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Determination of design criteria for composite drive shaft in automobiles

Otomobillerdeki kompozit şaft için tasarım kriterleri belirlenmesi

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Determination of Design Criteria for Composite Drive Shaft in Automobiles

Highlights

- *Composite drive shaft modelling and analysis were made for various angles and number of layers.*
- *The safest design criteria was determined in analysis.*
- *Carbon fiber and epoxy matrix were processed via the filament winding method to produce drive shaft.*
- *The design result was validated by experiment.*
- *Almost 80% weight reduction was achieved compared to steel shaft.*

Graphical Abstract

The configuration gave the safest design criteria was determined and applied in filament winding process.

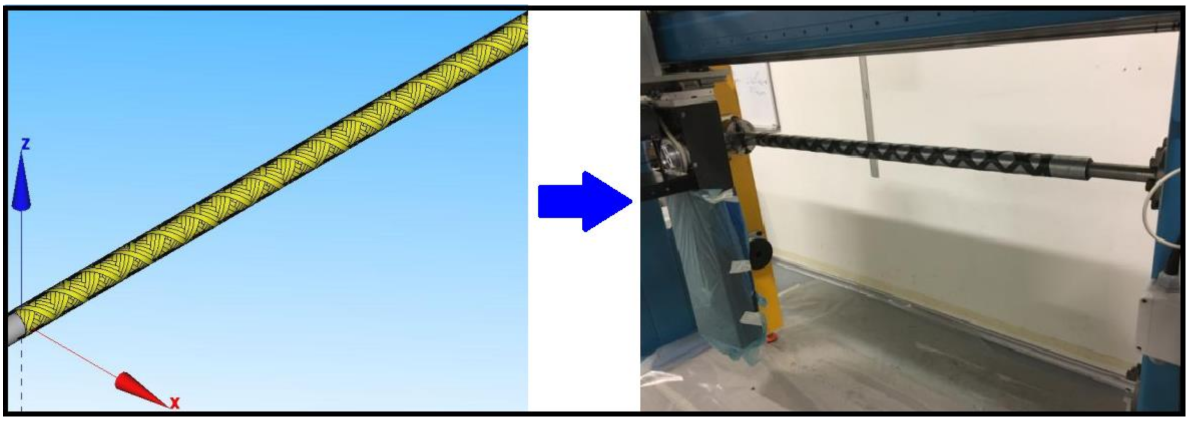

Figure. Modelling and production of composite drive shaft

Aim

Weight reduction with the sufficient mechanical performances was aimed for composite drive shaft. To ensure this, minimum number of layers in composite was tried to use in analysis.

Design & Methodology

Various winding angles and number of layers were modelled and analyzed. The safest configuration was determined and composite was produced. Filament winding method was performed.

Originality

Steel drive shaft are widely used in automobiles. However required mechanical properties are ensured with higher weights in these shafts. In this study, a composite alternative was designed to reduce the weight with the use of minimum number of layers.

Findings

The torsion test confirmed that the predicted winding angle and layer numbers were sufficient for composite drive shaft to be used in passenger cars. Besides ensuring adequate mechanical performance, nearly 80% weight reduction was provided compared to the steel shafts.

Conclusion

The weight in drive shafts could be reduced significantly with the use of carbon fiber reinforced epoxy matrix composite rather than steel.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Determination of Design Criteria for Composite Drive Shaft in Automobiles

Research Article

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ABSTRACT

Thanks to their superior properties such as light weight, higher strength and stiffness, corrosion resistance, the use of plastic matrix composites become attractive in many applications. The weight reduction in the automotive sector is one of these applications. By use of plastic matrix composites, weight and CO_2 emission reduction in automobiles could be achieved easily. In this study, carbon fiber and epoxy matrix were processed via filament winding method to produce composite drive shaft. Prior to production, finite element modeling were performed to determine the safest design parameters. Various winding angles were analyzed under torsional loading and number of layer was determined according to the failure index and strength ratio criteria. As a result of the numerical analysis, it was seen that the design with the minimum cost in terms of strength was the 10-layer model with a winding angle of +/- 45 degrees. To validate the design, the composite shaft was produced with the determined configurations and tested. The fiber volume fraction and the void content of the produced composite were found as ~46% was ~0.28%, respectively. No plastic deformation was observed in the torsion test. In the flattening and drift-expansion tests, plastic deformation occurred at 39 kN and 106.5 kN, respectively. Compared with a steel shaft, the obtained composite shaft has an 80% reduction in weight, and this could lead to a 1% fuel saving in passenger vehicles.

Keywords: Composite drive shaft, CO_2 emission, filament winding, weight reduction.

