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Investigation of Hybrid Composite Drive Shaft under Tensile, Bending and Torsion Testing

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ABSTRACT:

In this research work, an attempt has been made to develop drive shafts using composite materials such as E-Glass, Carbon fibers and hybrid composite layers of E-Glass, Carbon and S-Glass with different fiber orientations. Strength aspects of the fabricated composite drive shafts are studied by conducting tensile, bending and torsion tests. From the investigations, it is found that the hybrid composite drive shaft has shown very good strength properties along with the desired flexural stiffness when compared to other composite shafts.

KEYWORDS:

Composite materials; E-Glass; S-Glass; Drive shaft; Hybrid composite; Torsion test

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1. Introduction

Composite material is an assemblage of two materials of different natures which allow us to obtain a material whose performance characteristics is greater than that of the constituent components. A composite material is made by combining two or more materials - often ones that have very different properties. In the most general case, a composite material consists of one or more discontinuous phases (reinforcement) distributed in one continuous phase (matrix). The biggest advantage of modern composite materials is that they are light as well as strong. By choosing an appropriate combination of matrix and reinforcement material, a new material can be made that exactly meets the requirements of a particular application. An automotive drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle. The torque capability of the drive shaft for passenger cars should be larger than 3500 Nm and the fundamental bending natural frequency should be higher than 9200 rpm to avoid whirling vibration.

Drive shafts are usually made of solid or hollow tube of conventional materials such as steel or aluminium [1]. When the length of a steel drive shaft goes beyond 1.5m, it is manufactured in two pieces to increase the fundamental natural frequency. The natural frequency is inversely proportional to the square of the length and proportional to the square root of the specific modulus. The two-piece steel drive shaft consists of three universal joints, a supporting bearing at center and a bracket, which increases the total weight of an automotive vehicle and decreases fuel efficiency. The nature of composites, with their higher specific elastic modulus, e.g. carbon/epoxy exceeds four times that of aluminium [2], enables a replacement of the two-piece metal shaft with a single-component composite shaft which resonates at a higher rotational speed, and ultimately maintains a higher margin of safety.

For automotive applications, the first composite drive shaft was developed by the Spicer in 1985 [3]. A composite drive shaft offers excellent vibration damping, cabin comfort, reduction of wear on drive train components and increases tire traction. In addition, the use of single torque tube reduces assembly time, inventory cost, maintenance, and part complexity. Abu Talib et al. [4] implemented finite element analysis (FEA) to design composite drive shafts incorporating carbon and glass fibers within an epoxy matrix. A configuration of one layer of Carbon-Epoxy and three layers of Glass–Epoxy was used. Their results showed that the buckling strength is the main concern over shear strength in the drive shaft design. Arun and Vinod [5] replaced conventional two pieces steel drive shaft in to a single piece Hybrid Aluminium E-Glass/Epoxy composite drive shaft for an automotive application. They have considered the torsion strength, torsion buckling and bending natural frequency as the deciding criteria for the drive shaft. Further they have highlighted that increasing the number of layers enhanced the maximum static torsion approximately 66% for $[+45/-45]_{3S}$ laminates higher than the pure aluminium and mass reduction of 42% compared with of steel drive shaft.

Rangaswamy et al. [6] designed and analysed a composite drive shaft for power transmission applications. A single-piece drive shaft for rear wheel drive automobile was designed optimally by them using E-Glass/Epoxy and High Modulus (HM) Carbon/Epoxy composites. Further they have used Genetic Algorithm (GA) to minimize the weight of shaft which was subjected to the constraints such as torque transmission, torsion buckling capacities and fundamental natural frequency. The results of GA were used to perform the static and buckling analysis using ANSYS software and suggested that the stacking sequence of shaft strongly affects the buckling torque. Belawagi et al. [7] designed a single-piece composite drive shaft for automotive applications was designed and analyzed using ANSYS software respectively for E-Glass/Epoxy and HM-Carbon/Epoxy composites with the objective of minimization of weight of the shaft which is subjected to the constraints such as torque transmission, torsion buckling strength capabilities and natural bending frequency. Cylindrical local coordinate dataset has been defined in this research work to align the material direction of the composite lay-up and to apply end supports and loading. Comparison of drive shaft with steel and composite material by the authors has shown that composite shaft gives advantages in terms of strength, weight reduction and ultimately power consumption in automobile.

