EXAMINATION OF COMPOSITE DISC SPRINGS

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***Abstract*— This study aims to produce composite disc springs from carbon prepreg material, which is close to the characteristic curve of the steel disc spring or better than steel, which constitutes a group of machine elements. In this way, the design will be lightened without significantly diverging from the force/deformation ratio of the disc spring. For this, first of all, a standard steel disc spring was selected, and its characteristic curve was determined by the finite element analysis method. For the composite disc springs to be produced, the selected steel disc spring geometry was taken as reference, and different cone heights (taper angles) and different orientation angles of the carbon prepreg layers were determined as variable parameters. For all these parameters, finite element analyses were made for the carbon prepreg material in the ANSYS Workbench module, and the disc springs designed using these analyses were produced by the autoclave method in a closed mold and tested. As a result of compression tests, spring characteristics of steel and composite disc springs were obtained and compared. The results reveal that it is possible to obtain composite disc springs 70% lightweight and with characteristics close to or better than steel disc springs, regardless of the angular array orientation. On the other hand, based on the results, manufacturing carbon prepreg composite disc springs at high cone heights is not recommended.**

***Keywords*— Disc spring, Spring characteristic, Tapering angle, Carbon prepreg, Autoclave method.**

I. INTRODUCTION

Global warming and the decrease in oil reserves are among the most critical problems of today's world. Therefore, several measures are taken to solve these problems in the machinery industry. Especially in automobiles and airplanes, the weights are reduced, thus saving fuel and minimizing the carbon emissions that cause global warming (Abhishek *et al.*, 2016). For this, the bodies of vehicles and some internal structural elements are made of composite, but as these are not considered sufficient, the use of composites in machine elements is also becoming widespread. What is desired in this transformation is the absence of any disruption in the task of the machine element. Composite materials are widely used in almost every sector, because of their unique property combination of low density and high strength (Atlıhan and Ergene, 2018).

Thanks to their material properties and geometry, springs, which are power and energy accumulation elements, store the sudden force or impact they are exposed to, provided that they remain within the elastic region. Some of the stored energy is dissipated and the rest is converted into work as needed. With these features, springs serve as energy storage elements in machine designs. Springs have different classes, and one of the types is the disc springs.

Disc springs consist of conical discs. These springs, which are likened to a plate, are more commonly referred to as Belleville springs in the literature. The name comes from the civil engineer Julien Francois Belleville, who, although not the original inventor, took the patent in 1861. Belleville used the spring he patented to absorb the recoil of cannons in wars.

There are different studies on disc springs in the literature. In a theoretical examination of disc springs of constant and variable thickness (La Rosa *et al*., 2001), the authors performed an analysis based on the hypotheses of Almen-Laszlo, giving the stiffness curve and stress values depending on the different values of the geometric parameters. Another study examining springs with variable thickness (Pedersen and Pedersen, 2011) revealed that finite element analysis should definitely be used for different spring designs. A study of radial conical disc springs with parabolically varying thickness (Saini *et al*., 2007) determined that at a constant taper parameter, the weight of the radial conic disc spring is 3 to 8 percent less than the weight of the spring with linearly variable thickness.

Some studies on disc springs focus on program algorithms. In such a study, the authors created a program algorithm that makes the operation control and design of Belleville springs, outputs the load-deflection characteristics in graphics and tables, creates a dimensioned drawing, and also calculates the fatigue life and gives parallel/series coupling characteristics (Carfagni, 2002). Yet another study (Paredes and Daidie, 2010) focused on a tool that directly recommends Belleville spring arrangements according to the needs of the designers with the created algorithm.

A study comparing Belleville springs with diaphragm springs (Zhiming and Kaiyuan, 1990) compared the static response of both spring types with experimental methods and using finite rotation and large displacement theories of a beam and conical shell. Another study examined disc springs on the basis of four basic geometric dimensions: external diameter, inner diameter, free height and spring thickness, and emphasized the effect of serial and parallel coupling on the spring characteristics. Moreover, how the spring rate will be affected if the disc springs and the fasteners connecting these springs to the system are made with different materials, depending on the environmental conditions in which the disc springs will be used, was investigated. The authors reported that in the case of using different materials, connecting in series instead of parallel preserves the spring rate better (Davet, 1997).

Another study on disc springs (Curti and Raffa, 1992) investigated the compatibility of the finite element analysis results of the selected disc springs to the Almen-Laszlo theory. This analysis has proven that it is advantageous to apply the load to the nodes corresponding to the upper inner edge of the springs. In addition, in all of the models used, the supported node was constrained in the axial z coordinate. We also benefited from these findings in our study.

Today, composite materials are presented as new technological products in different fields (Ergene and Bolat, 2019) and under different material subheadings (Bolat *et al*., 2022) such as carbon fibers and glass fibers. The prepreg used in this study is the general name of the composite materials obtained by pre-curing the resin-impregnated fibers in the autoclave. This method is also called the autoclave method. The fiber/resin ratio in the prepreg is 1:1. It is mostly used in the aerospace industry as it is strong, light and easy to manufacture compared to other products in the composite sector.