Otomobillerdeki Kompozit Şaft için Tasarım Kriterleri Belirlenmesi

ÖZ

Hafiflik, yüksek mukavemet ve rijitlik, korozyon direnci gibi üstün özellikleri sayesinde plastik matrisli kompozitlerin kullanımı birçok uygulama için cazip hale gelmektedir. Otomotiv sektöründeki ağırlık azaltma çalışmaları da bu uygulamalardan biridir. Plastik matrisli kompozitlerin kullanımı ile otomobillerde ağırlığın ve CO_2 emisyonunun azaltılması kolaylıkla sağlanabilmektedir. Bu çalışmada, kompozit şaft üretimi karbon fiber ve epoksi matris ile elyaf sarma yöntemiyle gerçekleştirilmiştir. Üretimden önce, en güvenli tasarım parametrelerini belirlemek için sonlu elemanlar modellemesi yapılmıştır. Burulma yüklemesi altında çeşitli sarım açıları analiz edilmiş ve kırılma indeksi ve mukavemet oranı kriterlerine göre tabaka sayısı belirlenmiştir. Sayısal analiz sonucunda, mukavemet açısından minimum maliyetli tasarımın +/- 45 derece sarım açısına sahip 10 katlı model olduğu görülmüştür. Tasarımı doğrulamak için kompozit şaft belirlenen konfigürasyonlarla üretilmiş ve test edilmiştir. Üretilen kompozitin fiber hacim oranı ve boşluk içeriği sırasıyla ~%46 ve ~%0.28 olarak bulunmuştur. Burulma testinde herhangi bir plastik deformasyon gözlenmemiştir. Yassılaşma ve sürüklenme-genleşme testlerinde sırasıyla 39 kN ve 106,5 kN'de plastik deformasyon meydana gelmiştir. Elde edilen kompozit şaft, çelik şafta göre %80 daha hafiftir ve bu binek araçlarda %1 yakıt tasarrufu sağlayabilir.

Anahtar Kelimeler: Kompozit şaft, CO_2 emisyonu, elyaf sarma, ağırlık azaltma.

1. INTRODUCTION

Since global-scale studies started in the 1980s and established the Kyoto Protocol in 1997, it is known that air pollution is caused by emissions of greenhouse gases (GHGs) by high levels of manufacturing and economic activities [1,2]. Carbon dioxide (CO_2), methane (CH_4), and many carbonaceous compounds are the main GHGs [2,3]. One of the troubles caused by the emission of GHGs is climate change [4]. Also, countless diseases are induced by direct respiration of GHGs or by contamination of drinking water with GHGs penetrated rains [5].

Increasing population and human needs lead rising demand for energy which highly release GHGs. It is estimated for CO_2 emissions to increase by nearly 5% to 33 billion tonnes in 2021 [6]. Basic energy resources are coal, gas, and oil kinds of fossil fuel. However, obtained energy during combustion of fossil fuel release highly GHGs. Although green and renewable energy supplies are developing rapidly, utilization of fossil fuels are still so common that about 90% of total GHGs is due to carbon emissions from the combustion of fuels [7,8].

Having the portion of 28% of the total GHGs emitted, transportation sector is one of the major GHGs emissions

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sources [9,10]. According to United States Environmental Protection Agency (EPA) report on GHGs emission in transportation sector, cars and vans, called light-duty vehicles, have the largest share with 60%, while heavy-duty trucks are the second largest with 23% [10]. In this sector, reducing weight by replacing components with lighter materials is the primary solution which has been adopted by the industry to reduce fuel consumption and GHGs emissions [9,11]. If a 1% weight decline in a vehicle is achieved, almost 0.6% fuel can be saved [11,12], and if 1 kg of mass is reduced, 12.5 g CO_2 can be less emitted [9,13].

Due to inherent high density values of most metals, metallic parts are generally heavy. Automobiles also comprise many metallic parts like drive shafts, which are one of the heavier components [14]. Steel drive shafts are the most common because required performance can be ensured with minimum price and great manufacturability [15]. The driveshaft is the connector between the transmission and the wheels, and have transmitting duty that causes heavy torques on them. [15,16]. The high level of torsion and shear stress that these parts are subjected to can be reached at the high weights when steel is used [15]. Not only high weight but also permissive speeds and vibration damping are the shortcomings of steel shafts [17]. The utilization of composite materials can exhibit improved properties with reduced weight [17-24]. Especially, carbon fiber reinforced epoxy composite is a preferred alternative for this purpose [25-27], because it's specific stiffness is more than four times of steel [14]. Also, critical speed limitations can overcome with carbon/epoxy composites usage [28]. The axial-symmetric structure of drive shafts allows them to be manufactured with the filament winding process which is a continuous fiber reinforcing technique for composites [29,30]. In this process, the key variables are stacking sequence, number of layers, winding angles, layer thickness, fiber types and product geometry [29,30].

The studies in literature struggle with the optimization of the lightest polymer composite drive shaft without compromising its strength. Main aim of these studies is to have coherence results from composite shafts with steel drive shaft. Chougule et. al. designed and manufactured carbon fiber composite drive shafts with filament winding process with $[90/-45/45/-45/45]_s$, and determined a weight saving of 44.26% in comparison with steel drive shaft [14]. Bolshikh designed, manufactured and tested a carbon-fiber drive shaft with titanium tips composed of 12 plies with winding angles of + 54° and - 54°. It was found to be 43% lighter than the metal counterpart and had the same reliability [15]. The evaluation of vibration performance of carbon fiber-reinforced composite drive shafts was done by Sun et. al., and they stated reduction in natural frequency and increase in damping with the increasing ply angles from 15° to 65° [25].

