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Development of CFRP Tubes for the Light-Weight Propeller Shaft of 4WD SUV Vehicles

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4륜구동 SUV 차량용 구동축 경량화를 위한 CFRP 튜브 개발

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ABSTRACT

In this study, the one-piece propeller shaft composed of carbon/epoxy was designed and manufactured for 4 wheel drive automobiles that can bear the target torsional torque performance of 3.5kN.m. For the CFRP tube, braiding machine was used to weaving carbon fiber and it was formed the braided yarns with the braid angle ± 45° and axial yarns to improve strength of the lengthwise direction. The final CFRP tube of propeller shaft was evaluated through the torsional torque test. The CFRP propeller shaft satisfied requirement of the target torsional maximum torque of 3.5kN.m. Also, it was found that the one-piece composite propeller shaft with CFRP tube had 30% weight saving effect compared with a two-piece steel propeller shaft.

Key Words : Propeller Shaft(구동축), 4-Wheel Drive(4륜구동), Light-Weight(경량화), CFRP(탄소섬유복합재), Braiding Method(브레이딩공법)

1. Introduction

The interest in four-wheel drive passenger cars, which enable stable driving even in bad weather conditions, has significantly increased in recent years because the leisure market expands with the development of large-sized passenger cars, which results from the luxury strategy of the automobile industry in Korea.

The propeller shaft is a core part that transmits the driving power generated from the engine to the rear wheel axle via the transmission. Because the propeller shaft is mounted at the lower end of the passenger seats in four-wheel drive cars, it has a drawback that the noise

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and vibration are directly transmitted to the driver and passengers. The use of fiber-reinforced composite has increased to achieve lightweight automobiles because the technical development of improvements in energy reduction and efficiency through the lightweight auto parts is urgently required.[1] Accordingly, many studies on lightweight materials such as aluminum, magnesium, and carbon fiber have been conducted in advanced nations including those in Europe as an alternative to existing steel materials.[2,3] Among them, carbon fiber has been known as an excellent material for lightweight automobile because it has significantly lower density than steel but notably high strength. Thus, active studies are conducted on the development of auto parts with carbon fiber composite.[2,3] Among many auto parts, the propeller shaft is a power transmission unit that transmits power from the engine to the axle via the transmission. It requires high torque and high stiffness. The previous study reported that this performance could be satisfied by carbon fiber composite[4]. There are several manufacturing methods and molding technologies of carbon fiber composites and various experimental and analytical study results for performance evaluation. The braiding technique is considered one of the optimized methods to manufacture lightweight and high-strength carbon composite parts because of the superior mechanical characteristics and productivity, low production cost and short molding time.[5,6] Yo et al.[7] fabricated a carbon-epoxy composite specimen and evaluated the effect on the vibration and strength characteristics in the propeller shaft. Kim et al.[8] aimed to identify the principle of changes in angular velocity because of torsional vibration at the power transmission system in a vehicle. In addition, Kim et al.[9] compared the characteristics of the static torque transmission capability according to a critical yoke thickness in the joint where the propeller shaft is attached after applying composite materials. Shin et al.[10] evaluated the physical properties of the propeller shaft and studied a structural analysis of the propeller shaft where the braiding technique was applied.

However, these studies were limited as foundational studies of evaluation on the physical properties and fabrication process of carbon-fiber composites and performance evaluation of the propeller shaft, or they did not satisfy the required torsional fatigue strength in finish cars[10, 11].

This study modifies the braid weaving pattern to overcome the vulnerable part[10] in a carbon-fiber-reinforced polymer (CFRP) propeller shaft fabricated with the existing three-dimensional (3D) braiding technique to produce a tube that can endure a certain level of torsional torque. We also compare the performance characteristics with those of steel propeller shafts through the torsional fracture test.

