NANOSILICA-MODIFIED EPOXY RESINS FOR USE IN LIGHTWEIGHT FILAMENT-WOUND DRIVE SHAFT APPLICATIONS

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Abstract

This paper explores and illustrates the enhanced properties of filament wound carbon-fiber tubes resulting from significantly increased matrix stiffness. Properties for a high modulus nanosilica-modified matrix resin (3M™ Matrix Resin 4833) and unfilled control resin were measured. Filament winding was used to create carbon fiber composite tubes using the resins. The axial and hoop stiffness of the tubes were measured and compared to theory. Lightweight driveshaft structures are featured through the application of the nanosilica resin technology.

Background

The performance of a composite material drive shaft is usually considered to be dependent on the fiber properties and winding angles with little effect of the matrix properties. However, the design of carbon composite drive shafts involves consideration of several behaviors that are related to shaft axial and hoop stiffness, both of which depend on the matrix modulus. The elastic modulus of conventional epoxy resins can be varied only in a narrow range, so matrix resin choice is often driven primarily by other considerations, such as processing and cost. In bulk applications of polymers, inorganic fillers are often used to increase stiffness and hardness, decrease cure shrinkage and the coefficient of thermal expansion (CTE), and modify other properties relevant to advanced composites applications. However, conventional inorganic filler technology is not appropriate for fiber composite matrix resins because the particles are filtered out of the resin during fiber impregnation. In addition, the increase in resin viscosity from high levels of conventional fillers is typically too great for composite processing.

Nanosilica-Modified Thermoset Systems: The improvements from inorganic particle incorporation can be realized in thermoset fiber-reinforced composites by using nanoscale inorganic particle technology. Appropriately surface-functionalized spherical nanoscale particles enable production of non-aggregated dispersions in cured epoxy resins with levels over 50 wt% (Figure 1a shows a TEM image of a resin with a concentration of 55 wt%). Unlike larger inorganic particles, these can be evenly dispersed throughout a fiber composite structure without filtration by the fiber array during matrix infiltration of the fibers. Figure 1b show field-emission SEM micrographs of polished cross-sections of representative composite laminates from this study having 42 wt% nanosilica of nominally 142 nm diameter. The particles have penetrated between 7 µm diameter carbon fibers and fill the interstitial areas between the fibers. This produces a homogeneous mechanical environment for the fibers.
Past work by the present authors and others has shown that the incorporation of spherical nanoscale amorphous silica can improve matrix resin properties that translate into improvements in fiber-reinforced composite processing and properties.[1-7] The present investigators have demonstrated the benefits of incorporating a high loading (up to 45 wt%) of nanoscale silica into epoxy matrix materials for unidirectional carbon fiber prepregs for both 121 °C (250 °F) and 177 °C (350 °F) curing.[1-2] Additionally, neat resin and carbon-fiber composite properties of nanosilica-modified epoxy and bismaleimide resins designed for composite tooling applications were studied extensively.[7] Furthermore, nanosilica-containing, low viscosity resins, suitable for filament winding processes, have been studied for use in composite overwrapped pressure vessels.[8] Composite matrix resin mechanical properties including modulus and fracture toughness showed significant, monotonically increasing improvement with increasing nanosilica concentration. Desirable changes in coefficient of thermal expansion, cure exotherm, and hardness were also measured. Silica concentration levels did not adversely affect the cured glass transition temperature or composite processing. Properties of carbon fiber laminates made with unidirectional prepregs or with fabrics of varying silica loading levels revealed significant improvements in compression strength, in-plane shear modulus, and 0° flexural strength. In general, the benefit of matrix modification with nanosilica is increased with increased loading levels.

**Current Study:** This paper explores and illustrates the enhanced properties of filament wound carbon fiber tubes resulting from significantly increased matrix stiffness. This matrix modulus increase is achievable by incorporating surface-modified nanosilica into the matrix resin at a very high weight fraction. Buckling torque, first natural frequency, and torsional vibration response are examined by exercising design equations for a candidate winding construction. (These are not the only considerations in tube design and material choice; however, they are primary properties governed by matrix stiffness.) Inputs to the tube design equations are calculated by applying the Halpin-Tsai micromechanics equations to determine lamina properties from matrix and fiber properties, which in turn are used to calculate the laminate properties relative to the axial and hoop directions of a tube.