Shinle and Sawant produced glass/epoxy composite drive shaft with 60% fiber volume fraction and with the stacking sequence of $[\pm45/\pm45/\pm45/\pm45/\pm45]_{2s}$, and they found the torsional strength, natural frequency and critical speed were above the requirement with a 73% weight reduction compared to steel one [31]. On the other hand Karimi et. al. suggested a combination of glass and carbon fiber reinforced epoxy as a hybrid solution for the lightest and the most cost effective shaft alternative [29].

Nayak et. al. fabricated carbon/epoxy composite drive shafts with a $[85_2/\pm45_2/25_2]_s$ fiber orientation. They found a 60% weight loss with an 8.5% increase in torsional strength, and concluded that the carbon/epoxy shaft could be a good alternative to the steel shaft [33]. In the study of Tataroglu et. al. done with carbon/epoxy composite material for the heavy commercial vehicles drive shaft, 35% weight is saved in the structure [34]. In the paper of Khoshravan et. al., about 72% weight reduction was achieved by designing a one-piece composite drive shaft rather than a two-piece steel drive shaft [35]. Tariq et. al. investigated the effects of carbon fiber winding layer on torsional characteristics of composite hollow shafts with hoop and helix winding layers, and it was concluded that adding helix winding layer to sequence highly increased the torsional strength [17]. It was deduced from the literature that it is crucial to design the number of layers and the orientation of fibers within each layer for lighter driveshaft production.

In this study, carbon/epoxy composite was designed and manufactured in order to contribute the weight saving in drive shafts compared to steel alternatives. For model simulation Cadwind® software and for mechanical simulation Simcenter® software were used to analyze various number of layers and winding angles. At the optimized process conditions filament winding process was applied in the drive shaft form with a minimum number of layers. The performance of the produced shafts was determined with torsion, tube flattening and drift-expanding tests besides some physical test in order to obtain fiber volume ratio and density of the parts.

2. MATERIAL AND METHOD

2.1 Design and Analysis

Possible filament winding angles can vary from 0 to 90 degrees, where 0° provides reinforcing in the axial direction and 90° contributes to strength in the hoop direction [40]. To evaluate improvement in strength in both directions winding angles changing from +/-15 to +/-75 were implemented in the FE analysis. Five different winding models with winding angles of +/- 15, +/- 30, +/- 45, +/- 60 and +/- 75 were created, each with 8 layers, in order to examine the effects of the winding angle on the mechanical properties of the composite shaft. These models were created using Cadwind® software. The finite element models for each winding model seen in Figure 1 were also created with this software. In the finite element model, a 3D finite element model was constructed in accordance with the design geometry. Since it is a cylindrical geometry, a hexahedral element type was chosen. In order to obtain accurate analysis results, the models were analyzed with different mesh sizes and the most appropriate mesh size was determined according to the resulting values. The finite element model created for each model was also shown in Figure 1.b.

Models varied according to winding angle and number of layers as follows: “Model number 1” has +/- 15 winding angle and consists of 8 layers. “Model number 2” has +/- 30 of winding angle and consists of 8 layers. “Model number 3” has +/- 45 winding angle and consists of 8 layers. “Model number 4” has +/- 45 winding angle and consists of 10 layers. “Model number 5” has +/- 60 winding angle and consists of 8 layers. “Model number 6” has +/- 75 winding angle and consists of 8 layers.

After the finite element model was created for each winding model, a torque was applied to all models with the help of Simcenter® analysis software and torsional strengths were examined. 3,500 N.m torque was performed, because the torque transmission capability of the drive shaft should be larger than this value [32, 36]. Failure Index and Strength Ratio values were obtained for each model and suitable number of layers and orientations were determined according to these values.

2.2 Materials

AKSACA® A-42 24K carbon fiber from DowAksaTM, Istanbul was used as the reinforcement. Its yarn is composed of 24,000 individual carbon filaments with a yield tex of 1600 g/1000 m. The tensile strength of the fiber is 4200 MPa, the tensile modulus is 240 GPa, the elongation of 1.5%, and the density is 1.78 g/cm3 [37].

A medium viscosity epoxy based resin system was procured from Duratek®, Kocaeli. It is the DURATEK 2400 System that consists of one resin (DTE 1000) and two hardeners (DTS 4004 and DTS 4010) suitable for filament winding production technique [38]. The neat polymer has a tensile strength of 58-63 MPa, tensile modulus of 2.7 – 3.2 GPa and tensile elongation of 2.8 – 3.3 % for curing 2 hours at 70ºC+3 hours at 120ºC [39]

2.3 Fabrication of Drive Shafts

Induction chrome-plated steel shaft with a diameter of 60 mm and a length of 1500 mm was used as the mold material for the production of composite shafts. After production, the mold surface was waxed in order to easily remove the produced part, and then it was connected to the winding machine shown in Figure 2.a. Afterwards, the epoxy resin/hardener at a ratio of 79/21 by weight was mixed with the help of a mixer and poured into the resin bath shown in Figure 2.b.