Due to the advantages of composite materials, currently, studies are carried out on the production of various machine elements from composite materials (Yalçın and Ergene, 2018). A study on the application of composites in disc springs (Dharan and Bauman, 2007) examined the possibility of replacing steel with composite material. The aim was to remanufacture the steel disc spring from composite with significant mass savings, considering identical load-displacement characteristics and maximum loading capacity. For this purpose, several prototype disc springs were produced, tested, and compared with the performance of equivalent steel springs. The results showed that accurate repeatability of the load-displacement characteristics of the steel spring and about 80% savings in mass can be achieved by using composite material. The failure mode (overloading the composite disc) consisted of a radial fracture from the circular load, as theoretically predicted. These results suggest that replacing steel with composite in disc springs will provide significant mass savings.

Our study reviewed the basic approaches present in the literature and investigated the performance of disc springs by examining the analysis and experiment results together. Examination of disc springs produced at different taper angles is the strong aspect of this study, which distinguishes it from the literature.

This study aims to produce a composite disc spring with characteristics close to or better than the characteristic curve of the steel disc spring. Initially, an average-sized steel disc spring was selected from the catalogs, and its characteristics were determined by finite element analysis using experimental data, and then it was compared with the characteristics of the designed and produced composite disc springs (Karasu, 2014).

II. METHODS

The implemented work plan consists of 5 stages, as shown in Fig. 1. First of all, an average-sized steel disc spring was selected, its characteristics were determined by the finite element analysis method using the experimental data, and then it was compared with the composite disc spring characteristics.

Figure 2 shows a disc spring with its basic dimensions. These are the outer diameter indicating the size of the spring, the inner diameter indicating the space inside the spring, the spring height, the spring thickness, and the cone height, which significantly affects the characteristic of the spring. The geometric properties of the selected disc spring are given in Table 1.

To obtain the characteristic curve of the disc spring, firstly, a compression test was performed on the Shimadzu Autograph AG-X device shown in Fig. 3a. Disc springs were centered between the metallic pressing jaws as shown in Fig. 3b. The jaws were lubricated to eliminate the friction effect between the lower surface of the spring and the lower jaw as a result of the applied force to the disc spring. Compression speed was determined as 0.25 mm/min.

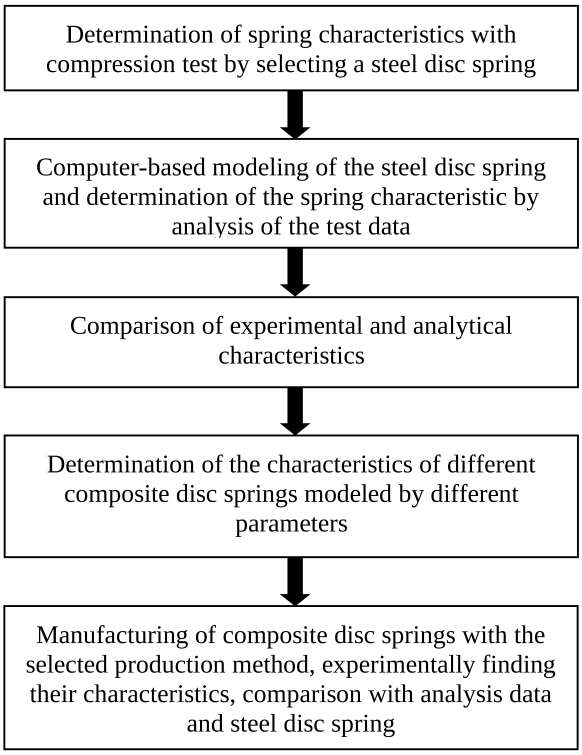

Figure 1: Implemented work plan

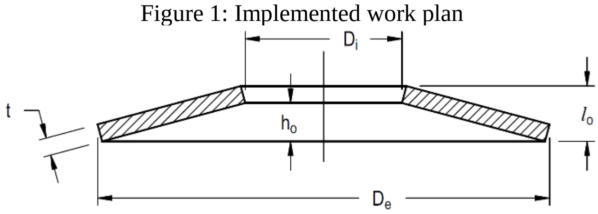

Figure 2: Schematic view of the geometric dimensions of the disc spring (Dimensions on the figure: D_i: Inner diameter, D_e: Outer diameter, t: Thickness, l_0: Height, h_0: Cone height)

Table 1. Geometric properties of the selected disc spring

D	**d**	**t**	**h**	**l**
50 mm	20.4 mm	2 mm	1.5 mm	3.5 mm

Figure 3: a) Compression test device on which the tests were applied b) Appearance of the disc spring on the compression test device