An experimental study was performed in order to support and illustrate the effects studied by calculation, as well as to provide a check on the overall calculation scheme. First, resin properties for a nanosilica-modified matrix resin (4833, 1) and unfilled control resin were
measured. The modulus increase relevant to tube properties is illustrated along with a number of other unique property increases. These relate to processing, residual stresses, and durability; all of interest for drive shaft applications. Second, filament winding was used to create carbon fiber composite tubes using the resins. The axial and hoop stiffness of the tubes were measured. The comparison of the control and nanosilica-modified tubes illustrates the increase in tube stiffness achievable; comparison of measured and calculated stiffness supports the applicability of the calculation procedure for the design study.

In the following, the theory behind the design calculations is presented, then the experimental procedures and results. Finally, the results obtained for tube properties as a function of matrix modulus are presented.

**Theory**

**Effective Laminate Properties:** The elastic properties of filament wound tubes were predicted following the model proposed by Chou et al. [9] Originally the model was developed for flat laminates but it is used here for predicting the properties of curved laminates (i.e. tubes). It will be shown later that this model predicts the elastic properties of the tubes fairly well by comparing the predicted engineering constants with the experimentally measured values on tube specimens.

The predictions begin by estimating the lamina level properties using Halpin-Tsai equations. The lamina is assumed to be transversely isotropic. The Halpin-Tsai equations used are given below for reference.

\[
E_{11} = E_f V_f + E_m V_m \quad (11\text{-fiber direction})
\]

\[
E_{22} = E_m \left( \frac{1+\xi\eta V_f}{1-\eta V_f} \right); \quad \eta = \left( \frac{E_f}{E_m} \right); \quad \xi = \left( \frac{E_m}{E_f} \right) \quad (22\text{-transverse to fiber direction})
\]

\[
G_{12} = G_m \left( \frac{1+\xi\eta V_f}{1-\eta V_f} \right); \quad \eta = \left( \frac{G_f}{G_m} \right); \quad \xi = 1 \quad (12\text{-plane described by directions parallel & perpendicular to fibers})
\]

After determining the lamina properties, the laminate properties are predicted using the model proposed by Chou et al. [9] The coefficients of the effective laminate stiffness matrix, \( \tilde{C}_{ij} \), are given by

\[
\tilde{C}_{ij} = \sum_{k=1}^{n} V^k \left[ \tilde{C}_{ij}^k - \frac{c_{23}^k c_{13}^k}{c_{33}^k} + \frac{\sum_{l=1}^{n} \nu^{l} c_{13}^k}{c_{33}^k} \right] \text{ for } (i, j = 1, 2, 3, 6)
\]

\[
\tilde{C}_{ij} = 0 \text{ for } (i = 1, 2, 3, 6; j = 4, 5)
\]

\[
\tilde{C}_{ij} = \left[ \frac{\sum_{k=1}^{n} \nu^{k} c_{ij}^k}{\sum_{k=1}^{n} \nu^{k} c_{44}^k} (\tilde{c}_{44}^k c_{55}^k - \tilde{c}_{45}^k c_{54}^k) \right] \text{ for } (i, j = 4, 5)
\]

\[
\Delta_k = \tilde{c}_{44}^k c_{55}^k - \tilde{c}_{45}^k c_{54}^k
\]

Page 3
where \( \tilde{C}_ij^k \) is the reduced stiffness matrix of the \( k \)th layer in the global coordinate system. In the global coordinate system the fiber direction is measured from the axial direction of the tube. The orientation of fibers in each layer is needed relative to the axial direction of the tube to determine \( \tilde{C}_ij^k \).