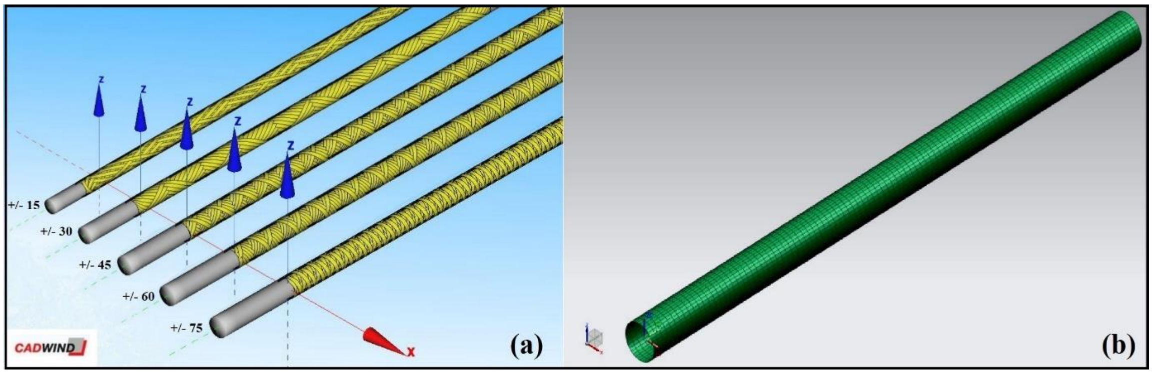

Figure 1. (a) Winding models, (b) Finite Element Model

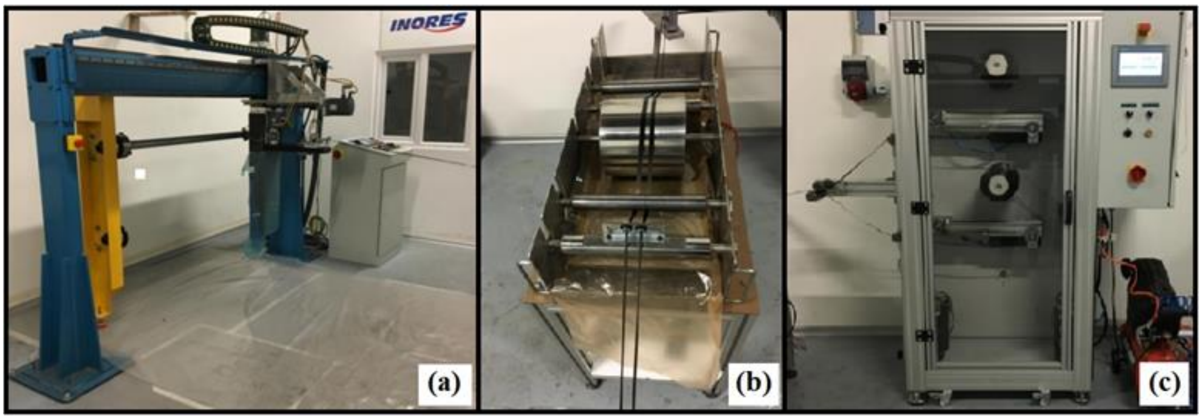

Figure 2. (a) Filament winding machine, (b) resin bath, (c) tension cabinet

In the final stage of the preliminary preparation part of the production, carbon fiber bobbins were placed in the tension cabinet shown in Figure 2.c and production started according determined conditions of winding angle and number of layers.

After the fiber winding process was completed, the surface of the part was covered with shrink tape from Dunstone®. Removal of the excess resin and better surface roughness was aimed with shrink tape application. The winded part was placed in the curing oven. The curing was ensured at the temperature-time conditions given in Figure 3.

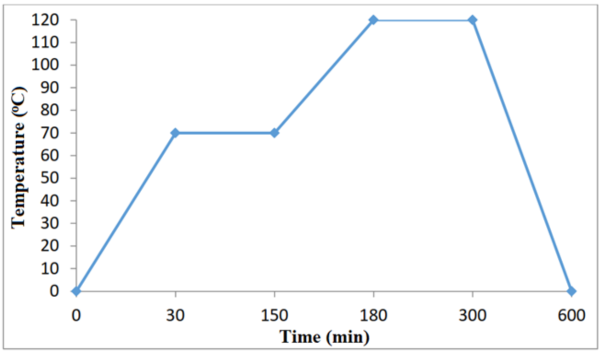

Figure 3. Temperature – time graph of the curing process

This curing process was carried out according to the technical specifications of the epoxy resin. The temperature of the curing oven was first increased to 70ºC in 30 minutes. At this temperature, the part was pre-cured for 120 minutes and the part was rotated around its own axis with the help of a rotation motor to ensure that the epoxy resin spreads uniformly within the part. Afterwards, the furnace temperature was increased to 120ºC in 30 minutes. At this temperature, the part was cured for 120 minutes. In the final stage of the curing process, the part was left to cool in the oven. After the curing process was completed, the composite part was taken out from the curing oven and the Shrink Tape was removed from the surface of the part. Finally, the composite part was removed from the mold and the production of the composite shaft was completed. Figure 4 shows the produced composite shaft. The weight of the produced plastic matrix composite shaft was approximately 4 kg. This value is approximately 1 in 5 of the steel shafts used today. Almost 80% weight reduction was achieved compared to steel shaft.