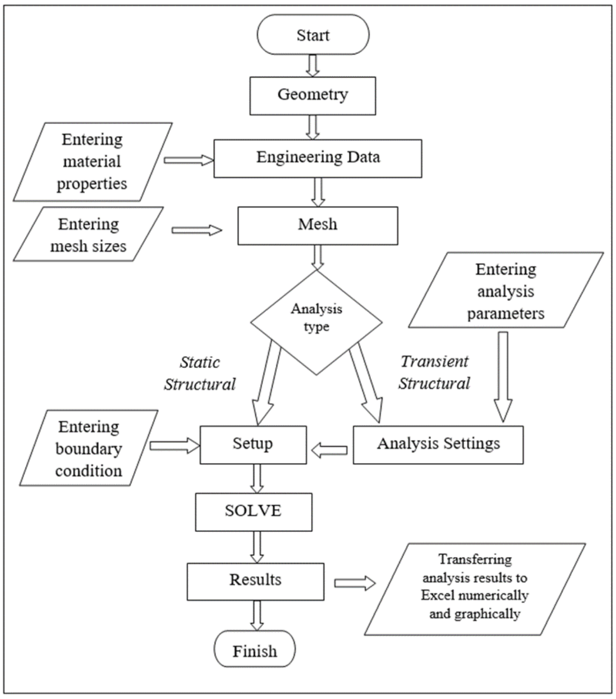

Figure 4: ANSYS Workbench process diagram

The cone height of the selected disc spring was 1.5 mm. This cone height gives the maximum amount of deflection of the disc spring. However, if the disc spring is deformed by 1.5 mm, the taper angle will become zero and flatten. Therefore, compression in the analyses and experiments was performed without reaching this maximum amount of deformation threshold.

Finite element analyses were performed using the ANSYS Workbench package program. The mechanical properties used in the analysis were obtained from the mechanical properties of the steel and the data obtained from compression tests. The flowchart applied for the finite element analysis is presented in Fig. 4. The mesh structure applied to the disc spring and the displacement and force application locations are shown in Fig. 5. For the mesh process, the element size was determined as 0.1 mm and the minimum edge length as 0.064 mm. After the mesh process, 25756 nodes and 13981 elements were obtained. The distributed load was exerted on the upper plane of the disc spring. Boundary conditions were defined to ensure that the disc cannot move from the spring's base part in the direction of the force with a force F to be applied, and it will show a slight circular opening in other directions only with the effect of springing. After the completion of the analyses, the steel disc spring characteristics obtained through experimentally and analytically were compared and examined.

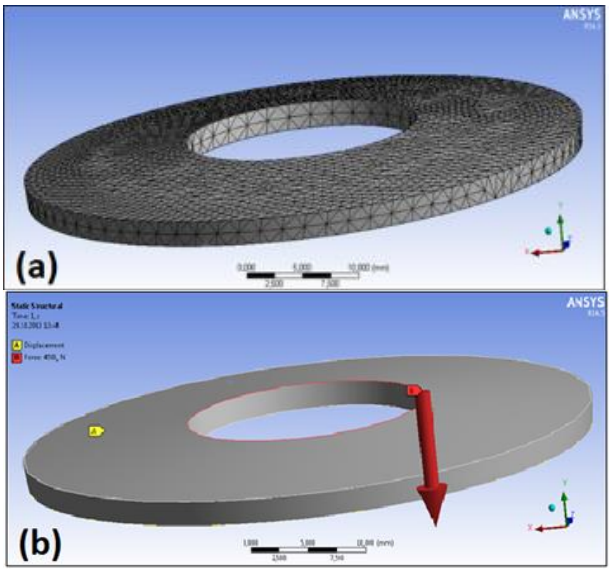

Figure 5: a) Mesh structure applied to the disc spring in the analysis b) Applied displacement and force positions.

Table 2. Mechanical properties of the selected carbon prepreg material (Sigrafil, 1999)

E_1 (GPa)	E_2 (GPa)	υ_{12}	$X_ç$ (MPa)	$Y_ç$ (MPa)
121	59	0.27	1831	627

Table 3. Taper values of different types of spring geometries

Disc Spring Number	Cone Height	Taper Angle
1	1.5 mm	5.79^0
2	2 mm	7.70^0
3	4 mm	15.12^0
4	6 mm	22.07^0
5	8 mm	28.39^0

Carbon prepreg, whose mechanical properties are shown in Table 2, was used as the material for the subsequent composite disc spring analysis. Here E_1 is the modulus of elasticity along the fiber direction; E_2 is the modulus of elasticity in the perpendicular direction to the fiber υ_{12} is the Poisson's ratio; X_c is the tensile strength in the fiber direction; Y_c is the tensile strength perpendicular to the fiber.

Angular orientations and taper angles were changed so that the number of carbon prepreg layers to be applied remain constant for each sample. For cone heights, 4 different cone heights were determined, starting from 2 mm and increasing by 2 mm, up to a cone height of 8 mm, and a total of 5 different disc spring geometries were obtained together with the 1.5 mm cone height of the selected steel disc spring. All these data are shown in Table 3, along with the taper angles varying with the cone height. The inner and outer diameters of 5 different disc springs are all equal.

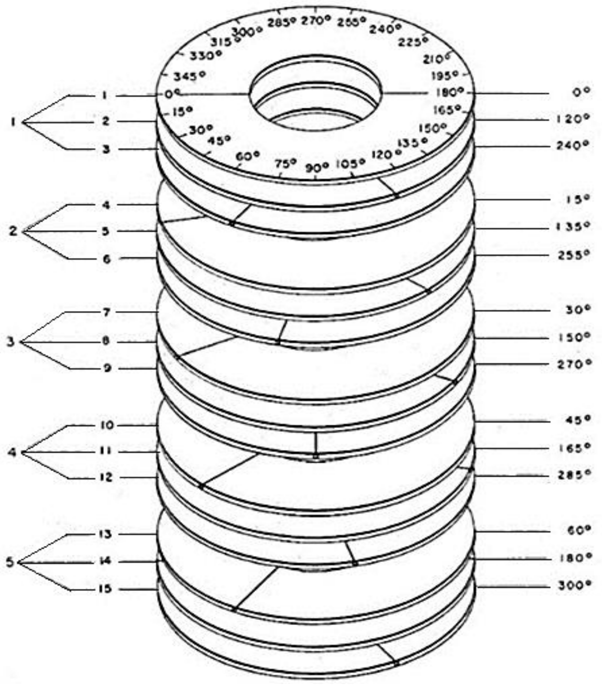

Figure 6: Layer arrangement [0/120/240] (Huchette and Hall, 1972)

