DEVELOPMENT OF COMPOSITE DRIVE SHAFT TUBE FOR AUTOMOTIVE INDUSTRY

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Abstract
Weight, vibration, fatigue, and critical speed limitations have been recognized as serious problems in drive shafts in automotive industry for many years. Conventional drive shaft is made up into two parts to increase its fundamental natural bending frequency. This present work deals with the replacement of conventional steel drive shaft with a composite counterparts. The benefits of eliminating the two piece shafts are significant reductions in weight, noise, vibration and harshness. In this work, one-piece propeller shaft composed of carbon/epoxy and glass/epoxy composites have been designed and manufactured for a rear wheel drive automobile. The performance measures are static torque transmission capability, torsional buckling and the fundamental natural bending frequency. The tubular composite shaft samples are being manufactured by using filament winding technique. To predict the torsional properties, fatigue life and failure modes of composite tubes for different fiber orientation angle and stacking sequence, finite element analysis (FEA) has been used. The predicted and experimental values has been reported for comparison. The next phase of work consists of optimization of shaft for the objective function as weight and fundamental natural frequency considering different stacking sequence and fiber orientation.

1 Introduction
Composite materials has become an important material for reducing weights, CO_2 emissions in the automotive industry because of increasing legal sanctions for limiting greenhouse gas emissions from vehicles. The automotive sector aims to conserve materials, energy and capacity. As a result the strength / density ratio that will increase and fuel consumption will decrease. Substitiuting composite structures for conventional metallic structures has many advantages because of higher specific stiffness and higher specific strength of composite materials. The purpose of this study is to develop a fiber-reinforced polymeric composite based propeller shaft tube that can be used in commercial vehicles to replace the conventional two-piece steel drive shafts with a single piece composite one. The goal of this ongoing study is to attain optimized designs at minimum weight.

The first composite cardan shaft was developed in 1985 by the Spacer-joint division of the Dana Company for Ford Econoline Van models [1]. In addition, many researchers have been conducted research to develope composite drive shafts. The application of composites in the automotive industry to produce composite elliptical springs, driveshaft and leaf springs are described in the study by Weeton et al. [2]. Beardmore and Johnson investigated the potential of composite materials, the possibility of using polymer matrix composites in suspension applications[3] . Faust et al. [4] reported development of light weight drive shaft in their work for automobile industry. Badie M.A. et al. [5] investigated the effect of fiber orientation angles and stacking sequence on torsional stiffness, natural frequency, buckling force, fatigue life, and failure modes of composite tubes. There are many parameters that affect the performance of composite drive shafts such as orientation of the fibers, stacking sequences, layer thicknesses and number of layers. Finite element analysis (FEA) was used to estimate the fatigue life of composite cardan shaft (CDS) using linear dynamic analysis for different stacking sequences. Mahmood M. et al.[6] studied the effect of fiber orientation on the fatigue strength of composite tubes.Based on experimental work, composite tubes exhibited a higher load carrying capacity and torsional stiffness with the fiber orientation of ± 45°[6]. Bert and Kim[7] developed an analytical solution to calculate the torsion buckling of the composite driveshafts. They can calculate the composite driveshaft's torsional buckling load of torsion and torsion-bending taking into account the effect of axial stiffness and bending moment. Chen and Peng [8] have developed a method using finite elements to study the stability of composite shafts under combined loading conditions. With this method, they predict the critical axial load of the composite driveshaft under rotation. Leslie et al.[2] studied the design of four single-piece drive shaft that have 1270 mm long, 76.2 mm diameter from composite, aluminum, steel, and titanium materials. The metallic driveshaft has heavy weight, low critical speed and vibration characteristics. In 1960, Mazziotti [9] published a study of torsional vibrations associated with power trains. By specifying the sources of non-uniform motion causing the vibration problems, they have established a relationship with the natural frequency value of the power trains. In their study, rubber springs, flywheels, flexible couplings and other natural frequency reducing additives were proposed since the technology of designing and producing carbon composite shafts in the 1960s were not possible. Reddy et al. performed the design and performance comparison of 3 cardan shafts with 1250 mm length of glass / epoxy, carbon / epoxy, boron / epoxy materials to meet 3500 Nm of torque. After meeting all the requirements such as static, free vibration and torsional buckling analysis, they compared the optimum stacking order and the optimum four layers of glass / epoxy, carbon / epoxy and boron / epoxy composite cardan shaft according to weight and wall thickness. It has been found that a stacking sequence is a significant effect on fatigue by forming a hybrid model containing both carbon-epoxy and glass-epoxy. A weight loss of 97% compared to the steel drive shaft was achieved at maximum[10] . Finite element analysis was used to design a composite cardan shaft containing carbon and glass fibers in an epoxy matrix. A 0°, 45° and 90° configuration of a layer of carbon-epoxy and three layers of glass epoxy was used. The four layers arranged as + 45° glass, -45° glass, 0° carbon, 90° glass. Rousseau et al. [11] investigated the damage behaviors of filament winding tubes under various loads experimentally. They have characterized the effect of the filament winding patterns on the mechanical performance of composite tubes. Cohen et al.[13] investigated the relationship between fiber volume ratio and damage pressure in filament winding composite structures. In another work by Cohen [14] , the filament winding parameters have shown effects on the production and design quality of composite structures. They have examined the influence of these parameters on strength, fiber volume ratio and fiber stiffness.