2. Design and production process of the CFRP propeller shaft

2.1 Design change of the propeller shaft shape for lightweightness

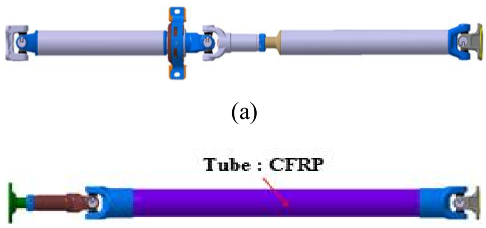
Fig. 1(a) shows the model in the current propeller shaft in vehicles, and (b) shows the developed propeller shaft model where the tube was replaced with CFRP material, and other parts were made of steel in this study.

The currently used propeller shaft in vehicles (a) was manufactured with two separated structures, which consist of connecting joints that connect the axles and axle support bearings for the car body attachment. The outer diameter, thickness, and tube length in the front and rear sides of the steel tube were 63.5 mm, 2 mm, 374 mm, and 499 mm. The total length of the steel propeller shaft was 1,391.8 mm including the connecting joint and axle support bearing. The material of the propeller shaft was STKM 13B carbon steel pipe for the mechanical structure. The weight of the steel propeller shaft was approximately 14 kg. The developed CFRP propeller shaft (b) in this study was a simple structure, where the axle support bearing and bracket for body attachment and one constant-velocity joint were removed. The tube length was 1,059 mm, and the design was made to reduce the weight of the existing steel propeller shaft.

2.2 Preform design and production

The mechanical behavior of composite materials depends on the fiber orientation, fiber properties, fiber volume fraction, and matrix properties[6]. The process variables in the braid preform fabrication must be expressed as a function of the fiber volume fraction and geometric structure, which can be represented as follows.

Here, the fiber volume fraction is related to an orientation angle of braid yarn and the total number of braid yarns, and the fiber geometry can be related to the orientation angle and final shape of the fiber[5].



(a)

(b)

Fig. 1 Propeller Shaft. (a) Steel, (b) CFRP

$$d_0 = M N_{ply} A_y \,/\, (\pi T V_f \cos\theta) + T \qquad (1)$$
$$d_i = M N_{ply} A_y \,/\, (\pi T V_f \cos\theta) - T$$

where,

d_0 : outer diameter of the braided composite;

d_i : inner diameter of the braided composite;

T : thickness of the braided composite,

M : number of carriers, N_{ply} : number of plies;

A_y : cross-sectional area of the braid yarn,

θ : orientation angle of the braid yarn to the mandrel shaft,

V_f : fiber volume fraction (= braid preform cross-sectional area/composite cross-sectional area)

The braiding angle, fiber volume fraction, and number of plies can be easily calculated using Eq. (1) to make a braid preform. With 45° orientation angle of braid yarn with regard to carbon fiber 24K, 48 carriers can be implemented, the carbon fiber is 9 mm wide, and the expected weight of the preform is 106.3 g/m. The number of layers to implement 3 mm thickness was four when the maximal outer diameter of the CFRP tube was set to 74 mm to satisfy the static torsional torque capacity of the steel propeller shaft. The two-dimensional braiding method was applied to the braid preform considering the above process variables, where two braid yarns were crossed at a certain angle to implement the braid preform. The

Fig. 2 Fractography of CFRP Tube

carbon fiber was T700SC 24K. However, shrinkage occurred in the axial direction because the tube surface was twisted when the torsional test was performed with the product as shown in Fig. 2.

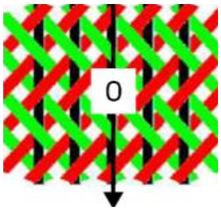
Thus, an axial yarn was inserted in the axial direction to prevent damage to the braid yarn because of torsion in the tube surface of the propeller shaft. Macander et al.[12] also reported that the tensile strength in the axial direction was reduced by at most 50% when an axial yarn was inserted in the axial direction in addition to the braid yarns.

In addition, the design of the braiding pattern was conducted using 2×2 regular pattern of 48 braid yarns and 24 axial yarns considering the stiffness and durability against torsion. Fig. 3(a) shows the braiding pattern design, and (b) shows the braid composite specimen weaved by the pattern design. Fig. 4 shows the braiding manufacturing machine and preform in the above conditions.

