EXPERIMENTAL EVALUATION OF COMPOSITE HELICAL SPRINGS

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ABSTRACT

Helical springs made of composite material such as glass fibre, carbon fibre, and glass-carbon fibre have an increasing interest in automobile industries and manufacturing of machines where absorption of impact forces is regular scenario. Being lightweight with comparable mechanical strengths (e.g., high-strength, flexibility, and stiffness) like steel helical springs, helical springs made of the lightweight composites (glass fibre/ carbon fibre/ glass-carbon fibre) have been promoted in the industries over conventional steel/ stainless steel-based helical springs. The demand of an alternative of steel in spring manufacturing is not only because of the reduction of weight, but also, to increase efficiency. Hence, an alternative composite material has been using glass fibres, and glass-carbon fibres that has comparatively similar elastic property like steel, but its density is less than steel. Therefore, a helical spring made of this composite material was expected to have comparatively similar pseudoelastic response. This research has investigated the compression stiffness of four different type of helical springs. The variations adopted in the experiments consist of types of composite materials (glass fibre reinforced polymer, and glass-carbon fibre reinforced polymer), and differences in number of coils in the same free length (i.e., pitches). The compression load was applied to the springs up to 450 N with a consistent rate (deformation control). The springs were kept in a corrosion chamber for 48 hours where the salt spray method was used to generate a corrosion environment. The wet and dry automatic cycle was applied through a controller. The springs were again tested by applying compression load with the same speed rate. The stiffnesses at two phases such as rising of initial compression load and rising of compression load after 48 hours of salt spraying were estimated. The glass-carbon fibre-reinforced polymer-based springs had insignificant change in stiffness compared to glass-fibre-reinforced polymer-based springs after applying salt spray. The spring with smaller number of coils had less stiffness than that of the spring with higher number of coils, i.e., spring with larger pitch had less stiffness.

DECLARATION

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university
2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

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I certify that I have read this thesis. In my opinion **it is**/is not (please circle) fully adequate, in scope and in quality, as a thesis for the degree of Master of Engineering Science (Mechanical). Furthermore, I confirm that I have provided feedback on this thesis and the student has implemented it minimally/partially/**fully** (Please circle).

Signature of Principal Supervisor....... Youhong Tang ....

Print name of Principal Supervisor..........Youhong Tang..

Date.......21-Oct.-2022...

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CHAPTER 1 INTRODUCTION

1.1 General Background

Spring is an elastic body that is designed to deform when it is loaded and then to return to its original shape when the force is removed (Khurd, et al., 2016). Springs are essential components of an automobile's suspension system. They are required to reduce the vertical vibrations, impacts, and bumps that are caused by the imperfections of the road to give a pleasant ride. As a result, the optimization of the spring plays a significant part in the improvement of the car's dynamics (Wahl, 1963). The vast majority of springs are fabricated from metal, and although there are many different alloys available today, non-metallic materials like as reinforced plastics and ceramics are increasingly being used in manufacturing around the globe. Part of the most used composite springs in the modern-day market includes the helical springs.

High-carbon steels are the material that is used most of the time in the production of springs for vehicle suspensions. The manufacturing of smaller springs involves winding pre-heated stock around metal dies, whereas the production of bigger springs involves winding annealed steel over the same dies and then hardening the springs after they have been constructed. These steel springs have a lower cost, are readily available, straightforward to produce, and used extensively (Rajurakar & Swami, 2016).

Helical springs with a tighter coiling pattern have a lower helix angle, often about 10 degrees. Shear stresses are created in helical springs because of the twisting action that occurs during loading. In most cases, the load that is being applied will either be perpendicular to or along the axis of the spring. On the other hand, open-coiled helical springs have a longer pitch length, which results in a bigger helix angle. This is because the coils are twisted in such a manner as to increase the pitch length.

Emission gas restrictions and the vehicle's fuel economy are the two primary factors that should be taken into account while designing an efficient car. The use of composite materials in the construction of cars allows for significant weight reduction, which in turn leads to improvements in the vehicles' fuel economy. Composites made of carbon or glass fibre that have been treated with resin are suitable for use in the production of composite coil springs. These springs have a great NVH (Noise, Vibration, and Harshness) property, which means that they have the potential to deliver enhanced weight reduction in comparison to standard materials such as steel.

A coil spring is typically made from a single length of metal rod, which is then heated and coiled on a cylindrical die to form the desired shape. This process is done in order to generate the spring in the desired form. The spring rate or load bearing capacity of a spring is determined by the wire diameter of the spring, the spring's mean diameter, the spring's cross-section, and the coil pitch. Failure of helical springs is often caused by excessive cyclic fatigue, during which the stresses created should stay below the level of yield strength, as well as by inadequate material qualities (Lavanya, et al., 2014).

Composite springs may be substituted for metal springs to save weight and increase corrosion resistance. However, metal springs have the benefit of being manufactured in a variety of sizes and stiffness values. The fabrication of composite springs is costly and complicated due to the anisotropic character of these materials; hence, the use of composites in spring manufacture is uncommon (Budan & Manjunatha, 2017). Part of the composite springs currently in use includes the composite helical springs.

Helical spring (HS) is a widely used mechanical spring consisting of a constant coil diameter and a uniform pitch to store elastic potential energy under compression, tension, or torsion forces. It is used in machineries (mechanical systems) and automobiles to reduce the intensity of any impact forces on the body and to improve the performance of vibration isolation system (Jun, et al., 2022) through storing those forces as energy and releasing equivalent energy as an inverse force. Steel is generally used in producing helical spring due to its high stress resistance within the elastic limit; however, as weight of HS is an important aspect for achieving higher energy saving, finding an alternative lightweight material for HS has been a primary focus of research in current age. About 50% of weight reduction of helical spring has been demanded by researchers adopting composite helical spring in place of steel helical spring (Choi and Choi, 2015; Jang and Jang, 2014). Stephen, Selvam and Suranjan (2019) reported that composite material is beneficial to use replacing steel helical spring not only for reduction of weights, but also for improving the corrosion resistance, durability which are directly related to the functional life of the springs in automobile, and heavy machineries. Shokrieh and Rezaei (2003) suggested that utilizing fibres in manufacturing the spring wire makes spring excellent in fatigue resistance, enhance ductility (fail-safe capability), improve corrosion, and obtain natural frequency. A composite helical spring is generally manufactured combining fibres; hence the composite helical spring should have better performance in terms of energy saving and operational life, comparing with those of steel helical spring (Manjunatha and Budan, 2012; Kara, 2017). Thus, researchers suggested to develop suitable helical springs using composite materials replacing conventional steel springs (Ekanthappa, et al., 2016).

The use of fibres as part of a composite material in helical spring, might be a new concept, however, this technique is generally an old 100-year-old techniques. Fibre has been used in many composite materials, such as in concrete, and reinforcing bars. The technique of utilizing fibre in a composite with polymeric reaction is generally known as fibre-reinforced polymer composite (FRPC). The first application of FRPC can be found in manufacturing boat hull in middle of 1930's where fibreglass was used as the reinforcing fibre in a polyester resin (Hensher, 2016).

Though a significant number of research on composite helical springs have been conducted, still more effort is required to develop a composite spring of low cost, but highly efficient that can compete the consumers' demand. Hence, the Youhong Tang's research group in Flinders university has been conducted to develop such a highly efficient, economically competitive, and made using available material. This research is a part of the continuation of the development of that level of composite helical spring. However, the scope of this research does not comply to develop the spring, instead to evaluate the performance of developed composite helical springs fabricated by Flinders' university Youhong Tang's research group.

This research intends to examine the mechanical performance in terms of compression stiffness of composite helical springs made of glass fibre-reinforced polymer and glass-carbon fibre-reinforced polymer in two environmental conditions: normal/ ambient environment and attempting to corrode the spring through automatic corrosion chamber applying salt spray and dry cycles continuously. The outcome of this research will allow the developed composite helical springs to identify their use in machineries/ automobile/ train/ aircraft.