The number of layers to be applied was determined as 15. Three different orientations were applied in the alignment of the composite layers. These are [0/45/90], [0/90/0] and [0/120/240]. Although the first two angular orientations are frequently encountered in the literature (Das *et al*., 2019), the variation [0/120/240] is more specific. This arrangement was based on the patented design by Huchette and Hall (1972), in which the layers were divided into groups of three and placed with 15-degree differences to prevent stresses between each group of three from piling up in the same regions. As seen in Figure 6, the layers of the first group were placed as 0, 120, 240, and the next group of three was placed at 15, 135, 255 degree angles.

Finite element analyses of composite materials were performed using the ACP (ANSYS Composite PrepPost) module of the ANSYS Workbench program. The flow diagram applied for the ACP module is presented in Fig. 7. “Epoxy Carbon UD 230GPa Prepreg” was chosen as the material from the ANSYS Workbench material database library. The properties of this material are shown in Table 4. The composite disc spring characteristics obtained from the analysis were evaluated by comparing them with the characteristics of the steel disc spring with a 1.5 mm cone height.

After determining their characteristic curves, composite disc springs were produced using the closed mold method. Carbon prepreg layers with Sigrefil CE 1250-230-39 prepreg and E201 resin were cut circularly for each sample to fit the desired disc spring geometry as shown in Fig. 8. The cut layers were placed on top of each other in the molds suitable for the taper angle of the disc spring to be produced, as in Fig. 9. The parts of the mold that come into contact with the prepreg material were covered with Teflon to prevent sticking.

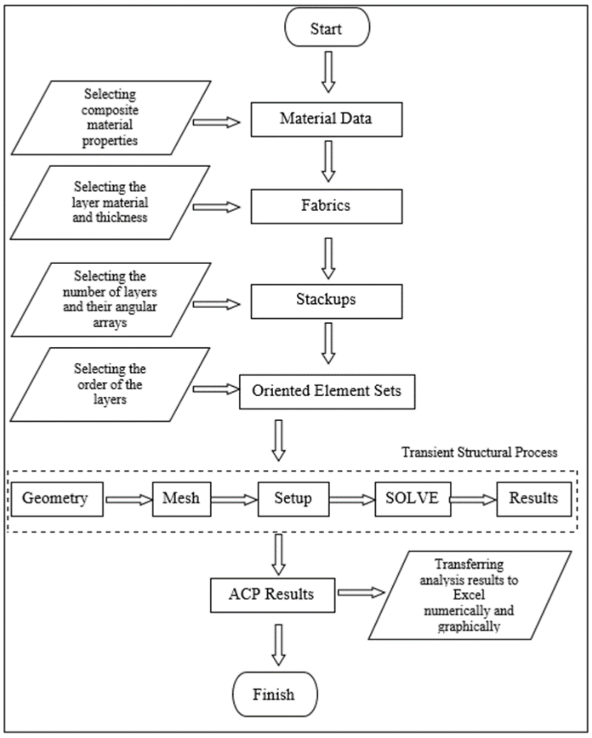

Figure 7: ANSYS Workbench ACP (ANSYS Composite PrepPost) process diagram

Table 4. “Epoxy Carbon UD 230 GPa Prepreg” material properties (ANSYS Workbench material database library)

Young's Modulus X direction (MPa)	1.21e+005
Young's Modulus Y direction (MPa)	8600
Young's Modulus Z direction (MPa)	8600
Poisson's Ratio XY	0.27
Poisson's Ratio YZ	0.4
Poisson's Ratio XZ	0.27
Shear Modulus XY (MPa)	4700
Shear Modulus YZ (MPa)	3100
Shear Modulus XZ (MPa)	4700

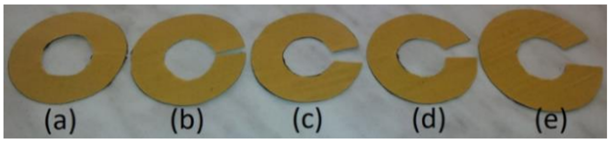

Figure 8: Prepreg layers cut and prepared according to the cone height: a) 1.5 mm cone height b) 2 mm cone height c) 4 mm cone height d) 6 mm cone height e) 8 mm cone height

Considering the 5 different cone heights of the disc springs to be produced, 5 different molds were designed, with closed shapes as presented in Fig. 10. The molds consist of lower mold, upper mold, bolt, spacer to be used for the bolt to distribute the necessary pressure force on the mold surface, nut, and two pins. When there is no prepreg material in between, it is completely closed so that there is no space between the upper and lower molds, and also between the cylindrical part of the lower mold and the fragment in the upper part. Depending on the number of prepreg layers put in between, the space here increase equally. To distribute the pressure force evenly, the diameter of the part of the bolt used to transmit the force is equal to 50 mm, which is the outer diameter of the disc springs produced. Details of these molds are shown in Fig. 11.

