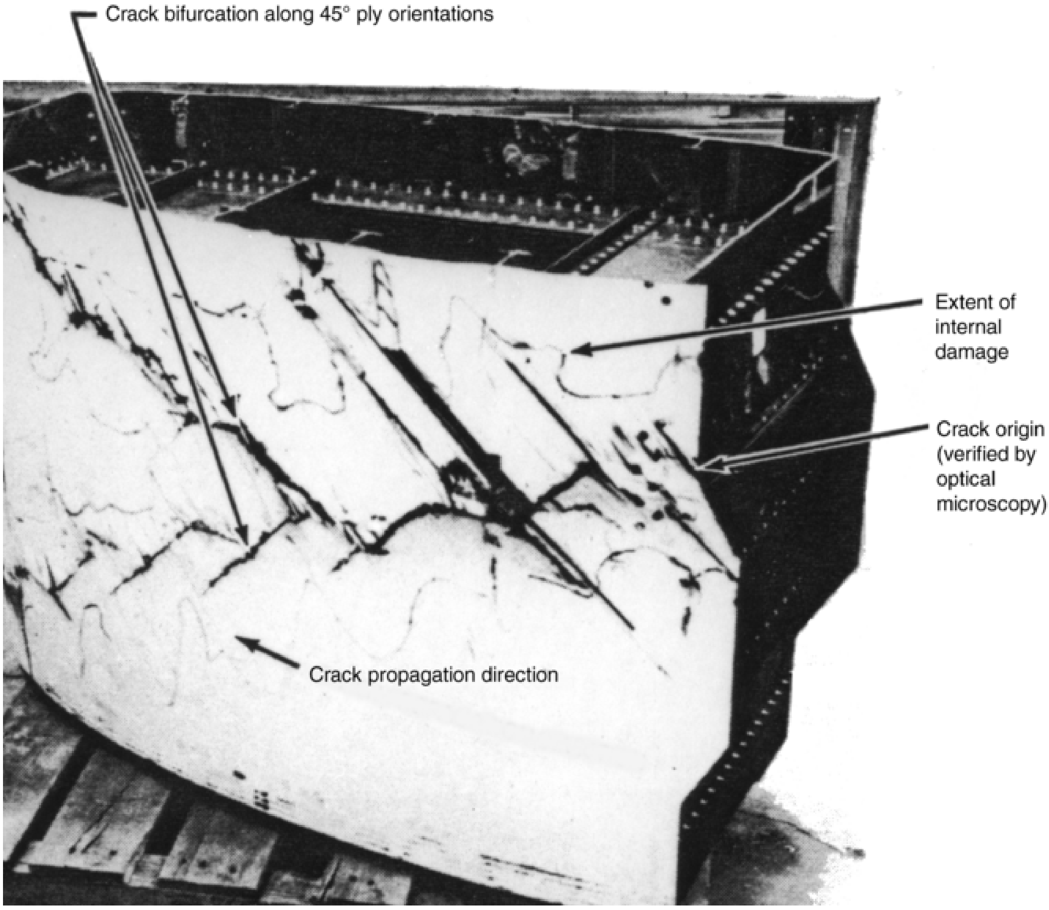

Figure 2.28: Visual inspection of crack propagation in transverse fracture (Reproduced from [77]).

the surface a fracture can help identifying other important aspects of the failure mode such as the crack growth and its direction. An indication of such features is represented as crack in the spar section of a graphite epoxy composite wing in Figure (2.29), which shows a crack penetration along the length of the delaminated spar interface. This failure is a flutter failure mode, where it is not necessarily caused by an excessive loading, but rather during a continuous small dynamic loading.

2.5.6 Non-destructive test

One of the important and essential test to characterise or predict a fraction and failure in composites is the non-destructive tests (NDT). These types of tests can be performed during an in-service or real-time operation in the lab. The general problem associated with the NDT methods, however, is that different techniques can generate different results for a same fracture type. This issue increases the need for combining different NDT techniques on the specimen to achieve the most accurate and reliable result. Fracture types such as crack or de-bonding in matrix, delamination in plies, and the breakage of fibres, as well as those types related to the manufacturing flaws (e.g., as voids or misalignment of the fibres) can all be identified by the NDT methods. Other supplementary techniques to the NDT in order to increase the reliably of the results are, for example, to remove the section of the failed material

Figure 2.29: Flexural failure of an airfoil (Reproduced from [77]).

in order to assess the ply, number of layers, and orientation of the fibres. In addition, other techniques such as finding the glass transition temperature (T_g) to understand if the resin has been properly cured are also helpful steps towards achieving reliable results to support the NDT tests results. Other important analysis is performed with the optical and scanning electron microscopy which is necessary to identify the failure initiation, crack propagation and penetration, and crack defects [78].

Generally, failure of the composite materials can be wither due to the design and manufacturing imperfections or in use of the product. The anisotropic nature of the composite material has however the main contribution to what can cause the failure of them. However, the point to be taken into account is that although, anisotropy provides difficulties in analysing the stress within the composite materials, but it is actually this nature of the composite that provide the interesting properties which can be utilized to have different strength in different directions within the structure. For instance, the polymeric fibres can have different moduli in the tension which can be different from that in compression test. Therefore, even for a unidirectional laminate under the bending test the moduli for the compression and tensile loads differ.

Thus due to this difference the testing criterion in compression and tensile tests should be defined separately. This variation does not only lie in the mechanical test and properties of the composite, but in the thermal properties as well. The difference in thermal expansion of the composites can reach to even 10 times variation form longitudinal to the transverse direction LUBIN (1982). According to the ASM handbook of composite [79], some graphite fibres have a negative thermal expansion coefficient in their longitudinal direction which would lead to the shrinkage of the part after being exposed to the heat. This is very important in the multiply laminates with different ply orientations where unequal thermal expansion coefficient can result in induction of the internal stresses within the material. This can additionally increase the load or stresses and lead to a advance failure of the material; in particular when the composite is attached to the other materials with different thermal coefficient.

Another factor which can contribute to the failure of composite is the interfering parts and connection means such as joints (bolt, holes, notches and etc.) that can pioneer the fracture point too far less than the actual material ultimate stress. Even the edges of composite plates with plies oriented at significant angles to each other need to be considered; the large ply stress gradients are not always considered and sometimes lead to premature failure. Manufacturing process can significantly affect the properties of the composite and consequently failure mode. This can exhibit some problems such as extra brittleness and consequently crack prematurely characteristic as a result of additional or extra curing; on the other hand, a resin which is not completely or properly cured can result in softness and consequently inability to transfer the load to the reinforcements accurately. In addition, the chemical and thermal resistances of the matrix are all depended on the proper and accurate proportions of the resin and hardener mixtures [80].

2.5.7 Fractography

There are two common fracture modes in studying composites failure. Mode I, which is caused by a tensile or a combination of tension and fatigue lading; mode II failure, which is caused by a combination of shear or a combination of shear and fatigue loading; mode III, which is caused by an out-of-plane shear force [81]. Fractography analysis has shown that the first mode of fracture (shear and fatigue) in brittle matrix materials will have a glossy surface appearance, while the resin can still be seen on the surfaces of the fibres. The combination of such appearance will more be seen as what is called “river-pattern”; which can sometimes help to identify the direction of a crack opening within the structure (Figure (2.30)).

The initiation of failure mode II is also within the matrix. However, the whole part may fail only when a fracture reaches the fibres interlaminar. In terms of the appearance of the surface of the fracture mode II, this mode is usually recognized from its rather whitish colour. Study of this mode of failure has shown that the fractured surface can be recognised by a “hackles” appearance (Figure (2.31)). This phenomenon occurs when a large number of micro-cracks in 45^o direction are shaped due to a shear loading condition (Figure (2.32)). The fracture surface appearance and the form of the hackles are all depended on the proportional variation between failure mode I and II, the proportion between resin and fibre, and most importantly, the reinforcement’s orientation with respect to the applied load. Understanding whether the first mode or sencod mode has been responsible for a composite failure may not alwyas be an easy task, especially when these modes are mixed – having a river-pattern appearance. These river marks can sometimes be used to help in determining the crack-

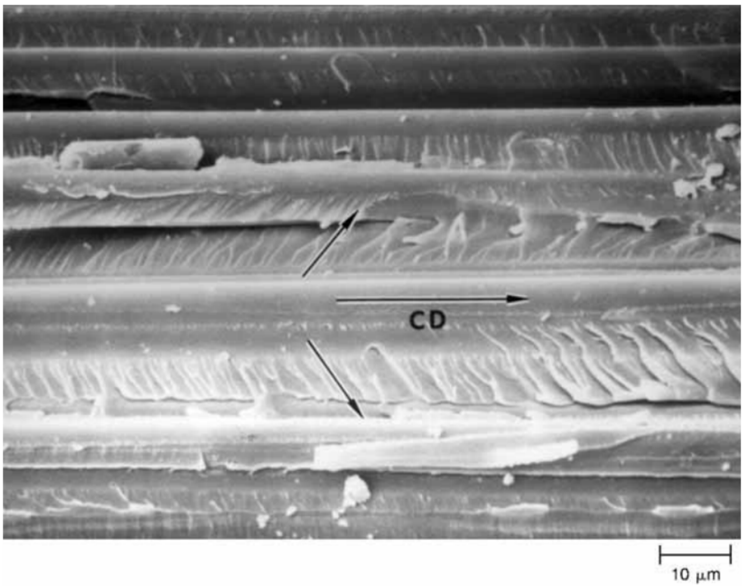

Figure 2.30: River patterns on the surface of a mode I tensile failure (Reproduced from [81]).

