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Composite Driveshafts: Technology and Experience

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ABSTRACT

Trucks, buses, automobiles and industrial equipment are negatively affected by the intrinsic weight, vibrational characteristics and critical speed of metal driveshafts. It has been proven that composite driveshafts are effective in overcoming these limitations. Indeed, the very nature of the composite materials (fiber and resinous binder) allows driveshafts to be designed to meet specific critical operational characteristics, and thus tailored to match the requirements of individual applications.

1.0 SUMMARY AND BACKGROUND

Weight, vibrational, fatigue, and critical speed limitations have been recognized as serious problems in automotive and industrial drivetrains for many years. The associated effects and possible solutions have been subjected to detailed analysis. Numerous solutions such as flywheels, harmonic dampers, multiple shafts with additional bearings, and heavy rubber shock (vibration) absorbers have shown limited success in overcoming the problems, but always at the expense of increased weight, rotational inertia, and resistance in the drivetrain.

Composite tubing has long been recognized to offer the potential of lighter weight driveshafts. Aerospace development efforts also demonstrated that correctly designed composite components have inherently superior fatigue and vibration damping characteristics to metals. Finally, the advent of higher modulus graphite fibers combined with these lighter weight and vibration damping characteristics allowed the design of driveshafts with much higher critical speed capabilities.

These improvements have been realized and the reliability of composite driveshafts has been proven in heavy trucks, on race tracks, in automobiles and light trucks, and in industrial applications. ACPT, Inc. has been designing and producing carbon fiber composite driveshafts for these applications since 1982.

2.0 DRIVETRAIN VIBRATION PROBLEMS

Vibration in drivetrains has been recognized as a major problem and has for many years been the subject of much theoretical analysis and trial-and-error vibrational control/reduction experimentation.

2.1 TRUCKS - Mazziotti[1] in 1960 published a review and analysis of torsional vibrations associated with drivelines. He delineated some of the sources of non-uniform motion, which result in vibrational excitation of the drivetrain and presented a detailed mathematical analysis relating those sources of excitation to the physical dimensions, mechanical properties, and rotational speeds of driveshafts. He reported data firmly establishing the relationships between non-uniform motion sources and the natural frequency of the driveline components. He concluded that vibrations can be amplified or subdued while being transmitted through the driveline and recommends that (with metal shafts) the driveline be operated at no less than 1.5 times the natural frequency (torsional) of the system. Herein it was assumed that rubber springs, flywheels, flexible couplings and other natural frequency reduction additions were the best way to modify the natural frequency. In 1960 the technology did not exist to design or produce carbon fiber composite driveshafts.

Mazziotti also stated that, “a resonant condition can produce objectionable disturbances as follows:

1. The high oscillating torque value can result in failure in rotating members.
2. Variable reactions on supporting members can be a source of objectionable noise and vibration.
3. Damage to gears, bearings, and other components can occur because of non-uniform loading.”

All of these predictions have been proven to be accurate and are still sources of aggravation for truck designers, builders and operators.

In recognition of, and in order to assist in the design of better truck drive systems, SAE paper #942322,[2] published by Spicer, division of Dana, describes a detailed torsional analysis computer simulation of truck drivetrains. The paper supports Mazziotti’s work and concludes, “torsional vibrations cause comfort problems for occupants and produce component failures.” “Torsionals also introduce dynamic loads on top of the mean static torque transmitted through the power train.” “...could easily cause catastrophic dynamic fatigue failures.” “At least responsible for wear problems at springs, splines, gear teeth, etc, eventually leading to the failure of these components.” This paper also presents a fairly detailed list of references on the subject of vibrations and their effect on automotive drivelines.

Higher specific modulus (modulus/density) gives carbon fiber shafts the ability to run longer one piece lengths than metal shafts. A composite shaft, of the same length as a metal shaft, will start to resonate laterally at a much higher speed and have correspondingly increased margin of safety at the higher

RPMs. This allows one piece composite shafts to replace two piece steel shafts. The benefits of eliminating the two piece shafts are significant reductions in weight, noise, vibration and harshness. The composite shafts have also proven to dampen vibration and absorb shock, greatly reducing wear on other drivetrain components as well as increasing tire traction.

In a test started in August of 1994, a one piece carbon fiber driveshaft was installed in a garbage truck operating in Texas, Figure 2-1 and 2-2. This shaft replaced a two piece steel shaft and a center bearing, Figure 2-3. The resultant weight savings was about 80 lbs. The shaft has now seen daily use for the last two years in what has been described as one of the most torturous commercial truck applications possible. Absolutely no problems have been recorded. The operator is maintaining records of repairs with which to compare histories with other driveline components of identical trucks in the fleet. It is still too early to draw any conclusions from these records. It can be said, however, that the carbon fiber shaft is performing flawlessly.

