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A Study on the Tube of Integral Propeller Shaft for the Rear-wheel Drive Automobile Using Carbon Composite Fiber

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Abstract

In this study, we proposed an integral propeller shaft using carbon composite fiber T700 and epoxy resin. First, the integral propeller shaft was designed considering the assembly space of the automobile. In order to verify the safety of the integral propeller shaft, the buckling torque, the transmission torque, and the natural frequency of bending were calculated by the basic design theory of composite materials. Torsional strength analysis, buckling analysis, and natural frequency analysis according to the winding angles were also performed using the finite element method. As a result of the analysis of the buckling torque, the transmission torque and the bending natural frequencies calculated by the composite basic design theory and the torsional strength, the buckling analysis, and the natural frequency values according to the winding angles calculated by the finite element method, it was found that all the values were within the safe range. Therefore, the integral carbon fiber propeller shafts proposed in this study will contribute to the weight reduction for improving the fuel efficiency of automobiles in the future since they have the advantages of not only easy to manufacture due to its simple structure, but also higher specific stiffness than conventional steel propeller shafts.

Key words: carbon fiber propeller shaft; propeller shaft design verification; torsional strength analysis; buckling analysis; modal analysis;

INTRODUCTION

In recent years, automobile manufacturers have been urged to improve fuel efficiency by strengthening regulations on fuel consumption and automobile emissions, as the pollution problem in the world is emerging globally. Improvements to the fuel economy of automobiles include improvements in engine performance, improvement in efficiency of the power transmission system, reduction in running resistance, and weight reduction. Of these, research on engines, power transmission systems, and driving resistance has reached its limit and it is hard to expect further improvement in fuel efficiency. However, weight reduction of automobiles and automobile parts to lighten the weight of automobiles still has a lot of room for fuel economy improvement [1].

Particularly, the subject of interest in this study for the weight reduction is the propeller shaft part. The propeller shaft is an important part of the automobile that performs the steering function while directly transmitting the rotational force generated by the engine to the wheels to obtain high efficiency of the power transmission. There are two types of propeller shafts: two-stage separable and single body. Conventional two-stage separable propeller shafts are manufactured using steel, because it is difficult to manufacture as a single body because of the low specific stiffness, which is the mechanical property of the material. If the propeller shaft is manufactured as a single body using steel, since the bending first natural frequency is located within the operating frequency range, there arises a problem that the resonance occurs and the whirling vibration occurs. In addition, the conventional two-stage separable propeller shaft is more complicated to manufacture and the performance is poorer than the single body type.

In this study, to solve these problems, an integral single body propeller shaft was proposed using carbon fiber composite material (T700). Carbon fiber composites have the advantage that specific stiffness is four times greater than steel [2]. First, the integral propeller shaft was designed considering the assembly space of the car. Next, to verify the safety of the integral propeller shaft, the buckling torque, the transmission torque, and the natural frequency of bending were calculated by the composite basic design theory. As a result of the analysis of torsional strength, buckling analysis, and natural frequency analysis according to the winding angles, it was confirmed that the carbon composite propeller shaft product satisfies the engineering specifications of the conventional two-stage separable propeller shaft product.

DESIGN OF BASIC STRUCTURE OF CARBON COMPOSITE PROPELLER SHAFT

Propeller shafts, one of the power transmission devices for automobiles, must have a static torque transmission capacity of $350 kg_f \cdot m$ or more, a transmission speed of $650 rpm$ or more, and a diameter of $100 mm$ or less due to space constraints of the automobile. In this study, the propeller shaft is fabricated using carbon composite material. The stress components of each ply generated by the torque transmitted to the power transmission shaft are obtained by using the classical lamination theory for the basic design for manufacturing. First, the torsional buckling torque of a hollow shaft made of anisotropic material is obtained as follows.

$$T_c = 0.272(2\pi r^2 t)\left(E_x {E_h}^3\right)^{0.25}\left(\frac{t}{r}\right)^{1.5} \quad \textbf{(1)}$$

Here, t and r are thickness and radius, respectively, and E_x and E_h are the axial elastic modulus and the circumferential elastic modulus, respectively. These are obtained as follows according to the composite material stacking angle.