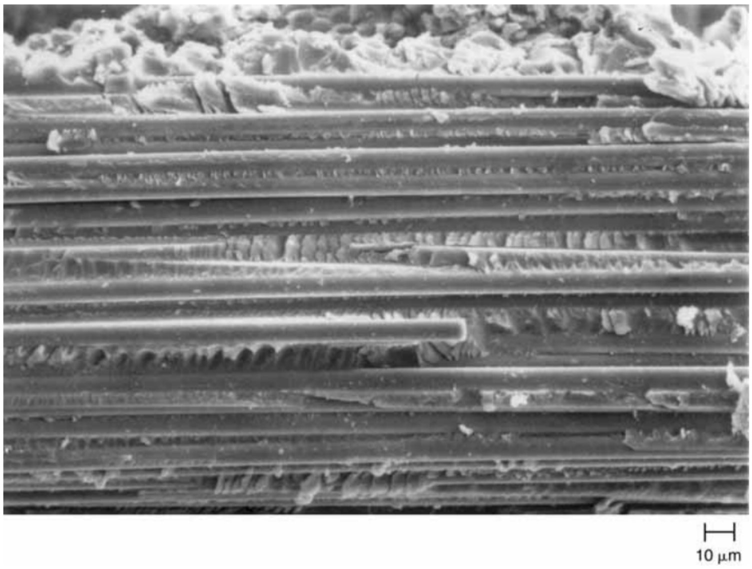

Figure 2.31: Hackles in the resin of a carbon/epoxy (Reproduced from [81]).

growth direction [81].

Another aspect of fractography studies on the structure is to determine the fracture within the fibre itself. This is known as a translaminar fracture which identifies the fracture effects at the fibre ends. It has been evident that translaminar fractures under tensile loading are associated with a relatively large number of fibre pull-out failure. This in microscopic analysis is referred to as “fibre radials” (as shown in Figure (2.33)).

These patterns in fibres can be observed in an integrated forms. These patterns can specially be seen in fractures across the laminate and could depict the crack propagation direction. However, it is necessary to first identify the fibres direction, by sketching a vector

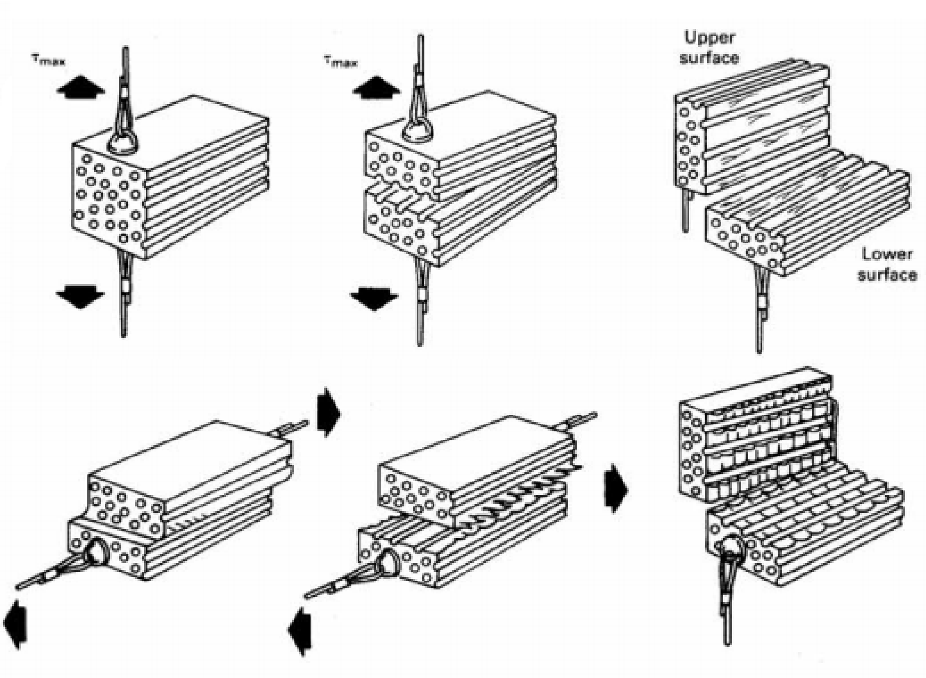

Figure 2.32: Schematic of mode II interlaminar shear failure (Reproduced from [81]).

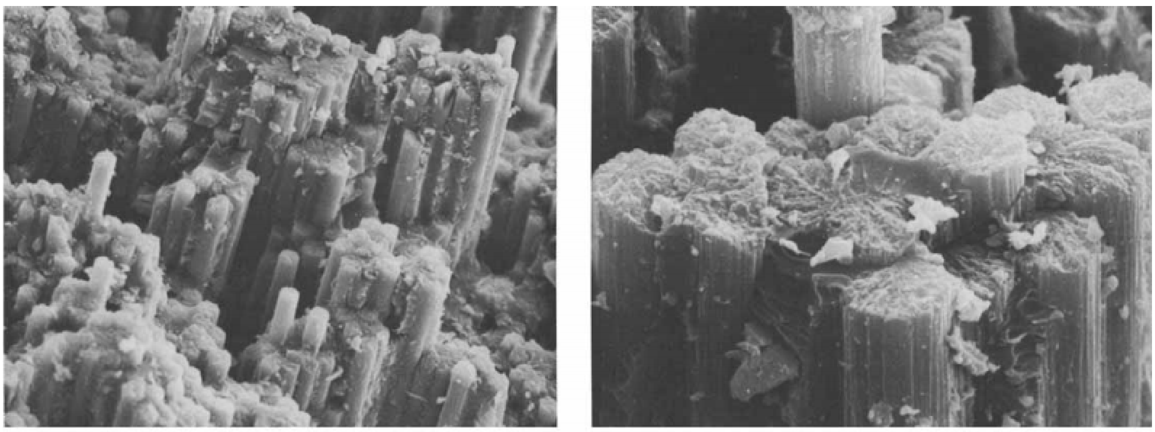

Figure 2.33: Examples of translaminar tension fractures (Reproduced from [81]).

connecting the initiation point of the fibre (where the lines can be seen at the end of the fibre radiating outward) to a 180° opposite point across the fibre surface. This should be applied for every possible and visible surfaces by which then the crack propagation and direction can be achieved from adding the vectors . Failures in composites due to modes I and/or II can be investigated using the fractography features. This technique however can offer varieties of features for every types of composite material in a rather unique result; mainly depend on the type of material, their manufacturing process, their response within their working environment, and loading specifications. The results of such investigation can provide information about the fracture behaviour, location at which the cracks are more likely to initiate, crack growth, and their direction. The important point is that with even all information achieved form the fractography analysis, it is yet not showing the specific cause of the failure within the structure. Therefore, it is always necessary to analyse the fractures mechanism with other mechanical testing methods, such as stress analysis.

Chapter 3

Experimental Work

3.1 Overview

This chapter discusses the manufacturing process of a series of CFRP composite coil spring prototypes. For this aim, first, a solid aluminium bar was formed into the shape of a helical mandrel using a lathe machine. The reinforcement fibres were then embedded within the grooves of mandrel and processed to be cured under vacuum at an elevated temperature. This is the most common low-cost and repeatable method of manufacturing composite coil springs which has been reported in the majority of studies in the literature [65].

Prior to starting the stack up process (using hand lay-up method), the surface of mandrel was coated with a release agent and waxed in order to facilitate the part's removal after curing. The experimental procedure regarding the sampel preparation and fabricaiton of the composite coil springs are discussed in thsi chapter. Furthermore, as a part of the experimental work, two industrial visits were carried out, first, to a spring manufacturing company known as "Performance Spring Ltd"; second, to a composite manufacture centre, known as "Advanced manufacturing research centre (AMRC)". Informal accounts of these journeys are presented in Appendix (A) and Appendix (B), respectively.

3.1.1 Carbon fibre reinforced leaf spring fabrication

A number of composite leaf springs were fabricated in order to understand better the experimental procedure and material handling during the hand lay-up manufacturing process. The reinforcement was a UD carbon fibre prepreg (Figure (3.1)(a)), which were cut into the dimensions of the final mould (Figure (3.1)(b)). The mould was a convex (C-shape) aluminium part, which was first coated with three layers of a release agent and a peel ply, and then the prepreg material was stacked up on it (Figure (3.2)).

Finally, another peel ply was added on top of the prepreg, followed by placing a breath cloth on top of all layers. This cloth helps to circulate the air within the medium, as well as allow any excess resin, which is expelled out of the mould, to be absorbed during the curing process (Figure (3.3)).