A design method and a vibration analysis of a Carbon/Epoxy composite drive shaft was presented in [8]. The design of the composite drive was focussed on the shaft and its coupling. Some parameters such as critical speed, static torque, fiber orientation and adhesive joints were studied. Tsai-Hill failure criterion was implemented by the authors to control the rupture resistance of the composite shaft and then they have carried out its critical speed analysis and modal analysis using ANSYS. The substitution of composite drive shaft has resulted in 72% weight reduction compared to conventional steel shaft. Furthermore, results revealed that the orientation of fibers had great influence on the dynamic characteristics of the composite shaft. Pollard [9] studied different applications of composite drive shafts for automotive industry. He compared the advantages and disadvantages of them at various conditions. Rastogi [10] implemented a FEA approach to design and analyze a composite drive shaft with its couplings in different conditions. Rangaswamy et al. [11] optimized and analyzed a single-piece composite drive shaft using GA and ANSYS. They reported that the fiber orientation of a composite shaft strongly affects the buckling torque. Kumar [12] performed an optimum design and analysis of a composite drive shaft for automobile application using GA. He optimized the design parameters with the objective of minimizing the weight of the composite drive shaft.

Chowdhuri et al. [13] replaced a two-piece steel drive shaft by a single-piece steel shaft. They proposed two different designs consisting of Graphite/Epoxy and aluminium with Graphite/Epoxy. Badie et al. [14] conducted FEA to study effects of design variables on the drive shaft’s critical mechanical characteristics and fatigue resistance. They found out that stacking sequence has an obvious effect on the fatigue resistance of the drive shaft. A review of hybrid composite shaft can be found in [15]. From the literature review, it is established that there is only limited number of studies relating to experimental tests of composite shafts and thereby evaluate their tensile, bending and torque performance. This paper details the performance of composite drive shafts which were manufactured using E-Glass, Carbon and S-Glass fiber reinforcements in Epoxy matrix under tensile, bending and torque loading. Based on the test results, an optimum combination of composite layers is determined by investigating the failure strength and stiffness.

2. Composite drive shaft specimens

Epoxy LY556 of 100g is made to water consistency and the respective mixing ratio of 10 g of Hardener HY951 has been taken in a bowl and heated to make it into liquid form and then both are mixed and well stirred. The releasing agent is applied on the PVC pipe which is already made for this purpose according to the dimensions. The fibers were wound according to the winding angles as 0/90° and ±45°. The epoxy and hardener solution is then applied over the wound fibres which were hand-laid on the PVC pipe. Curing was done at 150 °C for 2 to 3 hours. The dimensions of the specimens were taken as per ASTM standard E2207 for bending, torsion and tensile test. A summary of geometry and composite material specification is given in Table 1. Test specimens were prepared from seven different composite materials and layer orientations as illustrated in Table 2 and are considered in this experimental investigation.

Table 1: Materials & geometry of fabricated composite shaft

Description	Value
Length	1000 mm
Inner diameter	44 mm
Outer diameter	50 mm
Fiber	300 gsm E-Glass
Matrix	100 g Epoxy (LY556) 10 g Hardener (LY951)

Table 2: Composite drive shaft specimen numbers

Specimen #	Composite stack & fiber orientation
CDS1	0/90 E-Glass
CDS2	0/90 E-Glass / ±45 Carbon
CDS3	0/90 E-Glass / 0/90 Carbon
CDS4	0/90 Carbon / 0/90 E-Glass
CDS5	±45 E-Glass / ±45 Carbon
CDS6	±45 Carbon / ±45 E-Glass
CDS7	0/90 E-Glass / 0/90 Carbon / 0/90 S-Glass

3. Results and discussions

Tensile tests on the drive shafts of various composite materials are conducted to evaluate the mechanical properties such as ultimate breaking load (F_{max}), maximum displacement at ultimate breaking load (δ_{max}), ultimate tensile stress (σ), % of elongation (ε) and yield stress (σ_y). Tensile specimens had a gauge length of 270 mm are tested. Yield stress has been calculated by means of offset method as per ASTM E8 at 2% strain offset. The tests have been conducted in TAAL Ltd., Hosur, Tamilnadu using AUTOMake Universal Testing Machine. The fabricated composite drive shaft specimens before and after tensile testing are shown in Fig. 1. Fig. 2 shows a sample load vs. displacement curve for hybrid composite drive shaft.Table 3 provides the tensile test output data for the composite drive shafts for seven combinations of the composite materials.

