International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2016): 79.57 | Impact Factor (2015): 6.391

A Review on Composite Materials over Current Trends

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Abstract: ***The importance of materials in modern world can be realized from the fact that much of the research is being done to apply new materials to different components. However it is natural for a design engineer to rely on trusted and tested materials, but now the world is changing .Today composite materials have changed all the material engineering. The evolution of composite materials has given an opportunity to various designers to use new and better materials resulting in cost reduction, increase in efficiency and better utilization of available resources. Composite materials are finding their applications in aerospace industry, automobile sector, manufacturing industries etc. This paper presents design method and vibrational analysis of composite propeller shafts. In this paper, the aim is to replace a metallic drive shaft by a two-piece composite drive shaft. Designing of a composite drive shaft is divided in two main sections: design of the composite shaft and design of couplings. In composite shaft design some parameters such as critical speed, static torque and adhesive joints are studied; the behavior of materials is considered nonlinear isotropic for adhesive, linear isotropic for metal and orthotropic for composite shaft. Along with the design all the analyses are performed using finite element software (ANSYS). The results show significant points about optimum design of composite drive shafts.***

Keywords: automobile sector, composite materials, latest developments, drive shaft, composite.

1. Introduction

Nowadays, composite materials are used in large volume in various engineering structures including space crafts, airplanes, automobiles, boats, sports' equipments, bridges and buildings. Widespread use of composite materials in industry is due to the good characteristics of its strength to density and hardness to density. The possibility of increase in these characteristics using the latest technology and various manufacturing methods has raised application range of these materials. Application of composite materials was generally begun only at aerospace industry in 1970s, but nowadays after only three decades, it is developed in most industries. Meanwhile, the automotive industry considered as a mother one in each country, has benefited from abilities and characteristics of these advanced materials. Along with progress in technology, metallic automotive parts are replaced by composite ones.

1.1 Materials

The term composite could mean almost anything if taken at face value, since all materials are composed of dissimilar subunits if examined at close enough detail. But in modern materials engineering, the term usually refers to a “matrix” material that is reinforced with fibres. For instance, the term “FRP" (Fiber Reinforced Plastic) usually indicates a thermosetting polyester matrix containing glass fibres, and this particular composite has the lion's share of today's commercial market.

Many composites used today are at the leading edge of materials technology, with performance and costs appropriate to ultra-demanding applications such as spacecraft. But heterogeneous materials combining the best aspects of dissimilar constituents have been used by nature for millions of years. Ancient society, imitating nature, used this approach as well: the Book of Exodus speaks of using straw to reinforce mud in brick making, without which the bricks would have almost no strength.

Table 1: Properties of Composite Reinforcing Fibers

Material	E (Gpa)	σb (Gpa)	ε b (%)	P (Mg/m3)	E/ρ (MJ/Kg)	σb/ρ (MJ/Kg)
E-Glass	72.4	2.4	2.6	2.54	28.5	0.95
S-Glass	85.5	4.5	2.0	2.49	34.3	1.8
Aramid	124	3.6	2.3	1.45	86	2.5
Boron	400	3.5	1.0	2.45	163	1.43
HS Graphite	253	4.5	1.1	1.80	140	2.5
HM Graphite	520	2.4	0.6	1.85	281	1.3

As seen in Table 1, [1] the fibers used in modern composites have strengths and stiffness’s far above those of traditional bulk materials. The high strengths of the glass fibers are due to processing that avoids the internal or surface flaws which normally weaken glass, and the strength and stiffness of the polymeric aramid fiber is a consequence of the nearly perfect alignment of the molecular chains with the fiber axis. Of course, these materials are not generally usable as fibers alone, and typically they are impregnated by a matrix material that acts to transfer loads to the fibers, and also to protect the fibers from abrasion and environmental attack. The matrix dilutes the properties to some degree, but even so very high specific (weight-adjusted) properties are available from these materials. Metal and glass are available as matrix materials, but these are currently very expensive and largely restricted to R&D laboratories. Polymers are much more commonly used, with unsaturated styrene-hardened polyesters having the majority of low-to-medium performance applications and epoxy or more sophisticated thermosets having the higher end of the market. Thermoplastic matrix composites are increasingly attractive materials, with processing difficulties being perhaps their principal limitation.