$$E_x = [\frac{1}{E_1}\cos^4\theta + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1}\right)\sin^2\theta\cos^2\theta + \frac{1}{E_2}\sin^4\theta]^{-1} \quad \textbf{(2)}$$

$$E_h = [\frac{1}{E_1}\sin^4\theta + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1}\right)\sin^2\theta\cos^2\theta + \frac{1}{E_2}\cos^4\theta]^{-1} \quad \textbf{(3)}$$

Where E_1 and E_2 are unidirectional elastic stiffness, and θ is a lamination angle. Next, the transmission torque T of the composite propeller shaft is obtained as follows

$$T = 2\pi r^2 {r_m}^2 t\tau_1 \quad \textbf{(4)}$$

In equation (4), r_m and τ_1 are the mean radius and the in-plane shear stress, respectively. Next, the bending moment is obtained in order to check the safety in the operation range of the propeller shaft made of the carbon composite material. The propeller shaft is assumed to be a simple support beam. Based on the Bernoulli-Euler Beam theory, it is obtained as follows.

$$f_{nbe} = \frac{\pi}{2L^2}\sqrt{\frac{E_x I_x}{m_1}} \quad \textbf{(5)}$$

In equation (5), I_x and m_1 are moment of inertia in the axial direction and mass of the fiber-resin composite per unit length, $m/L(kg/m)$ respectively.

ANALYSIS AND RESULTS OF PROPELLER SHAFT TUBE MADE OF CARBON COMPOSITE FIBER

Polymer composites have excellent specific strength and specific stiffness of materials and are used in automobile, aircraft, etc. In this study, propeller shaft of carbon composite fiber T700 and epoxy resin material was designed. In order to verify the validity of the propeller shaft design made of carbon composite fiber, buckling torque, transmission torque and bending natural frequency were calculated by theory, Also, the analysis of torsional strength, buckling, and natural frequency according to the winding angle were performed by finite element method.

Figure 1 shows a drawing view of an integral carbon fiber propeller shaft designed considering the assembly space of an automobile. The design dimensions of the inner diameter, outer diameter, and length are $\emptyset 66mm$, $\emptyset 74mm$, and $1664mm$, respectively. This propeller shaft is manufactured by a filament winding process using helical and hoop.

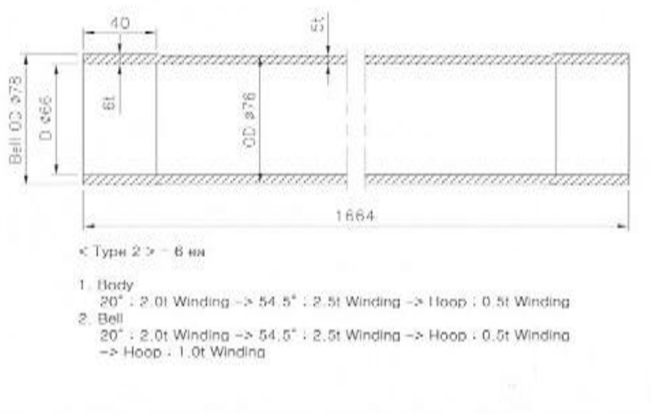

Figure 1: Design drawing of the Propeller Shaft made of Carbon Composite Fiber

According to the basic theory of composite design, the buckling torque, the transmission torque, and the natural frequency of bending of the integral carbon fiber propeller shaft are $646kg_f \cdot m$, $553kg_f \cdot m$, and $160rpm$, respectively. It can be seen that all satisfy the specifications of automobile propeller shaft. Figure 2 shows the three-dimensional model of a propeller shaft tube made of carbon fiber.