The mould was then vacuum bagged and sealed properly. Next, it was enclosed and placed into the autoclave machine to be cured in an oven at a curing temperature of 140°C,

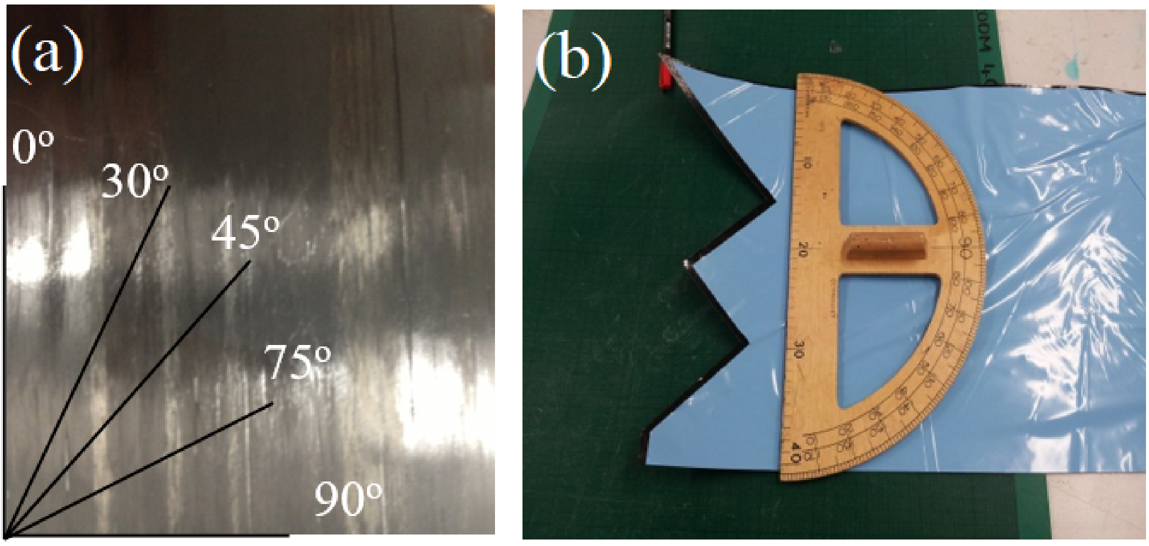

Figure 3.1: Unidirectional carbon fibre prepreg used for the fabrication of composite springs.

Figure 3.2: Hand lay-up process for fabricating a leaf-spring.

Figure 3.3: The final stage of the stack-up process.

under a pressure of 60–70 psi. In addition, an extra force of 50–60 kN was set to be applied on the both ends of the autoclave during the process so as to prevent the hot pressurised air to leak outside and essentially exploding the mould (Figure (3.4) and (3.5)). This pressure was not participating in the curing process. After about 30 minutes, the part was cured and ready to be opened and separated (Figure (3.6)).

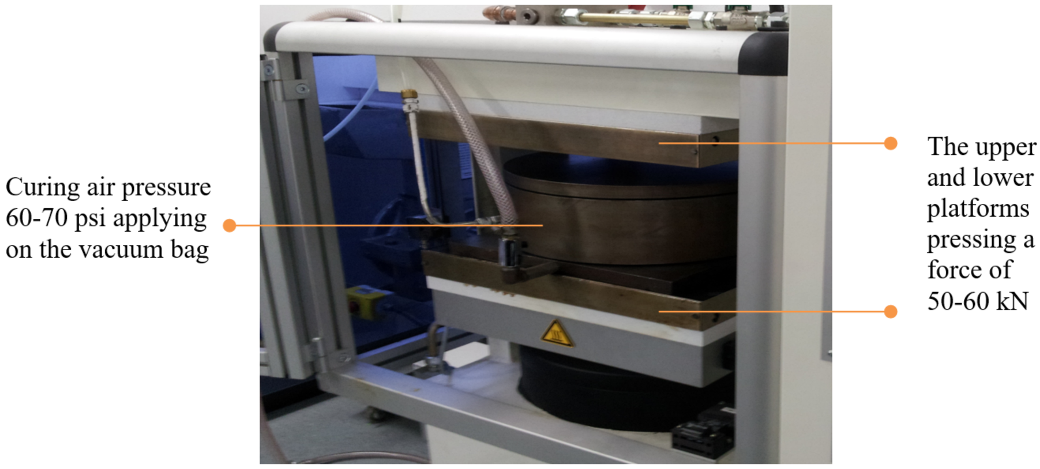

Figure 3.4: Hot press equipment used for compression moulding manufacturing process of the leaf spring.

Figure 3.5: The curing temperature adjusted on the oven.

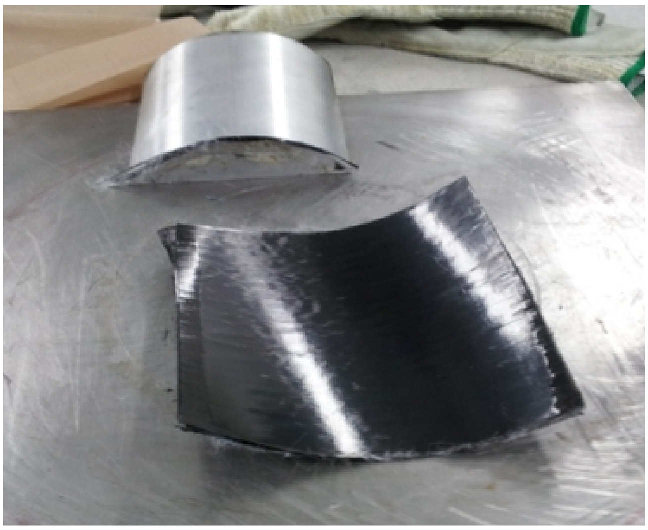

Figure 3.6: The fabricated leaf spring.

3.2 Fabrication of composite coil springs

3.2.1 Mandrel production

The manufacturing process of a coil spring started by preparing a helical mandrel out of an aluminium bar (Figure (3.7)). The mandrel was prepared using a CNC machine, and the experimental procedure are illustrated in Figure (3.8)).

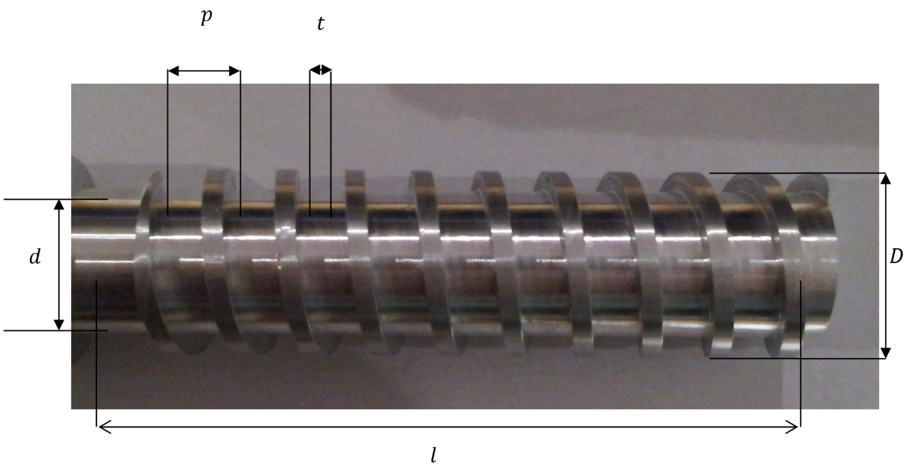

Figure 3.7: An aluminium helical mandrel produced for fabricating composite coil springs.

Figure 3.8: Fabrication process of the helical mandrel.

3.2.2 Experimental setup

In general, the fabrication process of all composite springs included these steps. First, all surfaces of teh mandrels were coated with a release agent and wax in order to facilitate the unwinding process after curing, as well as producing a high qulaity surface finish. For this aim, a release agent (Number 8 mould Release Wax ™ was purchased form the Easy Composites[82]) (Figure (3.9)). The agent was applied three times; each time it was left for about 15 minutes to dry and then was cleaned before the next coating layer was applied. This particular release agent was mainly suitable for use with the polyester, vinyl ester and epoxy resin systems where usually a high curing temperature (over 50°C) is required.

Next, the reinforcement material was cut and prepared for the stack up process. The stack-up process started was carried out by first placing a release paper on top of the mould,

Figure 3.9: Image of the release agent (Reproduced from [83]).

and then laying down all the reinforcement material on top of that. Finally, a breath cloth was placed on top of layers in order to hlep both to circulate the air within the mould, and to absorb any excess resin which might expel out of the lay-up during the curing process due to vacuum pressure and temperature.

Next, a vacuum and resin inlet tubes were inserted at two opposite sides of the mould, and the whole setup was covered with a vacuum bag and carefully sealed on its all sides – similar to the experimental procedure performed elsewhere [33]. A negative pressure (vacuum) was applied to replace the air inside the bag with resin. Ideally, the higher the vacuum pressure, the better the final surface finish of the part will be. The experiential setup were similar to that which was used during the fabrication process of a leaf spring in terms of the pressure and temperature settings.

After 30 minutes of curing, the first instruction was to reduce the air pressure inside the autoclave, followed by cooling the bottom and top platforms with an internal water circulation system embedded within the autoclave. Once the temperature of platforms reached the room temperature, the mandrel was taken out and spring was unwound.

3.2.3 Sample types

Overall, 7 composite coil springs were fabricated. Among these, four were made from UD prepreg carbon fibre, two from 2D (0/90) woven fabrics, and one form a dry tubular braided carbon fibre sleeve. All springs were manufactured using a hand lay-up process, however, in terms of the tooling, specimens 1, 2, and 3 were made using a solid Al bar helical mandrel (Figure (3.10)), specimens 4, 5, and 6 by using a hollow Al cylinder mandrel (Figure (3.11)), and specimen 7, by using an actual steel spring (Figure (3.12)).

3.2.3.1 Specimen 1

The first specimen was made using UD carbon fibre prepreg which were cut into narrow films (10 mm wide), and then wound around the fabricated helical aluminium mandrel. All the

Figure 3.10: An aluminium solid bar mandrel prepared in the form of a helical spring to fabricate composite spring specimens: 1, 2, and 3.

Figure 3.11: An aluminium hollow bar mandrel used for fabricating composite springs specimens: 4, 5, and 6.