1.2 Fibres

The primary function of the reinforcement in composites reinforced with continuous fibres is to provide strength and stiffness and to support the structural load. The purpose of the matrix is to provide shape and form, to protect the fibres from structural damage and adverse chemical attack, to distribute stress, and to provide toughness. The matrix also stabilizes the composite against buckling in compressive loading situations. Fibres, also known as filaments, have finite lengths of at least 100 times their diameter, and are prepared by drawing from a molten bath, by spinning, or by chemical vapour deposition on a substrate such as tungsten or carbon. They are grouped into bundles or strands of 500 to 12 ,000 filaments. The bundles or strands may be chopped into short fibres, or twisted into yarns suitable for the weaving of fabrics or three dimensional performs, using a variety of weaving patterns. The strands may be further combined to form tows, with as many as 40,000 to 3,00, 000 filaments each. Woven fabrics and tows can be processed into chopped fabric squares or chopped fibre tows. In the plain-weave pattern, yarns are interlaced in alternating fashion over and under every other yarn to provide maximum fabric stability and firmness, and minimum yarn slippage. At the time of their formation, the fibres or yarns are sized, to protect the surface and aid the process of further handling such as weaving. Before the fibres are finally used in the fabrication of a composite, the size is usually removed by heat cleaning or washing.

Fibres are also now becoming available as mixtures. An advanced producer of composites, Textron Specialty Materials (TSM), has started to market a continuous-fibre epoxy resin prepreg tape that contains a mixture of large boron fibres and smaller-diameter carbon fibres, with a fibre density of 70 to 80 percent. While carbon is good in tension, it lacks good compressive properties. This deficiency is overcome through the use of boron fibres that exhibit their best properties in compression. The combined material has good flexural properties, which are of importance to the manufacturing of submersible structures, sporting goods, and medical equipment [2]

2. Composite Systems and Developments

2.1Composites with polymer matrices

Polymer-matrix composites (PMCs) have matrices of thermoplastic or thermosetting polymers-traditionally glass fibre available in the form of woven material embedded in polyester. These materials are utilized at temperatures of not more than 200°C in commercial, industrial, and transportation applications, including chemically resistant piping, valves, pressure vessels, and reactors. The large numbers of resin formulations, curing agents, and fillers provide an extensive range of possible properties. Because they are superior to polyesters in resisting moisture and offer superior mechanical properties, epoxies have been the commonest thermosetting matrix material for more demanding applications. Bismaleimide resins (BMIs), on the other hand, possess many of the same desirable properties as epoxies, such as handlability, relative ease of processing, and good mechanical properties, and have service temperatures of up to 250°C compared with 180°C for epoxies. Thermosets are constantly being upgraded to tougher grades of higher heat resistance. Newly developed polyimide (PI) resins, for instance, can withstand exposure to temperatures of more than 300°C.However, when these polymerscure, volatile matter is released, which produces undesirable voids in the final product. Although this problem has been solved, polyimides are too brittle for very demanding applications. phenolic resins suffer the same disadvantage but are used for applications that demand relatively high heat resistance .Difficult to ignite, phenolics produce less smoke, and are less toxic when they do burn. They are therefore used for the interior panels of aircraft, where combustion requirements justify lower properties. Also, these materials and the newly developed thermoplastic polyethersulphone contain additives that react to fire by emitting contained water as vapour, which extinguishes the firell. Attempts to improve the hot-wet performance and impact resistance of thermosetting resins like epoxies and BMls are continuing. Thermoplastic matrix materials exhibit high strain to failure, and are ideally suited for use as matrix material combined with high-strength and high-strain carbon fibres. These materials include resins such as polyetheretherketone (PEEK), with a melting point of 334°C, polyphenylenesulphide (PPS), poly etherimide (PEI), polyamideimide (PAl), and polyether sulphone (PES). In general, they have an unlimited shelf life, and offer lower-cost composite processing because they can be potentially remoulded by the application of heat and pressure. Composite thermoplastics are very different from the general commercial thermoplastics such as polyethylene, polyvinyl chloride and polystyrene. These thermoplastics are tougher and can withstand higher service temperatures.