Figure 2-1: Garbage Truck Operating with One Piece Carbon Fiber Driveshaft

The garbage truck shaft replacement was a cooperative effort with Inland Empire Driveline Services, Ontario, CA. They have been instrumental in helping us to develop and supply carbon fiber driveshafts to the automotive community. Inland has successfully developed and employs aluminum welding techniques, which resulted in moving torque testing failures from the weld joint to the U-joint. They have provided constant support in obtaining information and hardware mating carbon fiber tubing to the correct driveshaft fittings. Inland Empire Driveline Services continues to be of great technical assistance and currently performs all of the welding and balancing required in the manufacture of our carbon fiber driveshafts.

Other direct experience is being obtained from OEM's. Three major OEMs have run composite driveshafts on test tracks and have performed extensive laboratory evaluations. One of these companies is now running "on the road" fleet evaluations.

2.2 AUTOMOTIVE AND LIGHT TRUCKS - The vibration problems in automobiles and light trucks are not so much "catastrophic failures", but rather more of weight, noise, harshness and passenger discomfort. Component failure can still be a problem at high speeds, as natural resonant frequencies of the driveshaft are approached. GKN[3] states that, "the Mark VIII is top speed limited by its long steel driveshaft to 128 mph. Above 128 mph the driveshaft gets into a bending and vibration frequency that would eventually tear it apart." They continue that, "to eliminate this problem most high speed European cars usually have a two piece shaft connected through a center bearing." Carbon fiber driveshafts can alleviate this problem.

2.3 INDUSTRY - Heavy duty industrial drivetrains, such as pump shafts and cooling tower driveshafts, suffer from similar torsional vibrations, natural frequency, and critical speed problems as heavy duty trucks and buses. The industrial community has demonstrated that composite driveshafts will reliably solve these problems.

Figure 2-2: One Piece Carbon Fiber Driveshaft, Garbage Truck Application

Figure 2-3: Two Piece Steel Shaft, with Center Bearings, Removed from Garbage Truck

As an example, two reports[4,5] and personal discussions with A. Rossoni,[**] demonstrate the existence of natural frequency, secondary exciter induced, critical speeds in large steel driveshafts. As shown in Figure 2-4, critical speeds in long pump shafts can be reached at only 260 to 360 rpm. Rossoni presents detailed data on six different sources of torsional excitors and the level of vibration (cpm) which are induced into a 183” long vertical sewage pump drivetrain. He also gives precise information on the level of TIR (Total Indicated Runout) increase experienced in these shafts as a result of operation at critical rotational speeds. In the first paper Rossoni recommends that the critical speed of the two piece steel shaft (see Figure 2-5) “be changed so that it will not be excited.” In his later report, April 1991, he demonstrates that this was accomplished through the installation of a one piece carbon fiber composite driveshaft (see Figure 2-6). Rossoni also makes the general recommendation that critical speeds be avoided by at least 10%.

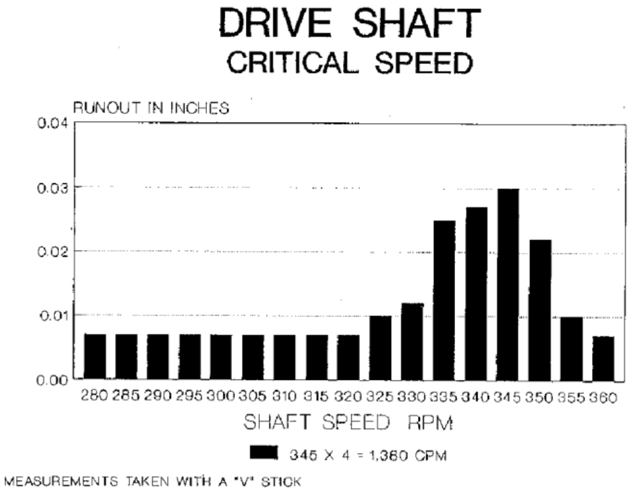

Figure 2-4: Pump Shaft Critical Speeds

VanLaarhoven[6] describes drivetrain problems and solutions in a large cooling tower being operated by Montana Power Company. The installation used two steel driveshafts for power transmission. A carrier bearing, rigidly mounted on a pedestal midway between the motor and gear case “was the most prevalent area of failure. The solution was to install one piece carbon fiber drivelines, eliminating the carrier bearing.” This substitution also reduced the driveline assembly by 256 lbs. VanLaarhoven notes, as secondary benefits from this substitution, much better corrosion resistance and a near zero coefficient of thermal expansion. The latter provides the assembly “the ability to withstand greater misalignment than conventional shafts.” It is also noted, “After the installation of two carbon fiber shafts (in two other units) in 1987, only routine maintenance was performed on those fans.” As a result of this experience, 12 additional carbon fiber drivelines were purchased by Montana Power. Single piece composite driveshafts are now the standard in cooling towers.