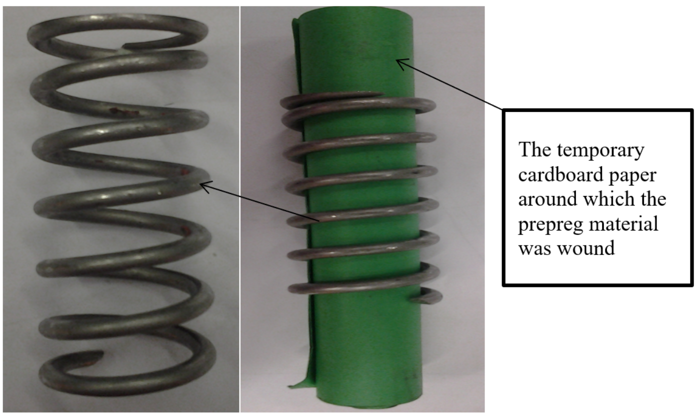

Figure 3.12: An actual steel spring used as a mandrel to fabricate composite spring: specimen 7.

experimental procedure performed afterwards was similar to the procedure described above in section (3.2.2). Finally, after 30 minutes, the curing process was completed and the mould was cooled to the room temperature so that the spring could be unwound from the mandrel (Figure (3.13)).

Figure 3.13: Specimen 1 produced using a solid Al bar helical mandrel.

3.2.3.2 Specimen 2

The second composite specimen was made using a woven (0/90) carbon fibre prepreg laminate. The reason as to why a prepreg type was chosen over a dry type fabric was that the former provides a better stability and handling during the sample preparation process (as dry fabric would fall apart when cut to small widths, e.g., 10 mm). The curing temperature and pressure for this specimen was 140°C and 1 hour, respectively. The final springs are shown in Figure (3.14).

3.2.3.3 Specimen 3

The third specimen was produced using a braided carbon fibre tube, which was initially intended to be used as a core material within the coil springs. This material was dry as it did not require any trimming (since the width of the tube was already small enough to fit in the grooves of the mandrel). The tube was then impregnated with a resin epoxy system, using a mixture of resin and hardener (30*wt*:1*wt* ratio); the mixture was then left to cure at room temperature for 24 hours (Figure (3.15)).

Figure 3.14: Specimen 2 produced using a solid Al bar helical mandrel.

Figure 3.15: Specimen 3 produced using a solid Al bar helical mandrel.

3.2.3.4 Specimen 4

Specimen 4 was produced using a similar UD prepreg material as was used for the specimen 1. However, a different mandrel was used this time, which was a hollow aluminium cylinder. The cylinder was marked with a similar pitch as that of the solid Al bar mandrel. Similarly, the release film and wax were both applied onto the surface of the tube. This method though was less accurate, it provided a much easier fabrication procedures, unwound, and cost of manufacturing associated with the mandrel. However, another problem occurred after the curing process which was the shrinkage of the carbon layers. This was mainly due to the absence of the physical pitches between the fibre laminates as they were with the mandrel; therefore, the external shrinkage tape which though prevented the fibres to unwound the tube, but this caused the fibres not to have a space to expand and therefore expanded in the longitudinal direction which caused the layers to stick to each other. After opening the mould, the spring was unwound from the tube using a screw driver. Other specimens were made with the same procedure and material (Figure (3.16)).

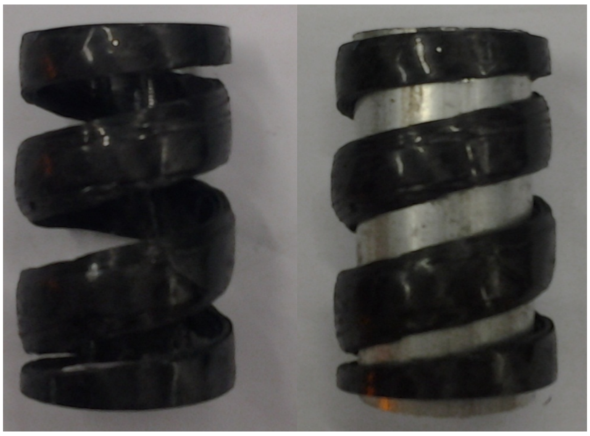

Figure 3.16: Specimen 4 produced using a hollow Al bar mandrel.

3.2.3.5 Specimen 5

The fabrication process of specimen 5 was identical to the specimen 4, however, this time an aluminium cylinder mandrel with a small diameter was used (D 4 mm).

Figure 3.17: Specimen 5 produced using a hollow Al bar mandrel.

3.2.3.6 Specimen 6

Specimen 6 was made through a similar method as described for specimens 4 and 5. However, this time the pitch and spring's wire diameter were chosen to be small (5 mm and 5 mm, respectively). Again the releasing process associated with this method was easy and comfortable except with the undesirable shrinkage occurred after the curing process. This caused the pitches to lose their dimensions and accuracy and consequently due to the maximum shrinkage the stiffness of the spring was decreased (Figure (3.18)).

Figure 3.18: Specimen 6 produced using a hollow Al bar mandrel.

3.2.3.7 Specimen 7

Finally, specimen 7 was fabricated using UD prepreg carbon fibre straps wound around an actual metal spring, which was used as a mandrel. The challenging part of this process was that the grooves between the pitch of the spring were empty, hence, there was no physical surface upon which the prepreg material could be stacked. Therefore, in order to produce a temporary physical surface on which carbon fibre could be wound, a piece of a cardboard paper was rolled and inserted into the hollow space within the spring. The benefit of using a cardboard was that this part could be easily dismantled and removed after the part is cured – so the composite spring can easily be unwound and released. After curing was completed, the unwinding process was carried out simply by rotating the composite spring in an opposite direction of the pitch of the steel spring (Figure (3.19)).

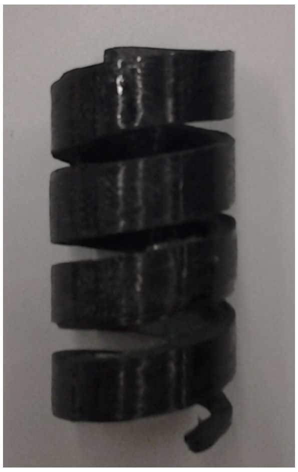

Figure 3.19: Specimen 7 produced using an actual steel spring as a mandrel.

Chapter 4

Results and Discussion

4.1 Overview

The objective of this report was to study and research the feasibility of manufacturing the carbon fibre coil spring for automotive suspension system. The different specimens were made from carbon fibre unidirectional and woven fibres; amongst which two leaf springs from unidirectional carbon fibres were made with different fibres laminate' angle using the vacuum bag pressure (autoclave machine). The research into the composite materials and their applications, in the literature review, could represent the broad versatility and the extensive benefits could be achieved from the composites. Among different types of reinforcement and matrices the continuous carbon fibre (PAN-based cursor) represents the highest load bearing capability along the fibres direction. In compare with the steel, for example, carbon fibre can represent specific strength of about 2 GPa, tensile modulus of about 240 to 400 MPa, with density of 1.75 gr/cm^{-3}; whereas, the steel can have a 1860 MPa, 240 MPa, 7.8 gr/cm^{-3} for specific strength, tensile modulus, and density respectively. These values however, can be achieved by a rather accurate consistence process of manufacturing where in terms of the coil spring one aspect which clearly affected the result was the orientation of fibres. Since, the coil spring resist the application of load by torque, and the best torque configuration is at 45^{o}, the best fibre orientation should have been in this direction.

This project was aimed for understanding the feasibility of the composite materials, particularly carbon fibre-reinforced plastic composites, to be used as an alternative material to the metal materials to be used in coil spring for automotive suspension system. In this project the characteristics of composite materials, their applications, and a comparison between composites and metal materials were reviewed. From the several aspects of the research, in the literature review, it was perceived that the carbon fibre reinforcement materials can be selected as the coil spring material since they have some interesting properties with compared to other reinforcements or metal materials. For example, their strength can be about five times more than that of the 1020 steel with only a fifth of the steel and half of the aluminium weight. Carbon fibre reinforcement materials can exhibit very good fatigue properties and with a proper resin combination, are considered to be as the most corrosive resistant materials. In terms of the thermal properties, carbon fibres can introduce three times more conductivity than the copper. In addition, compare to the other types of composite materials, the carbon fibre composites can introduce two important properties (tensile strength and tensile modulus) relatively much higher than that of the other composites materials.

4.1.1 Reinforcement

The PAN-based carbon fibres are the most commonly used type in the commercial applications due to their lower cost of manufacturing. Although, they can also be used for aerospace applications depend on the type of the precursor used. The pitch-based carbon fibres however, can introduce higher modulus, thermal conductivity, and lower thermal expansion coefficient mainly because of different stretching temperature, gas species during pyrolysis process, and onset of evolution to the PAN-based type. That is why the pitch-based types have a higher temperature response, density, and thermal conductivity than the PAN-based types. In this project different carbon fibre coil springs were manufactured from unidirectional prepreg carbon fibre materials due to better accessibility and economical aspects.

The unidirectional fibres are one of the most common types of the reinforcements in structural applications. The resin impregnated longitudinal fibres provide rather flexibility and cost-effectiveness benefits for the designer. However, the unidirectional type did not provide the required shear strength in the transverse direction to the fibres. Therefore, few other numbers of springs were made using woven carbon fibre type. This type is consisted of at least four weaving yarns (two warps and two fills which are repeated) and provide a tight structure which can resist inter-planar shear forces. The point however about these type of fibres was that they had to be from impregnated type; this is because of the geometer and size of the mandrel grooves where dry woven fibre material could not be cut to that size and easily either the warps or fills fell apart and were destructed as soon as were cut; whereas prepreg woven fibre enabled cutting the laminates into tapes of small sizes as 10mm width which were otherwise impossible to be cut from dry fibre sheets. One important result is to use preferably prepreg materials; as the result of section 3.4.3 (specimen 3) the dry fibre needed to be impregnated with the resin afterwards by the user which this method did not really guarantee an accurate, proper, and even applicable result in the first place of the final product.