Figure 9: Prepared mold

Figure 10: Molds prepared for 5 different cone heights

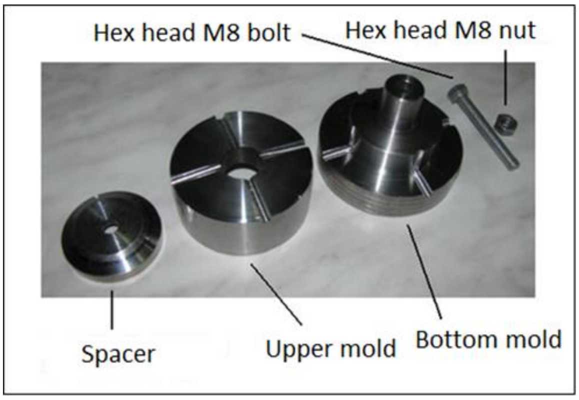

Figure 11: View of a single mold with its parts

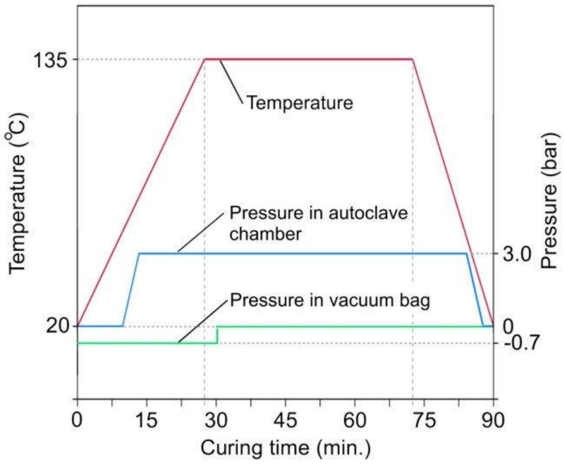

Figure 12: Curing curve of the resin in the prepreg material

The molded carbon prepreg disc springs were then placed in the industrial furnace for curing. The pressure and temperature conditions provided in the furnace during the curing phase are given in Fig. 12. These values were obtained from the catalog data of the prepreg material used in the study.

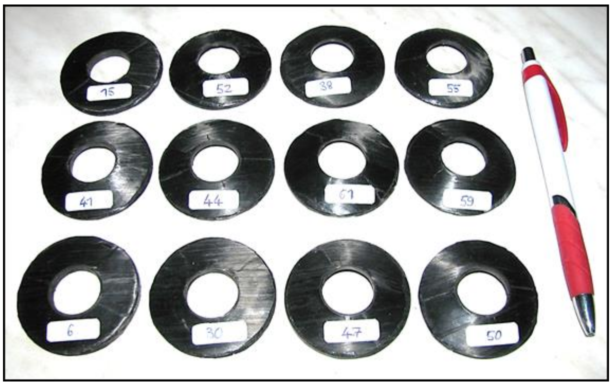

Figure 13: Completed samples of composite disc spring

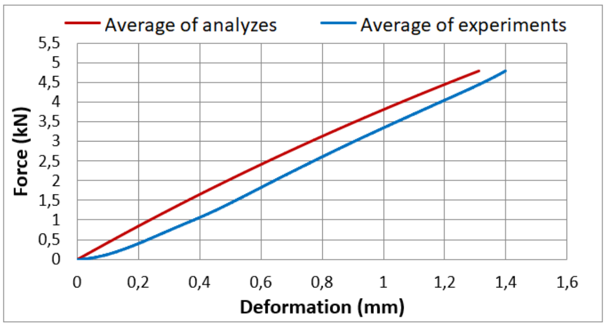

Figure 14: Comparison of average spring characteristics of steel disc springs

These produced disc springs, examples of which are shown in Fig. 13, then underwent compression tests on the Shimadzu Autograph AG-X test device with a compression speed of 0.25 mm/min. The results were compared with the analysis results and the steel disc spring characteristic. Finally, the masses of the produced disc springs were measured on precision scales, and the mass reduction rate for different taper values was compared to steel.

III. RESULTS

The comparison of the characteristic curve obtained from the finite element analysis of the selected steel disc spring with the experimental characteristic curve is presented in Fig. 14. For a deformation value of 1.3 mm, which is the maximum value determined for the analysis, the steel disc spring carries a force of approximately 4800 N. Collective examination of the analysis and test results reveals a proportional increase in the deformation in both when the load of 500 N is exceeded. In addition to being an expected result, this also shows that the analysis and experiment results are compatible and the model was set up accurately.