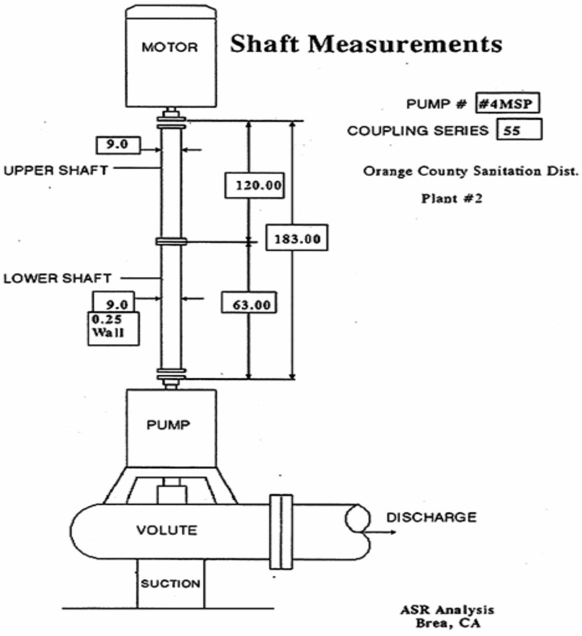

Figure 2-5: Steel Pump Shafts

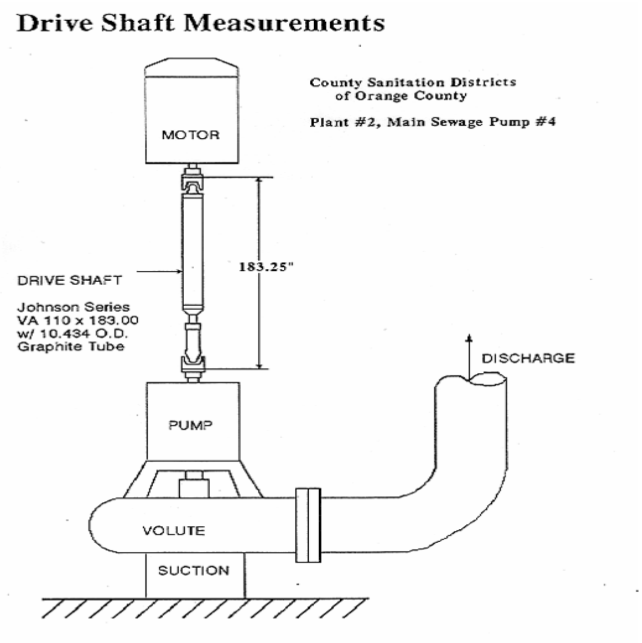

Figure 2-6: Carbon Fiber Pump Shaft

[**] Angelo Rossoni, ASR Analysis, 1315 W. Walling Avenue, Brea, CA 92821, 310-694-4634.

3.0 COMPOSITE MATERIALS

As applied to composite driveshafts for trucks and buses, composite materials can be defined as load carrying, high strength/high modulus fibers structurally stabilized by an organic (resin) matrix. For the purpose of this paper, these are carbon or graphite fibers in an epoxy matrix. For special purposes or as a protective layer, a small percentage of fiberglass may also be included. These carbon fiber composite driveshafts are made by bonding steel or aluminum end fittings into an all composite, filament wound tube. The bonding technique used to install the end fittings has been in use for years in the aircraft and aerospace industries.

3.1 FIBERS DOMINATE MECHANICAL PROPERTIES - In composite structures, including driveshaft tubing, the mechanical properties are determined mainly by the mechanical properties of the fibers and the orientation of the fibers within the tube. The fibers are available in many different types, each providing different mechanical properties. The resin acts mainly as a binder, retains the fibers in the shape into which the composite materials were formed, and transfers stresses and strains from fiber to fiber. For illustration, fiber reinforced composites can be likened to reinforced concrete where the re-bar content has been increased to a near maximum.

As an example, in composite driveshafts the highest torsional strength achievable would be in a tube with high strength fibers orientated at +/- 45° angles. The highest critical speed shaft, as a direct function of lateral natural frequency only, would be made from a high modulus fiber with the fibers all in the axial or 0° direction. Please note, an all 0° fiber orientation would not produce a useful driveshaft. Strength and modulus can be adjusted by changing the type of carbon fiber used as well as the angles to which they are oriented.