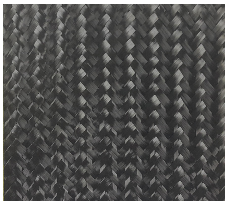
2.3 Preform molding

The resin to mold the finally produced preform in Fig. 4(b) is a thermoset. Table 1 presents the physical properties of the resin. A resin was injected to the preform inserted to the mold using the pneumatic cylinder pump device, heated at 120 ℃ (high temperature)[13], and cured for seven minutes.

After demolding the completely molded CFRP tube from the mold, both ends of the tube were cut. The burr at the end was removed through post-processing work, trimming and surface processing by sanding. The fiber volume fraction, which was one of the important factors in the physical properties of the composite material, was verified before the finally molded tube was attached to the yoke. When a total weight of the preform was 550 g/m, a weight of the CFRP tube was 820 g/m, the volume of the preform was 309 cm^3, the volume of injected resin was 235 cm^3, and the fiber volume fraction was approximately 57%.

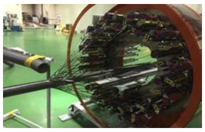


(a)

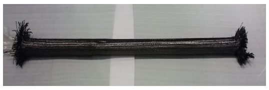


(b)

Fig. 3 Braiding pattern design. (a) Schematic of braids, (b) Braided composite specimen



(a)



(b)

Fig. 4 (a) Braiding M/C and (b) CFRP Preform

Table 1 Properties of the epoxy resin

Property	Unit	Value
Tensile Strength	Mpa	78
Tensile Modulus	Gpa	2.6
Tensile Elongation	%	5~6
Flexural Strength	Mpa	124
Flexural Modulus	Gpa	2.9
Compressive Strength	Mpa	170
Volume shrinkage	W/mk	0.2
Conductivity	%	2~5

2.4 Joint of dissimilar materials

To prevent a departure because of the force delivered in the front and rear sides and to transmit the rotational torque from the engine without problem[14], a shape of the joint between both ends of the CFRP tube and the steel tube yoke was made octagonal, which was structurally optimal. In addition, the joint between the CFRP tube and the yoke was approximately set to 50 mm long, and inserting and bonding were performed in the joint. Fig. 5 shows the prototype of the propeller shaft where dissimilar materials were joined.

3. Experiment results and discussion

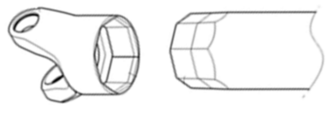
3.1 Structural stability of the CFRP tube

Prior to the torsional test of the CFRP propeller shaft, a non-contacting optical 3D shape-measuring instrument was used to measure the CFRP propeller shaft to verify whether that the molded tube surface was uniform, and their shape was constantly maintained[15]. Fig. 6(a) shows the computer-aided design (CAD) data of the CFRP propeller shaft and (b) the shape measurement result of the propeller shaft. A difference between two data, 3D shape measurement data and CAD data, was measured at a regular distance based on the CAD data by overlapping the CAD data with the 3D shape measurement data to compare them.

Fig. 7 shows the comparison result after overlapping Figs. (a) and (b) and comparing them at a regular distance to observe the difference. The level bar in Fig. 7 represents a deviation distribution of 3D shape measurement data based on the CAD data. -The above results indicated that a deviation was not that large, which was in a range of –0.25 mm to ±0.1 mm. Thus, it verified that the surface in the CFRP propeller shaft manufactured with the braiding method was uniform, and its shape was stable. Based on the above results, a torsional test of the CFRP propeller shape was conducted.

3.2 Torsional test

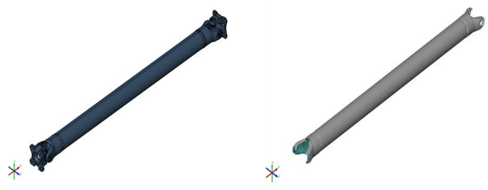
The currently used propeller shafts in vehicles require a level of 3.5 kN.m static torque transmission capability in the design because of the characteristics that perform strong torsion and high-speed rotation[10,16]. Thus, the reliability test was conducted according to the torsional fracture test method of “Propeller Shaft for Vehicles” in RS R 0088 to identify the performance of the fabricated CFRP propeller shaft.