The characteristic curves of the composite disc springs in the [0/45/90] angular orientation, obtained from the analysis, are given in Fig. 15 together with the characteristic curve of the steel disc spring. In the analysis, the maximum force on the composite disc springs was 4800 N. The graph shows that the deformation values corresponding to this force are 1.1 - 1.2 mm for springs with 1.5, 2, and 4 mm cone heights, while they are 0.7 - 0.8 mm for springs with 6 and 8 mm cone heights. It is seen that the characteristic curves of springs with 1.5, 2, and 4 mm cone heights are closer to the curve

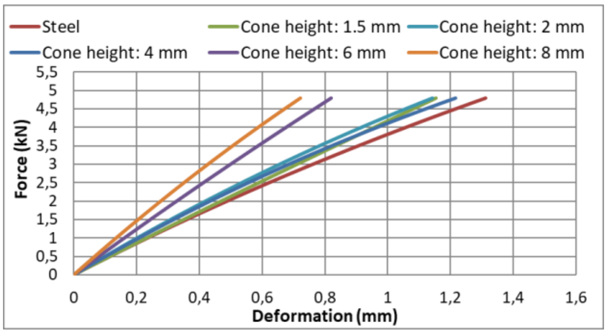

Figure 15: Analysis results of disc springs with different cone heights for [0/45/90] angular orientation

of the steel disc spring than the characteristic curves of springs with 6 and 8 mm cone heights. The disc springs with [0/90/0] and [0/120/240] angular orientation yielded similar results.

Comparison of the characteristics of the produced composite disc springs obtained from the compression tests with the analysis characteristics and the characteristic of the steel disc spring is shown in the graphs in Figure 16 for [0/45/90] orientation, in Figure 17 for [0/90/0] orientation, and in Fig. 18 for [0/120/240] orientation.

For the [0/45/90] orientation, the characteristics obtained from both the experiment and the analysis of the disc spring with a cone height of 1.5 mm were quite similar. Maximum deformation values were around 1.1 mm. Besides, these curves were determined to be close to the characteristic curve of the steel disc spring. The disc spring with a cone height of 2 mm experimentally yields a progressive characteristic curve. On the other hand, there is a degressive increase in the characteristic curves of disc springs with 4, 6, and 8 mm cone heights. The characteristics of the springs with 6 and 8 mm cone heights display irregularities. After a force of 3000 N was observed in the curve of the disc spring with 8 mm cone height, although deformation increased, the force decreased. The graphs indicate that the characteristics of the composite springs with 1.5, 2, and 4 mm cone heights are closer to the analysis results, but the characteristics of the composite springs with 6 and 8 mm cone heights differ from the analysis results.

For the [0/90/0] orientation, the test and analysis results were close to each other in the disc spring with a cone height of 1.5 mm, but the composite disc spring yielded a lower performance than the steel. In disc springs with 2 and 4 mm cone heights, results were close to steel disc springs, but a progressive curve was obtained in the disc spring with 4 mm cone height. Disc springs with 6 and 8 mm cone heights followed a characteristic performance quite far from the steel disc spring, as in the previous [0/45/90] orientation. The disc spring with 6 mm cone height could not exceed about 3000 N, and the disc spring with 8 mm cone height could not exceed about 2250 N.

For the [0/120/240] orientation, the test and analysis results were close to each other in the disc spring with 1.5 mm cone height. Besides, the composite disc spring

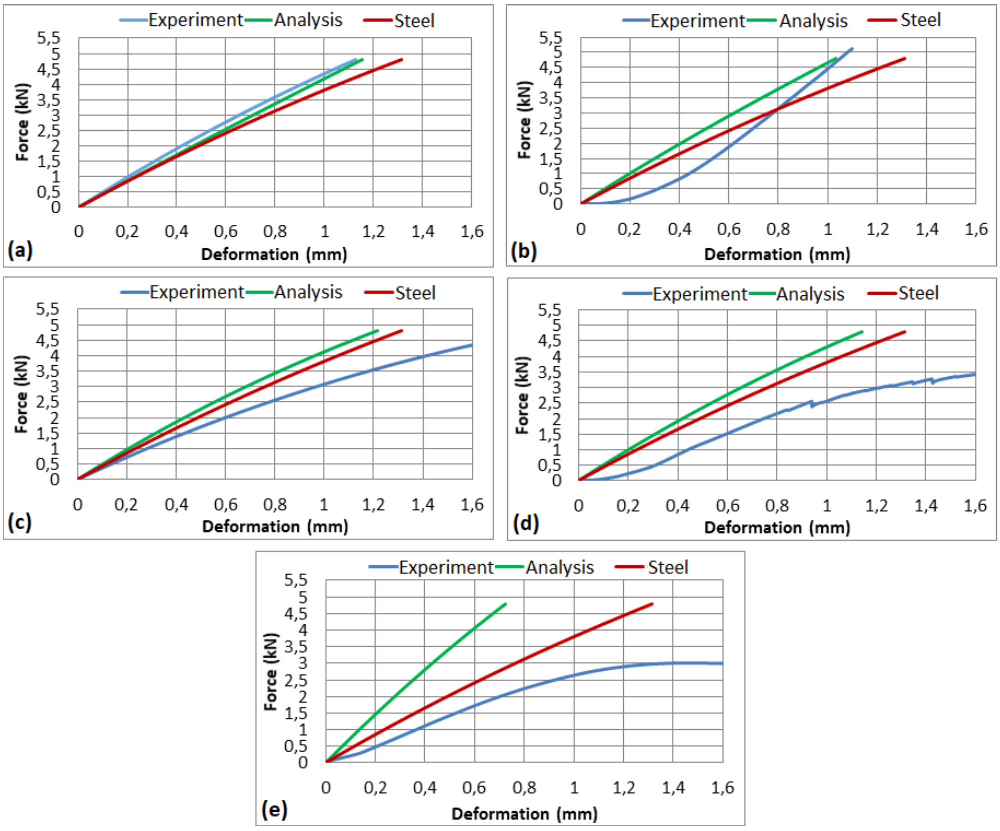

Figure 16: Test and analysis results of composite disc springs produced in [0/45/90] angular orientation a) 1.5 mm cone height b) 2 mm cone height c) 4 mm cone height d) 6 mm cone height e) 8 mm cone height