The engineering constants including the axial young's modulus, \( E_x \), hoop modulus, \( E_\theta \), radial modulus, \( E_r \), the shear moduli, \( G_{x\theta}, G_{\theta r}, G_{xr} \) and the major and minor poisson's ratios \( \nu_{xr}, \nu_{x\theta}, \nu_{xr} \) and \( \nu_{x\theta}, \nu_{\theta r}, \nu_{rx} \), respectively could be determined from the elements of the compliance matrix as expressed below and in Table I:

\[
\bar{H}_{ij} = \tilde{C}_{ij}^{-1}
\]  

(7)

### Table I. Engineering Constants Used in This Study

<table>
<thead>
<tr>
<th>Constant</th>
<th>#</th>
<th>Constant</th>
<th>#</th>
<th>Constant</th>
<th>#</th>
<th>Constant</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_x = 1/\bar{H}_{11} )</td>
<td>8</td>
<td>( G_{x\theta} = 1/\bar{H}_{66} )</td>
<td>1</td>
<td>( \nu_{x\theta} = -H_{12}/H_{11} )</td>
<td>1</td>
<td>( \nu_{\theta r} = -H_{23}/H_{22} )</td>
<td>1</td>
</tr>
<tr>
<td>( E_\theta = 1/\bar{H}_{22} )</td>
<td>9</td>
<td>( G_{\theta r} = 1/\bar{H}_{44} )</td>
<td>1</td>
<td>( \nu_{\theta r} = -H_{12}/H_{11} )</td>
<td>1</td>
<td>( \nu_{rx} = -H_{12}/H_{11} )</td>
<td>1</td>
</tr>
<tr>
<td>( E_r = 1/\bar{H}_{33} )</td>
<td>1</td>
<td>( G_{xr} = 1/\bar{H}_{55} )</td>
<td>1</td>
<td>( \nu_{xr} = -H_{12}/H_{11} )</td>
<td>1</td>
<td>( \nu_{rx} = -H_{12}/H_{11} )</td>
<td>1</td>
</tr>
</tbody>
</table>

For this study, all calculations used the properties reported by the manufacturer for T700SC-24K-50C Toryaca carbon fiber, which was used in the experiments.[10] For predictions of tube stiffness used for comparison with experimental values, the matrix properties measured using ASTM D638, and reported in Table II, were used. For the design study, the matrix properties were varied over a range from the control to those of resin 4833.

**Composite Drive Shaft Design**

The engineering constants of a thin-walled hollow tube often considered in design of a drive shaft are its axial, hoop, and shear modulus. Of the three moduli, the axial and hoop relate to stability against torsion buckling and lateral vibrations and the shear modulus is considered important for torsional vibrations. There are various mathematical treatments available in the literature for determining the buckling torque and flexural and torsional vibration stability of thin-walled hollow tubes.[11-16] For the purpose of this investigation, the following expressions were used based on their simplicity and extensive use to determine an order-of-magnitude solution for designing a drive shaft. These equations are empirical and are based on experimental studies.

The critical buckling torque is given as

\[
T_{buckling} = \frac{1.854}{\sqrt{L}} \times E_x^{0.375} \times E_\theta^{0.625} \times t^{2.25} \times D^{1.25}
\]  

(20)

where \( E_x \) and \( E_\theta \) are the elastic modulus in the axial and hoop direction of the composite tube respectively, \( t \) is wall thickness of the tube, \( D \) is the diameter of the mid-plane of the tube wall, and \( L \) is the length of the tube.\(^{13}\)

The equations used for predicting the lateral natural frequencies are shown next.[14] These
equations are based on Timoshenko beam theory and account for lateral shear deformations. With the shear deformations included the expression for natural frequency is given by

$$p_n = K_s \frac{30\pi n^2}{L^2} \sqrt{\frac{E_x r^2}{2\rho}} , \quad n = 1, 2, 3, \ldots \ldots [RPM]$$

$$\frac{1}{K_s} = 1 + \frac{n^2 \pi^2 r^2}{2L^2} \left[ 1 + \frac{f_s E_x}{G_x \theta} \right] , \quad f_s = 2, n = 1, 2, 3 \ldots \ldots$$

where \( r \) is the radius of the mid-plane of the composite tube wall and \( L \) is the length of the tube. The torsional natural frequencies are given by

$$p_n = \frac{1}{2\pi} \sqrt{\frac{G_x \theta}{L l_m}}$$

where \( j \) is the polar moment of inertia of the composite tube and \( l_m \) is the effective mass moment of inertia, dependent on the system. From the previous expression it can be seen that the torsional vibrations are directly proportional to the in-plane shear modulus of the composite tube.[16]