Driveshaft tubing designs can be optimized for specific applications. Fibers are selected which provide the best trade off of strength, stiffness and cost. Fiber orientation is calculated to provide the desired torque strength and axial stiffness. For most applications, length is fixed, but diameter and wall thickness can also be used as variables in tailoring composite shafts to specific applications. Materials' properties are reviewed below. Specific examples of tailored driveshafts and direct comparisons to metal shafts are presented later in this paper.

3.2 MATERIAL PROPERTIES - It is beyond the scope of this paper to provide in-depth data on specific design calculations or material properties. To our knowledge, there are no specific texts dealing with the design of composite driveshafts. ACPT, Inc.'s designs are based upon composite structural design theory combined with driveshaft design principles.

Material properties and generalized composite structural design considerations may be found in references 7, 8 and 9. Also current materials (fiber and composite) data may be obtained directly from fiber manufacturers. Some of the data and information specific to the design and understanding of composite driveshafts are presented below.

3.2.1 Strength, Stiffness and Price of Graphite (Carbon) Fiber - Both the strength and stiffness of a composite lamina may be estimated, in the fiber direction, as the product of fiber strength or modulus and the fiber volume of that lamina. A lamina is defined as a layer of a composite structure in which the fibers are all oriented in the same direction. The contributions of a lamina to the properties in any other direction are also subject to calculation. The properties of the structure are then the sums of the contributions of each lamina.

Table 3-1 summarizes properties and prices for a range of typical graphite (carbon) fibers. As shown, the price generally increases with modulus. Also noteworthy is the fact that there are two totally different types of graphite fiber, one made from PAN (polyacrylanitrile) precursor and one made from pitch. In general the PAN material is characterized by higher strength and the pitch material by higher modulus. Strength, modulus, weight, and price are the major variables, which should be used as determining factors in optimizing the design of composite driveshafts. Table 3-1 illustrates a few of the many different grades of fibers available from only one of many suppliers.

Table 3-1 Mechanical Properties and Prices of Typical Graphite Fiber[*].

Material Name	PAN/ Pitch	Density lbs/in^3	Tensile Kpsi	Modulus Kpsi	Price/ Pound
T-300	PAN	0.064	530	33.5	$ 23
T-650/92	PAN	0.064	730	42.0	$ 50
T-40	PAN	0.065	820	42.0	$ 59
T-50	PAN	0.065	420	57.0	$ 90
T-1000G	PAN	0.065	924	42.7	$ 75
P-55S	Pitch	0.072	275	55.0	$ 52
P-75S	Pitch	0.072	300	75.0	$ 385
P-120	Pitch	0.079	350	120	$ 800
K-1100	Pitch		350-550	130	$1,750

The fibers in Table 3-1 can be obtained from Amoco Performance Products, Inc., Alpharetta, GA. All data were taken from Amoco's sales literature. Some of the other current fiber suppliers include Toho *Carbon Fibers, Inc.* in Palo Alto, CA (Subsidiary of Toho Rayon, Japan); *Grafil, Inc*., Sacramento, CA*; Mitsubishi Chemical America*, Tokyo Japan; *Toray*, Tokyo, Japan

3.2.2 Vibration Damping - Composites are generally far superior to metals in damping vibration. One of the first publications to show this was prepared by Fourney and Poesch[10]. Their paper is summarized in Figure 3-1 in which two oscilloscope traces are presented. These traces show the vibration decay in two bars subjected to identical excitation. As is shown and as concluded by Fourney and Poesch, "the damping results demonstrate that disturbances in structures made from graphite composites will be damped much faster than structures made from metals". Damping characteristics will also vary between separate composite designs, depending on fiber type and orientation.

It is also well established that the vibrational damping of composites enhance the fatigue life. Since the vibrations are damped, their amplitude is not transmitted and the net result is to have a less stringent fatigue loading away from the vibrational source and in connecting parts.