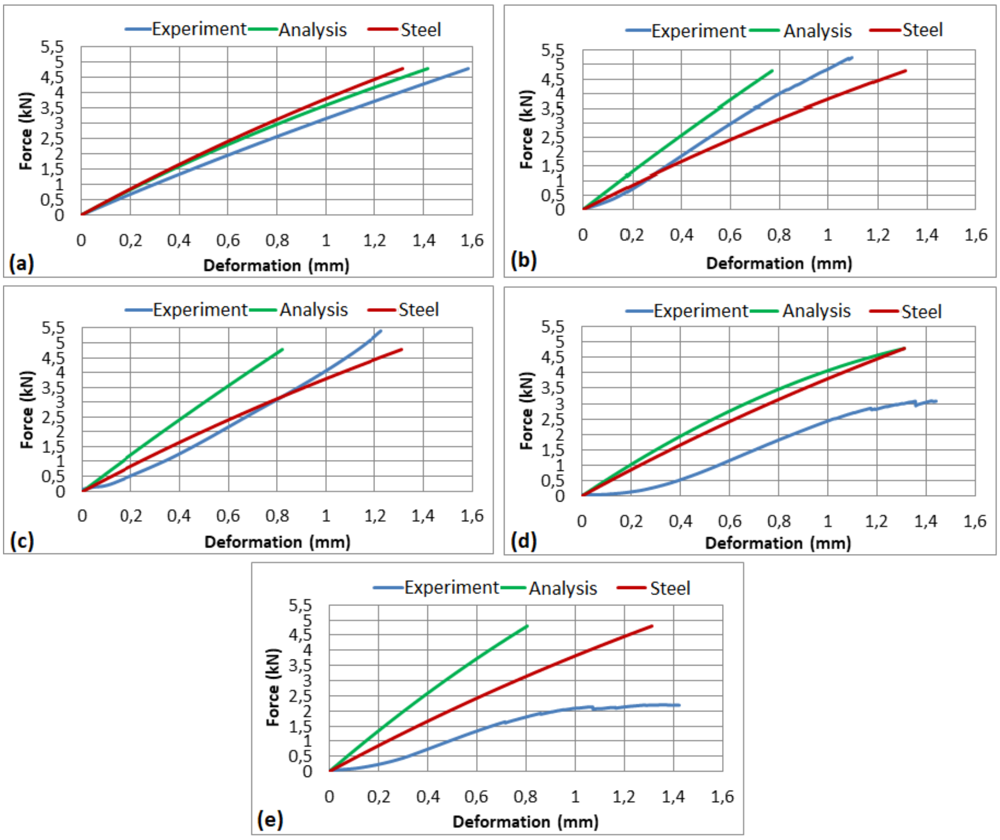

Figure 17: Test and analysis results of composite disc springs produced in [0/90/0] angular orientation a) 1.5 mm cone height b) 2 mm cone height c) 4 mm cone height d) 6 mm cone height e) 8 mm cone height