Experiments with a blowtorch on aluminium and a carbon fibre-PEEK composite showed that the latter withstood the flame much better .Apart from the cost aspect, the choice of a polymer for a specific application must be based on a full knowledge of the material properties required for the intended service temperatures and loads. Excellent accounts are available covering these aspects for epoxies, polyimides, bismaleimides, thermoplastic systems, and high-temperature polymers. DuPont recently announced its thermoplastic engineered preforms (Tepex), which consists of a consolidated sheet composite that can be formed into complex parts in less than 60 seconds, avoiding labour intensive, time consuming, and costly fabrication techniques. It is reported that end-users can choose from a wide selection of resins-from low performance types to the more exotic polymers' such as PEEK-and also make a selection from different continuous fibre systems (fabrics, and unidirectional or, non-woven systems) of varying types such as glass, Kevlar, carbon, and hybrids. New grades of performance polymers increasingly appear on the market. Among the newcomers is a family of polymers based on poly-cyclo-hexylene-dimethylene-terephtalate or PCT, which is a high-temperature, semi-crystalline, thermoplastic polyester that melts at 285°C and is capable of long-term service temperatures of up to 170°C.

2.2 Composites with metal matrices

Metal-matrix composites are currently the focus of intense world-wide research and development. These materials are fabricated by liquid-infiltration techniques, such as high pressure infiltration casting, squeeze casting, vacuum infiltration casting, compo casting, and pressureless metal infiltration. Other methods of fabrication include powdermetallurgical techniques, plasma spraying of matrix material over properly laid fibres, physical-vapour deposition, hot pressing, and self-propagating high-temperature synthesis or reactive synthesis. In addition to improved strength, stiffness, and abrasion resistance, and reduced density, MMCs are capable of providing increased oxidation resistance at high temperature operating limits. Fibre reinforcements in metal matrix materials of particular interest include carbon graphite/copper, graphite/aluminium, SiC/aluminium, SiC/magnesium, and SiC/magnesium. Although not precisely termed MMCs, reinforced ordered intermetallic composites, such as titanium and nickel aluminides, are becoming important because the aluminides exhibit the unusual characteristic of increased yield strength with temperature.

The unique properties of MMCs (wear resistance, strength, and stiffness) have already led to more than the laboratory scale manufacture of automotive components such as brake callipers, pump housings, gears, valves, pulleys, drive shafts, brake rotors, engine blocks, connecting rods, and pistons. Systems reinforced with continuous fibres, such as aluminium tubing and sheets reinforced with SiCfibre, that can be used for structural applications, are also available commercially. Whereas a great deal of development has taken place with respect to the use of fibre preforms or other methods in the fabrication of tough, wear-resistant composites, there is also interest in the development of tough metal-matrix composites based on particulate iron having extraordinary wear resistance and cutting performance.

3. Case Study

3.1 Background

Drive shafts are usually made of solid or hollow tube of steel or aluminum. Over than 70% of single or two-piece differentials are made of several-piece propeller shaft that result in a rather heavy drive shaft. Fig. 1and 2 shows a photographic view of two-piece steel and a sample composite drive shaft respectively. Composite drive shafts were begun to be used in bulk in automotives since 1988. The graphite/carbon/fiberglass/aluminum driveshaft tube was developed as a direct response to industry demand for greater performance and efficiency in light trucks, vans and high performance automobiles. The main reason for this was significant saving in weight of drive shaft; the results showed that the final composite drive shaft has a mass of about 2.7 kg, while this amount for steel drive shaft is about 10 kg. The use of composite drive shafts in race cars has gained great attention in recent decades. When a steel drive shaft breaks, its components, are thrown in all directions such as balls, it is also possible that the drive shaft makes a hole in the ground and throw the car into the air. But when a composite drive shaft breaks, it is divided into fine fibers that do not have any danger for the driver.