Hybrid composite shaft has higher ultimate tensile strength as compared to other composite drive shaft specimens. An interesting observation had been made that the reversing of the fiber orientation does not have any significant effect on the mechanical properties of the drive shafts. The maximum displacement found in the composite drive shaft is higher for the case of ±45° E-Glass/Carbon fiber, which indicates that the elastic nature of the particular composite. The ultimate tensile stress is lower for the 0/90° E-Glass and is gradually increased as an additional layer of new materials are presented in the composition. The ultimate tensile stress of hybrid composite material is found to be doubled as compared to the drive shaft made from 0/90° E-Glass. Due to the presence of S-Glass fiber and its orientation, the yield stress of the hybrid composite drive shaft is higher than the others.

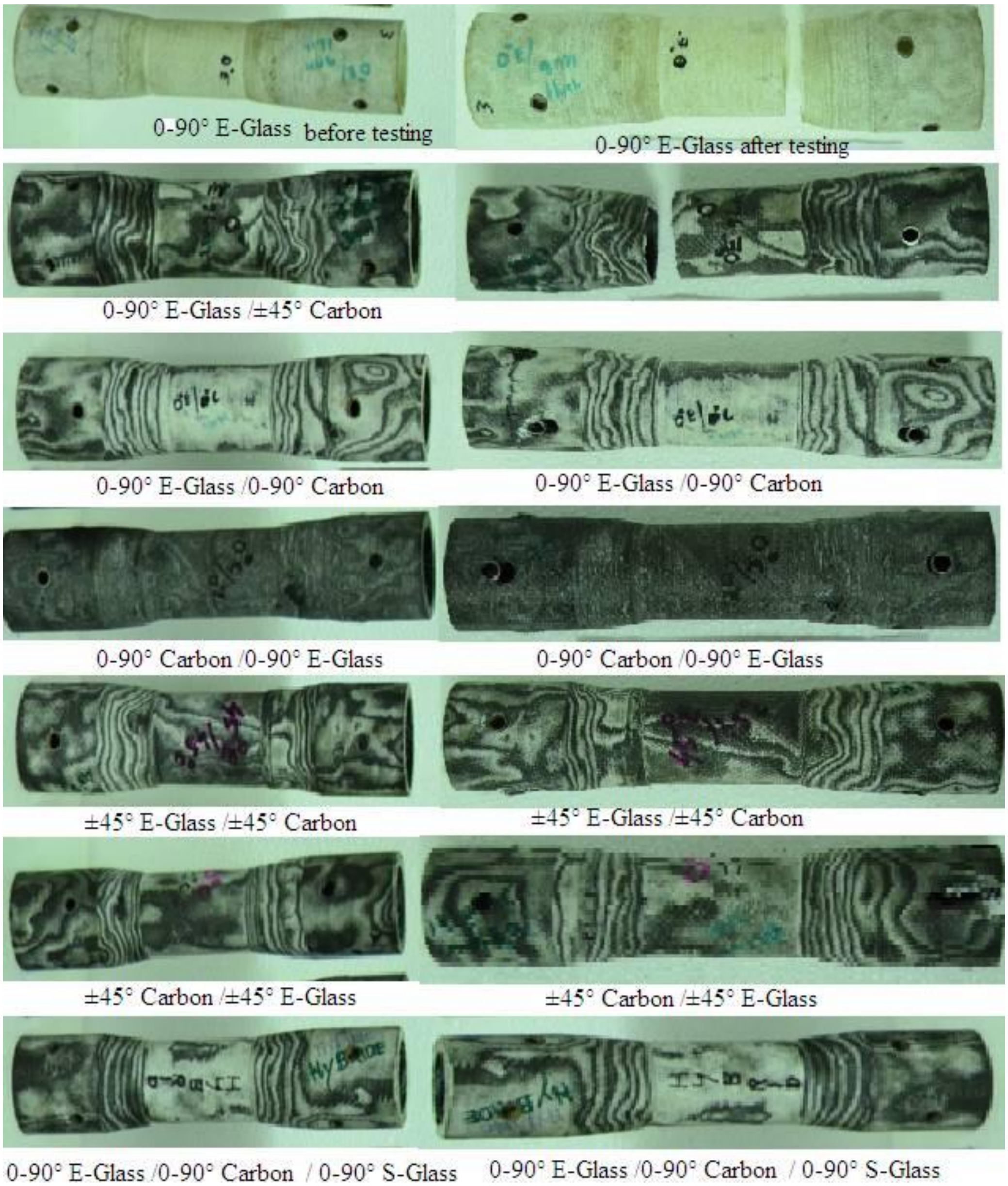

Fig. 1: Composite drive shaft specimens before & after tensile test

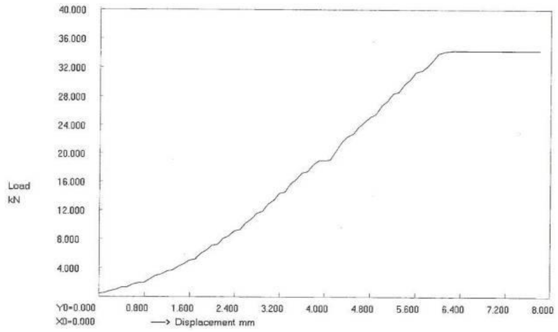

Fig. 2: Load vs. Displacement for hybrid composite drive shaft

Table 3: Tensile test results

Specimen	F_{max} (kN)	δ_{max} (mm)	σ (MPa)	ε (%)	σ_y (MPa)
CDS1	24.69	5	82	0.719	82
CDS2	26.84	5	101	0.722	101
CDS3	28.52	5	108	0.741	108
CDS4	28.52	5	108	0.741	108
CDS5	27.46	11.8	120	1.852	120
CDS6	27.46	11.8	120	1.852	120
CDS7	34.32	6.20	150	1.852	150