1.2 Helical Springs

The most distinctive representation of helical springs is a continuous rod or wire wound into a cylindrical shape with a set distance between neighbouring coils. This type of profile shape can have various diameters or profile figures based on the design requirements of the application. Due to the fact that these are the most prevalent shapes, the vast majority of helical springs will be able to conform to one of the profile shapes shown in Figure 1.1. These geometries are suited for the majority of the duties because they meet the space requirements, loading range requirements, load condition requirements, and material property requirements. There might be some cases when the profile geometry can be reorganized into a different shape to serve a very particular function, although those cases are quite rare

Figure removed due to copyright restriction

Figure 1.1. Types of spring shapes (a) variable pitch, (b) barrel, (c) hourglass and (d) conica (Shigley, et al., 2004).

On helical springs, the cross-sectional form of the wire is typically circular, although square or rectangular cross-sections can also be utilized well. The variance of the cross section is determined by the available area for the spring, the material presentation, the process of manufacturing, and the design specifications. In Figure 1.2 it can be noticed the difference between the cross-section kinds of springs.

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Figure 1.2. Cross section of helical springs with various wire configurations (Shigley, et al., 2004).

The end type of the wire that is utilized for the helical springs is another feature of the springs that distinguish them. When it comes to the quick response of the spring's behaviour against the load condition, the influence of the end type is significant. Plain, squared, and ground end coils are the most frequent types of end coils. Some of the most significant distinctions between spring ends are dependent on the response they produce when a load is applied to the spring; for instance, the following spring ends give a different response:

- Springs with plain ends lack interrupted helicoids at the ends and are the same as if a long spring were divided into parts.
- A spring that has been crushed between two rigid plates can be deemed to have fixed ends if its ends have been squared and ground.
- By deforming the ends to a zero-degree helix angle, it is possible to create a spring with squared or closed ends.
- For critical applications, springs must be regularly squared and ground, as this results in a more efficient load transfer.

A spring may be made of virtually any material; however, the ideal material should have a high ultimate strength, a high yield point, and a low modulus of elasticity (Childs, 2003). These characteristics will allow the spring to store the most amount of energy possible. High-strength steels, glass, nylon, titanium alloys, and glass fibre reinforced polymer (GFRP) are some examples of potential alternatives to the substance nylon. The options typically consist of simple carbon steels, alloy steels, stainless steels, high-nickel steels, and copper-based alloys for the majority of applications. Important features of spring design include determining the material and dimensions of the spring. This is done to guarantee that the spring will not fail under static or varied loads. One of the design requirements for springs is that they must not buckle or deform beyond permissible limits under load. In most cases, the material's inherent vibration frequencies are significantly higher than the frequency of motion that the springs will control.

The rate at which a spring deforms under a given stress is referred to as its spring rate, and it is a property that can be measured. The slope of the force-deflection curve of a spring is the definition of this property. If the slope remains the same, then the deflection may be calculated using Equation 1.1, where k is the spring rate, F is the applied force, and δ is the deflection.

$$k = \frac{F}{\delta} \qquad (1.1)$$

According to Shigley, et al., (2004), one technique to determine the spring's deflection is with the following formula, shown in Equation 1.2:

$$\delta = \frac{64Fr^3N}{d^4G} \qquad (1.2)$$

which is determined by the characteristics of the material as well as the geometry, where G represents the shear or torsional modulus and N represents the active number of coils, r represents the mean diameter of the spring, d represents the coil diameter, and F represents the load that is being applied to the spring.

1.3 Manufacturing of CHSs

Sureshkumar et al. developed a laminated composite spring made of carbon fiber and discovered that the composite spring's impact and tensile qualities were superior to those of a steel spring (Sureshkumar et al., 2014). Choi used computational and experimental techniques to calculate the ply angles and wire diameters of carbon fiber/epoxy composite coil springs. Additionally, a spring rate comparable to that of a comparable steel component was produced (Choi & Choi, 2015).

With the adaptability of the filament winder, Sancaktar et al. established a unique process to build composite cylindrical helical springs utilizing glass and carbon fibres embedded in an epoxy resin matrix. Their technology enables springs to easily change spring dimensions. This is done in three steps. The first step is to choose the resin and hardener. A resin bath is used to thoroughly wet the glass and carbon fibres, which are then enclosed in PVC tubing of three different inner diameters. These fibre-filled tubes are coiled on PVC mandrels of three different sizes. To build prototype composite coil springs from widely accessible glass fibre and epoxy materials, Sardou MA et al Chiu et al. propose modifying current lost mould and winding procedures. These solutions were built with scalability and automation in mind. Several prototype composite helical springs have been tested. Thus, filament winding is a low-cost and low-difficulty procedure. However, since the process is still manual, the final quality is not reliable enough to meet engineering application requirements. Scholars have employed the sophisticated resin transfer moulding (RTM) technique to make helical springs as shown in **Figure 1.3.** For example, Choi et al. and Sancaktar et al. used RTM to make a CFRP helical spring. During RTM, a carbon fibre freeform is filled with epoxy resin and crosslinked under vacuum.

Some researchers developed a novel manufacturing method called splineTEX. Stacks of originally straight tubular braids (balanced and unbalanced) are put into a flexible tube. The latter is used to inject the polymer resin. The helical form is achieved by coiling the tube before the resin cures. Some researchers have researched manufacturing process parameters. Many exploratory experiments determined the production process of composite spiral spring and analysed the impact of processing technology and spring structural parameters on bending resilience, recovery rate, and tension qualities. Based on the findings, the bending mechanical characteristics of a composite spring are closely connected to the inner diameter, twist of the fibre bundle, strand count, and outer diameter. Although much study has been done on composite helical spring manufacturing, there is no developed technological framework for mass production. Further study is required to increase mould reuse frequency and product quality stability.

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Figure 1.3 Representative manufacturing process for composite helical springs (Chiu et al., 2007)

However, owing to the unique helical shape formed during composite processing, the design and optimization of composite springs continue to face significant hurdles. Using a multi-objective evolutionary system, Zebdi et al. improved composite helical springs with three braided reinforcements. There are many downsides to filament winding, including a high scrap rate and expensive production costs. Composite springs, on the other hand, are prone to surface roughness.

1.4 Research problems (questions)

It is significant to know the stiffness properties of any helical spring before applying those in practice. Also, the springs will remain active almost continuously in their functional life. So, any adversity of corrosive environmental condition during the operational life may affect its stiffness. Therefore, any development of helical springs using any new composite materials is required to examine practically to identify the mechanical property and its long-term efficiency. According to the candidate's knowledge, the developed helical springs made of a new composition of glass-fibre and glass-carbon fibre yet examined its performance in adverse/ corrosive environment. Therefore, it was required to examine their stiffness, as well as to estimate the modulus of rigidity which has filled up through this research.

1.5 Research aims and objectives

The aim of this research is to evaluate the stiffness of the composite helical springs made of glass-fibre and glass-carbon fibre/ polymer. Following objectives have been complied to achieve above aim.

Objective 1: To experiment glass fibre and glass-carbon fibre based composite helical spring with two variations of pitch by applying compression load at a constant rate of deformation/ speed

Objective 2: To study the short time corrosion effect on the stiffness of the springs.

Objective 3: To estimate the stiffness of springs and modulus of rigidity of the composite springs.

1.6 Outline of the thesis

This thesis contains seven major chapters including Introduction, Literature review, Methodology, Results, Discussion, Conclusions, and Future works. The details are shown below:

Chapter 1 Introduction: It describes the significance, aims, and objectives of this research.

Chapter 2 Literature review: A comprehensive, and past research works those are closely related to the aims and objective of this research has been included in this chapter. However, more literature has been reviewed to explore the research gaps.

Chapter 3 Methodology: The experimental set up and specification of the springs have been included in this chapter.

Chapter 4 Results: Compression load and deformation results and calculated stiffness of spring, and estimated modulus of rigidity of the spring wire have been discussed in this chapter.

Chapter 5 Discussion: The effect of variations in types of composite material in spring, and variations in pitch/ number of coils have been explored in this Chapter.

Chapter 6 Conclusions: The summary of the findings have been discussed in this section.

Chapter 7 Future work: This chapter suggests future works those required to carry out before applying this spring in operation.