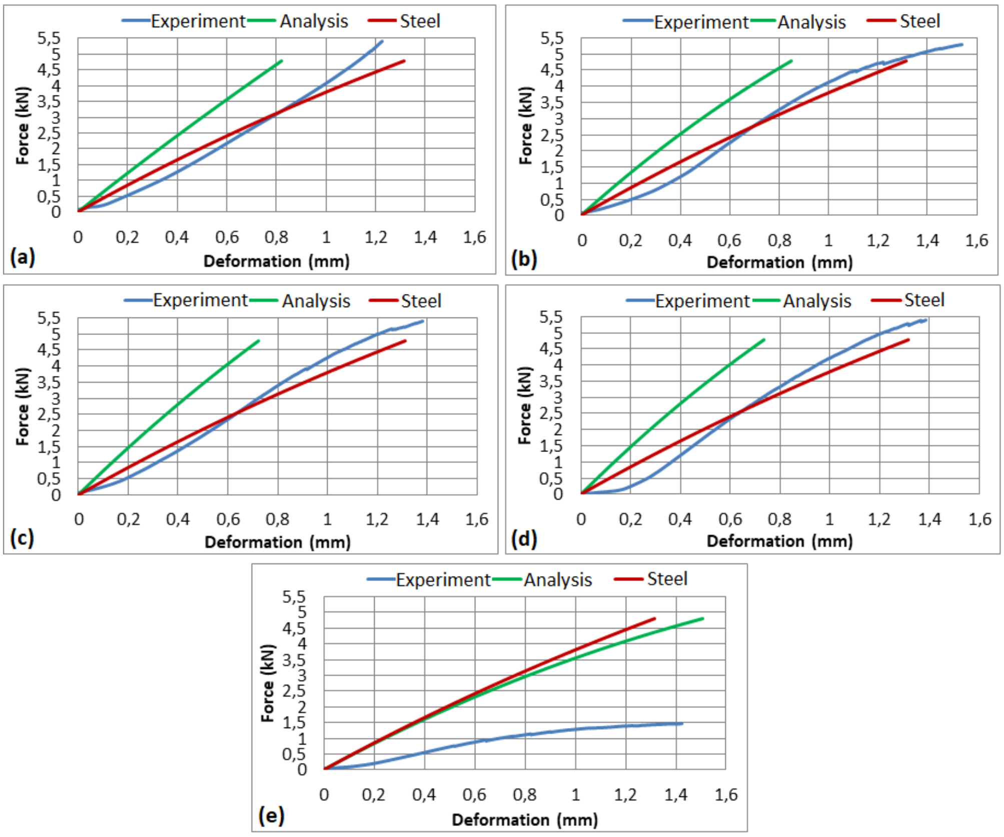

Figure 18: Test and analysis results of composite disc springs produced in [0/120/240] angular orientation a) 1.5 mm cone height b) 2 mm cone height c) 4 mm cone height d) 6 mm cone height e) 8 mm cone height

Table 5. Comparison of the masses of the produced composite disc springs and the steel disc spring

	Mass (g)	**Change in Mass Compared to Steel Disc Spring (% Decrease)**
Steel disc spring (Reference)	24.648	-
Composite disc spring with 1.5 mm cone height	11.054	55.15
Composite disc spring with 2 mm cone height	9.450	61.66
Composite disc spring with 4 mm cone height	8.159	66.89
Composite disc spring with 6 mm cone height	7.462	69.72
Composite disc spring with 8 mm cone height	7.654	68.94

yielded a higher performance than in the steel disc spring. Disc springs with 2, 4 and 6 mm cone heights have very similar characteristics. In these, the experimental characteristics initially had a progressive curve, while in the later stage the curves became degressive. In the disc spring with 8 mm cone height, the force could not exceed 1500 N and the steel disc performed quite far from the spring.

The average masses of the produced disc springs measured on a precision scale are given in Table 5. A decrease in the mass of the composite disc spring compared to the steel disc spring is an expected result. Here, the main issue to be examined is the differences in mass changes in composite disc springs with different cone heights. While the decrease in the mass of the composite disc spring with a cone height of 1.5 mm compared to the steel spring is 55%, this change is around 69% in the spring with a cone height of 8 mm. There is a mass change difference of approximately 14% between disc springs with maximum and minimum cone height. As the cone heights increased, the masses decreased in the same manner.

It has been proven that there is a mass reduction of up to 80% in composite disc springs made of carbon prepreg (Dharan and Bauman, 2007). The experimental results obtained were similar to the results in the literature.

V. CONCLUSIONS

In the study, the characteristics of steel and composite disc springs were investigated experimentally and compared using the finite element method. In the production of composite disc springs, which were designed based on analyses, the cone height of the springs was taken as the basis. Five different molds were designed for five different cone heights, and composite disc springs prepared from carbon prepreg were manufactured in these molds by curing in an industrial furnace. Three different orientations were applied in the arrangement of the composite layers in the molds. These are [0/45/90], [0/90/0] and [0/120/240]. For each angular orientation and cone height, the characteristic curves of the disc springs produced according to the analysis results were compared with the results of the finite element method and the characteristic of the steel disc spring.

The finite element analysis for the [0/45/90] orientation revealed that the deformation per unit force decreased as the cone height increased in carbon prepreg disc springs. Although the results were close to the steel disc spring at 1.5 mm, 2 mm, and 4 mm cone heights, deviations from the analysis results and the steel disc spring characteristic increased as the cone heights increased. These deviations are considered to be caused by the mandatory processes applied during the production of the disc spring with prepreg material in the mold. The prepreg material was cut with a gap at a certain angle to ensure that placing it in the mold by making a cone opening to form the layers of the composite disc spring causes no overlap in that layer. Since this gap increases with the cone height, it causes distortion in the orientation angle of the layers while the prepregs are placed in the mold in disc springs with high taper values. It is thought that this problem can be solved by changing the number of layers.

The results for the [0/90/0] orientation were similar to that of the [0/45/90] sequence. Although the steel disc spring characteristics at 1.5 mm, 2 mm, and 4 mm cone heights were close to the results of the analysis, there were significant decreases in the force per unit deformation at 6 mm and 8 mm cone heights.

The [0/120/240] orientation is a patent-based unique layer sequence, and its experimental application was made for the first time in this study. While the characteristic curves of composite disc springs with 1.5 mm, 2 mm, 4 mm, and 6 mm cone heights are similar to steel disc springs, the disc spring with 8 mm cone height yielded a significantly lower characteristic performance than the steel disc spring. Although the [0/120/240] orientation gives similar results to the theoretical study, it is thought that more precise results will be obtained with a different number of layers.

Comparison of the masses of the produced disc springs revealed a mass reduction of 55% - 69% in composite disc springs, compared to steel disc springs. This range varies depending on the conicity of the springs. With the increase in cone heights, the rate of decrease in mass also increased.

Based on these results, it can be concluded that, regardless of the angular array orientation, especially at low and medium cone heights, it is possible to obtain composite disc springs 70% lightweight and with characteristics close to or better than steel disc springs. On the other hand, based on the results, manufacturing carbon prepreg composite disc springs at high cone heights is not recommended.

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