A driveshaft is a rotating tube that transmits power from the engine to the differential gear of a rear wheel drive vehicles. As the resonant frequencies of the cardan shafts produced from steel material can not reach 6500 rpm, 1.5 m long shafts are manufactured in two parts to increase the fundamental bending natural frequency. However, the two-piece shaft is complex, costly and heavy. Also, the critical speed limits the minimum tube diameter and maximum wall thickness, as well as the maximum permissible length of the drive shaft.

The two piece steel drive shaft consists of three universal joints, a center supporting bearing and a bracket, which increase the total weight of a vehicle as shown in Figure 1. A cardan shaft must perform the following functions.

a) It must transmit the torque form transmission to the differential gear box
b) The drive shaft must also be capable of rotating at very high speed as required by the vehicle.
c) The drive shaft must also be operate through constantly changing angles between the transmission, the differential and the axels.
d) The length of the drive shaft must also be capable of changing while transmitting torque.

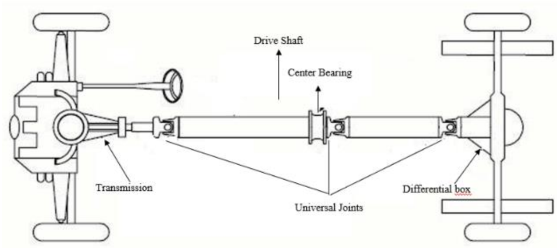


Figure 1. Two-Piece Driveshaft in a Rear Wheel Drive Vehicle[10]

There are two different approaches for analyzing and designing the composite shaft of an automobile. The first approach is based on the strength of materials resulting in simplified, closed-form analytical expressions. Another approach is modelling the shaft with Finite Element Analysis (FEA). Filho et. al. [16] tested different configurations of carbon epoxy and compared with the Finite Analysis Models (FEM). The numerical and experimental results showed good fit for the torque capacity and the first natural frequency. However, it is reported that the FEM of [+-89/+-45] configuration diverged by 50% from the experimental results. Sevkat et al.[17] investigated the torsional behavior of hybrid shafts (glass+carbon) experimentally and numerically. They have reported that the stacking sequence highly affects the torsional behavior and it can be seen as a critical parameter. Moreover, the FEA results are compared with experimental results and the maximum divergence is reported to be 25%[17]. Ding, et al. [18] worked on the validation of FEM based modal analysis comparing with the experimental modal analysis of CFRP shaft. Impact hammer test is conducted to find the natural frequency of the shaft with steel joints at both ends. The model and the experimental results showed consistency with up to 25% fluctuation. When it comes to the torque capacity of the shaft, failure criteria of Lamina shall be well defined to make good prediction on capacity. In literature, one of the most used failure criteria is Tsai-Wu which provides good results for anisotropic materials [20]. Tsai-Wu criteria doesn't check for only a single failure mode, the interactive combination of failure modes can be handled [20] .Thus, to obtain the Tsai-Wu limits, a comprehensive knowledge on the material is required. On the contrary, stress and strain limits are simpler to check if the material properties are not very well defined. Yet, one should be aware of limitations of stress and strain limit criteria such as under-predicting the strength and lack of consideration of the combined actions of in-plane stress [21].