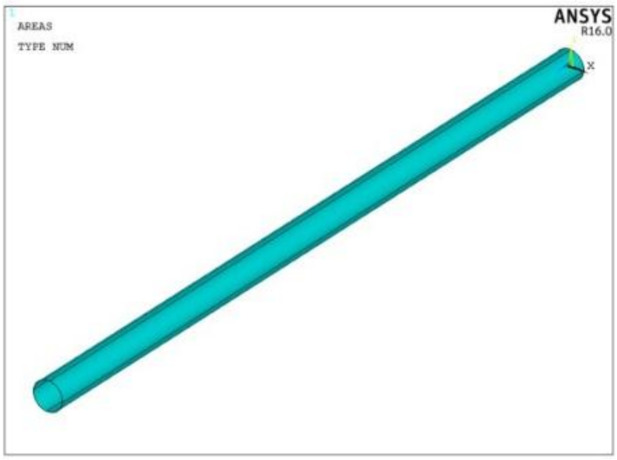

Figure 2: Three-dimensional model of the propeller shaft tube made of carbon composite fiber

Figure 3 shows the finite element model of the propeller shaft tube made of carbon fiber composite. Here, the element type is

Shell181 element to which the composite material property can be applied.

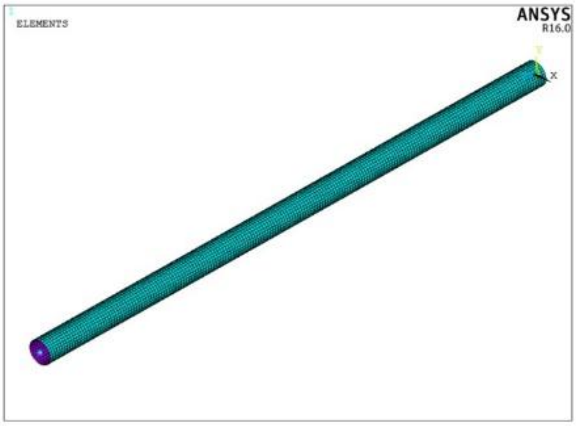

Figure 3: Finite element model of the propeller shaft tube made of carbon composite fiber

Table 1 shows the material properties of the integral carbon fiber propeller shaft, calculated using the rule of mixture.

Table 1: Materials properties of T700

Material (T700)		Property
Elastic modulus (GPa)	E_1	120.78
	E_2	8.55
	E_3	8.55
Shear modulus (GPa)	G_{12}	3.35
	G_{23}	2.68
	G_{13}	3.35
Poisson's ratio	ν_{12}	0.25
	ν_{23}	0.42
	ν_{13}	0.25

Table 2 shows the equivalent property values of the carbon composite material according to the winding angles of the carbon fibers when the carbon fibers and the resin are laminated. Here, the composite material properties are calculated in consideration of the lamination angle of the ply and the lamination thickness for each layer [4].

In this study, these equivalent property values were calculated using MSC PATRAN software [5].

Table 2: Equivalent material properties of T700

Material (T700)		± 30	± 50	± 60	90
Elastic modulus (GPa)	E_1	37.9	12.20	8.28	8.55
	E_2	8.28	12.20	37.9	120.8
	E_3	9.33	10.00	9.33	8.55
Shear modulus (GPa)	G_{12}	24.40	31.4	24.4	3.35
	G_{23}	2.85	3.02	2.85	2.68
	G_{13}	3.18	3.02	2.85	2.68
Poisson's ratio	ν_{12}	1.47	0.82	0.32	0.018
	ν_{23}	0.29	0.07	-0.22	0.25
	ν_{13}	-0.22	0.07	0.29	0.42

Figure 4 shows the displacement boundary conditions of the composite tube. One end of the tube was fixed in x, y, z direction constraint, and the other end was allowed to be twisted.

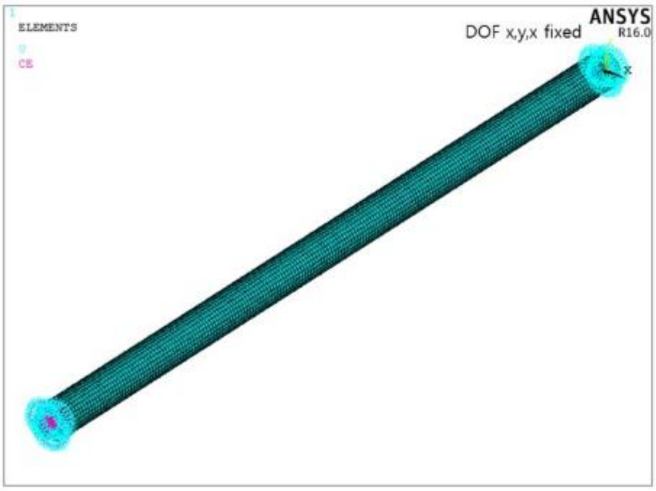

Figure 4: Displacement boundary conditions

Figure 5 shows the load boundary conditions. In this study, a torsional load of $3{,}500 kg_f \cdot m$ was applied to one end of the tube to determine the safety of the tube through calculating the torsional strength and the fracture index and buckling analysis of the tube depending on the winding angle.