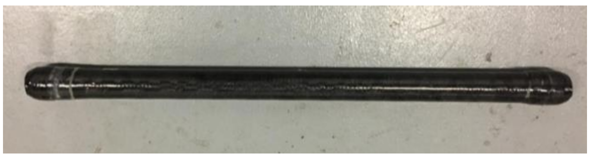

Figure 4. Produced composite shaft.

2.4 Tests and Observations

Torsion was applied to the composite shaft to determine the mechanical performance of the produced part. Test was performed by fixing the prepared test specimen at one end and applying a torsion moment at the other end. Shear stresses occur in the test specimen due to the torsional moment. The application of test and specimen fixture to torsion device was described in deal in ASTM D5448/D5448M – 16. However, the described fixture is quite complex comprises many pieces, and has risks of failure to specimen called as grip failure. In this case, the test is considered to be inappropriate.

In order to perform the torsion test with easier assembly and less risk of failure was dealt with a simple apparatus and technique. The suitable apparatuses for the test device were produced from 6061 Al – Mg alloy due to its high strength properties and easy workability. In Figure 5, used test apparatuses and the sample preparation step for torsion test is seen. To improve bonding between the fixture apparatuses and the specimen, the surface tensions of the touching point parts of the apparatus and the composite shaft were increased by the Openair® plasma. The purpose of this process is to ensure well adhered parts. The Openair® plasma method increases the energy of the material's surface by providing surface modification and makes the surface to improve wettability. After this process, a two-component adhesive DP8005 produced by 3M™ Scotch-Weld™ was applied on apparatuses and the apparatuses were attached to the ends of the composite shaft. The test specimen was conducted on SM 21 torsion test device at a rotation speed of 225 degrees/minute.

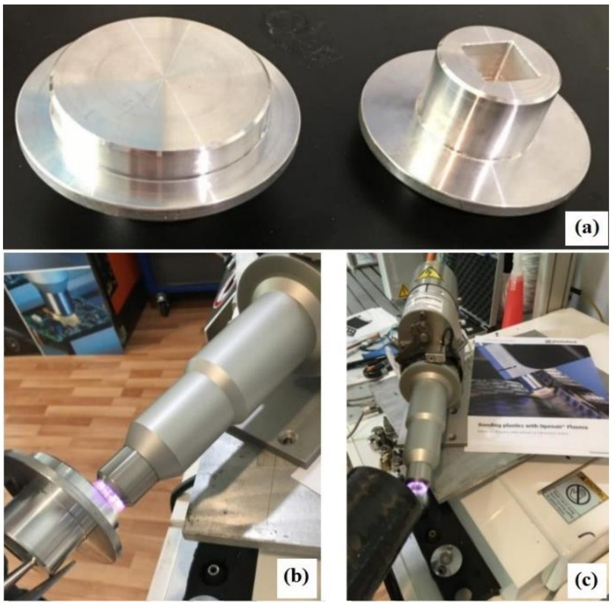

Figure 5. (a) Torsion test fixture apparatuses, (b) plasma application on fixture, (c) plasma application on specimen

The flattening test was carried out at a speed of 5 mm/min using the Mohr – Federhaff 7079 universal tensile test device with 100 kN loading capacity under compression mode. The flattening test was carried out by application of compressive load in a direction perpendicular to the longitudinal axis of the specimen according to EN ISO 8492 standard. However, this test standard is for metallic pipe testing with the aim to determine the plastic deformation capability. With the same aim, this test was performed on produced composite tubes and loading value caused fracture was determined.

The drift-expanding test was performed on Alşa Laboratory Devices Ltd universal tensile test device which have 200 kN loading capacity under compression mode. It was carried out at a speed of 5 mm/min, with a 60º conical mandrel. The load was applied to the tube one end with the conical mandrel in the longitudinal direction according to EN ISO 8493 standards. Although this standard was also developed for metallic pipes which show higher plastic deformation capacity, it could also be used for testing brittle composite tubes in order to evaluate their failure strength. According to standard, no cracks should observed on specimen with naked eye when mandrel compressed. However, brittle composite tubes could not exhibit that much deformations without any fracture. So load value at which failure occurred was taken as the test result.

In order to obtain fiber volume fraction and void fraction of the produced samples, chemical dissolving and density tests were applied to the composite shaft. Test specimens were cut in 10 mm width and 20 mm length according to EN 2564. Before the chemical dissolving, density of the specimens were measured with immersion method according to ASTM D792. Before and after the density measurement, specimens were conditioned at 50°C at least 2 hours. Then specimens were subjected to hot concentric sulfuric acid for 2 hours followed by hydrogen peroxide instillation up to color change. After cooling the solution to room temperature, remained carbon fiber was washed with distilled water and dried at 120°C for 1 hour. From the weight measurements before and after the dissolving, fiber volume fraction was calculated.

Fractured surfaces were observed in Scanning Electron Microscope (SEM) (JSM 6335F - JEOL and JSM 6510LV – JEOL, Japan). Prior to the observations, specimens were sputter-coated with gold (Polaron SC7640, Quorum Technologies, UK).