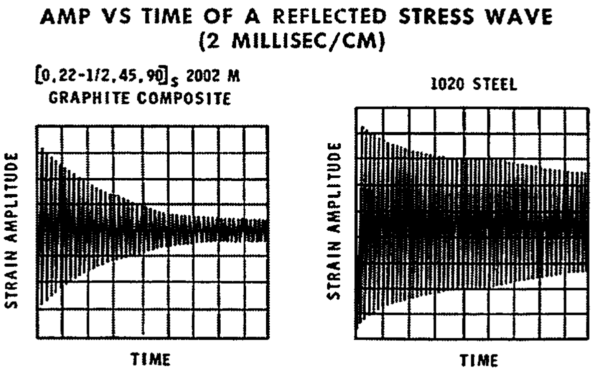

Figure 3.1 Vibration Damping

3.2.3 Fatigue - Composites are capable of much higher fatigue life cycles than metal! This phenomenon has been demonstrated many times and is one of the major reasons for the switch from metal to composites in helicopter blades. The mechanism is mainly one of the crack stopping characteristics of composites as opposed to natural notch sensitivity or crack propagating/stress intensifying characteristics of metal. In composites, micro cracks in the resin can only propagate a very short distance before running into a natural crack stopper in the form of a round hole occupied by a fiber.

4.0 DESIGN OPTIMIZATION

The composite torque tube must, at a minimum just as in the design of a metal shaft, meet all of the performance requirements with a sufficient margin of safety. An optimized composite torque tube must also have a balanced level of stresses in all of the directions of loading. Since the laminate that offers the maximum shear strength (at ± 45°orientation) does not provide sufficient axial stiffness (which requires fibers to be oriented in the longitudinal direction) for high speed operation, the designer often selects an optimal composite laminate structure that offers both sufficient allowable shear strength and sufficient longitudinal stiffness. In other words, an optimized design will have all the fibers oriented at an angle that compromises between shear strength and stiffness, or will have layers of different angles of winding to provide for both. Once again, different grades of fiber may also be used.

Equations are presented below to illustrate to the reader the interrelationship of the physical dimensions and the mechanical properties as used in designing carbon fiber driveshafts. The equations presented are accurate, but have been summarized to allow an understanding of these factors without going into the detail of a precise design calculation.

4.1 TORSIONAL STRENGTH

The limiting torsional capability of a driveshaft tube may be controlled by either of two mechanical properties: The in-plane strength (S_{ip}) or the torsional buckling strength (S').

4.1.1 Shear Strength - The torsional strength (T_s) is a direct function of the material's in-plane shear strength, polar moment of inertia (J), and the tube radius (R).

$$T_S = \frac{S_{ip} J}{R} \qquad (1)$$

Both J and R are determined by physical dimensions. The tube size may be limited by the application, but the in-plane strength is a function only of the composite material. By selecting the correct fiber(s), fiber orientation(s) and laminate stacking sequence, a maximum strength may be achieved while minimizing the amount (or cost) of the material. To date, torsional strength has not been a limiting factor in the design of carbon fiber driveshafts.

As an example, carbon fiber driveshafts have been accepted for "competitive use" by several race sanctioning organizations.[11] Much of this initial race development was for pro-stock drag racing. The major consideration was meeting the torsional requirements of 1200 hp engines with 3.5" diameter shafts and 1350 series aluminum end yokes. Designs were evolved such that testing the shaft to failure results in 100% U-joint failure. Early on, both bond joint and aluminum weld failures were encountered. Designs and manufacturing procedures were improved to eliminate these weak points. Subsequent testing at Moser Engineering[12] showed consistent failure of the 1350 cross joints at around 4,200 ft-lbs of torque with no bond joint or weld failures. It is also significant that in all tests of composite driveshafts, no permanent deformation was recorded. In comparative testing with aluminum and steel shafts, with 1350 fittings and 3.5" tubing, permanent deformation in the range of 3° to 4° was measured.

4.1.2 Torsional Buckling Strength - Similarly (and unlike metals which have isotropic mechanical properties) the torsional buckling strength (S') of a composite tube can be tailored to match its shear strength. This is accomplished by balancing the longitudinal and circumferential moduli. Roark's[13] equation for torsional buckling may be simplified to:

$$S' = C\left[\frac{E_T}{1-\nu^2}\right]\left[\frac{t^2}{L^2}\right] \qquad (2)$$

Where C = a constant for any given geometry, ν = Poisson's ratio (for composites $\nu^2 = \nu_{12}\,\nu_{21}$), t = tube wall thickness, L= tube length and E_T =effective modulus of the tube and is a product of the longitudinal (E_{11}) and circumferential (E_{22}) moduli:

$$E_T = E_{11}^{0.625}\, E_{22}^{0.375} \qquad (3)$$

4.2 STIFFNESS - The critical speed of a driveshaft is a function of its lateral stiffness, while its torsional vibration behavior is directly related to its torsional stiffness. Both must be considered in optimizing carbon fiber driveshaft designs.