2 Manufacturing Techniques

Carbon/epoxy and glass/epoxy material systems are being used to fabricate composite drive shafts within the present study. Carbon/glass hybrid fibers are also considered to optimize performance requirements against cost of the product in tube design. The filament winding method is being used because of the tube geometry. This allow the design to be optimized for weight, torsional stiffness, axial stiffness, bending stiffness or other structural properties. Products with different mechanical properties are being obtained by continuous embedding of continuous fibers in different angles.

In filament winding method, when the mandrel is placed on the winding bench, then the car moves back and forth at appropriate speeds to rotate the mandrel to be folded over. The computerized control system used in CNC winding looms controls the movements and ensures the precision of the winding process. After the wrapping process is finished, a plastic film that does not stick to the piece is wrapped on the piece. This allows the part to be compressed and the film is removed after the curing process is finished. After winding, the mandrel is placed in a furnace. The thermoset resin material, which is heated to provide a specific heating profile, cures and hardens after a while. The mandrel is then removed by placing it in a removal press.

3 Analysis of The Drive Shaft

In this study, Finite Element Model (FEM) is being used to predict the behavior of the drive shaft. FE models were created to investigate the effect of different fiber types on the torsional strength of the shafts for both carbon/epoxy and glass/epoxy systems. At this stage, constant angle stacking is applied for all plies and the model is tried to be validated. On this ongoing research, carbon/epoxy and glass/epoxy based shafts are being produced and modal parameters are measured using impact hammer test. The experimental data is compared with the model and analytical results. In the next stage of the research, the FE model will be calibrated and used in a framework to optimize the shaft for weight and cost effectiveness. The same framework will be used to design optimum hybrid stacking of carbon/epoxy and glass/epoxy configuration.

Table 1. Material Properties and Geometry of carbon/epoxy and glass/epoxy composites

Carbon/Epoxy Composite Properties			**Glass/Epoxy Composite Properties**		
E1	110	GPa	E1	40	GPa
E2	10	GPa	E2	11.5	GPa
G12	4	GPa	G12	4	GPa
$v12$	0.33		$v12$	0.287	
T12	0.08	GPa	T12	0.08	GPa
Geometry of Carbon Fiber Based Shaft			**Geometry of Glass Fiber Based Shaft**		
Inner diameter	70	mm	Inner diameter	70	mm
Outer diameter	82	mm	Outer diameter	82.6	mm
Length	1535	mm	Length	1540	mm

The design sequence and the number of layers will meet the requirements such as torsional strength, critical torsional buckling load and minimum natural frequency. In this study, the main goal is to design composite drive shafts to withstand the maximum transfer torque and rotational speed values in light commercial vehicles and produced by filament winding method. In the filament winding method, the optimum winding angle and number of turns are selected to achieve the intended operating conditions.

3.1 Analytical Calculations

Analytical calculations are being done to obtain the first mode frequency and the critical buckling torque. The bending natural frequency is defined as [22];

$$f_n = \frac{\pi}{2} * \sqrt{E_{xeff} * \frac{I}{mL^4}} \tag{1}$$

where m: Mass per unit length, E_{xeff}: Effective modulus in x direction, I: Moment of inertia around the orthogonal axis to x, L: Length of the shaft

Effective moduli in x, E_{xeff} and hoop direction, E_{heff} are determined as follows[23];

$$Q_{11} = \frac{E_1}{1-\nu_{12}^2 * \frac{E_2}{E_1}} \qquad Q_{22} = \frac{E_2}{1-\nu_{12}^2 * \frac{E_2}{E_1}}$$
$$Q_{12} = Q_{21} = \frac{E_2 * \nu\_12}{1-\nu_{12}^2 * \frac{E_2}{E_1}} \qquad Q_{66} = G_{12} \tag{2}$$

Given that Tr is the transformation matrix;

$$\overline{[Q]} = [Tr(\theta)]^{-1}[Q] *= [Tr(\theta)]^{-T} \tag{3}$$

$$A_{ij} = \sum_{k=1}^{n} [\overline{Q_{\iota,J}}]_k \tag{4}$$

$$E_{xeff} = [A_{11} - A_{12}^2/A_{22}] * 1/t \qquad E_{heff} = [A_{22} - A_{12}^2/A_{11}] * 1/t \tag{5}$$

where t: total thickness, A: In plane stiffness matrix, Q: Reduced stiffness matrix, Another important parameter that need to be checked is the buckling torque, which is critical when the wall of the shaft getting thinner relative to the radius. Buckling torque, T_{cr} is highly affected by the hoop resistance as it can be seen in the formula below [7]

$$T_{cr} = (2\pi r_m^2 t)(0.272) * (E_{xeff} E_{heff}^3)^{0.25} * \left(\frac{t}{r_m}\right)^{1.5} \quad (6)$$

