Development Method, Manufacturing Process of Fibre Reinforced Polymer Composite Type Helical Springs: A Review

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1 Introduction

Coil springs or helical springs are the most important and commonly used machine components which aid in vibration reductions, protection against impacts and to certain limits even acts as dampers. Nowadays, vehicular gas emission and fuel efficiency are of major concern [1]. To achieve this, weight reduction of an automobile is being carried out which improves its performance thus saving energy. Also, the current generation is heading towards electric and hybrid vehicles hence reduced weight would be effective in increasing the overall range of vehicles with such powertrains [1]. Combination of two or multiple materials such as a composite can yield improved mechanical behaviour and properties. Essentially a composite made of FRP possesses higher strength to weight ratio and improved elastic strain storage capacity on contrary to alloys.

Initially, FRPC-based technology emerged in the early 1900s. In the mid-1930s, FRPC saw its first application in boat hull components which was basically polyester resin reinforced with fiberglass [2]. The recent research in the field of FRPC has created components which can resist even high speed impacts the example includes bulletproof vest made of aramid fibre which can stop bullets. Even the aircraft carriers make use of FRPC components in the design. A good example is a passenger aircraft carrier Airbus A380 which is one largest of its kind makes use of nearly 20% FRPC parts of which the prime parts are made of carbon fibre reinforced composites [1].

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FRPCs are not just restricted to aircraft but also finds their applications in spacecraft, marine vehicles such as boats, ships and submarines, along with on land automobiles, sports-related equipment and also in bridges and buildings.

The above-mentioned reasons are justified in the switch of spring materials from conventional stainless steel to FRPC. Compared to different types of mechanical springs, coil springs/helical springs are merged as a part of various mechanical systems, thus incorporating a FRPC coil spring reduces the weight of the suspension system and also does not affect the load-carrying capacity of the system [1]. The leaf spring emerged as a first practical design, the material of which was FRPC in early 1981. Such FRPC leaf springs which were developed by Daugherty then found their application in heavy-duty trucks [3]. Currently, the research work on FRPC-based coil/helical spring is very limited in number yet attracts the interest of scientists in this particular area.

The aim of this paper is on reviewing the gathered open source research articles and analyses the viability of FRPC coil/helical spring. Various methods used by the current research work are studied and accordingly their competency is analysed.

2 Literature Survey

The practical approach with FRPC-based helical spring is not much popular in the technical field. Research paper that is available based on such application is much minimal. Short review on available research papers has been presented below.

T. S. Manjunatha and D. Abdul Budan fabricated FRPC-based spring and performed experiments for the spring's strength. For the study, three different types of springs are fabricated using glass fibre, carbon fibre and glass/carbon fibre in + 45° orientation and tests are conducted to check the mechanical behaviour of the springs. The helical spring is fabricated using Filament Winding Technique (FTW), for which a mandrel made of cast iron having the profile of the spring is fixated between the centres of the lathe. Silicone gel is applied throughout the mandrel body which acts as a mould releasing agent. Due to shear load acting on the spring, the fibres are cut at 45° angle. These fibre tapes are wound on the mandrel by dipping them in the bath of epoxy resin. This is done till the desired thickness is achieved. Tests are performed on the spring after curing process which took 24 h. Mechanical properties such as stiffness, shear stress and failure load maximum compression are determined by the researchers. The findings of the experiments showed that the spring rate of carbon fibre is 24% more compared to the glass fibre and 10% more than that of glass/carbon fibre (Table 1).

To conclude with the results of the experiment, the weight of spring in test is lesser than that of steel spring and comparatively provides good stiffness [4] (Fig. 1).

Mehdi Bakhshesh and Majid Bakhshesh performed the experiment for the steel spring with that of composite helical spring of three types namely, E-glass/Epoxy, Carbon/Epoxy and Kevlar/Epoxy. The researchers have been modelled using SOLID-WORKS software followed by analysis on ANSYS software. The results achieved,

Table 1 Mechanical properties of the FRPC spring

Properties	Glass fibre	Carbon fibre	Glass/carbon fibre
Spring constant (N/mm)	4.83	6.36	5.75
Shear stress (N/mm^2)	83.00	79.67	95.49
Failure load (N)	1000	1500	1200
Maximum compression (mm)	83	80	77

Stainless Steel Mandrel Springs after curing

Fig. 1 Manufacturing of FRPC helical spring [4]

i.e., the numerical ones and the theoretical ones were found to be on par with each other. The stresses acting on the composite helical spring are lesser compared to the steel spring also the value is more when the fibre strands are aligned to the direction of the applied load. Though the spring weight has been reduced, changing the percentage composition of fibres in carbon/epoxy composite does not affect the overall weight of the spring. The safety factor in consideration for fibre alignment must be perpendicular to the loading as mentioned by the researchers and the choice of material would be Carbon/Epoxy for the spring. The manufacturing of the spring has been carried out by Resin Transfer Moulding (RTM) process.