All of the above expressions were used to theoretically determine the effect of matrix modulus on the performance of composite drive shafts.

**Experimental**

**Matrix Resin Characterization**

Castings were made of 4833 containing 42% nanosilica by weight and an industry standard control without nanosilica modification. These were cured in a forced air oven at 4h at 125 °C. The cured resin specimen preparation and testing methods used to obtain neat resin properties have been described previously.[1-2] All testing was conducted under ambient laboratory conditions.

**Filament Winding Process for Carbon Fiber Tube Production**

In collaboration with QA1, a manufacturer of advanced composite drive shafts, tubes were manufactured by filament winding to allow experimental confirmation of the theoretically predicted composite tube properties. Composite tubes containing 4833 and a non-silica industry control were created via a wet winding process. Figure 2 depicts the process of making a composite tube with the nanosilica resin on a McClean Anderson Super Hornet filament winder with an electronic fiber tensioning system.
Figure 2. Filament Winding Operation with 4833 (1)

Epoxy carbon fiber tubes with dimensions of 8.63 cm inner diameter, 0.4 cm thickness and approximately 0.3M length, were wound utilizing a ca. 8 cm diameter aluminum mandrel. Winding was conducted with T700SC-24K-50C Toryaca fiber at 7 lb of fiber tension. A 6 ply ±30, ±30, ±45, ±45, ±30, ±30 winding pattern was used for both the control and 4833-containing system. The QA1 tube winding programs were developed using the Flexwind and Composite Designer Software from McClean. Wound tubes were covered in Dunstone 212 HT Shrink Tape at 5lbs of tension. The tubes were cured at 150 °C for 2 hrs.

Carbon Fiber Composite Tube Test Methods

Axial Compression

To validate the predictions of analytical modeling, the axial stiffness of the tubes was measured. 15.2-cm long tube sections were subjected to compression in axial direction while measuring axial strains at the mid location on the outer diameter of the tube specimens. Two strain gages were bonded at the outer diameter located diametrically opposite to each other. The strains were monitored to ensure the tubes were loaded uniformly and averaged to determine the axial modulus of the tubes. The tubes were loaded up to 2500 micro strains and a linear curve was fit to the stress-strain data between 1000 to 2500 micro strains to calculate the axial modulus. The stress was calculated by dividing the measured load with the cross-sectional area of the tube. Two tube specimens were tested for each of the control and nanosilica resins. Both types of specimens have an inner diameter of 86.4 mm and a nominal wall thickness of 3.94 mm. The tubes were loaded in compression using spherical seat platens at 1 mm/min while measuring strains at 10 Hz.

Tensile Hoop Modulus

The hoop modulus of tubes was measured by loading 1.27 cm wide rings cut from the tubes using a split-D fixture. In this loading method, two semi-circular metal inserts are pulled apart using a pin and clevis arrangement to apply load in the hoop direction. Two strain gages located at 45° and 70° from the split were bonded on the outer diameter of the ½-inch wide rings cut from the tubes. The strain gage locations were chosen based on the recommendations by Yoon et al. The rings were loaded at 1 mm/min in tension while recording the strains at 10 Hz. In an attempt to overcome the effects of friction between the ring and the fixture, a 0.125 mm thick Teflon sheet was used in between the surfaces. This sheet is not expected to eliminate frictional effects completely, but is intended to allow measurement of a hoop modulus value that compares well to predictions. The rings were loaded up to 3000 micro strain and then unloaded.
The strains between 1000 to 3000 micro strain were used to fit a linear curve to the stress-strain data to calculate the hoop modulus. For each strain gage the hoop modulus values were calculated for loading and unloading case and then averaged. The averaged values for each of the two strain gages at different locations were further averaged to report the experimentally-measured values for each ring specimen.