CHAPTER 2 LITERATURE REVIEW

2.1 Background

In recent years, more than 20% of the parts of one of the largest passengers carrying aircraft (Airbus A380) has been manufactured using carbon fibre composite, and glass fibre reinforced aluminium (Kara 2017). This implication of first fibre composite polymer achieved 25% higher strength and 20% lighter than conventional airframe aluminium (Airbus A380 Specifications). The first major application of fibre reinforced polymer is found in literature as the application of composite leaf springs for heavy trucks in 1981 by Daugherty (McGeehin 1982). Four types of composite helical springs consisting of laminates, rubber core (inner), outer braid at various combinations were investigated by Chiu et al (2007). The laminates were maintained unidirectional to loading direction.

Several researchers have investigated the suitability of composite springs for vehicle applications and determined that weight reduction is possible by switching to composites. They have also attempted to improve the manufacturing process for these springs. Several of the research are summarized here.

According to Budan & Manjunatha, (2017), the strain energy of a material is the most important aspect to consider when designing a spring. Specific strain energy in the material can generally be expressed as

$$U = \sigma^2 \frac{\rho}{\mathrm{E}} \tag{2.1}$$

This demonstrates that a material having a lower Young's modulus (E) or density (ρ) will have a higher specific strain energy for a given stress (σ). Consequently, composite materials are both strong and lightweight.

Using FEA analysis, Rajurakar & Swami, (2016) investigated helical coil springs constructed of hard carbon steel and chrome vanadium spring steel with circular and rectangular cross sections. The values for shear stress and deflection were obtained. Comparisons were made between the shear stress and deflection values of hard carbon steel and chrome vanadium spring steel for circular and rectangular cross sections. Budan & Manjunatha, (2017) investigated the use of fibre-reinforced plastic in springs. The design and fabrication of three distinct coil springs utilizing glass fibre, carbon fibre, and glass/carbon fibre in a +45-degree orientation. Experiments were conducted to investigate the mechanical behaviour of the springs. The possibility of employing a fibre-reinforced composite helical spring for automotive suspension was addressed. Through an examination of the literature, they determined that the energy storage capacity of a spring with a rectangular cross-section is greater;

they also discovered that less research has been conducted on this form of spring. Consequently, they used a rectangular cross section for the experiment. The mechanical behaviour of composite springs with various reinforcing material combinations having a rectangular cross-section was investigated.

Research on E-glass, carbon, Kevlar-based composite helical springs (three different composite materials) were conducted by Bakhshesh and Bakhshesh (2012). An optimum design of fibre volume with epoxy was suggested in this research. The developed helical spring with the three different composite materials were examined applying the loads and measuring the corresponding deformations. The results were compared with conventional steel helical spring of equivalent geometrical parameters. Besides the experimental approach, a finite element, and an analytical approach have been used to get the spring shear stresses and deformations which were compared with the experimental results for validation. After validating the numerical and analytical approach, parametric study has been conducted which shows that highest amount of shear stress is distributed in spring when the fibre orientation was aligned with the loading direction. It means that fibre oriented towards loading direction in a helical spring provides the most efficiency in a helical spring and in design purpose, it was suggested to be consider maximum safety factor while the fibre orientation is perpendicular to the loading direction.

In a very close duration of research of Bakhshesh and Bakhshesh (2012), another research works on composite helical springs of three different composite materials consisting of glass fibre, carbon fibre, and glass-carbon fibre were conducted by Manjunatha and Budan (2012) in which the fibre orientation angle in respect to loading direction was considered +45° to investigate the mechanical responses. Filament winding technique (FWT) had been used manufacture the composite helical spring. A mandrel made of cast iron were used as mould for getting desired shape of the spring. A mould release agent was used to on the internal surface of the mandrel. A continuous winding process had been followed to get the desired shape of the helical spring. Manjunatha and Budan (2012) evaluated the stiffness, shear stress, and failure load (maximum compression) were recorded. The weight of the manufactured composite helical spring had less than that of the steel helical spring of equivalent geometrical parameters. The experimental results shew comparable and, in some cases, better performance than conventional helical spring. Choi and Choi (2015) investigated the role of static spring rate on the stiffness of carbon fibre-reinforced epoxy composite coil springs (CFRPCS). In this research, CFRPCS was manufactured through resin transfer modelling process where a mould with a shape of wire to be part of helical spring, was filled up with composition of carbon fibre and epoxy. This composition was then hardened in a vacuum condition to remove all air bubbles and ensure proper compaction of the resins. The fibre volume and void volume ratio were reported as 64.4% and 3.5%, respectively. Choi and Choi (2015) pre-examined the harden composite wire to design a speed rate of loading. The twist angle was pre-determined using which the equivalent shear modulus of composite was estimated relating to the shear modulus of the wire. The developed composite helical spring was found 55% less weight than steel helical spring of equivalent geometrical parameters.

Researchers (Jithu and Mohan, 2022; Zhang, et al., 2022) have attempted to use various alloys contained of Nickel (Ni) other than steel or fibre/epoxy composite to manufacture the helical spring such as LaNi5 (Lanthanum-Nickel) and NiTi (Nickel Titanium/ Nitinol) to get a more efficient helical spring. Jithu and Mohan (2022) developed a model to analyse the helical spring from the material property. The parametric studies were conducted for the helical spring made of LaNi5 (Lanthanum-Nickel) alloy. The heat generation due to continuous application of cyclic load on spring were investigated. It was reported that the dissipation of heat was constant for the associated stresses at same unwound length (free length). Coil diameter, and pitch had influence in shear strength: reduction of coil diameter reduced shear capacity and increase of pitch reduced the shear strength.

Geometric dimensions of the CHSs include the wire diameter d, the screw pitch P, the helical angle α, the spring diameter D and active number of turns, n, as illustrated in Fig. 2.1. As presented in existing literature sources, the cross section of the CHSs can either be rectangular or circular. Moreover, there are four categories of spring wire cross section structure, namely, the BUR, BU, AU and UR, as shown in Fig. 2.1. These geometrical dimensions of the CHSs play a crucial role in optimizing static performance of the CHSs. Some researchers manufactured CHSs and explored mechanical performance of CHSs based on geometry (Ke, et al., 2020).

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Figure 2.1 Typical structure of CHS with a circular cross section; circular spring wire (Ke, et al., 2020)

The compressive behaviours of CHS with spring diameters of 100 mm, 200 mm, 300 mm, 400 mm and 500 mm have been studied and were presented in various publications (Liu, et al., 2021). The study conducted by Liu, et al., (2021) showed significant decrease in the compressive stiffness of CHSs with the increase in the spring diameter, indicating that the spring diameter is a key factor affecting the compressive stiffness of CHS. Moreover, analysis of the load-displacement curve of the CHSs with different screw pitch demonstrates an increase in the slope of the load-displacement curve with increase in the screw pitch of CHSs (Heidari, et al., 2016). Existing literature sources demonstrate that spring stiffness can be determined by the ratio of the load difference to the displacement difference at any two points under compression, so the slope of the curve represents the spring stiffness. Therefore, increasing the screw pitch of the composite helical spring can improve its stiffness and subsequently, increase its bearing capacity (Ke, et al., 2020).

In addition, since different materials have different properties such as elastic modulus, shear modulus, Poisson's ratio and density. Material type not only has a crucial impact on the mechanical properties of the CHSs, but also closely relates to the weight of the CHSs. Some of the potential materials used in in CHSs includes epoxy-glass composite and epoxy-carbon composite (Stephen, et al., 2019). The weight of the CHSs was found to be at least 75-80% lower than that of steel. These can be attributed to the lightweight effect of the composite materials used in the structural design of the helical spring. Evaluation of performance of composite helical springs is fundamental to realizing their scientific verification and approve of their engineering application. Several researchers have conducted performance investigations in this particular field using various kinds of tests as illustrated in Fig. 2.2

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Figure 2.2 Schematic diagrams showing the various tests fundamental in evaluating the performance of CHSs (Ke, et al., 2020)

The performance of CHSs is conducted in according to various ASTM standards such as ASTM A 125-2001, ASTM B 593-1996, and ASTM F 1566-1994, among many others (Ke, et al., 2020). There are numerous experimental, theoretical and numerical studies that have been conducted by various researchers on stiffness of the helical spring (Yildirim, 2016; Pawar & Desale, 2018), helical strength (Kaiser, et al., 2011) and compressive stability. It can be seen from the above literature that the geometry and material type are important to the static and dynamic performances of CHSs. Zhang et al. (2022) investigated the temperature evolution from NiTi (Nitinol/ Nickel Titanium) shape memory alloy-based helical spring applying cyclic tension load and releasing tensions up to 40 mm, 60 mm, and 80 mm deformations achieved. Three loading rates such as 0.3 mm/s, 1 mm/s, and 5 mm/s were used to apply tensions. Experimental results found a different level of temperature released during the cyclic loading. Zhang et al. (2022) reported that this release of temperature was due to the phase transition between austenite and martensite phases (crystal structural phases). The summary of the literature is shown in Table 1.