In this study, steel spring has been replaced by FRPC-based composite spring including g E-glass/Epoxy, Carbon/Epoxy and Kevlar/Epoxy. On these springs, FEM analysis were performed to obtain the shear stress. The loading conditions are taken to be static. SOLID45 was the element selected for the analysis which has three degrees of freedom at each node allowing up to 250 multiple types material layers. The results from analysis showed that the shear stresses acting within the spring is more, with the fibres in the direction of loading. If fibre directions are perpendicular to the load acting, shear stresses acting would be zero [5]. Ekanthappa et al. manufactured composite cylindrical helical spring in order to replace conventional steel spring used in vehicles by means of Spring winding technique. For the manufacturing purpose, a steel-based reusable mandrel which is of the required spring shape is used. This mandrel is fixated between the lathe and a mould releasing agent such as the silicone gel is applied on the mandrel. As the mandrel is rotated, E-glass fibres are passed through the polymer bath and are laid down on the mandrel till the required spring dimension is attained. The spring after curing for 48 h is carefully removed from the mandrel.

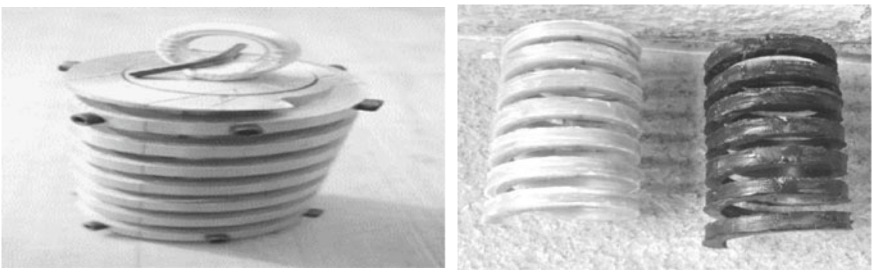
The various spring parameters are noted by testing it on UTM by following all the test procedure according to ASTM standards. The test parameters are as follows (Table 2).

In this study, the average values of the test results indicate a linear curve for load versus deflection analysis. And the spring stiffness is found to be 9.95 N/mm. The study states that the fabrication of reusable mandrel which is made of mild steel is rather easy and therefore makes the fabrication of FRPC spring simpler. The Spring winding technique is cost effective and simple to perform [6] (Fig. 2).

Chang-Hsuan Chiu et al. fabricated and studied four different types of composite helical springs, namely unidirectional laminates (AU), rubber core unidirectional laminates (UR), unidirectional laminates with braided outer layer (BU) and rubber core unidirectional laminates with braided outer layer (BUR). The study tries to understand the significance of the rubber core and braided outer layer on the spring's

Table 2 Test parameters of FRPC spring

Properties	Values
Spring constant	9.95 N/mm
Max compression	56 mm
Load at Max. compression	550.00 N
Shear stress	81.76 N/mm^2
Fibre volume fraction (%)	60
Weight of the spring	424 g

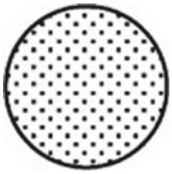
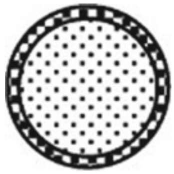


Reusable Mandrel

End products: Fibre Reinforced Plastic Springs

Fig. 2 Fabrication of FRPC helical spring using a reusable mandrel [6]

Table 3 Cross sections of four different types of FRPC Springs indicating different structures [7]

Structure name	AU	UR	BU	BUR
Structure materials	All unidirection	Unidirection + Rubber core	Outer braided + Unidirection	Outer braid + Unidirection + Rubber core
Cross-sections				
Dimen-sions	76.53×41.5 cm^2	76.53×37.5 cm^2 3 mm rub-ber core	76.53×37.5 cm^2 3 K carbon fibre outer braid (one layer)	76.53×37.5 cm^2 3 K carbon fibre outer braid (one layer)

mechanical properties. Overall conclusion drawn after the studies indicates that all four types of springs are lighter as well as stiffer compared to the conventional steel springs. And amongst all the four springs, BUR spring structure shows failure load due to compression, i.e., 3297 N with spring constant almost equates to 160 N/mm. The study also shows that with rubber core, the failure load in compression is increased to about 12%, whereas the spring with braided outer layer improves the spring constant by 16% and increases the failure load in compression by 18%. The following Table 3 gives the illustration of spring structure:

Suresh G. et al. performed analysis on FRPC coil spring which had reinforcement of woven roving fibre (WRF) and polymer used was thermoset (epoxy resin) with four different level additions of nanoclay (Garamite). The varying amount of nanoclay composite was of order 0, 1, 2, 3%. The aim of the study was to identify the load sustaining capability, the spring stiffness and the amount of weight savings compared to that of a steel spring. The researchers used similar dimensions of an existing light commercial vehicle's suspension spring and fabricated a composite spring.