4.2.1 Lateral Stiffness, $E_{11}I$ - The lateral critical speed (CS_L) of a driveshaft may be calculated from:

$$CS_L, (rpm) = \frac{30}{\pi}\sqrt{\frac{g}{y}} \qquad (4)$$

Where g=gravitational constant, y= the static deflection and is calculable by:

$$y = 0.789\frac{5wL^4}{384E_{11}I} \qquad (5)$$

Where w = weight per inch of tube and I = the moment of inertia, therefore

$$CS_L, (rpm) = \frac{654.8D}{L^2}\sqrt{\frac{E_{11}}{\rho}} \qquad (6)$$

As shown in equation 6, the lateral critical speed of a tube (driveshaft) is a function of its geometry and specific modulus (modulus divided by density) and is nearly constant for all metals currently used in driveshafts. As a result, for any given tube of fixed dimensions, the composite driveshaft can be designed to operate at higher speeds than comparable metal driveshafts.

4.2.2 Torsional Stiffness - The torsional stiffness, T/θ, θ being the twist angle, may also be calculated from the property of the material (torsional modulus, G) and the physical dimensions of the tube (the polar moment of inertia, J, and the length, L).

$$\frac{T}{\theta} = \frac{GJ}{L} \qquad (7)$$

The torsional critical speed (CS_T) of the driveshaft is directly related to T/θ. Again the composite can be designed through selection of the correct materials and fiber orientation to vary the torsional modulus toward an optimum level. While J and L are constant for a given geometry, the G of carbon fiber shafts can be tailored between 1 and 5.5 Mpsi.

5.0 CARBON FIBER DRIVESHAFTS

Composite driveshafts have solved many industrial and automotive problems. The technology is proven; it only remains for potential users to recognize these advantages and make the shift away from metal tubing.

As in the introduction of most new concepts, there has been much misunderstanding (overstatements, understatements and just plain mis-statements) about the capabilities of carbon fiber driveshafts. It is our objective that the information presented below will help to clarify this situation.

5.1 NOT A NEW TECHNOLOGY - A patent search conducted in September 1987[14] provided 15 patents dated from January 1966 through July 1987. Most of these deal with materials and methods of production for automotive driveshafts and propshafts. Some of them referred to other patents dated as early as 1926.

One of the subjects most often covered had to do with unique attachments of metal ends to the composite tube. This problem has been solved by the development of high strength adhesives. Transferring large loads from metal to composite (and the reverse) is now a *fait accompli* and is widely practiced in aerospace and industrial applications. Bond strengths of 4,000 psi and greater are achieved on a routine and repeatable basis.

The patents also delineate the advantages of the composite driveshafts in resisting torsional buckling and increased stiffness. In 1979 Yates *et al*[15] concluded that the composite shafts would be "light weight and surprisingly capable of yielding reliable service in the absence of harmful secondary powertrain resonance and the concomitant noise associated therewith." Yates also delineates and illustrates the ability to vary and predict critical speed capabilities by modifying the tubes' geometry, materials, and fiber winding angles.

5.2 COMPARITIVE DRIVESHAFT DESIGNS - Data presented below compare typical driveshaft designs. Both automotive/small truck and large truck/bus designs are considered.

5.2.1 Light Truck/Automotive Driveshafts - Table 5-1 presents a materials comparison for a typical light truck driveshaft. The analysis is for a 50" long shaft with a nominal 3" diameter. Materials considered were carbon fiber, aluminum, steel and titanium. The data of Table 5-2 were calculated based upon the four designs presented in Table 5-1. Considering first the weight, where a one piece shaft replaces a one piece shaft, the metal tubes would weigh from 36% to 108% more than the comparable composite shafts. The resultant dynamic inertias show similar improvements, but are slightly lower due to the larger diameter of the carbon fiber tube. Only the steel is equal in bending stiffness to the carbon fiber shaft. The torsional spring rate varies from 24% higher in the aluminum to 107% higher in the steel. (It is shown later that while the torsional spring rate is fixed for a metal tube, it can be tailored in composite tubes.)

Table 5-1 Typical Light Truck Shaft Designs

Material	Carbon Fiber	Steel	Aluminum	Titanium
Axial Modulus, E_{11}, (Mpsi)	10.0	29.0	10.0	14.8
Torsional Modulus, G (Mpsi)	2.1	11.5	3.8	6.5
Density, (lb/in^3)	0.059	0.283	0.098	0.175
O.D., (in)	3.280	3.000	3.000	3.000
I.D., (in)	3.000	2.870	2.750	2.820
Wall t, (in)	0.140	0.065	0.125	0.090
Shaft Length, (in)	50.0	50.0	50.0	50.0

Table 5-2 Driveshaft Comparisons
a. Calculated Data

	Carbon Fiber	Steel	Aluminum	Titanium
Tube Weight, (lbs)	3.7	7.8	5.1	6.6
Rotational Inertia , GJ (lbs-in^2)	9.3	16.8	10.5	14.0
Axial Stifness, E_{11} I (Mpsi)	17	19	12	13
Torsional Spring Rate (in-lbs/deg)	2,700	5,600	3,400	4,300
Critical Speed (rpm)	10,700	7,800	7,600	7,000
Max. RPM	8,000	5,800	5,700	5,300

Maximum speed of operation is calculated using 75% of the critical speed. This is the recommended value by Dana[16].