3. RESULTS AND DISCUSSION

3.1 Analysis

The torsion analysis of automobile shafts that will be produced using composite materials with a certain winding angle can be done by using the finite element model. According to the results of the analysis, whether the design is safe or not can be interpreted by looking at the failure index and strength ratio values. The failure index and strength ratio parameters used in analysis studies with the finite elements model are commonly used design criteria for composite materials. Accordingly, the failure index value used in the design of composite materials should be less than 1 and the strength ratio value should be greater than 1 [41]. While the failure index value defines the ratio of the load applied to the composite to the strength of the material, the strength ratio value defines the ratio of the strength of the composite to the strength value of the material. In the analysis program used, the relevant calculations were made according to the following formulas in accordance with the definitions made [42]:

$$FI\ (Failure\ Index) = \frac{\sigma}{F} \tag{1}$$

$$SR\ (Strength\ Ratio) = \frac{F}{\sigma} \tag{2}$$

After the finite element model was created for each winding model, a torque value of 3500 N.m, which is the minimum value required for the drive shaft of a passenger car, was applied to all models and torsional strengths were examined. Numerical results of torsion analysis were given in Table 1. When the data in Table 1 were examined, it is seen that the Failure Index value for each model is below 1. When the Strength Ratio values are examined, the values of all models consisting of 8 layers remained below 1. Although the lowest failure index and the highest strength ratio was obtained at the winding angle of +/- 45, strength ratio was still not sufficient. Thus, layer numbers was increased to 10 layers for winding angle of +/- 45, and strength ratio enhancement was observed.

Table 1. Torsional Analysis Results

Model Number	Winding Angle	Number of Layers	Failure Index	Strength Ratio
1	+/- 15	8	-0.68	0.72
2	+/- 30	8	-0.60	0.86
3	+/- 45	8	-0.59	0.88
4	+/- 45	10	-0.47	1.08
5	+/- 60	8	-0.73	0.67
6	+/- 75	8	-0.81	0.55

The model consists of 10 layers with +/- 45 winding angle was the only configuration that ensure both failure index and strength ratio requirements, which was selected as the safest design. As mentioned by Stedile Filho et.al. [43], layers with 45º are critical for the torque transmission strength, and this matches our findings. For that reasons, other angles need not have been produced, only a +/- 45 winding angle was applied an in 10 layers configuration.

The analysis results of each model were shown in Figure 6. As general all analysis, blue to red color scale expresses the stress distribution levels in structure from lower to higher. For the most models, the highest stress levels were observed mostly in the vicinity to end parts, because the structure was under torsion loading. For the 8 layers with +/- 15, higher levels of stress were observed equally in the body of the structure indicative of lower hoop strength was obtained due to lower winding angle was not supplied sufficient strength. With the increase in winding angle, stress distribution was moved from torsional affected end vicinities to internal parts of the body, which was caused by the lower axial strength of the material. This was seen obviously in the model of 8 layers with +/- 75.

3.2 Tests and Observations

The safest configuration was applied to manufacture the composite drive shift. To evaluate the safety requirements, torsion test was performed. This test is carried out to examine the behavior of materials in terms of yielding characteristics under large plastic loads.

According to Stedile Filho et. al. [43] the operating maximum in-service torque of a drive-shaft is 400 N.m and in their study performed with $[\pm45]_5$ reached a 95% higher torque load. Critical buckling torque (Tcr) can be calculated analytical with [44]:

$$T_{cr} = (2\pi r^2 t).(0.272).(E_X.E_Y^3)^{1/4}.\left(\frac{t}{r}\right)^{3/2} \qquad (3)$$

where r and t are the radius and thickness, Ex and Ey are the longitudinal and transverse modulus for the hollow shafts.

which proves the finite element analysis. Since the applied maximum torque was so lower than the Tcr, it was apparent that the composite shaft would not deform.

The flattening test applied to the composite shaft was carried out to examine the plastic deformation of the composite shaft under the transverse load. No plastic deformation occurred in the test specimen until the applied load value reached 39 kN. When the value of 39 kN was exceeded, plastic deformation occurred in the test sample. Figure 7.a shows the plastically deformed sample after the flattening test. At this load compressive strength value was calculated as 6.13 MPa by division of load value to lateral surface area of the sample. Because