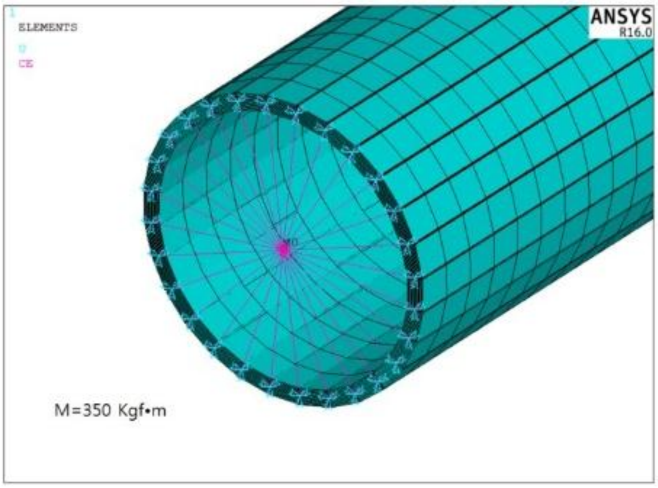

Figure 5: Load boundary conditions

Figure 6 shows the fracture index as a result of strength analysis according to the winding angle of the composite material. In Figure 6, when the winding angles are $\pm 20°$, $\pm 30°$, $\pm 45°$, $\pm 60°$, and 90° degrees, respectively, the fracture indices are 0.38, 0.27, 0.23, 0.30 and 0.39, respectively. It can be seen that the fracture index is the smallest when the winding angle is 45 degrees.

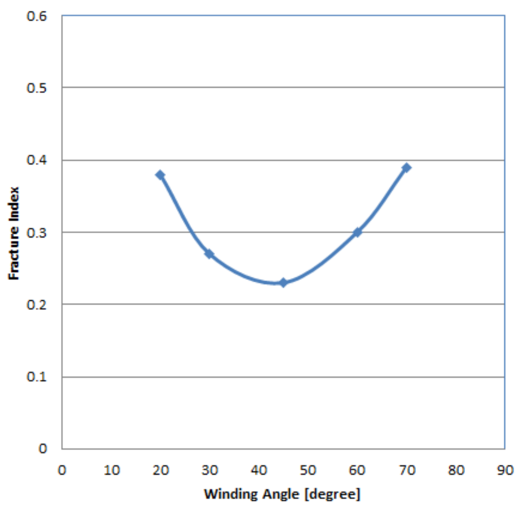

Figure 6: Fracture index by winding angle (Tsai-Wu Failure Criterion)

Figure 7 shows the displacement according to the winding angle. When the winding angles are $\pm 20°$, $\pm 30°$, $\pm 45°$, $\pm 60°$, and 90° degrees, respectively, the displacements are 12.8 mm, 7.86 mm, 6.11 mm, 7.86 mm, and 12.8 mm, respectively. It can be seen that the displacement is the smallest when the winding angle is 45 degrees.

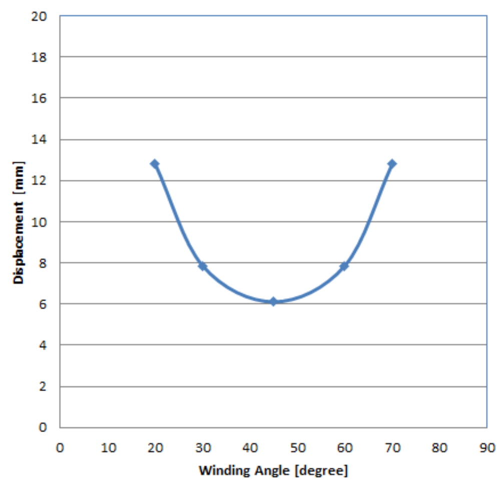

Figure 7: Displacement by winding angle

Figure 8 shows the buckling factor according to the winding angle. It can be seen that the buckling factors for the winding angles are 1.68, 1.98, 2.74, 3.35 and 3.83 when the winding angles are $\pm 20°$, $\pm 30°$, $\pm 45°$, $\pm 60°$, and 90° degrees, respectively. It can be seen that the larger the winding angle is, the larger it is.