This is mainly because of the fact that when the resin impregnation process is left to the end user there could be consequently few problems which can importantly change the final result. For example, improper mixture, curing time, and amount of resin applied can all lead to an improper part. In addition to consuming a relatively large amount of curing time; assuming all else carried out correctly. Therefore, having a prepreg material can already ease these processes and prevent any unnecessary mistakes. On the other hand, with the choice of using prepreg materials there are different options available in terms of the content and type of the resin and type of fibre. Moreover, the handling time and curing temperature can all be controlled.

4.1.2 Resin

One of the suitable bounding material could be used was the resin epoxy which is classified within thermosetting polymers; since, because of their molecular structure (cross-sectional) they can suitably be incorporated in relatively extensive type of applications. Resin epoxy can be one of the most suitable options in both high or low-temperature and structural or non-structural applications according to their glass transition temperature (T_g). This temperature is an important point where the behavioural of the material can change. If the temperature of curing is below than the Tg the resin behaviour would be more glassy whereas above this temperature the behaviour would be more rubbery. The factors affecting the Tg are both molecular cross-sectional as well as curing temperature in such way that by increasing the temperature of curing, the material will have a higher Tg and vice versa. This could be potentially one of the reasons most contributed to the softness ("rubbery") of the specimen 3 which was made using carbon fibre sleeve with cured at room temperature; whereas the prepreg materials used for specimens 1, 2, and 4 did exhibit far more stiffness because of being cured at much higher temperature.

In addition, typical process-related failures such as improper mixing and curing of matrix resins, which can have a number of effects on composite properties. For example, the resin which is cured far more than necessary can exhibit brittleness characteristics, crack initiation in-advance, and consequently condition which can face the fibres to the environments which may not otherwise be exposed to. On the other hand, a resin which is not adequately cured can represent a very soft material which is not able to properly transfer the load to the reinforcements [80].

4.1.3 Experiential results

7 springs were fabricated in this project one of which (specimen 1) was made using hot press mould and vacuum bag technique while others were simply heat-cured at 140oC in oven. The compression test was therefore applied on them to understand the difference type of resin, type of fibre and its configuration, and curing process can make. The compression test was also carried out on three metal springs in order to evaluate the result achieved form the campsite springs with them. The important point is that some of the springs did not adequately suit the compression test. This was because of the fact that some of them had some curing or less number of laminate on them which could not really result in a valuable result to be compared with the other samples, let alone the metal springs. Although, their manufacturing did really help to understand the alternative processes, techniques, and problems associated with different methods. It itself did provide rather valuable information which was used in improvement of the other samples. Therefore, among the 7 carbon fibre spring samples, only specimen 4, 5, and 7 which are shown in Figure (4.1)(a) and (4.1)(b) and (4.1)(c).

The spring performance of the fabricated composite specimens were compared to three conventional steel springs under compression tests (Figure (4.2)). Figure (4.3) and Table (4.1) show the results of compression tests obtained for these springs.

(a) (b) (c)

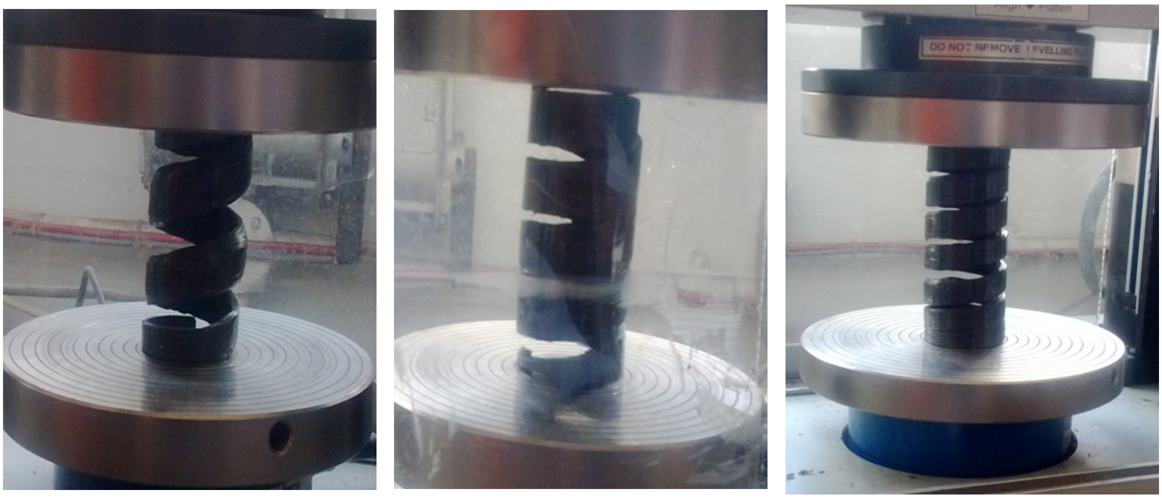

Figure 4.1: Compression tests of the fabricated springs, specimens (a): 4, (b): 5, and (c):7.

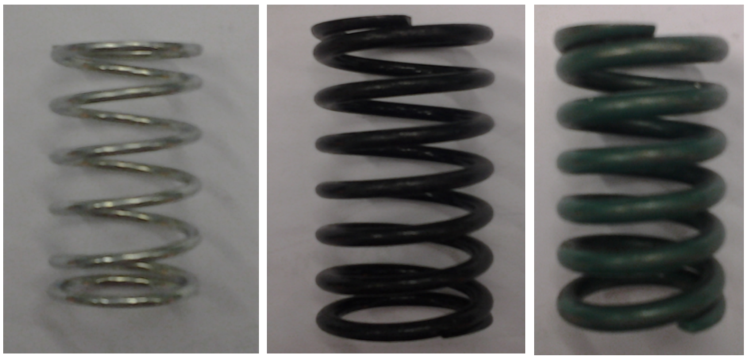

Figure 4.2: The three types of steel springs tested in this work.

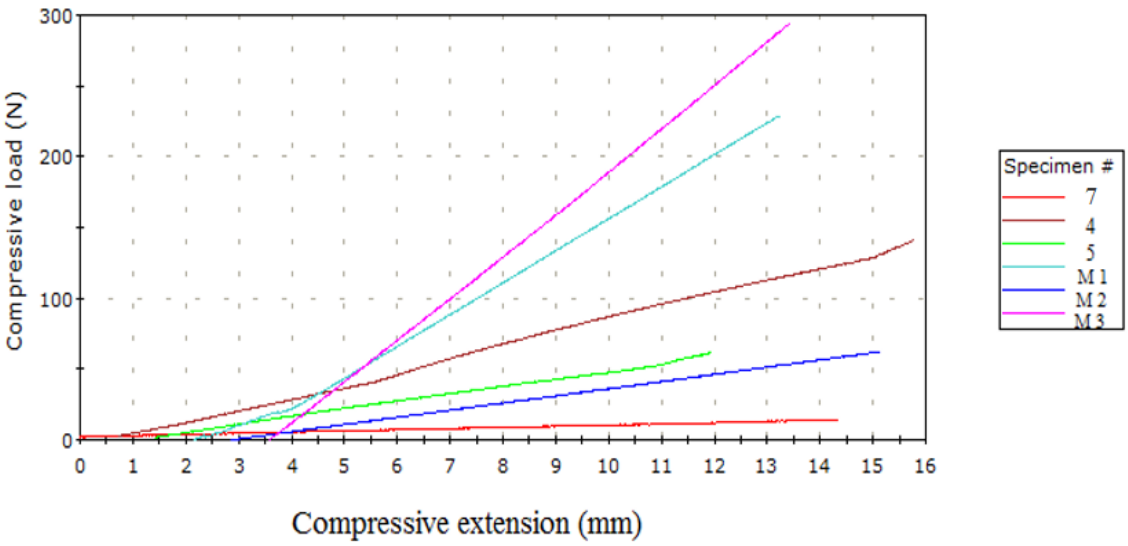

Figure 4.3: Compression test results of composite and steel springs.

Table 4.1: The results of compression tests on the fabricated composite specimens.

Specimen	Load (N)	Displacement (mm)	Spring constant k (N/mm)
CFRPC spring 4	140.827	15.8	8.9
CFRPC spring 5	61.563	11.85	5.2
CFRPC spring 7	22	14.1	1.5
Steel spring 1	225.4	229.241	0.98
Steel spring 2	57.3	62.342	0.92
Steel spring 3	284.5	295.280	0.96

As it can be seen from Table (4.1), among the three types of fabricated carbon fibre composite coil springs, specimen 4 has the highest stiffness (spring constant). Next, specimen 5 with 5.2 N/mm and specimen 7 with 1.5 N/mm. This clearly show that the composite springs have a better spring perforamcne in terms of the load-bearing capabilities. This difference is almost an order of magnitude higher than those of the steel springs. Furthermore, a noticeable difference between K in the composite specimen 4 and 7 can be explain by the manufacturing technique and tools variations, where, the former was produced using an Al-solid bar helical mandrel, whereas the latter, by using an actual steel spring to act as a mandrel. This shows that the use of a solid mandrel can significantly improve the final performance and quality of the spring.