According to the study, the developed composite springs were lighter than the steel counterparts but the stiffness achieved was lesser than the steel. In order to increase the stiffness, the dimension of the FRPC springs needs to be increased but this leads to increase in the weight of the spring. This fact limits the application of composite springs to mostly lightweight vehicles or EV's for which higher spring stiffness isn't a requirement. Also, the study states that manufacturing such helical spring is challenging and consumes time compared to the steel springs. But for mass production, use of CNC winding machines and automated processes might aid in cost reduction [8]. Anil Antony Sequeira et al. performed a comparative analysis on helical steel springs and composite springs by finite element method. Stiffness to weight ratio of the two springs is of prime importance in this current research. The behaviour of carbon and Kevlar composite springs and helical steel spring is investigated under static analysis. The objective of the research is to collate the various mechanical parameters of the composite springs to that of steel spring such as stiffness, maximum load-bearing capacity, weight reduction in FRPC spring. Here, all the necessary design parameters were kept same for all three springs. ANSYS software was used to study the mechanical behaviour of the springs. The study showed that specific modulus which is basically a ratio of Young's modulus to mass density of the material of Carbon FRPC spring is highest and the Kevlar FRPC spring is lowest. Mass of Kevlar FRPC spring is lower compared to Carbon FRPC spring yet the load & deflection characteristics of steel helical spring is better than that of composite helical springs. Use of Carbon FRPC spring would be beneficial over helical steel spring because of the lower weight advantage which in turn reduces the overall weight of the mechanical suspension system of the vehicle [9].

Sancaktar E. and Gowrishankar S. studied the natural frequency of composite-based helical springs. The fabrication method utilised is filament winding process and they were able to compare the effect of number of turns, ratio of cylinder diameter to wire diameter and material being used on the natural frequency of the helical spring. This experiment was performed on three different types of composite springs which had varying number of turns from 7 to 6 along with coil/wire diameters to understand the effect of these variables on the spring's natural frequency. For the springs, three different types of PVC tubbing are selected which decide on different wire diameters, followed by passing of fibre strands through these tubes which were dipped into the resin bath previously. The researchers have broken down the fabrication process into three stages. In the first stage, amount of glass/carbon fibres which can accommodate the PVC tube space is realised. The second stage helps in understanding the resin bath to fibre stand requirement and finally the third stage, mounting of the fiber-filled PVC pipe on the winder. The last stage determines the required cylinder diameter and fixes the desired shape for the spring to be fabricated. The natural frequency of the spring is recorded with the help of a digital camera. Results show that the natural frequency of these springs can be decreased by increasing the diameter of the coil and also providing for more number of turns. This novel approach of fabricating composite helical spring is more versatile and cost saving [10].

B. S. Azzam performed optimisation study for the design of composite helical spring in which, the aim is about minimisation of spring weight and also maximisation of spring stiffness. Mathematical formulations are used to state the objective functions and constraints and made into multiple-criterion optimisation problem in a non-linear and non-equality constraint forms. In the research, parameters affecting the above design aims are divided into three groups. Manipulation of functional properties of the spring consisting of the induced axial deflection and maximum stress in the spring belonging to the first group. The second group including the materials shear strength and shear modulus, here the properties depend on the reinforcement fibre materials, the fibre volume, angles to which fibres are braided in the spring wire. The third group is about the geometrical shape group of the spring. This optimisation study shows that spring index is directly affected by the helix angle also including mechanical properties of the composite material and the minimum helix angle should be restricted to 20°. The optimisation technique used in this particular research has the ability to give general optimum values for the spring parameters for multiple types of composite material for varying load [11].

Renugadevi K et al. made an attempt to fabricate a composite helical spring using natural fibres extracted out of Calatropis Gigantea (CG). A sub-tropical plant CG has high seasonality with high yield. The fibres are extracted from the stem of the plant. In the current study, the fibres are twisted and treated with different concentrations Level of sodium hydroxide aqueous solution comprising concentration of 1, 2, 5 and 6 wt% for approximately 1 h. After the process of cleaning with water of pH7 and drying at 70° in an oven, the fibres are then sealed in a polythene bag. Due to alkali treatment, the diameter of the fibre decreases from 1 to 0.7 mm. Araldite LY556 (Epoxy) is selected as a matrix material due to excellent adhesion to cleaner surfaces, greater dimensional stability, high resistance to chemical atmospheric corrosion and to this a 10% hardener (HY951) is added which improves the physical and mechanical properties and also aids in providing sufficient gel duration, viscous nature and also adds up to re-mould time.