**Results and Discussion**

**Neat Resin Properties.**

To illustrate the neat resin property enhancements produced through the inclusion of this high level of well-dispersed nanosilica, the nanosilica resin systems were compared to the unfilled control of otherwise identical compositions. Neat resin data for the 4833 resin system versus the appropriate control system are shown in Table II.

<table>
<thead>
<tr>
<th>Property</th>
<th>Epoxy Control</th>
<th>4833 (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica (wt %)</td>
<td>0</td>
<td>42</td>
</tr>
<tr>
<td>Tensile Modulus (GPa)</td>
<td>2.75</td>
<td>6.2</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>78.6</td>
<td>82.1</td>
</tr>
<tr>
<td>Tensile Strain (%)</td>
<td>4.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Fracture Toughness (MPa-m^1/2)</td>
<td>1.0</td>
<td>2.2</td>
</tr>
<tr>
<td>$T_g$ by tan delta peak (°C)</td>
<td>129</td>
<td>129</td>
</tr>
<tr>
<td>Barcol Hardness ($H_B$)</td>
<td>33</td>
<td>65</td>
</tr>
<tr>
<td>Nano-indentation Modulus (GPa)</td>
<td>4.06</td>
<td>8.55</td>
</tr>
<tr>
<td>Cure Exotherm (J/g)</td>
<td>442</td>
<td>246</td>
</tr>
<tr>
<td>CTE ($\mu$m/m/°C)</td>
<td>55</td>
<td>38</td>
</tr>
<tr>
<td>Linear Cure Shrinkage (%)</td>
<td>0.75</td>
<td>0.55</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>1.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

A differentiating feature of the nanosilica resin technology is the simultaneous improvement in tensile modulus and fracture toughness, while not influencing the glass transition temperature ($T_g$, Table II). Specifically, the tensile modulus for the 3M\textsuperscript{TM} Matrix Resin 4833 is more than doubled relative to the control resin. Silica incorporation leads to an increase in modulus, as seen in both macro-scale and nano-scale measurements. Modulus as quantified by nanoindentation further confirmed the much higher stiffness of the 4833 system as shown in Table II. The increase in nanoindentation modulus suggests that unlike larger filler particles, the nanoscale silica effectively increases modulus on a very small scale; the material is essentially homogeneous on the scale of the indenter. Table II lists the tensile modulus as well as the average stress and strain at failure. The failure stress and strain are believed to be lower bounds on the properties since they are significantly affected by defects in the resin castings. Consistent with previous studies, nanosilica modification produced similar or higher strength levels with reduced failure strain.[1-2] The improved tensile modulus is accompanied by a simultaneous improvement in fracture toughness, as shown by the results of resin fracture testing given in Table II. The increase in $K_{IC}$ shows that the resin is not embrittled even with a dramatic increase in modulus, but can be significantly improved. Matrix fracture resistance is a key matrix attribute relating to part fatigue performance and durability.
Additionally, silica incorporation leads to an increase in Barcol hardness, which uses an arbitrary scale to quantify the force needed to produce a fixed total (elastic and plastic) surface deformation by a stylus, increased twofold (Table II). High hardness is believed to enhance part surface quality and durability, which is particularly important for aggressive environments such as automotive applications.

As seen in previous work, the reduction of cure exotherm with increasing silica content was observed.[1-2] The cure exotherm as a function of silica content is shown in Table II. A 44% reduction of cure exotherm is measured by the addition of 42 wt% nanosilica. Nanosilica lowers the extent of exotherm during cure by simply reducing the amount of curable resin present. This may be very important for the fabrication of thick parts where heat management during cure is crucial. Also shown in Table II are the shrinkage values which show reduced shrinkage at high silica content. Reduced coefficient of thermal expansion is desirable for composite matrix materials in order to reduce thermal stresses and/or part distortion. Silica inclusion at 42 wt% resulted in a reduction in the coefficient of thermal expansion by 31% as shown in Table II. These property improvements are desirable for composite fabrication.