Table 5-2 Driveshaft Comparisons
b. Percentages

	Carbon Fiber	Steel	Aluminum	Titanium
Tube Weight	100%	208%	136%	177%
Rotational Inertia	100%	182%	114%	152%
Lateral Stiffness	100%	110%	69%	76%
Spring Rate	100%	207%	124%	158%
Critical Speed	100%	73%	71%	65%

Note that the critical speed of the carbon fiber shaft is approximately 30% higher than all of the metal shafts. Further the critical speed of the metal shafts cannot be substantially modified; the composites can be tailored to provide higher modulus and higher critical speeds without substantially increasing the density.

5.3 TORSIONAL SPRING RATE TAILORABILITY - As a result of some published misinformation claiming that carbon fiber shafts were "too stiff", torsional spring rates have been calculated for example designs A, B and C with the same dimensions (OD, ID and length) as shown in Tables 5-1 and 5-2. The results of these calculations are shown in Table 5-3. The values shown were attained by changing only the winding design. In designing shafts for specific applications, the materials and geometries used can also be varied to approximate more closely all desired operational requirements.

Table 5-3 Spring Rates: Carbon Fiber Driveshafts

Item	Design A	Design B	Design C
Spring Rate, (in-lb/deg)	1,751	3,572	9,630

5.4 LARGE TRUCK DRIVESHAFTS - One piece, lightweight carbon fiber driveshafts can be used to replace two piece steel shaft assemblies. Table 5-4a shows the design comparisons of a typical carbon fiber shaft vs. several conventional steel shafts. The calculated lengths listed in Table 5-4b are based on 2,700 rpm shaft operating speed (and critical speeds per equation 6). If a truck (in this example) required a driveline of 122" length, the one piece carbon fiber driveshaft would offer 60-80 lbs of weight savings vs. the conventional two piece steel shaft.

For evaluations, specific metal designs including center bearings and supports must be compared with specific carbon fiber drivelines. Reference 4, 5, and 6 give typical large driveshaft comparisons for industrial applications. Similar weight savings will be obtained for trucks and buses. In like manner, the driveline system calculations would show other results and conclusions directly comparable to or better than those presented in Tables 5-2 and 5-3. As previously described, (section 2.1 of this paper) these conclusions have been proven on test tracks and on the road by the use of carbon fiber driveshafts in large trucks.

Table 5-4 Typical Heavy Truck Shafts
a. Design Data

Item	Carbon Fiber	Steel	Steel	Steel
OD, (in)	6.480	4.000	4.095	4.500
ID, (in)	6.000	3.732	3.732	4.232
Wall t, (in)	0.240	0.134	0.181	0.134
Operating RPM	2,700	2,700	2,700	2,700

Table 5-4 Typical Heavy Truck Shaft
b. Calculated Maximum Lengths (One Piece)

Item	Carbon Fiber	Steel	Steel	Steel
Max L @ 2,700 rpm, (in)	122	84	85	90

5.5 SAFETY - Safety is greatly enhanced with composite shafts. Composites absorb energy upon impact. They can be designed to, and will normally, break apart during an accident rather than entering the passenger compartment catapulting the vehicle, or whipping a broken end through a tank or valuable cargo. Figure 5-2 shows a broken composite driveshaft. Note the broken pieces rather than the bent and twisted club that is usually left with metal. Impact with hard objects like frame rails will cause a composite shaft to disintegrate and quickly dissipate energy. A failure in a bond joint would simply result in a loss of power. The shaft would probably stay in place with the loose end spinning inside of it.

Figure 5.1 Carbon Fiber Driveshaft: Energy Absorbing Break

In one racing instance, Dick Anderson[17] was extremely pleased when a failed suspension component sawed a composite shaft in half and the driveshaft tore itself apart underneath his team's car. The shaft disintegrated with no serious secondary damage and no injury to the driver. Two previous accidents with Mr. Anderson's team using aluminum shafts ended differently. In one, the aluminum shaft came through the floorboards and broke the driver's foot. In the other, an aluminum shaft demolished the rear of the car and came to rest right behind the driver's head. Fortunately, he was not injured.