Table 2. 1: A comprehensive list of previous research on composite helical spring (CHS) relevant to this research project

Reference	Materials used in composition	Experiments	Investigations
Chiu et al (2007)	Rubber, laminates, braid composite, epoxy	Compression	Development of composite helical springs at four types of combinations of laminates, rubber, and braid in spring cross-sectional layer
Bakhshesh and Bakhshesh (2012)	E-glass, Carbon, Kevlar, epoxy	Compression, finite element analysis, analytical model development	Optimization of using epoxy with fibre; stiffness was investigated applying compression load; also, using a finite element analysis, and an analytical model.
Manjunatha and Budan (2012)	Glass fibre, carbon fibre, glass-carbon fibre, epoxy	Compression	Effect of fibre orientation in stiffness, shear stress distribution, and shear modulus were examined.
Choi and Choi (2015)	Carbon fibre, epoxy	Compression	Optimization of fibre-epoxy volume in wire
Heidari et al (2016)	E-glass fibre, epoxy	Model development	Fabrication and modeling of shape memory alloy springs.

2.2 Gaps in existing knowledge

It is significant to know the stiffness properties of any helical spring before applying those in practice. Also, the springs will remain active almost continuously in their functional life. So, any adversity of corrosive environmental condition during the operational life may affect its stiffness. Therefore, any development of helical springs using any new composite materials is required to examine practically to identify the mechanical property and its long-term efficiency. According to the candidate's knowledge, the developed helical springs made of a new composition of glass-fibre and glass-carbon fibre yet examined its performance in adverse/ corrosive environment. Therefore, it was required to examine their stiffness, as well as to estimate the modulus of rigidity which has filled up through this research.

2.3 Statement on gap in knowledge (/ research)

More investigations on the optimization of fibre, layer of various fibres, and type of epoxy are required. Specifically, before implementing any spring in practice, a thorough examination is required to know long run efficiency, and any impact on the overall performance of the spring at any adverse environment. This research, thus, investigated the compression stiffness of a developed composite spring applying short term corrosion and evaluated any change of performance due to the induction of corrosion.

CHAPTER 3: METHODOLOGY

3.1 Specimens

Four types of composite helical spring (CHS) comprising two types of composite materials (glass fibre reinforced plastic (GFRP) and glass-carbon fibre reinforced plastic (GCFRP)) and two variations in pitch (i.e., number of turns) were investigated. The CHSs are shown in Figure 3.1(a) and their geometrical dimensions are reported in Table 3.1.

GFRP2 GFRP1 GCFRP1 GCFRP2

(a)

Figure removed due to copyright restriction

(b)

Figure 3.1(a) Four types of composite helical springs (CHS) used in this research and (b) definition of geometrical dimensions

As seen in Table 3.1, wire diameters (d), mean diameters (D) of CHSs, helix angle (α), and free length (L_0) are considered identical for all types of CHS.

Table 3.1: Geometrical dimensions of CHSs as defined in Figure 3.1(b)

	Glass fibre-reinforced plastic CHS		Glass-Carbon fibre-reinforced plastic CHS	
	GFRP1	GFRP2	GCFRP1	GCFRP2
d	16.00± 0.44	16.00± 0.44	16.00± 0.44	16.00± 0.44
D	116.00± 0.44	116.00± 0.44	116.00± 0.44	116.00± 0.44
L_0	450.00± 0.44	450.00± 0.44	450.00± 0.44	450.00± 0.44
P	102.00± 0.44	130.00± 0.44	102.00± 0.44	130.00± 0.44
n	4.50	5.50	4.50	5.50

d = wire diameter in mm, D = mean diameter of CHS in mm, n = number of turns, P = pitch in mm, L_0 = free length of coil in mm.

The wire diameter, mean diameter, and pitch were measured using a digital vernier callipers at three locations of the coil (Figure 3.2(a)), and the free length was measured using a ruler (Figure 3.2(b)). The average dimensions of these measurements are reported in Table 3.1, the tolerances of these measurements are within ± 0.44 mm. Two variations of pitch (102 mm and 130 mm) were adopted to evaluate their roles in modulus of rigidity, strain energy, and spring stiffness.

Figure removed due to copyright restriction

(a) (b)

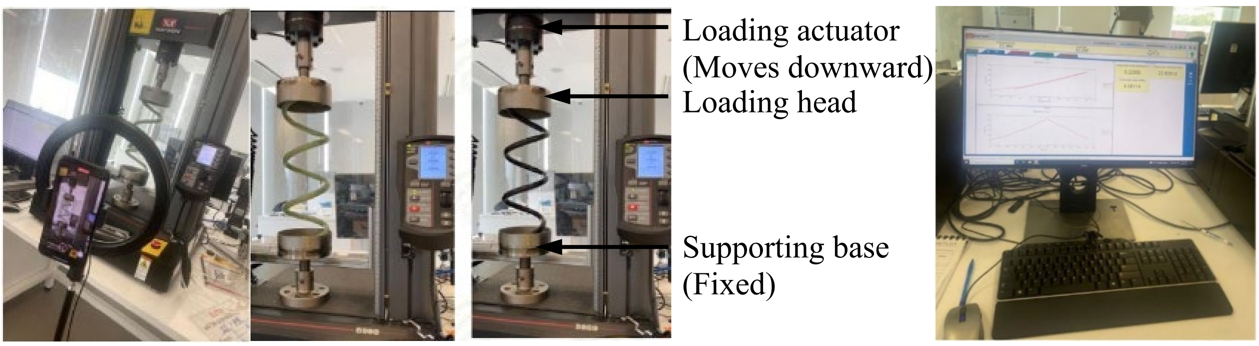
Figure 3.2 Measurements taken (a) using vernier calipers for wire diameter, mean diameter, and pitch and (b) using a scale for free length.

The stiffness of CHS specimens were examined in two environmental conditions: (1) normal environment: CHS specimens were just applied compression loads axially and the stiffnesses were calculated from the load-deformation curves, and (2) exposing in salt environment condition: same CHS specimens as used for above condition were kept in a salt environment before applying the compression load.

3.2 Experimental set-up

3.2.1 Stiffness test under compression load

The stiffnesses of springs were calculated from the compression load and displacement results measured using a universal testing machine INSTRON 5969 of a capacity of maximum 50 kN compression load. INSTRON 5969 had a clear space 1,212 mm vertically, and 412 mm laterally. A single spring of 116 mm diameter and 450 mm free length was installed axially between the loading head and supporting base of INSTRON as shown in Figure 3.3(a). The top and bottom faces of the springs were flat that enabled the springs to securely rest between loading head and supporting base under compression without having any lateral movement.



(a) *(b)*

Figure 3.3 (a) Installation of composite helical springs (GFRP and GCFRP) into a universal testing machine for applying compression load and (b) data recorded directly from the INSTRON 5969

The actuator was moved downward direction for applying the compression load at a constant rate of 10 mm/min, while the supporting base was always fixed. After 100 mm of deformation of spring (/actuator displacement) due to compression force, the actuator was moved upward direction at same rate. An in-built operating system recorded the applied load and deformation value in a computer (Figure 3.3(b)) for both times: applying load and releasing load after 100 mm deformation. A preliminary load was applied on spring adjusting the actuator manually to minimise error in the deformation measurement due to the mechanical set-up of INSTRON. So, the deflection recorded by the movement of actuator was considered accurate for the stiffness calculation.