The density of cured resin samples at 0 and 42 wt% nanosilica are displayed in Table II. The incorporation of nanosilica into a resin increases the density of the resultant system because the density of silica is higher than that of the base resin. The impact of this density increase on a representative carbon fiber composite with fiber volume fraction of 60% is a few percent. As will be seen, the accompanying gains in composite properties offer composite designers latitude in eliminating carbon fiber and other weight- and cost-saving strategies. These can result in an overall reduction in part weight for equal strength or stiffness.

**Effect of Silica on Filament Wound Carbon Fiber Composite Tube Mechanical Properties**

Experimental validation of the predictions for engineering constants is critical from the point-of-view of using these predictions for estimating the performance of a tube as drive shaft. In a high fiber volume composite the fiber orientation and volume as well as ply thickness are critical in determining the engineering constants. In order to accurately capture the fiber volume fraction and ply orientations for the composite tubes that were fabricated, cross-sections perpendicular to the axial direction of tubes were cut, mounted in epoxy, and polished. Micrographs were used to estimate fiber volume fraction, fiber orientation relative to the axial direction, and to determine the average layer thickness. This information was found critical in accurately determining the engineering constants of a tube as will be shown later. Figure 3 shows a typical micrograph used for measurements. The software ImageJ[^18] was used for analyzing the images. The fiber volume fraction was estimated from the area fraction of the fibers in the micrograph and the fiber orientation was determined from the ratio of the minor to major axis of the oval fiber sections as shown in Figure 3. Fiber volume fraction was estimated from area fraction. Table 3 lists the measured values for control and nanosilica tube specimens.
Figure 3. Scheme for fiber angle and volume fraction calculations.

The variations in fiber angles from the nominal winding angles are up to 3° as reported in Table 3. The axial and hoop modulus of tube specimens predicted using the measured values listed in Table III are compared with experimentally determined values in Figure 4. The results illustrate the sensitivity of predicted tube properties to small variations in angle related to the winding process and potentially fiber slipping during the curing.

It can be observed in Figure 4 that the predictions made using actual fiber angles are closer to the experimentally measured values than those made using the nominal winding angles. Another important observation is that the Halpin-Tsai calculations input to the Chou et al. [9] model predicts the axial modulus fairly well in this case and can therefore be used to study the effect of matrix properties on the performance of these shafts. The inherent assumption made here is that the compression modulus is same as tensile modulus for predicting the lamina level properties using Halpin-Tsai equations. The most significant observation from the experimental axial modulus values is that the increased modulus of the nanosilica-modified matrix resin translated into a large increase in composite tube axial modulus.

Table III. Fiber Orientation and Volume Fraction Distribution by Layer

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Control</th>
<th>3M Matrix Resin 4833</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fiber orientation, degrees</td>
<td>Fiber volume%, Vf</td>
</tr>
<tr>
<td></td>
<td>nominal</td>
<td>actual</td>
</tr>
<tr>
<td>Layer #</td>
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</tr>
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<td>1</td>
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<tr>
<td>2</td>
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<td>5</td>
<td>45</td>
<td>46</td>
</tr>
<tr>
<td>6</td>
<td>-45</td>
<td>-47</td>
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</table>
The hoop modulus predictions are compared to experimental values in Figure 5. A good correlation is seen for the nanosilica specimens but the experimentally determined value for the control is 32% higher than predicted. Some level of disagreement was expected due to the friction between the ring and the fixture. However a 32% disagreement for only one of the materials calls for additional explanation. One potential cause that can be conjectured is due to the difference in surface hardness of the silica and control specimens. The surface hardness of the silica resin is about twice that of the control as reported in Table II. If the control specimen experiences significant friction during the split-D loading, it would appear stiffer in measurements. A softer surface is more compliant and increases contact area when the two surfaces are pressed against each other. This increase in contact area would increase the friction between the surfaces. The harder nanosilica matrix material would minimize this effect.