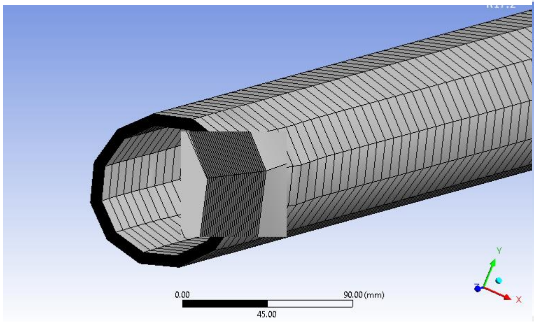
Finally, the maximum torque (T_{max}) capacity that the drive shaft can transferred is simply related to the shear strength and the geometry of the shaft.

$$T_{max} = \tau_{12} * \frac{J}{r_o} \quad (7)$$

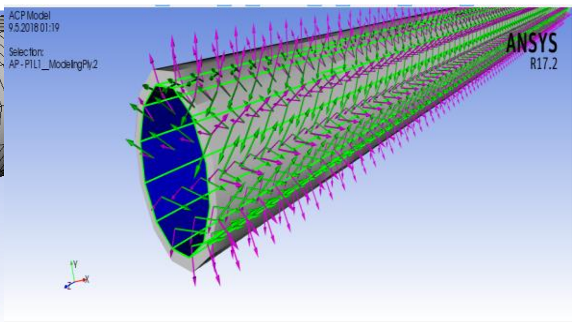
where r_m:mean radius, J:Polar moment of area, τ_{12}:Shear strength of the composite, r_o: outer radius of the shaft

3.1.1 Finite Element Analysis

In this study, the finite element analysis is being done for an carbon/epoxy and glass/epoxy composite shaft. The material properties and the geometry of the shafts are given in Table 1. Stacking sequences are {$[\pm55]_{15}$,t=0.2mm} and {$[\pm55]_{10}$,t=0.315mm} respectively, for carbon/epoxy and glass/epoxy shafts. Stacking angle of 55 degree is decided after prior numerical model trials for it's better performance under torsion. The model is created in ANSYS v17.2 [24] with ACP PrePost tool. The main goal behind creating simple configurations is to calibrate and validate the modelling technique, winding and testing processes. In the ACP model of ANSYS, the plies added starting from a constant mandrel diameter(d=70mm) and stacked in outward normal direction(Figure 2-b). Every ply is defined individually and this structure is converted into solid model by the software (2-a). This way of modelling enables the ply-wise examination of the failure and behavior. At this stage of the study , the model is created by excluding the nonlinear effects and material dampings. 3D model consists of 8-node 3D Solid Elements with orthotropic material properties (SOLID185) [19].



a)

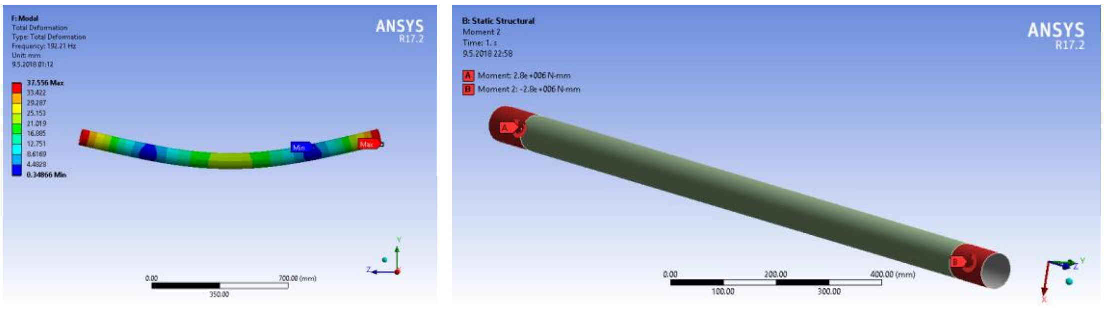


b)