3.2.2 Salt spray method for inducing corrosion

The wet (by salt spray) and dry technique was applied for 48 hours to induce corrosion on the surface of the same springs used for stiffness under compression load. An automated cyclic corrosion chamber was used to operate the chamber controlling the humidity, temperature, concentration of salt solution, rate of spray, drying temperature, and time in each cycle. Before keeping the springs in the cyclic corrosion chamber, all specimens were washed with demineralized water. The corrosion chamber consists of a solution storage tank, a pump, a bubble tower with compressed air inlet, a nozzle for spraying the salt water on the specimens, an in-built chamber heater, vents for releasing the vapours, and an automatic controller. A schematic diagram of the cyclic corrosion chamber is shown in Figure 3.4.

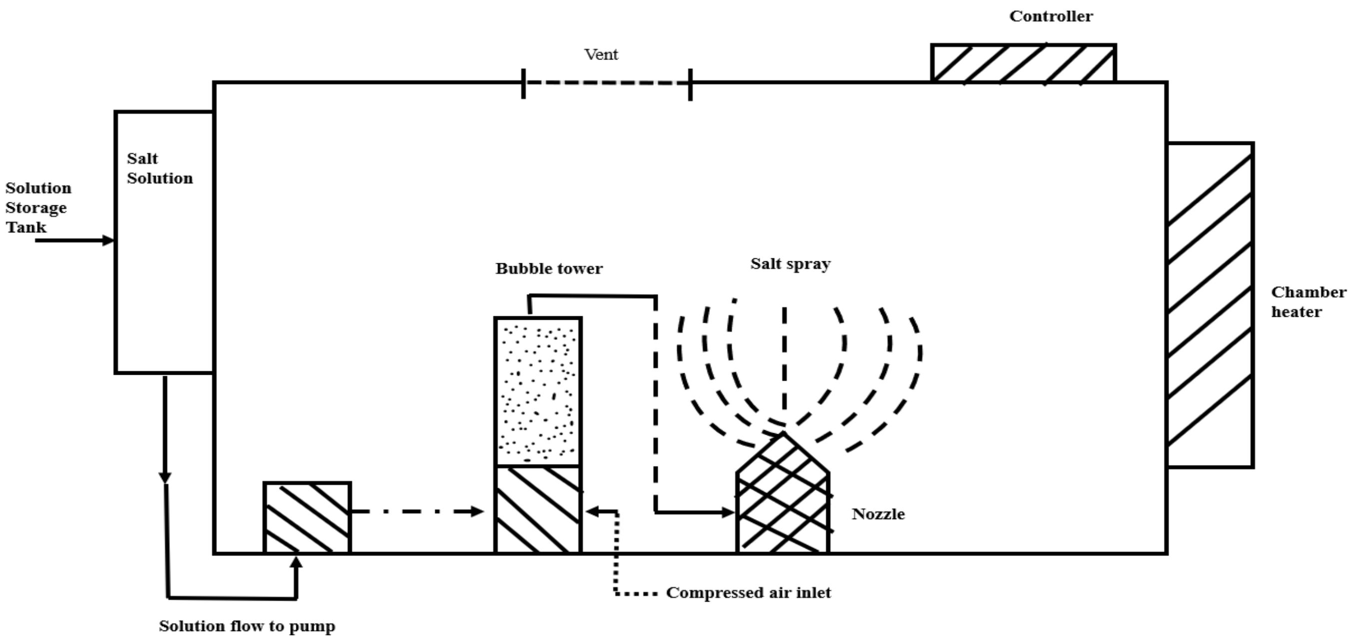


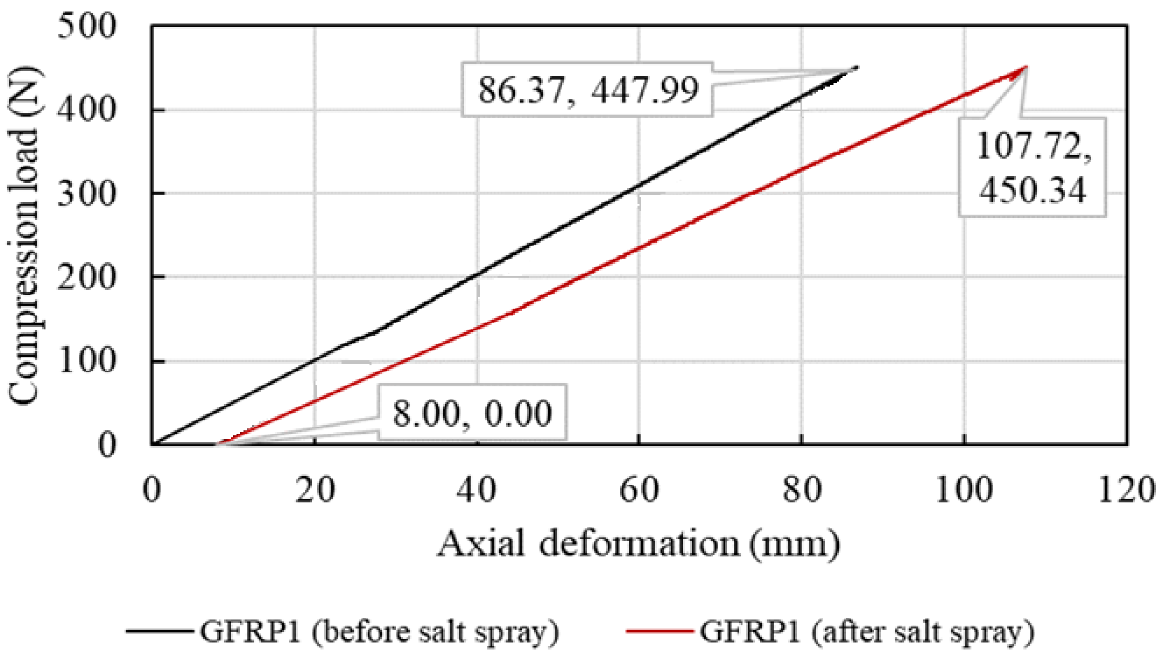
Figure 3.4 Schematic diagram of cyclic corrosion chamber

A salt solution with concentration of 35 gram per litter of NaCl were prepared manually which were stored in the solution storage. The controller is used to operate the pump to pump the solution from storage tank to the bubble tank automatically. The compressed air passed through bubble tower where the air was injected into the salt solution. Then the solution with air bubble was flowed to the nozzle which sprayed the salt on the springs at a constant rate. A heater is consisted in the chamber to generate heat (set as 40 °C) inside the chamber to evaporate the water from the chamber which passed out the vent. The humidity was about 90 – 98% during this process. After a complete defogging the chamber was set at a controlled humidity (90%) and temperature (40°C). These three processes (spraying of salt solution, defogging, and drying) were continued for 48 hours. The stiffness of the corrosion induced springs were then retested following above mentioned compression procedure.