Three point bend test has been conducted on test specimens of various composites to determine the bending strength properties such as breaking load (F_{max}), maximum lateral displacement (δ_{max}) and ultimate tensile stress (σ). The tests were conducted until the initiation of the first visible cracks on the outer surface of the composite specimens. The bending test setup for one of the composite drive shaft specimen is shown in Fig. 3.The test results are summarised in Table 4. The bending properties of hybrid composite shaft specimens are nearer to the properties of steel shaft.

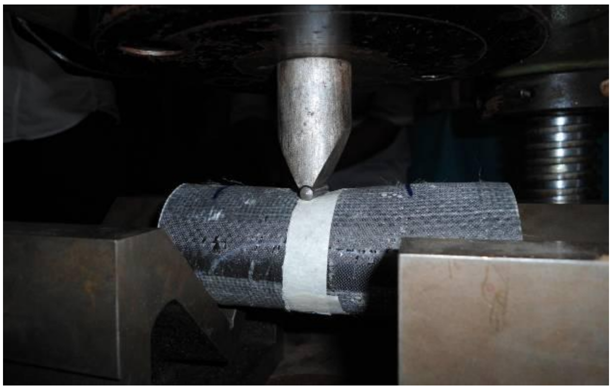

Fig. 3: Bending test setup and composite drive shaft specimen

Table 4: Bending test results

Specimen	F_{max} (kN)	δ_{max} (mm)	σ (MPa)
CDS1	2.77	4.7	6
CDS2	4.60	4.8	10
CDS3	7.51	6.5	25
CDS4	5.48	4.9	18
CDS5	7.24	5.6	24
CDS6	8.12	10.6	28
CDS7	8.71	11.5	29
Steel	13.97	21.1	53

Torsions tests have been carried out for the prepared samples of various composite materials to investigate the static and dynamic characteristics of the composite drive shafts. Fig. 4 shows a schematic representation of the test specimen after static torque testing. Fig. 5 shows the torque test results for various composite drive shafts. It is concluded that the hybrid composite drive shaft has the capability of taking large torque as compared to other composite materials considered in this research work. Based on the Scanning Electron Microscopy of post-test specimen as shown in Fig. 6, the nature of failure occurred in the composite drive shafts are brittle nature.