5.6 RECYCLABILITY - Recycling of composites must be taken into consideration. There are generally two classifications of composite materials: thermosets and thermoplastics. Thermoplastics can be softened and reshaped, and thus fit into a totally different set of recycling possibilities than thermosets, which do not soften (thus the possibilities of rework) with heating. This paper considers mainly composites using epoxy matrices that are thermosetting materials.

As the automotive industry is using more and more composite materials in body panels, springs, etc, much research is being done on recycling thermosetting composites, in particular, fiberglass. The result of this work will be generally applicable to glass/graphite composites. A typical analysis was presented by McDermott.[16] In this report McDermott quotes Chris Cloutier, Minnesota Office of Environmental Assistance as saying "the technologies are there - FRP recycling is doable, definitely." This statement along with the knowledge that a great deal of work is in progress in this area leads to the conclusions that the problems will be solved, particularly as the volume of composite scrap increases. Detailed discussions of recycling are beyond the scope this paper. It also noted that as a worst case scenario, graphite/glass/epoxy composites can be ground, added to powdered coal fuel and then burned producing heat and sand or ash.

5.7 COSTS - Industrial applications of composite shafts are saving money. Long, light weight composite shafts used in cooling towers and pumping stations are hand carried and installed without the need of a crane. Alignment of the shaft to the motor and gear box or pump is simplified with a single piece vs a 2 piece shaft. Total installed costs including the carbon fiber shafts are less than metal shafts. As previously stated, these are applications where composites are already replacing metal as the standard.

Similarly, when carbon fiber driveshafts are used, bottom line costs will be less for truck fleet owners. Bulk haulers will see an immediate return through revenue generated by the added hauling capacity. Reduced vibration should also reduce wear and tear on other components, thereby reducing down time and repair costs. When these factors are taken into consideration, the total cost of operation for the life of a truck will be less than with a conventional driveshaft.

6.0 RACE CAR APPLICATIONS

In 1987, a carbon fiber driveshaft helped Dan Gurney's All American Racers (Toyota Celica) win the IMSA GTO championship.[19] Gurney's team experienced a driveline vibrational problem that they could not overcome while using a metal shaft in a transaxle car. The driveshafts, between the engine and the transaxle, operated at maximum rpm in every gear. Severe harmonic resonance in the driveshaft imposed an artificial rpm limit below the engine's actual redline. Having unsuccessfully tried all possible metal shafts, Gurney's team tried a carbon fiber driveshaft. The result was dead smooth driveshaft performance all the way to the engine's limit of 9,000 rpm, instead of the metal shaft limit of 8,000 rpm, which contributed heavily to winning the 1987 GTO title.

Cars and Concepts, with Tommy Kendall driving a Chevrolet Beretta, experienced a similar problem in 1988. They also used a carbon fiber driveshaft to solve the problem. Cars and Concepts had similar results: they raised the red line 10% and won the 1988 IMSA GTU championship.

As mentioned above, carbon fiber driveshafts have been accepted for and used in NHRA competition. Top level drivers are using them and winning races. In 1995, Larry Nance's IHRA pro-modified car - capable of quarter mile times in the range of 6.5 seconds - set a new 60 foot time "door slammer" world record of .945 seconds. He attributes the carbon fiber driveshaft's unique characteristics with aiding his driver in setting this record.

For specific applications the carbon fiber driveshafts can, and have been, designed to be less stiff under torsional loading. This capability combined with the vibrational damping and lighter weight is currently resulting in improved performance for circle track racers. Freddie Smith[20], a favorite of dirt track fans, and currently running second in points in the HAV-A-TAMPA series (The leader of that series is also running a carbon fiber driveshaft) stated, "When we started running the ACPT carbon driveshaft, we gained a 200 rpm advantage. It allowed us to run a taller gear at less rpm. It has proven to be trouble free and also weighs about two pounds less than our aluminum driveshaft."

Carbon fiber driveshafts are becoming well known in many sectors of the automobile racing community. As the racing industry becomes educated, composite shafts are gaining more and more acceptance, and continually find themselves in the front-runner's cars.

7.0 CONCLUSION

Carbon fiber driveshafts can be used today to enhance the profitability of trucking operations. They will reduce the weight of the driveline and will reduce drivetrain vibrations, thereby reducing wear and tear in driveline and other components.

In light trucks and cars carbon fiber driveshafts will reduce noise, vibration, and harshness of ride, providing greater driver comfort. They can also raise current driveshaft-limited top speeds in certain performance automobiles. These conclusions have been proven in industrial, aerospace, and racing applications. The trucking industry is now evaluating carbon fiber driveshafts and is beginning to come to the same conclusions.

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