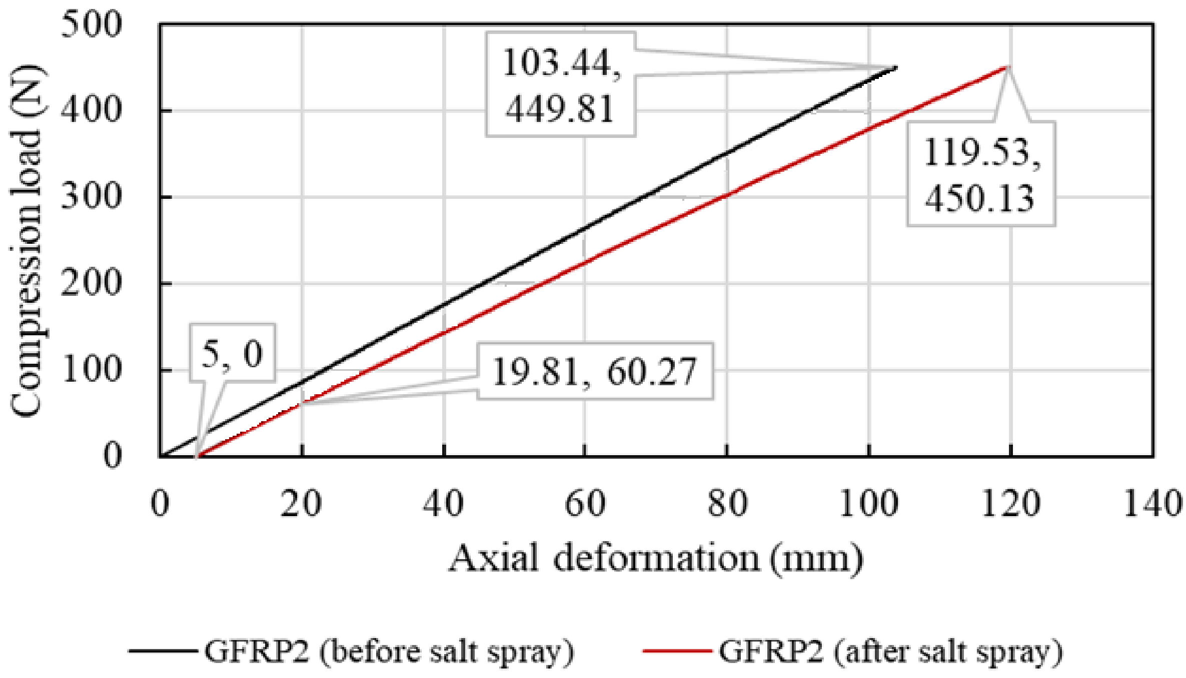
CHAPTER 4: RESULTS

4.1 Compression load vs Axial deflection responses

The compression load vs axial deflection (*P*-*δ*) responses of four types of composite helical springs (CHS) are shown in Figures 4.1 and 4.2. The variations of these tests comprise of types of composite materials of CHS and pitch (i.e., number of coils within a free length of 450 mm). The *P*-*δ* responses of glass fibre-reinforced polymer (GFRP), and glass-carbon fibre-reinforced polymer (GCFRP) based CHSs have been examined with variation in pitch as 102 mm (GFRP1 and GCFRP1) and 130 mm (GFRP2 and GCFRP2). Other parameters such as diameter of the wire of spring, free length, testing cycle, and speed (/ pace rate) of application of compression loads were consistent in all types of springs (GFRP1, GFRP2, GCFRP1, and GCFRP2).



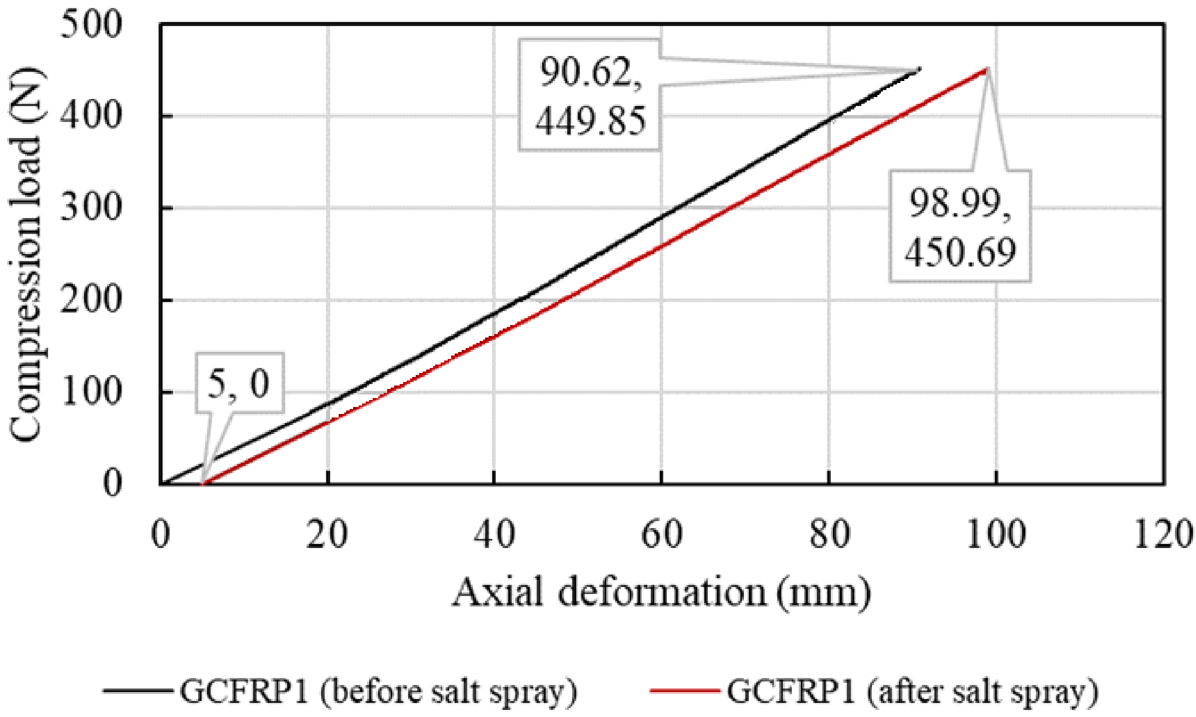
(a)



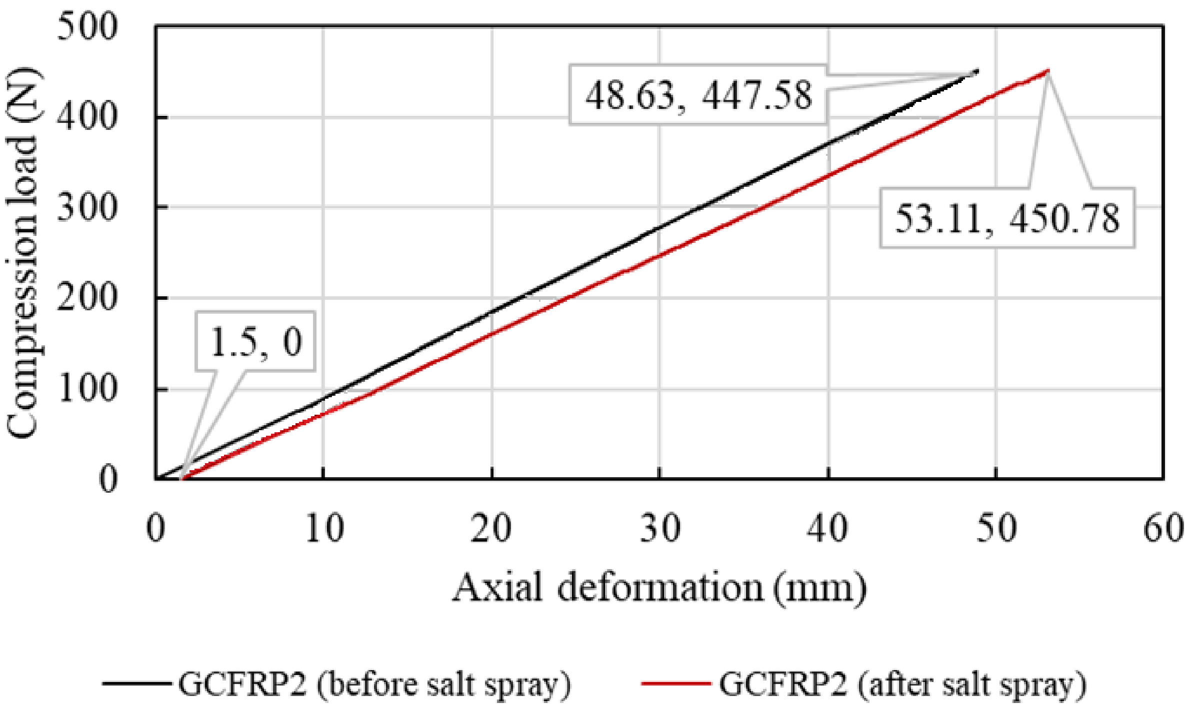
(b)

Figure 4.1: Compression load vs deformation of (a) GFRP1 (pitch = 102) and(b) GFRP2 (pitch = 130)

The INSTRON loading actuator was moved downward that applied compression loads up to 450 N (GFRP1), 450 N (GFRP2), 450 N (GCFRP1), and 450 N (GCFRP2) for deformations as 86 mm, 103 mm, 90 mm, and 48 mm respectively; at speed (10 mm/Sec) .