(a)

(b)

Fig. 5 (a) Tube yoke and tube, (b) Universal joint for a propeller shaft



(a) (b)

Fig. 6 (a) CAD data and (b) 3D Scanning data of CFRP Propeller shaft

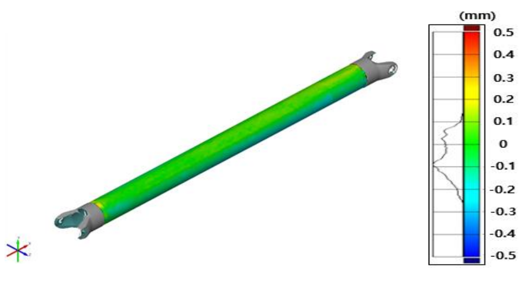
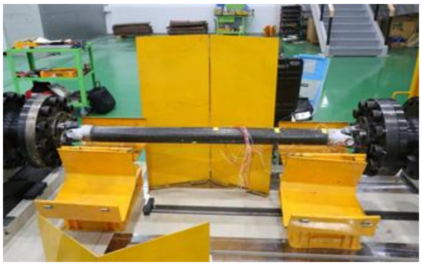


Fig. 7 Deviations of CFRP shaft

Four prototypes of the CFRP propeller shaft were mounted in the torsion testing machine at a starlight line as shown in Fig. 8, and torsion up to 3.5 kN.m was applied in a certain direction at a rate of 0.5 deg. per sec to measure the torque and angle. It was designed to have a forced termination at 3.5 kN.m, and the result shows that the static torque transmission capability of the four prototypes of the CFRP propeller shaft satisfies the performance requirements. In addition, the results of the performance comparison of the CFRP propeller shaft and existing steel propeller shaft showed a linear slope up to 3.5 kN.m and a level of torsion in both of two propeller shafts not that high, as shown in Fig. 9.

Finally, to verify the lightweightness of the CFRP propeller shaft, the weight was measured and the result was approximately 10 kg, which was 30% less than that of the steel propeller shaft, as shown in 14 kg.

(a)



(b)

Fig. 8 (a) CFRP propeller shafts (b) Torsional tester of 4 kN.m torque capacity

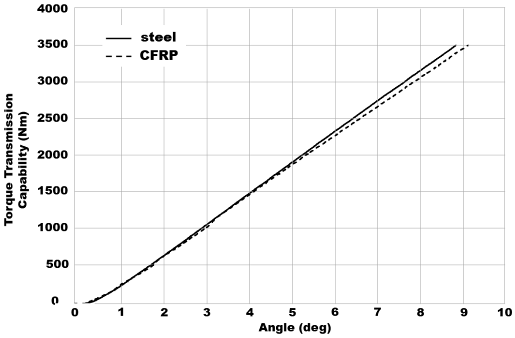


Fig. 9 Experimental results of the static torque transmission capabilities of the steel propeller shaft and CFRP propeller shaft

4. Conclusions

This study fabricated a CFRP tube using the braiding method in the steel propeller shaft, and a test for performance evaluation is ready the following conclusions.

1. To verify the structural stability of the CFRP tube fabrication using the braiding method, the design data and actually fabricated tube data were compared, and the result showed a minimal difference of ±0.1 m. This result indicates that the reproducibility and repeatability of the tube fabrication with uniform surface and constant shape are expected in the future.
2. The measurement result of the weight of the fabricated CFRP propeller shaft is approximately 10 kg, which reduces the weight by 30% compared to that of existing steel propeller shaft.
3. The torsional test results of the CFRP propeller shaft verify that a torsional fracture capability is 3.5 kN.m, which was a goal performance figure, without fracture while revealing a similar trend with that of steel propeller shaft.
4. The study results will be helpful in other studies such as strength improvement by evaluating the

physical properties of the material and prototypes according to a weaving pattern in the future.

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