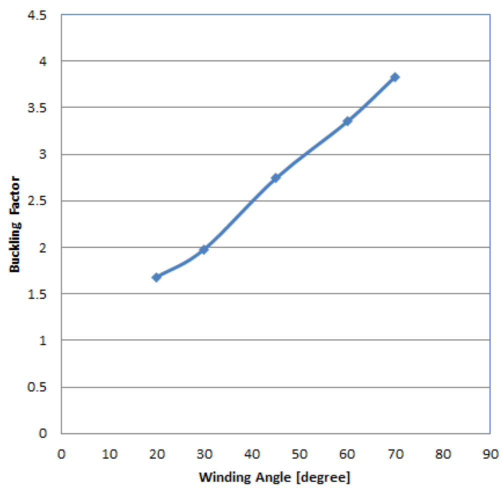

Figure 8: Buckling factor by winding angle

As described above, the fracture index and displacement according to the winding angle are the smallest at 45° degrees, and the buckling factor is larger when the winding angle is larger. Therefore, in this study, the winding angle was selected as 54.5° degrees considering the failure index and the buckling factor.

Figure 9 shows the fracture index of the carbon composite tube when the winding angle is 54.5° degrees. Here, the fracture index is 0.095 and the factor of safety is 10.5. The fracture index is less than 1 and it is safe. Also, since the factor of safety of composites is generally 3.0 ~ 4.0, carbon composite tube is about 2 ~ 3 times safer in this study.

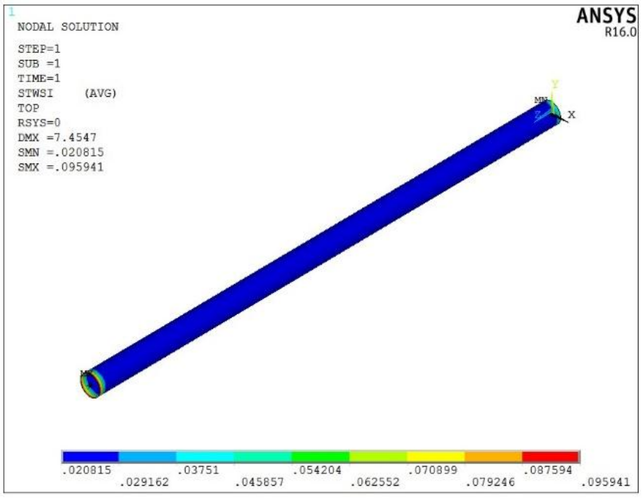

Figure 9: Fracture index at winding angle 54.5° degrees (Tsai-Wu Failure Criterion)

Figure 10 shows the displacement distribution of the carbon composite tube when the winding angle is 54.5° degrees. It can be seen that the deformed displacement is 7.86 mm.

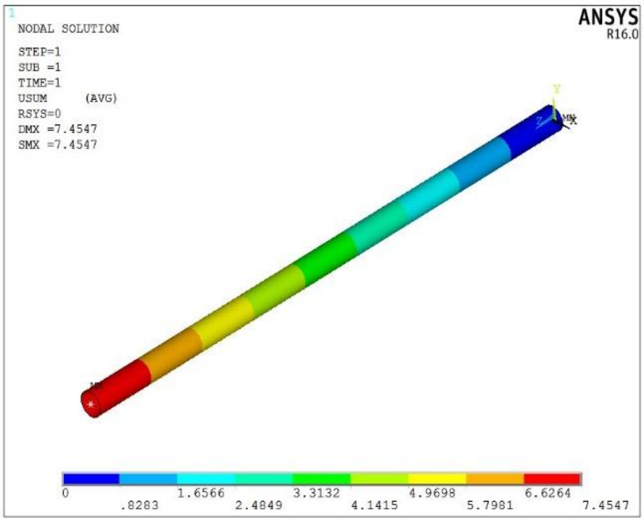

Figure 10: Displacement distribution at winding angle 54.5° degrees

Figure 11 shows the primary buckling mode of a carbon composite tube when the winding angle is 54.5° degrees. Here, the primary buckling load factor is 3.41. It can be seen that the safety factor is 3.41 since the buckling load factor is more than 1 and it's safe.