This is despite the fact that in specimen 7 there was 15 layers of carbon fibre stacks, whereas in specimen 4, it was only 10. Therefore, it is safe to conclude that the manufacturing tool can play a signification role in defining the final spring performance during the manufacturing process of a composite coil spring.

Another possible explanation for a noticeable difference between the results of k in specimen 7 (about 1.01 N/mm) and 4 (about 8.9 N/mm) can be said to be because of the absence of a physical groove and pitch between the layers of the mandrel used for specimen 7. This is an important factor as it was not possible to apply enough manual pressure on the layers the laminated carbon fibres, hence, a lot of void and wrinkle much have been induced within the invisible layers of this spring (as compare to specimen 4 which was properly pressed against the walls of the helical mandrel).

To further confirm the results in Table (4.1), the fabricated springs were taken to an external testing facility, the Institute of Spring Technology (IST), where the same composite specimens tested in Figure and were tested Figure (4.3) were subjected to a series of fatigue tests. As it can be seen from Figure (4.4) to (4.6), the experimental results obtained for the spring constants in these tests were in a significantly good agreement with the results obtained previously in Table (4.1).

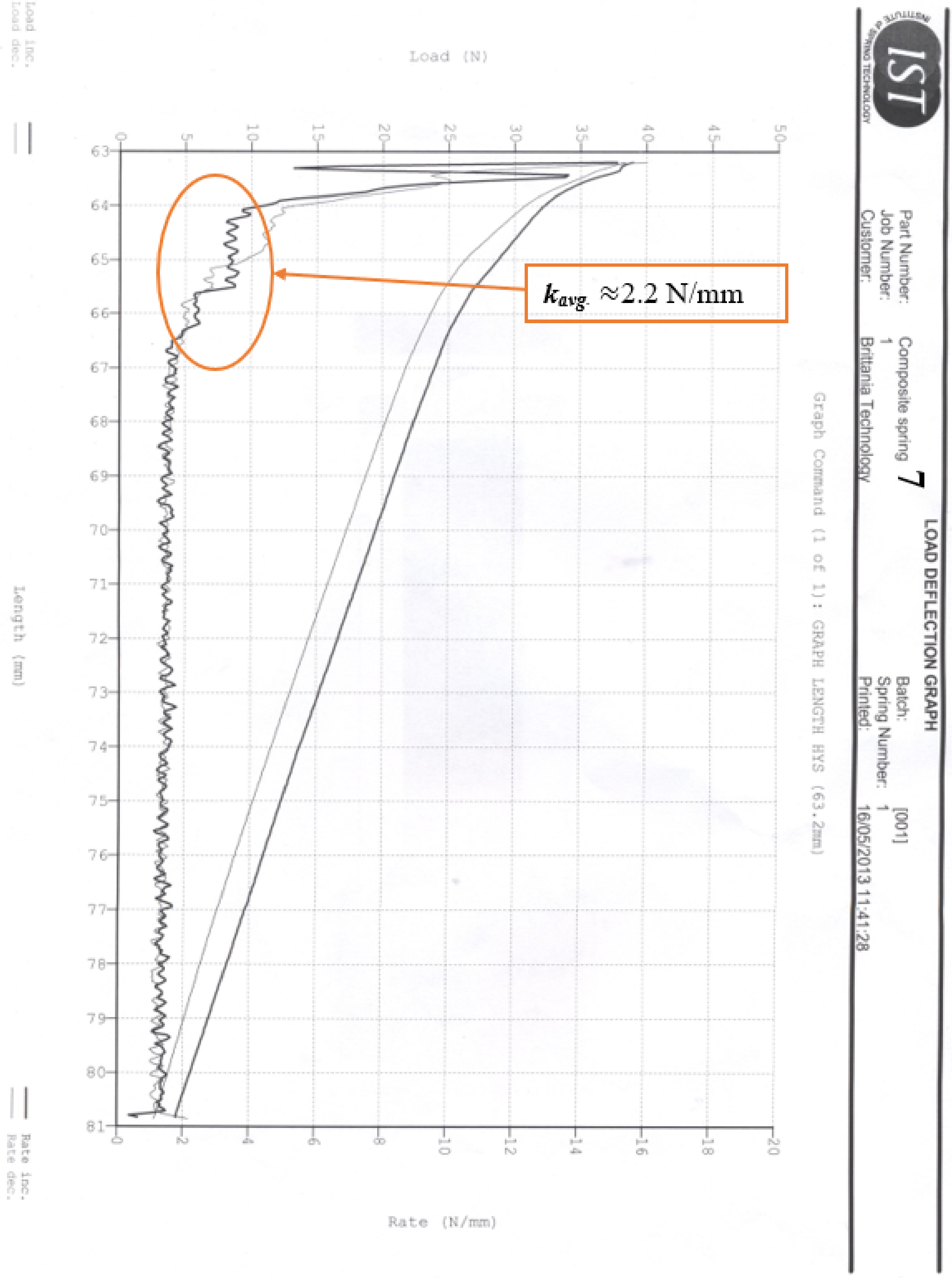

Figure 4.4: Fatigue tests of the fabricated composite coil spring: specimen 7.

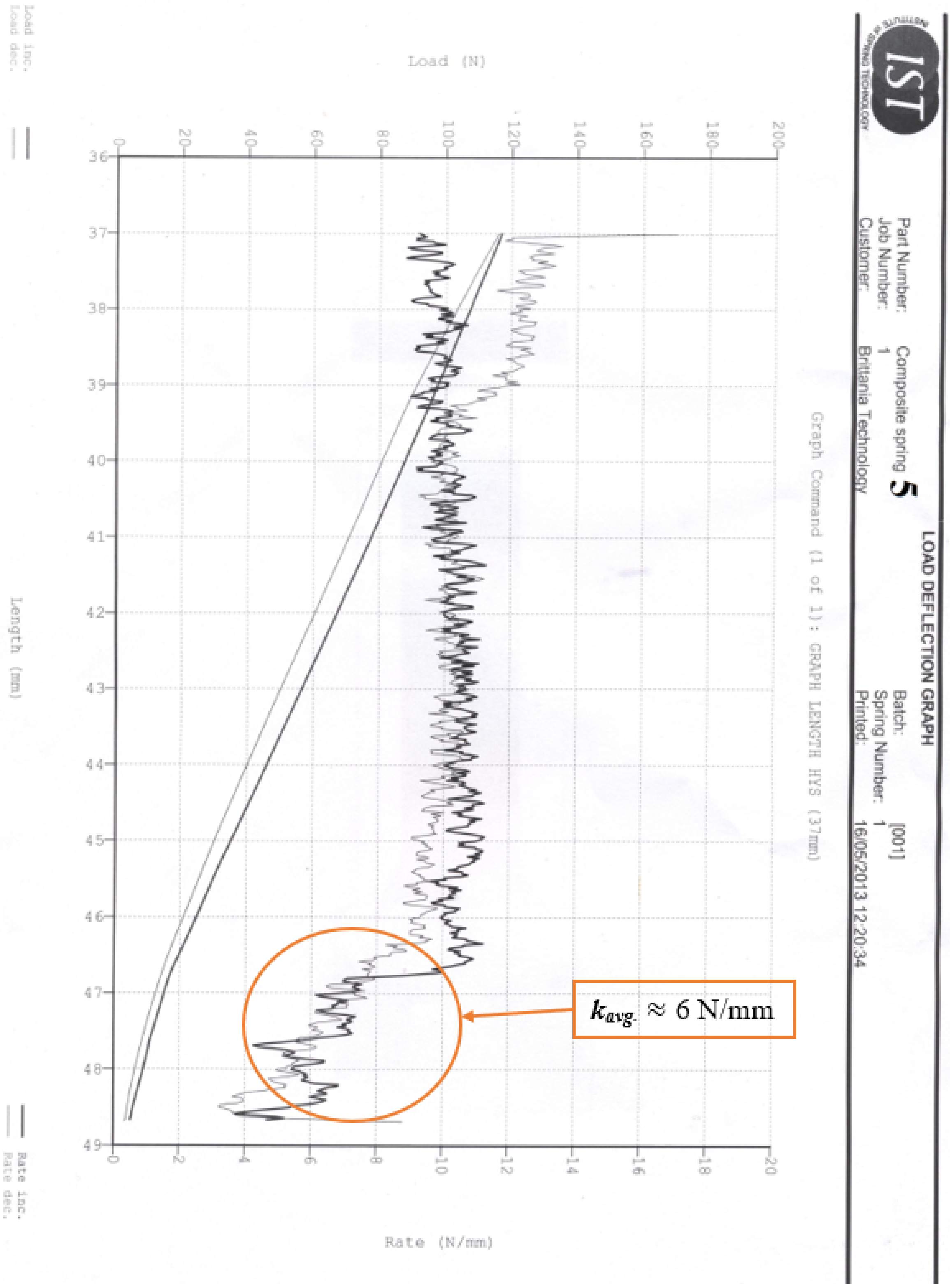

Figure 4.5: Fatigue tests of the fabricated composite coil spring: specimen 5.