The fabrication of spring involves the use of two-wheeler spring as a die element. A mild steel shaft is held on a lathe with either of its end fixated to the lathe. The spring die which has its surface covered with petroleum jelly is then inserted on the shaft with a 1 mm clearance. The petroleum jelly ensures easy removal of the product in the end. The alkali-treated fibres are then dipped in the resin and fed over the spring die. The chuck is rotated in clockwise direction until the fibres are fed completely over the die. After the curing process of the product, tests were performed according to the ASTM standards A125-96 of compression. The results for varying levels of NaOH have been listed in the following Table 4.

FEA analysis was performed, and it was found that 4 wt% NaOH-treated FRC spring does produce stiffness to amount of 1 N/mm with 1.3 GPa of shear modulus. Energy-dispersive X-ray analysis shows that the external surface has an O/C ratio of 0.07 thus indicating that the epoxy matrix behaves as a protective layer for the spring [12] (Fig. 3).

Choi B. L. and Choi B. H. introduced the carbon fibre as reinforcement for a composite coil spring taking into considerations the static spring rate. Resin Transfer Moulding (RTM) process was used to manufacture the spring. In this process, the fibres are filled with the epoxy resin and cross-linking hardening takes place; this happens in vacuum conditions. Displacement tests are performed, and the static spring rate of the spring is determined once the curing process is completed. The research paper also puts forward a deterministic approach in developing the helical spring with the use of computational and experimental methodologies. In this particular, study all the necessary design parameters in case of a steel springs that have been taken into consideration and based on these the composite spring has been designed. The fibre volume and void volume for the manufactured CFRP Coil spring are 64.4% and 3.5%, respectively. In the study, the shear modulus in case of composite of 45° ply angle is determined to be 16.8% of steel. The estimated shear modulus is found to be on par with the experimental results for the current research. A weight reduction of 55% compared to conventional steel springs has been achieved by the researchers [13] (Fig. 4).

Table 4 Compression tests over different levels of NaOH concentration [12]

Displacement (mm)	Load				
	1% NaOH	2% NaOH	4% NaOH	5% NaOH	6% NaOH
2	1.75	2	2	0	2
4	3	4	4	2	4
6	3.75	5	6	2	5
8	5	6	8	2	6
10	6	8	10	4	8
12	8.25	9	12	4	8
14	8.25	10	14	4	10
16	8.3	12	15	6	10
18	9.5	13	16	6	11.5
20	12	14	20	8	13
22	12	12	24	8	14
24	14.25	14	26	10	15
26	15	14	28	10	15.5
28	14.5	14	–	12	16
30	15	16	–	14	17.5
32	16	18	–	14	18
34	18	18	–	16	22
36	19.25	–	–	28	24
38	24	–	–	20	30
40	–	–	–	22	44
42	–	–	–	24	–
44	–	–	–	26	–
46	–	–	–	34	–
48	–	–	–	52	–

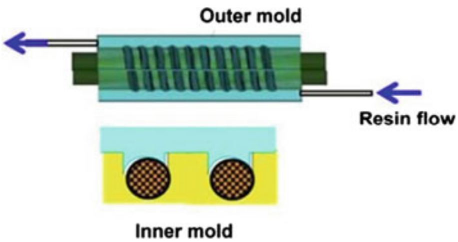
3 Conclusion

Currently, ever-changing innovation in technology demands for more energy savings, cost effectiveness, improved machine performance. To make this possible, composite material which is in fact lightweighted, high quality is being used. Hence, a composite helical spring certainly is an option to look for in place of conventional steel springs. Researchers have shown interest in this particular area, thereby giving various value-added benefits with the use of FRPC Helical springs.

FRPC Helical/coil springs are basically lighter than their steel counterparts. Their use can be categorised for light-duty vehicle which includes EVs or vehicles with smaller engine capacities. The issue with lower stiffness in composite springs can be overcome by increasing the size to reasonable amount.

Fig. 3 Calatropis gigantea fibre reinforced composite helical spring [12]

Fig. 4 RTM process being utilised for manufacturing of CFRP spring [13]



Manufacturing of FRPC helical spring is challenging as compared to the conventional steel springs. Manufacturing time required to make composite spring is more. Also, proper resin impregnation through the fibre strands is still a difficult process to achieve.

Most of the above researches use Filament Winding Technique (FWT) to manufacture FRPC springs with different mandrel setups. Improvement in such FWT systems have been carried out by some researches.

Majority cases show that FRPC helical springs have better mechanical properties against the steel springs. The challenge is with manufacturing of FRPC springs as these need special design process considering the dimensional optimisation and preciseness which is critical for the proper functioning of such springs. Various researches have used ANSYS software for proper analysis of FRPC springs.

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