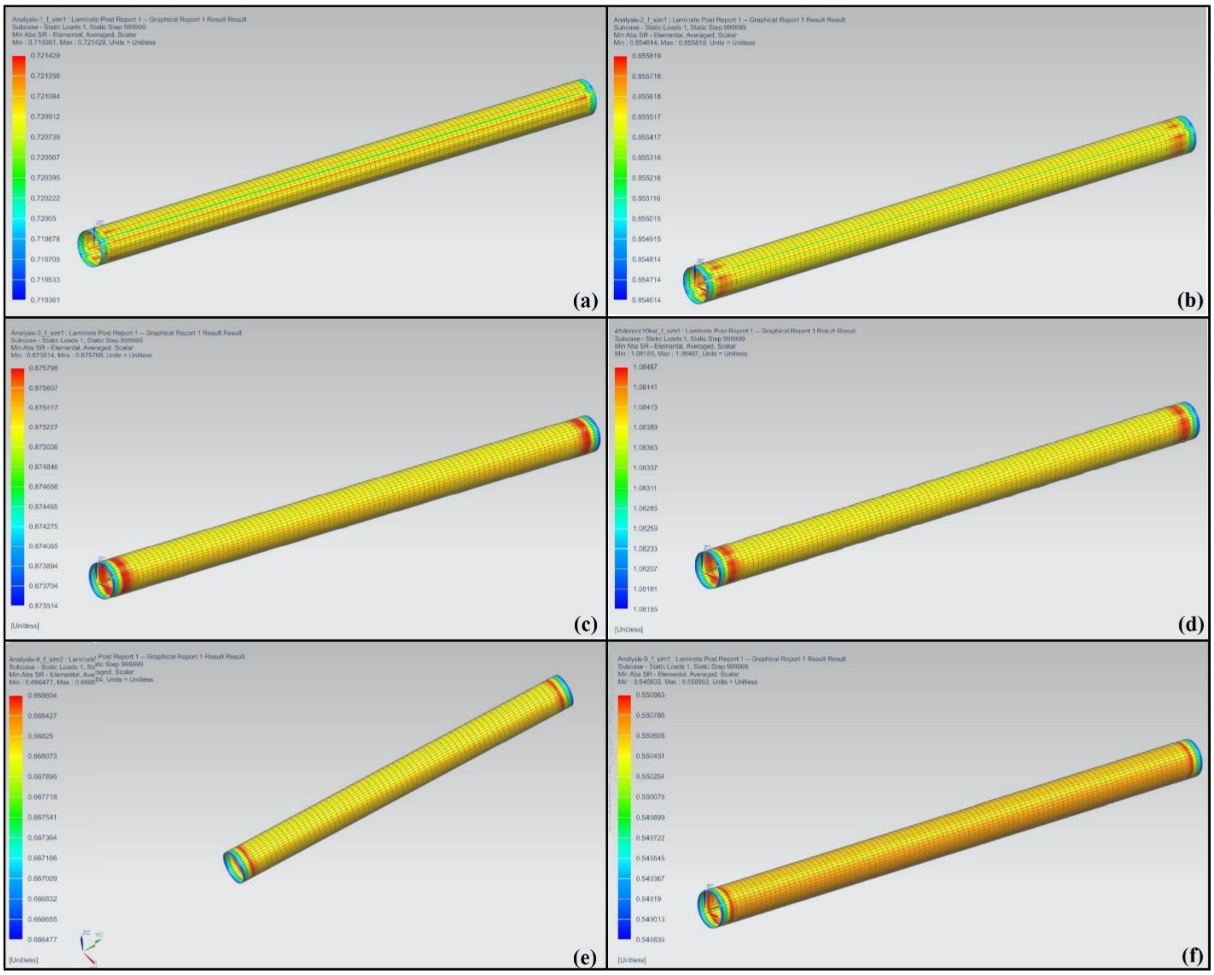

Figure 6. Torsion Analysis: (a) 8 layers with +/- 15, (b) 8 layers with +/- 30, (c) 8 layers with +/- 45, (d) 10 layers with +/- 45, (e) 8 layers with +/- 60, (f) 8 layers with +/- 75.

In this study, the maximum capacity of the test device was 200 N.m, and this torque value was conducted on the composite shaft for several minutes. However, no deformation occurred on the composite shaft and the angle of twist value could not be monitored from the device. Because of the high stiffness and strength values of the carbon fiber/epoxy composite neither elastic nor plastic deformation was observed on composite shaft. Also, no deformation was observed on plasma and adhesive-applied surfaces. The critical torque value for the manufactured shaft was calculated as 3793 N.m,

load causes radial stress in a hollow cylinder, lateral surface was taken in consideration. Stedile Filho et.al. [43] performed compressive test on [±45/±45] composite shafts at radial direction, and found deformation at 4.30 kN. According to our calculation considering stress formation on lateral surface area, 0.17 MPa compressive strength could be found on their shaft. This shows that not only fiber winding angle, but also number of layers have significant role on radial compressive strength of the composite shafts.

The drift-expansion test applied to the composite shaft was applied to examine the plastic deformation of the composite shaft under longitudinal loads. No plastic deformation occurred in the test specimen until the applied load value reached 106.5 kN. When the value of 106.5 kN was exceeded, plastic deformation occurred in the mandrel compressed end part of the test sample. Figure 7.b shows the plastically deformed specimen after the drift-expansion test. Considering the applied load was cos60 times the total load when compressing 60^o conical mandrel to sample, it was calculated that the axial compressive strength was ~133 MPa. Hashim et.al. [45] applied various winding angles between 53-78^o at helical pattern, and found maximum compressive strength as ~14 MPa at 53-55^o. This confirms that winding angle could also change axial compressive strength results.