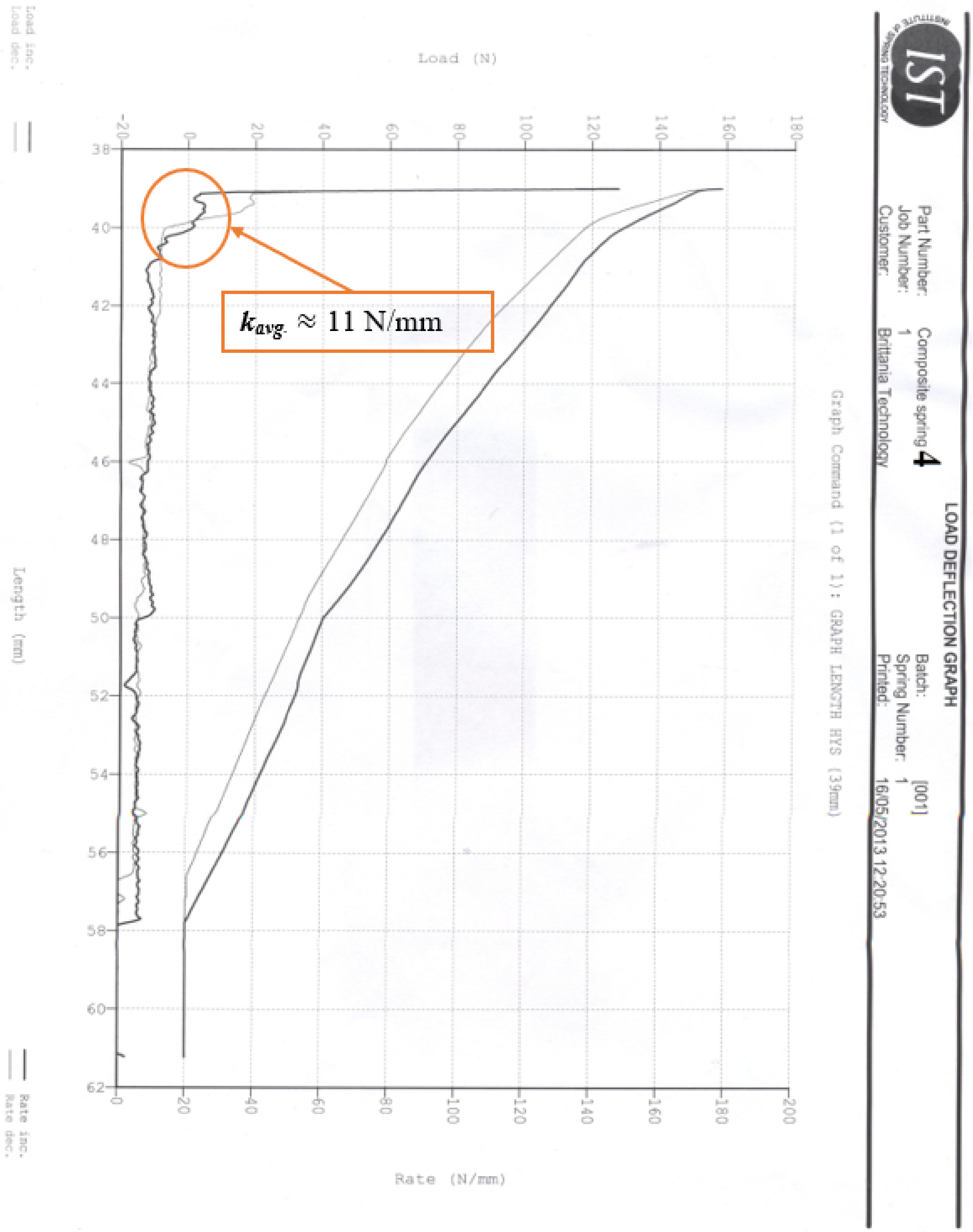

Figure 4.6: Fatigue tests of the fabricated composite coil spring: specimen 4.

Chapter 5

Conclusion

The unique mechanical properties of composite materials, in addition to the rapid technological advances in reducing the cost of manufacturing composite products have been the major driving forces in the aerospace and automotive industry to replacement many of their traditional steel-based components with composites. In this project the main objective was to understand the feasibility of producing a series of low-cost, high quality carbon fibre reinforced composite coil spring prototypes; moreover, the possibility to replace steel springs with composite springs was investigated by performing a series of fatigue and compression tests on three samples of each type. Accordingly, seven CFRP composite specimens were successfully fabricated, using three different reinforcement materials, and three different tooling techniques. The results showed that it is possible to fabricate a number of high quality composite coil springs using a very low-cost manufacturing technique (hand lay-up). In particular, it was found that the fabricated composite springs made out of UD carbon fibre prepreg material, which were wound around a solid aluminium helical mandrel at a ± 45 configuration, exhibited the highest springs constant k than all other specimens, yet, about one order of magnitude higher that that of those convention steel springs.

The project had a number of limitations as well. For instance, the manufacturing a carbon fibre reinforced spring was to some extent incredibly interesting and productive, nevertheless, a specific limitation in this project was that it was not possible to access a wider range of reinforcement materials (e.g., glass fibre), as well as to use different manufacturing techniques and equipments, such as, an RTM processing, an injection moulding machine, or a more spacious autoclave equipment, etc. In fact, the UD carbon fibre prepreg material was the only available material which could be used with a relatively less wastage restrictions during the sample preparation procedure. In terms of the woven fabrics, however, since the cost of material was high, it was only provided in a very small quantity. The problem with this was that during the material usually used to fall apart during the trimming and preparation process (especially when was cut to the width of mandrel (10 mm)). Hence, a lot of skill and time and effort was made to make sure that the final quality of the parts was acceptable.

Overall, the findings of this work were promising, although, the issue of producing springs with consistent mechanical and physical properties is an important area to be explored in further research.

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Appendix A

An industrial visit to the coil spring manufacturing process

A visit to: Performance Spring Ltd.

Report	**A visit from Performance Spring Ltd.**
Date	03/04/2013
Duration	7:00 – 17:00
Report Written by	Seyedalireza Razavi
Report For	Dr Abdul Hoque
Other Participant	Balaasaran Jaganathan
Host	Steve Williams Managing Director
Place	Scaffel Road Queensway Industrial Estate Lancashire UK
Aims	• Exploring the spring manufacturing processes, • Conducting possible business opportunities, • And introducing our project

As a part of the Composite Materials project, an outdoor activity took placed in order to develop and progress the project further in terms of the technical and marketing aspects. This report was written to represent the overall aspects of the visit, aims and objectives, tasks done during the meetings, and the overall achievements of the activity. The report is aimed to reflect the technical procedures happening during the manufacturing process as well as some technical information to be achieved and understood. The backgrounds of the participants are mainly Mechanical Engineering, Metallurgical Engineering, and Material scientists. The background of the project was on the Composite Coil Spring which required some understandings of the current typical manufacturing methods in the industry. Therefore, it had some advantages in terms of understanding processes and methods of manufacturing springs, identifying similarities and differences between our product with the Performance Spring products, and getting familiar with the testing equipment and laboratories which could probably be required for testing our prototype spring in the future.

Three members of the Britannia Technology company started a journey on the 3^{th} of April at 7:00 o'clock; first, Seyedalireza Razavi as the Product Development Engineer; Dr. Abdul Hoque as the Director Manager; and Balaasaran Jaganathan as the Material Scientist. The journey was to visit one of the front-line companies named, *Performance Spring Ltd*, which was established on the 1986 by Mr. Steve Williams, the Managing Director of the company. The meeting was arranged by Dr. Abdul for 10:30 at Steve William's own office. We arrived at about 10:20 and managed to meet Steve at about 11:00 o'clock. After greeting and introduction of our company and project, which was carried out by Dr Abdul, Mr. Steve also described their activities and types of customers, which included manufacturing, machining, and testing mainly steel springs for specific groups of well-known customers in automotive industry, and oil industry according to their needs and demands. We noticed the variety ranges of products in the Steve's office:

- Conical Springs (springs that are smaller at one end than the other),
- Variable-Pitch Spring (the springs that act more strongly under heavier loads than that when under normal loads),
- Snap-rings (simple ring springs), and
- Nested Compression Spring (were two springs are built-in each other which are stronger than one spring alone especially used for the engine valve spring).

After that, I presented a brief presentation on the background and objective of our project, specifically, my research area in the Carbon Fibre Coil Springs to Steve, which was followed by a very good short presentation by Balaasaran about his area of research on the Ceramic Coil Springs. There were some debates and discussions about some aspects of mine and Balaasaran projects by Steve which he specifically asked me the following questions:

- A further explanation of the manufacturing method of the composite carbon fibre coil spring from the presentation? I explained about one of the continuous loading/curing method of manufacturing, which I think he was keen to know about that technique more; because latter on after visiting his manufacturing line, I realized how similar the coiling method they used for steel spring was to the method we were investigating for the composite coil spring.
- Quotations about the type of material can be used for the matrix? Which I briefly explained the possible options such as prepreg carbon fibres with resins, polyester or polyethylene.
- The exact applications of the CFRP coil spring in industry? Which I explained some of the possible applications such as in the automotive suspension system, aerospace, sprints, oil industry, etc. during the presentation.
- How can we protect the polymeric matrices used in the composite materials from chemical de-bonding in the aggressive environments such oil valve spring? Which I could not really justify my answer, and realized that there is still more researches needed on the matrix side of the composites.