(a)



(b)

Figure 4.2: Compression load vs deformation of (a) GCFRP1 (pitch = 102) and (b) GCFRP2 (pitch = 130)

After testing *P*-*δ* responses, all tested CHSs were kept in the corrosion chamber for 48 hours for inducing corrosion through cyclic wet and dry technique. Then those springs were tested again for *P*-*δ* responses which are shown in Figures 4.1 and 4.2 at the red line. As the free length was reduced (ΔL_e) during the first *P*-*δ* (before salt spray test), *P*-*δ* response is drawn after an axial deformation of respective ΔL_e to compare graphically the change of stiffness of the springs. At this second round *P*-*δ* test, springs were deformed until the load reached to 450 N. The deformations were recorded as 99 mm, 114 mm, 94 mm, and 51 mm which are 14 mm, 11 mm, 4 mm, and 3 mm more than the deformations recorded in first *P*-*δ* test for GFRP1, GFRP2, GCFRP1, and GCFRP2, respectively.

The stiffnesses of springs as: ascending path (*k*) and descending path (*k'*) of *P*-*δ* responses of springs before salt spray and ascending path (k_{ss}) of *P*-*δ* response of same springs after salt spray have been calculated from the slope of linear responses of *P* and *δ* (Table 4.1). The stiffnesses of CHSs with less coils were less; for example, GFRP1 had pitch of 130 mm with 4.5 numbers of coil, whereas GFRP2 had pitch of 102 mm with 5.5 numbers of coil. Thus, the stiffness of GFRP2 is 1.2 times higher than that of GFRP1 (Table 4.1). Similar kind of results is noticeable for GCFRP1 and GCFRP2 in Table 4.1. The stiffness of GCFRP2 is 1.85 times higher than that of GCFRP2. Comparing the stiffnesses based on the type of composite materials, the stiffnesses of GCFRPs can be seen higher than GFRPs. The stiffness of GCFRP1 shows 1.14 times higher than that of GFRP1, whereas GCFRP2 has 1.77 times higher stiffness than GFRP2. Based on this observation, it is understood that stiffness of CHS depends on both material property and pitch (i.e., number of coils) if other geometrical parameters are considered identical. After salt spray, the stiffnesses of all four types of CHSs have been reduced 9.6% (GFRP1), 12.9% (GFRP2), 3.4% (GCFRP1), and 5.11% (GCFRP2). Based on this evaluation, GCFRP is found better than GFRP to use in a corrosive environment.

Table 4.1: Stiffnesses, k (N/mm) of composite helical springs before and after salt spray

	GFRP1	**GFRP2**	**GCFRP1**	**GCFRP2**
Before salt spray				
Ascending, k	4.349	5.187	4.964	9.204
After salt spray				
Ascending, k_{ss}	3.930	4.516	4.795	8.734

According to Chen,et.,2022, The modulus of rigidity of composite wires in springs has been estimated based on the following well-established equation used for helical spring:

$$G = \frac{k \times (64 \times D^3) \times n}{d^4} \tag{4.1}$$

whereas G = modulus of rigidity, k = stiffness of spring, D = mean diameter of helical spring, n = number of coils, d = diameter of spring wire. These parameters have been reported in Table 3.1, and 4.1. The estimated modulus of rigidity is shown in Table 4.2.

Table 4.2: Estimated modulus of rigidity, G (GPa) of composite materials

	GFRP1	**GFRP2**	**GCFRP1**	**GCFRP2**
Before salt spray				
Ascending, G	29.8	43.5	41.6	63.1
After salt spray				
Ascending, G_{ss}	26.9	37.9	40.2	59.9

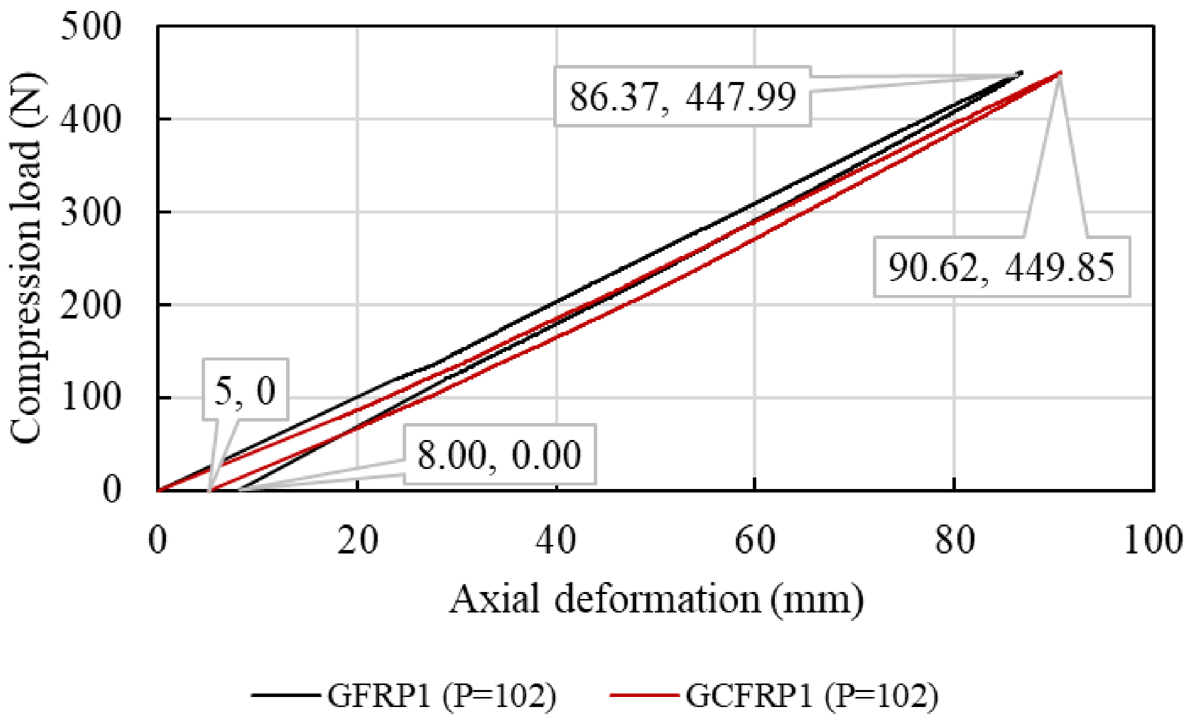
The modulus of rigidity of CHS made of GFRP is comparatively less than that of GCFRP. Rigidity of GCFRP1 and GCFRP2 are 1.4 times higher than that of GFRP1 and GFRP2. Again, comparing rigidity of spring of same composite material but variation in number coils, it shows that spring with 5.5 numbers of coils (pitch = 102 mm) has more rigidity than spring with 4.5 numbers of coils (pitch = 130 mm): rigidity of GFRP2 (pitch = 102) is 1.46 times higher than that of GFRP1 (pitch = 130), similarly, GCFRP2 (pitch = 102) is 1.5 times rigid than GCFRP1 (pitch = 130). The rigidity has been reduced after salt spray on all springs. The reduction of rigidity is estimated as 9.7% for GFRP1, 12.87% for GFRP2, 3.36% for GCFRP1, and 5% for GCFRP2 which indicates that GCFRP material-based spring is more durable in corrosive environment than GFRP based spring.