Figure 1: Photographic view of a two-piece steel

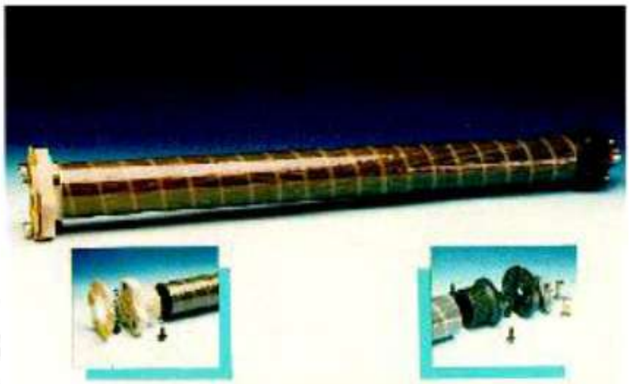

Figure 2: Photographic view of a one-piece composite drive shaft

3.2 Design of composite drive shaft

- **Specification of the problem:**

The torque transmission capability of the drive shaft is taken as 3000 N.m, the length and the outer diameter here are considered as 2 meters and 120 millimeters, respectively. The drive shaft of transmission system was designed optimally to meet the specified design requirements.

- **Assumptions:**

The shaft rotates at a constant speed about its longitudinal axis. The shaft has a uniform, circular cross section. The shaft is perfectly balanced, all damping and nonlinear effects are excluded. The stress-strain relationship for composite material is linear and elastic; hence, Hook's law is applicable for composite materials. Since lamina is thin and no out-of-plane loads are applied, it is considered as under the plane stress.

- **Selection of Cross-Section and Materials:**

The HM Carbon/Epoxy material with fiber volume of 60% is selected for composite drive shaft. The factor of safety is taken as 6. Table 1 shows the mechanical properties of each layer of the laminate.

- **Calculations:**

Composite drive shaft is studied to meet the three following requirements: torque transmission capacity, critical speed and tensional buckling capacity. Considering the equations and design correlations the optimum fiber arrangement of the composite drive shaft is obtained as [0deg/45deg/90deg].

Table 2: Mechanical properties of the each lamina of the laminate

Property	HM Carbon/Epoxy
$E_{11}(Gpa)$	190
$E_{22}(Gpa)$	7.7
$G_{12}(Gpa)$	4.2
V_{12}	0.3
$\sigma_t^1 = \sigma_c^1(Mpa)$	870
$\sigma_t^2 = \sigma_c^2(Mpa)$	540
$\tau_{12}(Mpa)$	30
$\rho(kg/m^3)$	1600
V_f	0.6

By using Hill theory, it would be possible to calculate the dimension for failure. With the thickness of 2.03 millimeters and the applied loads, the 00 fibers will not be ruptured. With the thickness of 2.2 millimeters and the applied loads, the 900 fibers will not be ruptured. Due to the torsion of the shaft, the buckling is negligible.

$$\left[\frac{\sigma_l}{\sigma_{lr}}\right]^2 + \left[\frac{\sigma_t}{\sigma_{tr}}\right]^2 - \frac{\sigma_t\sigma_l}{\sigma_{lr}^2} + \left[\frac{\tau_{lt}}{\tau_{ltr}}\right]^2 = \alpha^2$$

3.2 Critical speed analysis in composite drive shafts

The main point that attracts manufacturers to use composite materials in the drive shafts is that they make it possible to increase the length of the shaft. The relationship between shaft's length and the critical speed for both types of drive shafts are shown in Fig. 2. It is evident that for a specific application where the critical speed is about 8000 rev/min, the longest possible steel shaft is 1250 mm, while the composite one can have a length 1650 mm.

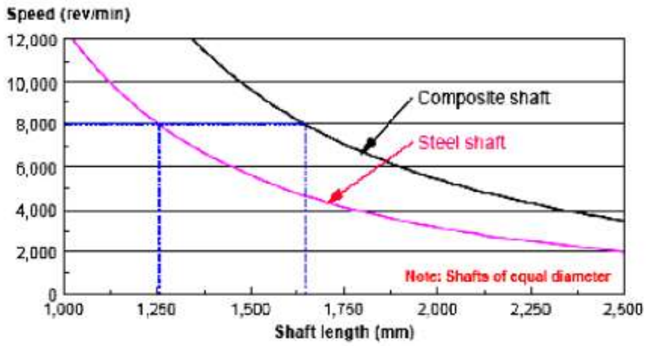

Figure 3: The effect of shaft length on critical speed

3.3 Design of adhesive joints in composite drive shafts

The joints used for connecting composite materials can be metallic or non-metallic. Steel fasteners due to the possibility of galvanic corrosion with carbon-epoxy materials, are mainly made of titanium or stainless steel. Other alloys such as aluminum or steel can be used provided that no contact with the surface is occurred. Joints are divided to metal screws and rivets. Non-metallic connectors are created from reinforced thermo set or thermoplastic resins. By using this connection, structural weight reduces and corrosion problems disappear. The thickness of the adhesive and length of adhesive bond are computed. The following correlations were used to calculate the required parameters:

$$\tau_{max} = \frac{a}{\tanh a} \times \tau_m$$

$$a = \sqrt{\frac{G_c l^2}{2Gee_c}}$$

Where l is the length of adhesive bond. For obtaining reasonable results the only possible way is to increase the value of e. so, the thickness of the adhesive and the length of the adhesive bond are obtained 12 millimeters and 4.5 centimeters, respectively. The details of the bond are given in Table 3.

Table 3: Mechanical properties of the adhesive

Property	Value
E	2.5 Gpa
G	1 Gpa
e_c	0.25
l	45 mm
Layers orientation	$[\pm45/0_6/\pm45]_r$

3.4 The weight comparison between composite and steel drive shafts

The entire of vehicle drive shaft is consisted of several rotating masses. About 17-22% of the power generated by the engine is wasted due to rotating mass of power train system. Power is lost because a lot of energy is needed to rotate heavy parts. This energy loss can be reduced by decreasing the amount of rotating mass. Table 4 represents the comparison of inertia moment between composite and steel drive shafts.

Table 4: Comparison of the inertia moment between composites and steel drive shafts

Table 4: A mass comparison between steel and composite drive shafts has been done

	$I(mm^4)$	$I_m(Kg.mm^2)$
Steel	0.57×10^6	18370.9
Composite	1.59×10^6	9945
Diffrence%	64.1%	45.8%

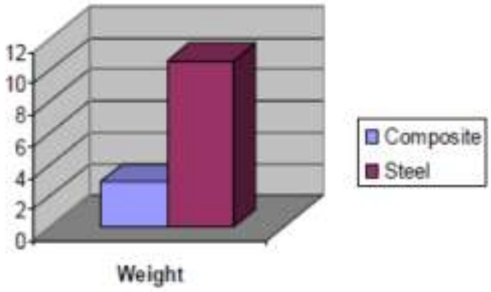

Figure 4: Mass comparison between steel and composite shaft

4. Results and Discussion

In this case study a one-piece composite drive shaft is considered to be replaced a two-piece steel drive shaft. Its design procedure is studied and some important parameters are obtained. The composite drive shaft made up of high modulus carbon / epoxy multilayered composites has been designed.

The replacement of composite materials has resulted in considerable amount of weight reduction about 72% when compared to conventional steel shaft. Also, the results reveal that the orientation of fibers has great influence on the dynamic characteristics of the composite shafts.[3]

5. Conclusions

Composites have attractive mechanical and physical properties that are now being utilized in automotive industry and aerospace on a grand scale world-wide. New fibres, polymers, and processing techniques for all classes of composites are constantly being developed. Research is also ongoing to improve repair techniques, recyclability, and the bonding between fibres and matrix materials. Because of the development of new fire-retarding constituents, the availability of polymers with higher temperature ratings, the relative ease of fabrication, and the fair costs, PMCs are being utilized more in structural and wear-resistant applications in mining and industrial environments. There is no doubt that, if processing costs can be substantially reduced, MMCs and CMCs will be increasingly employed in applications that require light weight in addition to toughness and wear- and abrasion-resistant properties as discussed in case study. CMCs will increasingly be used for high-temperature, oxidation-resistant, and wear- and abrasion-resistant applications where good corrosion resistance is also required. The new applications that are being found on an almost daily basis, and the continuous reporting of company investments and new ventures into the manufacture of MMC and CMC parts, tend to indicate that important progress has been made towards the reduction of processing and manufacturing costs. However, it is important to realize that the use of composites requires an integrated approach between user and designer/manufacturer to ensure functionality. This entails knowledge of the structural efficiency of the material, its isotropic or anisotropic behavior, environmental effects, and its manufacturing requirements, assembly, and repair.

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