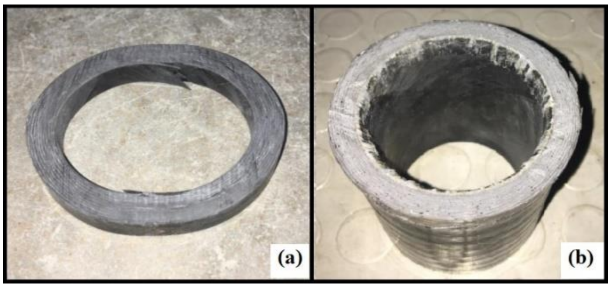

Figure 7. Fracture test specimens: (a) after flattening test, (b) after drift-expansion test

The fiber volume fraction (V_f) and the density values obtained for the samples were given in Table 2. The fiber volume fraction was calculated and the average fiber volume ratio was found to be ~46%. The theoretical density was calculated as 1.412 g/cm^3 according to the rule of mixtures. Experimental density was measured as 1.408 g/cm^3. Voids cause mechanical weakness in a composite part as a results of poor manufacturing. Volume fraction of voids were ~0.28% in manufactured specimens. It is a quite lower fraction for a composite obtained thanks to shrink tape application during manufacturing.

Table 2. Fiber volume fraction and density results

	Theoretical	Experimental
V_f (%)	-	45.9±0.004
Density (g/cm$_3$)	1.412	1.408±0.002

When microscopic images seen in Figure 8 were examined, typical brittle fracture for composite materials were observed. The fracture started with fiber breakage and continued with the fiber/matrix interface failure. At that stage, fiber pull-outs occurred in the fracture surface. There were many fiber pull-outs with epoxy resin residues. It is an evidence of good adhesion between epoxy resin carbon fibers. Also, the distribution of fibers in the epoxy matrix was fairly uniform and the fibers were impregnated well with the matrix. Almost no void was seen neither in matrix nor interface. This indicated that the physical interface bonding between fiber and matrix was strong and contributed to higher mechanical properties.

6. CONCLUSION

In this study, composite shaft designs were developed for the use in passenger cars. It was produced by fiber winding method using epoxy resin and carbon fiber. After the production, a number of mechanical and physical experiments were carried out on the composite shaft.

Since the shafts must show high performance properties, carbon fiber and accordingly the matrix material epoxy resin were chosen for the production of composite shafts. The fiber winding method was preferred, because it allows the use of continuous fiber and the properties in certain directions can be controlled. Whether the design was safe or not has been determined by the analysis. Analysis studies carried out before production minimized the errors that may be encountered in production and unnecessary material consumption.

The fiber volume fraction was approximately 46%. The use of shrink tape during production minimized the air gaps in the structure and lower void content to 0.28%. Therefore, no voids observed in microscopic

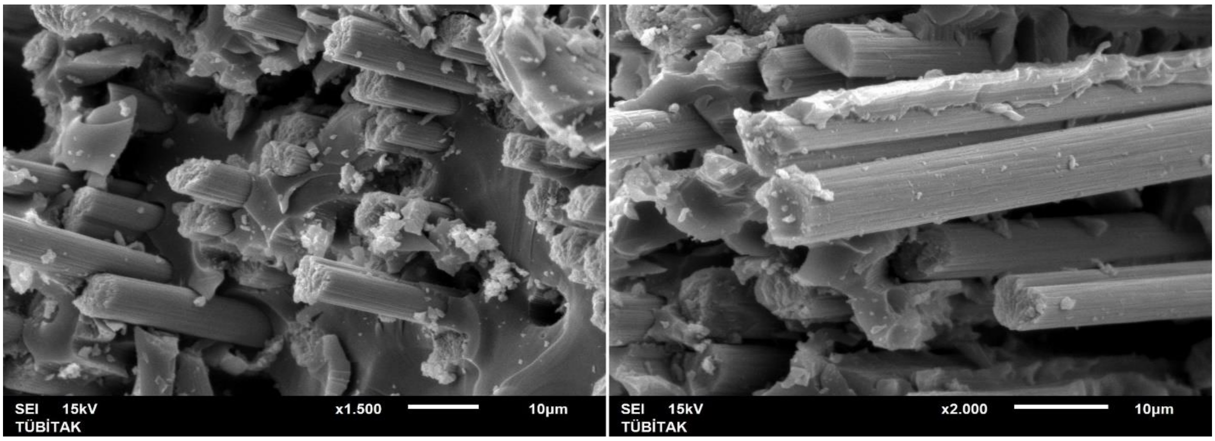

Figure 8. SEM images of fracture surface

investigations. In addition, it was observed that the matrix material showed a homogeneous distribution among the fibers in the structure with good interfacial bonding.

The weight of the produced plastic matrix composite shaft was approximately 4 kg. Almost 80% weight reduction was achieved compared to steel shaft that used nowadays. If such a composite shaft is used in a passenger car that uses gasoline as fuel, it is foreseen that 1% fuel savings will be achieved and the amount of CO_2 released to nature will be 230 g per 1 liter of fuel consumed.

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Beytullah ALTIN: Performed the analysis and the experiments, and analyzed the results. Reviewing and editing the manuscript.

Aylin ALTINBAY BEKEM: Analyzed the results. Writing, reviewing and editing the manuscript.

Ahmet ÜNAL: Analyzed the results. Reviewing the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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