CHAPTER 5: DISCUSSION

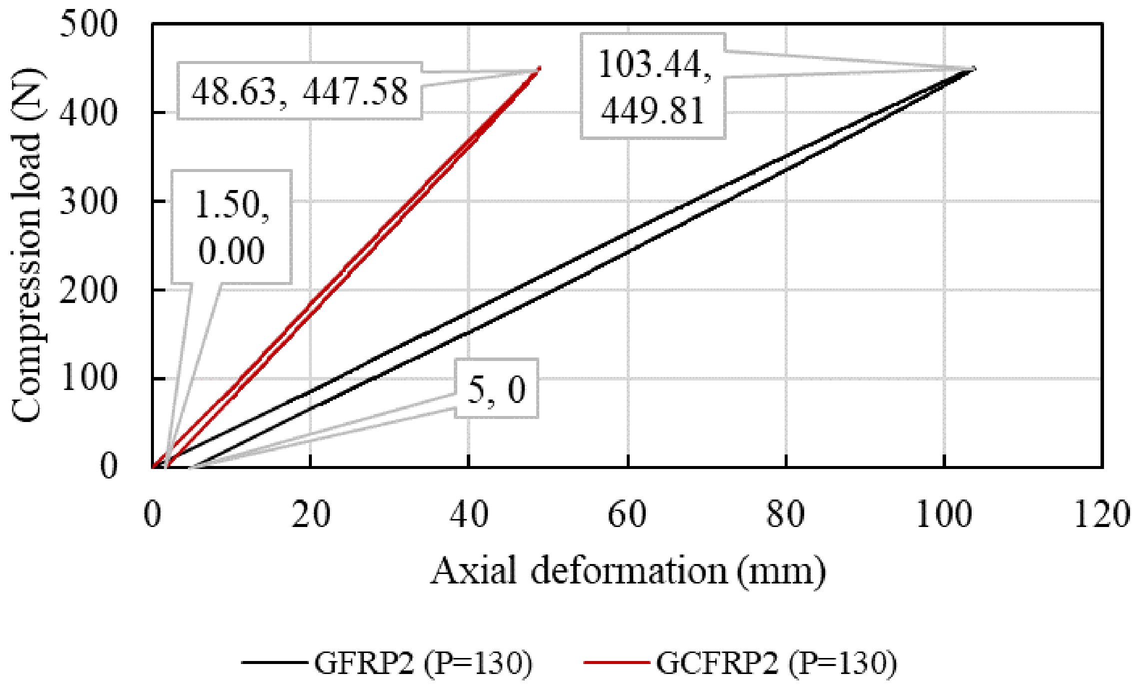
5.1 Effect of composite material in load-deformation responses

Two types of composite materials have been used in this research: glass fibre-epoxy, and glass-carbon fibre-epoxy composites. The overall performance of the spring depends on the strength (specially, the shear strength) of composite materials as the stresses produce due to the deformation of spring distribute to the whole spring through shear stresses on the wire. Thus, a comparison of strengths of two composites: glass- fibre and glass-carbon-fibre-based composites, are necessary. Glass-carbon fibre based composite material is generally stronger than glass-fibre-based composites due to presence of higher densified carbon. Swikker et al. (2022) investigated the mechanical strengths of composites made of glass-fibre, glass-fibre with graphene and glass-carbon fibre with graphene. Same kind of epoxy resin was used for bonding between fibres in composite and the volume of epoxy were adopted identical for each type of composites. Similarly, the proportion of graphene in glass-fibre and graphene-based composite and glass-carbon fibre and graphene -based composites, was maintained identical. Therefore, any change in strengths between these composites can be considered as the role of the glass-fibre and glass-carbon fibre. The tensile strength of glass-carbon fibre-based composites was slightly higher (1.1 times) than glass-fibre-based composite. However, in this examination, graphene was present as part of the composite material which had contribution in strength too. Comparing the results of tensile strengths between glass-fibre-based and glass- fibre with graphene-based composites as reported by Swikker et al. (2022), the contribution of graphene in tensile strength can be estimated as 20% approximately (i.e., 80% attributed to glass-fibre/ glass-carbon-fibre and epoxy). Hence, reassessing the tensile strengths as Swikker et al. (2022) found, the attribution to glass-carbon-fibre-based composites can be estimated as 1.1 times (average) higher than that to glass-fibre-based composites. Similarly, the compressive strength was found about 2 times higher for the composite consisted of glass-carbon fibre.

In this research, the rigidity of GCFRP was found higher than GFRP (Table 4.2). Because of high rigidity, the stiffness of GCFRP was higher too. Comparing Figure 5.1(a) and Figure 5.1(b), it is seen that the stiffness of GCFRP is always higher than that of the GFRCP (irrespective to the pitch). The stiffness of GCFRP2 is comparatively much higher than GCFRP1, which is due to the role of the pitch.



(a)



(b)

Figure 5.1: Compression load vs axial deformation responses of GFRP-based and GCFRP-based CHSs of comparable pitches (a) Pitch = 102 mm and (b) Pitch = 130 mm.

5.2 Effect of Pitch in stiffness

The pitch of the spring influence the overall performance of the spring. When any load is applied on the spring, the stress distributes through the wire to the whole spring. The magnitude of distributed of stresses depend on the angle of the coils in the helical spring. Therefore, it can be said that on overall performance of the spring, angle of the coil has direct contribution. The distributed stresses at a point of the wire have two components: vertical component and lateral component. Vertical component attributes to the shear stress and lateral stress attribute to the lateral deformation. However, the lateral deformation of the composite helical spring is insignificant compared to the vertical deformation of the spring. Hence, the vertical stress component has more role in spring performance. The resultant of vertical and lateral stress component is applied to as normal stress in wire.

At 45° helical angle (angle between coils), total applied force is equally distributed as lateral and vertical stress component. When the helical angle is increased, shear stress is more than lateral stress. Hence, the stiffness of the spring is reduced for higher helical angle. Similarly, at lower helical angles, shear stresses are reduced as well as deformation of spring is reduced. Thus, at lower helical angles, stiffness of the spring is increased. The pitch (centre to centre distance between two coil) as well as number of coils at a free length are directly related to the helical angle. At higher helical angles, number of coils within a free length is reduced, thus the pitch is increased. Similarly, at lower helical angles, pitch is shorter. For that, lower pitch of spring (i.e., lower helical angle) attributes to lower deformation (i.e., higher stiffness).

5.3 Effect of salt spray (/ corrosion) in stiffness of spring

Salt spray in a wet and dry continuous cycle, induces corrosion on the surface of the wire of spring. Specially, the corrosion may be induced on the carbon-fibre and due to producing an alkaline environment on the surface, epoxy at the out layer of the wire may be corroded too. As carbon is intake (surrounded by a layer of epoxy), the induction of corrosion in the early stage is not obvious. The outer epoxy layer will be required to corrode before it induces on carbon fibre surface. So, for a long-time corrosion test, this scenario (corrosion on carbon fibre) may be seen. But for a short period of corrosion test most likely, degradation and water absorption of epoxy is expected. Hence, in the short time corrosion test, GFRP is more affected than GCFRP.

CHAPTER 6: CONCLUSIONS

Helical springs which are a significant elastic component in machines, and automobiles to control vibrations, impacts, and bumps. In this research, two composite materials (glass-fibre-epoxy, and glass-carbon fibre-epoxy) have been used to develop the helical spring and their compressive stiffness and any adverse effect on compression stiffness due to a short period corrosion have been examined. The outcome of these examination will enable researchers to take a decision about the long period corrosion and fatigue investigation; also, it will help to further improvement of the composite material used in wire. Following findings can be summarised from this research project:

Rigidity of composites: Glass carbon-fibre-reinforced polymer composite (GCFRP) is more rigid than glass-fibre-reinforced polymer composite (GFRP) as carbon has high density. The higher rigidity of the material tends to less deformation and hence improves the stiffness.

Stiffness of composite helical spring: Due to having higher rigidity of GCFRP than GFRP, it has higher shear strength. Therefore, GCFRP has less tendency to deform than GFRP under shear stress induced in wire through the distribution of the applied compression force on the spring. Hence, GCFRP is stiffer than that of GFRP.

Effect of pitch/ number of coils in stiffness: Higher number of pitches means higher helical angle (angle between two coils). At higher helical angle distributed forces as shear component is more; thus, at higher helical angles, deformation of spring is higher, i.e., at lower amount of pitch, stiffness of spring is increased.

Short period corrosion effect: A short period corrosion might be induced on the epoxy only, and the carbon fibres might not be affected by corrosion in a short period, due to have a cover of epoxy around the surface. GFRP were affected significantly higher than GCFRP.

CHAPTER 7: FUTURE WORK

Further improvement of the composite proportion is recommended to improve the rigidity of the composite so that the spring is feasible to use in automobile.

Long-period corrosion investigation is required to investigate any adverse effect on the GCFRP as it contains carbon-fibre.

A long-term cyclic loading and unloading test through application of tension load and compression load can be conducted to evaluate if any change in stiffness due to pseudoelasticity between epoxy and fibre interface.

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