We had a short visit of the company's production line which were producing steel springs at the time. In brief, the production line included:

- Coiling The first stage was coiling which the automatic coiling machines carried out the process. The possible wire diameters to coil were 14 to 4mm by three machines. The coiling process was fully automated, although, two technicians were checking the sizes and conditions of some of the samples randomly and wrote them down. The mechanisms of shaping on the machines were briefly described by Steve as follow:
  - The wire feeding process which an elongated steel wire was fed into the machine. It was un-wrapped from a central core by three rollers asides; then, was aligned vertically and horizontally towards the four coiling rollers which provided the force for the wire to move towards the coilers.
  - The interesting mechanism of the coiling machine was so that, two main rollers were responsible to round the wire; a constant pitch device were inserted every time to give the pitch of the spring; and finally the cutter which would cut the spring to the desire length by receiving pulses when the spring reached to the certain length and a red light flashed at times.
- Stress relief oven: after coiling, the springs were taken to the oven to release the bending stresses which caused during the coiling procedure to be relived with almost no significant increase in size of the stainless steel.
- Grinding: This is the department where the ends of compression springs are ground. A lot of the work is done with automatic machines, which pass the springs between two large grinding wheels so that both sides of the spring can be ground at once. These machines consist of a round plate within which the springs are fitted. The plate then turns slowly round so extra curvature lips of the ends are flattened by two rotating wheels. Then they drop into a waiting box for inspection when they are thoroughly tested to make sure they comply both dimensionally and in their load requirements. At the end of the factory there were a few people handling the machining procedures on small size springs since the heat produced in the grinding can change the size of tiny springs significantly.
- Surface finish: A further machining were applied by other equipment which used very small metal pallets balls to blast at the spring to remove the surface debris and providing a smooth and more solid surface to the spring. The springs were then taken into the loading process in which the compression loads were applied in a room with two technicians. Afterwards, the springs were taken to the fatigue test machine where 10,000,000 cycles loading and unloading were applied on the springs. This process were said to last about 1 week, after which the sample and springs were taken to the next door laboratory where another technician was examining and inspecting the cross section area of the springs and to write the report for the corresponding customer whom spring was tested. She identified the possible cracks initiation points, any deformations, or changes in the mechanical properties of the springs under a 50x microscope. The meeting was finished at about 2:30 o'clock with our picture taken with Mr. Steve Williams. We then were introduced with Richard who had a carriage. His carriage

incorporated the leaf springs which he had problems with the flattening of the springs after a while. Therefore, Dr. Abdul took his Email address to suggest him possible solutions. He also explained briefly about repairing process about tempering the leaf springs, then oil quenching them and hardening them to increase their strengths.

Conclusion

I could realized the weakness points of the carbon fibre composite coil spring in the oil applications where the chemical reactions can take place between the polymer matrix of the composite and the environment it is working in. Therefore, I will try to extend my researches into the area of Metal Matrix Composites (MMCs) springs, which can be manufactured by Metal Injection Moulding process and there would be no issue with the material degradation. I realized that the second manufacturing technique of carbon fibre composite coil spring can be more interested for Steve (or any other potential investor). Because as I mentioned in the introduction part of the report, Steve had more interest and questions about the second type of manufacturing technique, because it was pretty much similar to the way they manufactured steel. The journey was beneficial in terms of familiarization with the current spring manufacturing techniques, understanding the interests of a potential investor for the project within both Carbon and Ceramic composite spring, and having promises of Steve about his contribution in the testing and analysing our prototype spring in future.

Appendix B

An industrial visit to the Composite Materials Manufacturing Techniques

A visit to: Advanced Manufacturing Research Centre (AMRC)

Report	**A visit from AMRC with Boeing**
Date	10/04/2013
Duration	12 – 14:00
Report Written by	Seyedalireza Razavi
Report For	Dr Abdul Hoque
Other Participant	Balaasaran Jaganathan
Host	Steffen Lee
Place	Advanced Manufacturing Park, Wallis way, Catcliffe, Rotherham, UK
Aims	• Observing the carbon fibre reinforcements, types, products • and manufacturing techniques • Discussing the possible cooperation possibilities

One of the important aspects of the composite coil spring project was to understand the carbon fibre reinforcement fabrication process and the techniques involved. Since, the main mechanical properties enhancements of the composite materials come from the reinforcements and their fabrication method. Therefore, as a part of the project, a visit to the Advanced Manufacturing Research Centre (AMRC) was organized in order to further develop and progress the composite spring project. This report is to reflect the overall achievements of the visit, in addition to identifying the best possible option of manufacturing a composite coil spring with carbon fibre. The technical procedures and information in this report are provided to the extent which was understood during the visit and more comprehensive data may be provided from the other sources (internet) to this report. The backgrounds of the participants are mainly Mechanical Engineering, Metallurgical Engineering, and Material scientists. The background of the project was on the Composite Coil Spring which required some understanding of the current typical manufacturing methods in the industry. Therefore, it had some advantages in terms of understanding the types of reinforcements, fabrications, and applications of the carbon fibres for our project. Start Three members of the Sheffield Hallam University planned a visit from the AMRC Boeing manufacturing plant on the 10th of April at 12:00 o'clock; Seyedalireza Razavi as the Mater Student in advanced mechanical engineering; Dr. Abdul Hoque as the project supervisor; and Balaasaran Jaganathan as a part of his internship project on the ceramic coil springs. The visit was arranged by Dr. Abdul from Sheffield Hallam University with Mr. Steffen Lee from AMRC. The AMRC was established in 2001 as£15 million collaboration between the University of Sheffield and aerospace giant Boeing, with support from Yorkshire Forward and the European Regional Development Fund. We arrived at about 12:30 and managed to meet Steffen at the time. After greeting Steffen suggested to start the visit with a tour around the company during which he explained the particular machines and manufacturing processes to us. The tour started with a description of their products samples where were typically produced by woven carbon fibres with epoxy resin. These products included the airplane landing gear (combination of carbon fibre reinforced composite with the steel), part of a turbine blade which two separate parts were bonded with the epoxy resin together, vehicle wheel ring, few woven carbon fibres in the plastic bags, snowboards, a huge round tube which was machined by water jet, and some natural fibres (bamboo fibres) products with mainly thermoset resins impregnated in the form of laminates. Steffen also mentioned that as a part of their collaboration with recycling companies, they work with TSP and FO7. The tour continued with the curing equipment and microwave ovens. One of the ovens was a typical INVERTER oven which could be used for small parts curing.

Next, there was a large curing oven which was nearly a year bought and still not in the full operation. The advantages of these curing ovens over the autoclave were that, no high pressure application was required during curing, more power efficient and faster time of curing. However, Steffen also mentioned that, there is a problem regarding to the unequal microwaves receiving by those sections of the part which are in contact with the oven stand support on which the part is sat. He mentioned that they are currently investigating to find a possible way of equally curing the part by making the least contacts between the part and the stand inside the oven. Another noble machine was the infrared curing machine which a mould section of the airfoil from carbon fibre was curing at the time. The main advantage of the infrared curing is a shorter cure cycles and the possibility of smaller floor space requirements when compared to convection oven curing. In addition, infrared curing machine can boost performance or line speed (HORINKA 2003). However, Steffen also mentioned that there is currently a problem about their efforts to in combination with existing convection ovens. IR can also be useful with heat sensitive substrates. Although there are many different manufacturers and types of equipment available, an understanding of the basics of IR cure will help to take away some of the mystery and myth which has been associated with this cure system. The next machine was the press mould by which fibres are placed within the mould and the resin is poured over the mould and the mould will be closed (cold press mould), or the reinforcements are located between a tool which has the cavity in the shape of the part, and by hydraulic press with a temperature of 130 to 170oC the resin and laminates are cured within 2 to 3 minutes (hot press mould). Next, type of manufacturing technique was the Resin Transfer Moulding (RTM). In this technique the reinforcement materials are pressed into the mould shape before being placed into a half of the mould. The other half will be closed and clamped. The resin is either injected into the mould with pressure (about 5 bars), or drawn in by a negative pressure due to vacuum. The RTM appeared to be relatively interesting method because of the simplicity and at the same time impregnating and curing the laminates. However, when it came to the curvature or bending shapes, it is needed to have the separate mould part designed. A main question which Dr. Abdul asked form Steffen was about the applicability of this technique to produce a solid round tube shape with this method? Which Steffen suggested to have a Male and Female moulds in order to create such curvature.

This appeared to be quite challenging. Steffen asked one of his colleagues who was working on a project that had produced a T shape model with this technique. Although, he claimed that this method has been around for about many years (more than 20 years), but still he could not clearly answer us about the question we asked. After that, we were taken into the automated manufacturing room where there was a automatic hand lay-up machine working with the unidirectional prepreg carbon fibre strands and by the use of a roller with pressure the strands were pushed upon the surface of the mould. The reasons for choosing the prepreg fibres were:

- An even distribution of resin on fibres.
- Very precise fibre/resin ratio.
- Better control of fibre placement and angle

Conclusion

This visit gave us an opportunity of having a direct observation on manufacturing methods of the composite materials. Since, all different types of machines were operating at one place, the differences, applications, pace, accuracy, and product ability of each of them could be seen. The automatic lay-up method could produce accurate and flexible shapes of products with both concavity and convexity objects. Among the curing oven machines, the IR oven was capable of curing relatively large objects with an excellent accuracy without occupying a large area or facility as the advanced curing oven did. In addition, no producing external heating sources which could potentially reduce the cost of manufacturing. The RTM method, had some advantages such as evenly curing and distributing the resins all over the laminate, fast and quiet process, and simplicity of the process. However, it was not suitable for a larger size parts, complex parts shape. Moreover, the facilities it required (resin bucket, pump, heating energy to keep resin liquid) were rather more than that the size of the part it was producing, which that part could have been produced by hand lay-up method. All in all, it was such a great experiment by which the most novel machines and techniques of fabricating composite materials were familiarized.

Those who put their hopes in GOD, will not be disappointed.