Fig. 4(a): Torsion test setup and composite drive shaft specimen

Fig. 4(b): Composite drive shaft specimen failed in torsion test

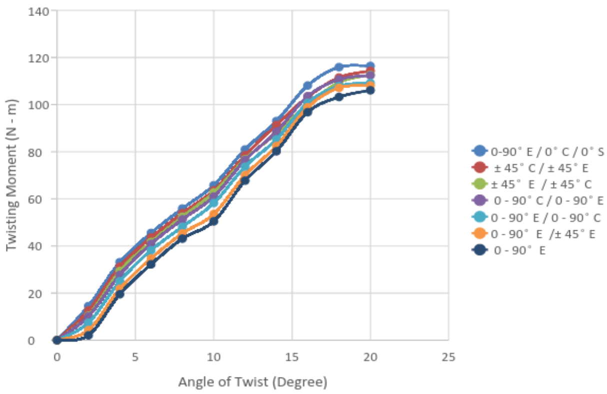

Fig. 5: Angle of twist vs. Torque for the tested composite shafts

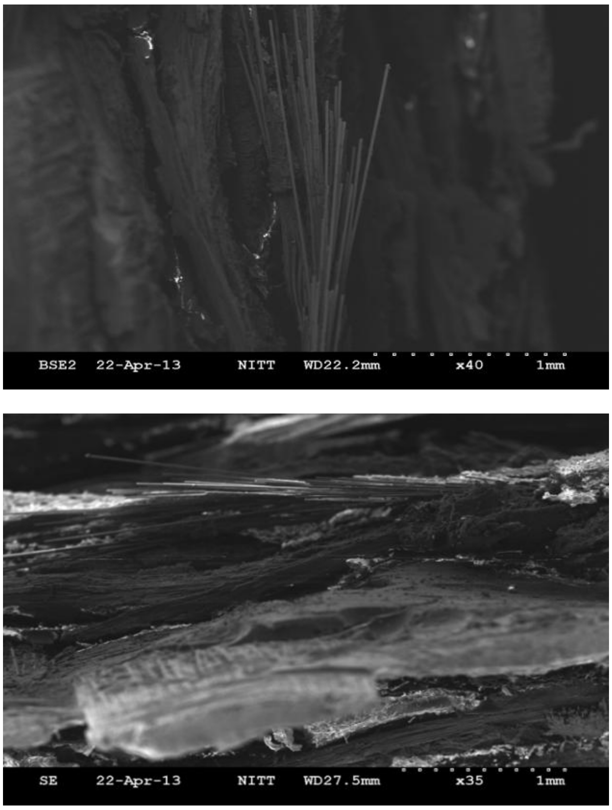

Fig. 6: Scanning Electron Microscopy of failure under torsion

4. Conclusions

In this research work, an attempt has been made to investigate the mechanical properties of a single-piece drive shaft made from various compositions of the composite materials and its orientations. Composite drive shafts made from three combinations of the layers such as E-Glass, E-Glass/Carbon and E-Glass/Carbon/S-Glass with different fiber orientations. Mechanical tests such as tensile, bending and torsion tests were conducted on the various composite drive shafts. Based on the test results, the following conclusions are arrived:

- Tensile properties of hybrid drive shaft are superior as compared to the other composite drive shafts involved in this research work.
- The hybrid composite shaft has shown higher yield stress and breaking load as compared to other composite drive shafts.
- The torque transmitting capability of the hybrid composite drive shaft is superior and holds as good as the aluminium/composite drive shaft.
- The hybrid composite drive shaft fabricated using 0/90 E-Glass / 0/90 Carbon / 0/90° S-Glass is found to be an apt replacement for metallic drive shafts found in light vehicles.

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EDITORIAL NOTES:

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