<table>
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![Figure 4](image_url)

*Figure 4. Axial modulus of tube specimens in compression.*

Clearly, the experimental results show that, as for the axial modulus, the hoop modulus is significantly increased when the matrix modulus is more than doubled. In light of the good agreement for the nanosilica-modified tube and the good agreement for the axial modulus predictions, the use of the modeling results for illustrating the effect of matrix modulus on composite tube properties was validated.
Figure 5. Hoop modulus of tube specimens in tension using split-D fixture.

Composite Drive Shaft Performance

The performance of a composite material drive shaft is traditionally considered to be dependent on the fiber properties and winding angles with little to effect of the matrix. In the following paragraphs it will be shown by exercising basic design equations that highly-filled nanosilica matrix resins can significantly enhance the performance and change the design of carbon composite drive shafts. The effects of matrix modulus on buckling torque, lateral vibration frequency, and torsional vibration frequency are shown in Figures 6-8. Curves show the absolute and relative changes in these tube properties as matrix modulus is increased between that of the control resin and the nano-silica modified 4833 matrix resin.

Figure 6. Effect of matrix modulus on buckling torque
A first order-of-magnitude analysis for composite drive shaft design shows an increase of up to 60% in buckling torque, 13% in lateral vibration frequency, and a 2.5% in torsional vibration frequency using 4833. These improvements in the performance of the shaft are solely due to the matrix. By increasing modulus of the matrix almost all the design constraints of a drive shaft can be pushed to a higher limit. It is notable that for this design the torsional frequency is much less dependent on matrix modulus than the other properties. The winding angles for the candidate shaft design considered here produce a fiber-dominated torsional stiffness. For a tube design with greater fraction of winding angles closer to 0 or 90 degrees, the dependence on matrix modulus will increase.

The substantial improvement in torque carrying capacity (for torsional buckling-critical designs) that is achieved by using a high-modulus matrix opens up the possibility of reducing the weight of a drive shaft by reducing the wall thickness. Figure 9 shows the variation in torque capacity as a function of reduced wall thickness of the drive shaft. The matrix modulus used for calculations is 6.2 GPa and fiber volume and orientation distribution is taken from Table III. Only the thickness of the layers was varied as shown by the x-coordinate of the graph in Figure 9.
Using 4833 with a modulus value of 6.2 GPa the layer thickness could be reduced up to 16% without sacrificing the torque carrying capacity of the drive shaft. This directly results in weight and cost savings as less material will be needed to meet specific requirements.

![Figure 9. Effect of thickness on torque carrying capacity of drive shaft with 4833.](image)

The tube properties explored in this section are based solely on the stiffness of the resin. It should be noted that previous work has established that the lamina compression strength in the fiber direction is increased significantly by incorporation of high nanosilica loading into the composite matrix. [1,6] This is due to suppression of the micromechanical compression failure mechanism of fiber microbuckling and kink band formation. It is expected that for shaft designs that are limited by compression strength during torsional loading rather than torsional buckling, shaft strength would be increased for a high modulus matrix resin.

**Summary**

The use of nanosilica-modified epoxy in high strength tube applications, such as drive shafts, has been demonstrated. Enhancements in matrix resin properties such as tensile modulus lead to enhanced tube properties. Improved hoop and axial modulus of tubes manufactured with 3M™ Matrix Resin 4833 has been demonstrated and the results compared favorably to theoretical modeling calculations. Based on the use of these models, the favorable effect of increased matrix modulus on buckling torque, lateral vibration frequency and torsional vibration frequency has been predicted.

**Future Work**

Future work suggested by this study includes a) experimental verification of the predicted buckling torque and natural frequencies, b) exercising the modeling methodology to explore matrix modulus effects on other winding angle combinations of interest, and c) experimental investigation of other shaft properties expected to be improved by nanosilica-modified matrix resins, such as durability and residual stress.

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References