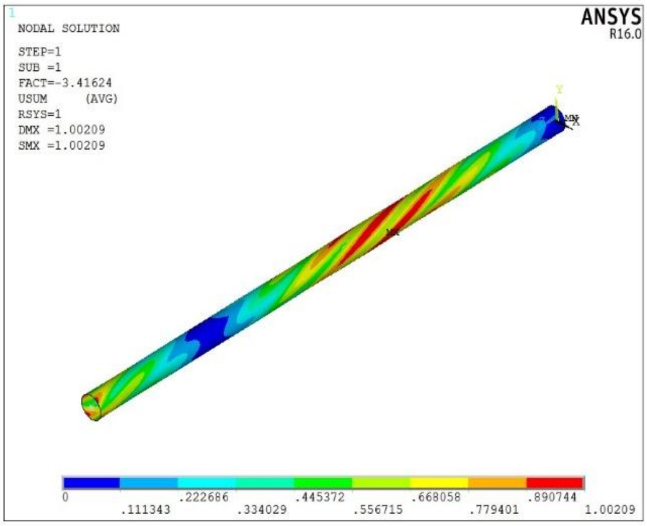

Figure 11: Primary buckling mode at winding angle 54.5° degrees

Figure 12 shows the first natural frequency due to bending of the carbon composite tube when the winding angle is 54.5° degrees. Here, the first natural frequency is 4.38 Hz (262.8 rpm). This is much lower than the rotational speed of a typical propeller shaft, so it can be seen that it deviates from the resonance frequency range.

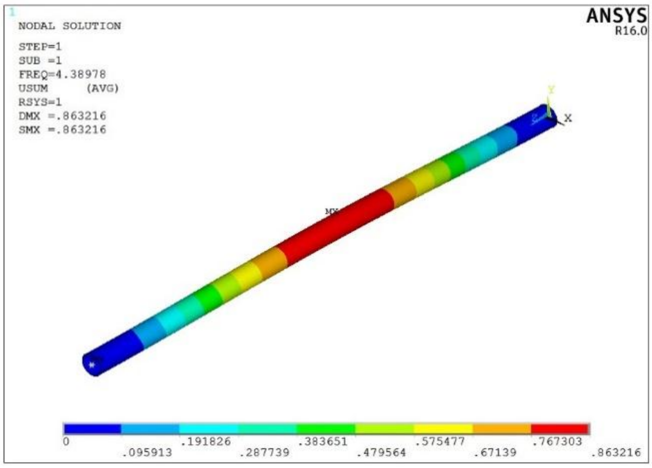

Figure 12: The first natural frequency mode due to bending at winding angle 54.5° degrees

As described above, in this study, an integral carbon fiber propeller shaft was designed to replace the two-stage steel propeller shafts for automobiles, and strength analysis, buckling analysis, and vibration analysis were carried out on the carbon composite tube of the designed integral carbon fiber propeller shaft. As a result, it was found that all of the engineering specifications for this propeller shaft product were satisfied.

CONCLUSION

In this study, the integral carbon fiber propeller shaft was designed considering the assembly space of the automobile In order to fabricate the designed integral carbon fiber propeller shaft tube, the winding angle was selected to be 54.5° degrees considering the fracture index and the buckling load factor according to the winding angle of the carbon fiber. As a result of fracture analysis, buckling analysis, and vibration analysis, the fracture index, buckling load factor, and first order natural frequency were 0.095, 3.41, and 4.38 Hz, respectively, to verify the safety of the integral tube. And all of them confirmed that they are within safety range. Therefore, the integral carbon fiber propeller shaft proposed in this study is expected to contribute greatly to the weight reduction for improving the fuel efficiency of automobile in the future because it is not only easy to manufacture due to its simple structure, but also has a greater specific stiffness than conventional steel propeller shafts

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