Figure 2. a) Solid model meshing **b**) Fiber directions and plying orientations

3.1.2 Modal Analysis

Modal behavior of the shaft is important for its applicability in vehicles since the operational frequency must not coincide with the natural frequencies of the shaft. Moreover, modal analysis results may provide useful information on the validation of the numerical model. No boundary condition is defined for the modal analysis. Thus first 6 modes are omitted which resulted 0 Hz due to rigid body motion.



a) b)

Figure 3. a) 1st Mode Shape of Composite Shaft (f_{carbon}=191Hz , f_{glass}=126Hz), **b**) Torque application on the shaft

3.1.3 Torsional Capacity

Torsional capacity of the shaft is the first property to be checked for the applicability of a design. The shaft should transfer the torsional force at one end to the other end. At both ends, some kind of socket type joint would be formed. To predict the torsional capacity, same magnitude of toque applied in opposite directions. This moment is applied to the innermost ply and uniformly distributed through the 100mm length from each end (Figure 3-b). This distribution is done to model the stress and strain distribution from load application point to the other layers better. When the torsion was applied through the edge line of the innermost layer, there were high stress concentration which was misleading to find out real straining points and failure limit. No other boundary condition is required to be defined for torsion analysis.

Once the geometry and stacking sequence defined in the model, torsional capacity is found by changing the applied moments until one of the failure limits violated. At this stage for both of the shafts, all built-in available failure criteria are controlled. For advanced failure criteria, detailed tests are needed to be conducted on materials. Therefore, stress and strain limits are the simplest limits to check. It should be noted that stress and strain failure criteria may lead to conservative results[5]. However, by using the built-in failure limits for similar materials provided in ANSYS, other failure criteria are considered as well in view of the fact that the results may deviate from correct limits. Table 2 lists the criteria that are used for the failure state.

Table 2. Failure Limits for the Torsional Capacity Analysis

	Failure Type
Max Strain	Fiber Failure
	Matrix Failure
	In-Plane Shear Failure
Max Stress	Fiber Failure
	Matrix Failure
	In-Plane Shear Failure
Tsai-Wu	Tsai-Wu
Tsai-Hill	Tsai-Hill
Hoffman	Hoffman
Hashin	Fiber Failure
	Matrix Failure
Puck	Fiber Failure
	Matrix Tension /Compression Failure
	Matrix Shear Failure

4 Impact Hammer Test for Modal Parameters

Impact hammer test is conducted on each of two shafts. The shaft is supported at four points with low stiffness supports. 3 piezoelectric accelerometer is attached on the shaft. Then impact is given by impact hammer. There are no additional boundary conditions. Test results are given in Table 3 for both of the shafts.

Table 3. Results and Comparison Table

	Comparison Table			
		Analytical	**FEM**	**Test**
Carbon	**1st Mode(Hz)**	212.8	191	110
	Max Torque(Nm)	4355	3420 (Max Strain)	-
	Critical Buckling Torque(Nm)	19719	22600	-
E-Glass	**1st Mode(Hz)**	176	126	100
	Max Torque(Nm)	2016	2800 (Tsai-Wu)	-
	Critical Buckling Torque(Nm)	16111	18560	-

5 Conclusion

This work deals with the design, material selection, modelling, optimization of stacking sequence, fabrication and performance testing of composite drive shaft for a small vehicle. It was revealed that it is possible to reduce the weight of the drive shaft considerably by optimizing the design parameters by satisfying the all constraints. This study aims to compare the performance of the composite drive shaft over steel drive shaft and suggested the suitability of composite materials in the automobile industry. Carbon/epoxy and E-glass/epoxy shafts are modeled, manufactured and tested for the natural modes. The drive shaft finite element model was prepared in finite element commercial software ANSYS. The FE models were tried to be validated by looking at the first natural mode frequency. The findings are tabulated in Table 3. It may be observed that FE model of the E-Glass give more reasonable estimation of the test results.
The static, free vibration and torsional buckling analysis are performed, which are critical parameters for rotating elements like drive shafts. Finally, with the replacement of one piece composite drive shaft with the two piece conventional one, the potential weight reduction is expected to be around 45 % .

Some final comments on results are;
-Epoxy carbon shaft FEM results leads to lower torsion capacity than analytical solution, it may be due to the conservative nature of the max strain criteria [5].
-The FE model will be improved by using calibration and torque tests that could be conducted next, would allow to better validate the FE model.
-Multiple identical specimens may be produced and tested to have a better understanding of winding related uncertainties.
-Critical buckling torque is not an important issue for this specific work since it is clearly much higher than the target design torque.

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