Materials and Design 66 (2015) 346–355

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Viscoelastic characterization and self-heating behavior of laminated fiber composite driveshafts

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ARTICLE INFO

Article history:
Received 22 July 2014
Accepted 29 October 2014
Available online 5 November 2014

Keywords:
Composite driveshaft
Dynamic mechanical analysis
Viscoelastic characterization
Self-heating

ABSTRACT

The high cyclic strain capacity of fiber reinforced polymeric composites presents an opportunity to design driveshafts that can transmit high power under imperfect alignment conditions without the use of flexible couplers. In weight sensitive applications such as rotorcraft, the design of highly optimized driveshafts requires a general modeling capability that can predict a number of shaft performance characteristics—one of which is self-heating due to dynamic loading conditions. The current investigation developed three new flexible matrix composite materials of intermediate matrix modulus that, together with previously developed composites, cover the full range of material properties that are of potential interest in driveshaft design. An analytical model for the self-heating of spinning, misaligned, laminated composite shafts was refined to suit the full range of materials. Inputs to the model include ply-level dynamic material properties of the composite, cyclic strain amplitude and frequency, and various heat transfer constants related to conduction, radiation, and convection. Predictions of the surface temperature of spinning shafts correspond well with experimental measurements for bending strains of up to 2000 με, which encompasses the range of strains expected in rotorcraft driveshaft applications.
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1. Introduction

Fiber reinforced composites are an attractive class of material in structural design because of the wide range of stiffness, strength, and mass density that can be designed into a laminate based on the selected constituents and reinforcement morphology. One particularly tailorable class of composites, known as flexible matrix composites (FMCs), consists of high strength continuous fibers such as carbon and an elastomeric matrix such as polyurethane. FMCs differ from conventional rigid matrix composites (RMCs) such as epoxies in that the former normally operate at temperatures above their glass transition temperature whereas the latter normally operate below their glass transition temperature. While the elastic modulus of FMCs in the fiber direction is similar to that of RMCs, the elastic modulus perpendicular to the fibers of FMCs can be an order of magnitude less than that in RMCs. Conversely, ultimate strains perpendicular to the fibers and in shear for FMCs can exceed those of RMCs by an order of magnitude.

An example application for FMCs is a one-piece rotorcraft driveshaft that can accommodate misalignment (compliant in bending) while transmitting power (high stiffness and strength in torsion). Thus, a single shaft can replace the typical multi-segmented driveline, thus reducing weight, complexity, and maintenance requirements. Current rotorcraft drivelines are often made of multiple, short metal shafts that are connected together via flexible couplers that accommodate inevitable misalignment due to manufacturing tolerances as well as dynamic flight loads. The flexible couplers prevent the potential for fatigue in a metal shaft due to misaligned operation. Hanger bearings fix the position of the couplers relative to the airframe. The multi-segmented driveline concept is widely utilized but leaves much room for improvement in terms of weight, complexity, and maintenance.

Hannibal and Avila [1] are widely credited with introducing the concept of a one-piece FMC shaft for transmitting power in a misaligned driveline. They demonstrated the promising potential of the concept for an automotive application and recommended that self-heating be considered when selecting the matrix material for shafts operating at high speed. Further development of the concept for helicopter applications was done by several researchers at Penn State University [2–7]. The work by Shan and Bakis [5] was the first to validate an analytical model for the self-heating of an FMC shaft spinning with misalignment. This validation was done with only one FMC material system and simple angle-ply shafts of $[\pm\theta]_n$ fiber orientation in relation to the longitudinal axis. Bakis et al. [6] improved the analysis in [5] by including mixed angle-ply

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http://dx.doi.org/10.1016/j.matdes.2014.10.083
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laminates of $[\pm\theta_1/\pm\theta_2/\ldots\pm\theta_n]$ fiber orientation. The analysis was validated utilizing simple angle-ply shafts consisting of a single FMC material system having a matrix elastic modulus higher than that used in [5]. The capability to analyze mixed angle-ply laminates is important because optimization studies done by Roos and Bakis [7] have shown that mixed angle-ply FMC shafts are preferred over simple angle-ply shafts for reducing rotorcraft driveline weight.

The aforementioned experimental and analytical work on the self-heating of FMC shafts has been limited by the investigation of only two FMC material systems to date, both of which used matrix materials with an elastic modulus of less than 0.25 GPa—an order of magnitude less than epoxy. Little information is available on composite material systems with matrix moduli between 0.25 GPa and 3.0 GPa, which is a potentially viable target range for shaft design. The objectives of the present investigation are threefold: (1) manufacture three new carbon fiber reinforced composites with intermediate matrix moduli; (2) characterize the viscoelastic properties of five composite material systems with matrix moduli spanning the full range of interest for shaft design—0.25–3.0 GPa; (3) validate the viscoelastic properties for purposes of predicting self-heating in composite shafts of several different lamination arrangements and three different material systems. Inputs for the model are obtained at the ply level using a mixture of dynamic mechanical analysis for matrix-dominated behavior and experimental measurements and standard composite mechanics equations for fiber-dominated behavior. Thermal properties such as convection cooling coefficient and thermal conductivity are obtained using established methods from the literature. The current investigation significantly extends the database of viscoelastic properties of prospective composites shaft materials and will increase the effectiveness of future driveshaft design efforts by confirming the validity of the self-heating model over a wide range of material systems and laminates.

2. Constitutive behavior

The well-known time–temperature superposition principle [8] was used to create master curves of storage modulus, loss modulus, and loss factor based on a sets of dynamic mechanical analysis data obtained over suitable ranges of temperature and frequency [9,10]. Each isothermal data set was shifted horizontally by a multiplicative shift factor, α_T, to create the master curve for a particular property. The variation of α_T with respect to temperature, T (°C), could be represented reasonably well by the Williams–Landel–Ferry (WLF) equation (Eq. (1)), as will be shown in the results.

$$\log[\alpha_T] = \frac{-C_1(T - T_r)}{C_2 + (T - T_r)} \tag{1}$$

For convenience, the reference temperature, T_r, was taken as 60 °C. Since T_r was not set equal to the glass transition temperature of the composites, no physical meaning can be ascribed to the values of C_1 and C_2. Constants C_1 and C_2 were found by curve fitting $\log[\alpha_T]$ versus T data as part of a reduced gradient optimization routine elaborated on further in subsequent discussion. The WLF equation is usually used to characterize shift factor behavior near to and above a material's T_g, which is appropriate for the flexible polyurethanes used in the current investigation. Additionally, the WLF equation and the time–temperature superposition principal in general can be used below the T_g provided physical aging effects are negligible—for example, in short term (momentary) testing of polymer composites [11,12].

Temperature- and frequency-dependent viscoelastic behaviors in the transverse and longitudinal shear directions of the unidirectionally reinforced (transversely isotropic) plies were characterized using a fractional derivative constitutive model. The model was originally developed for neat polymers by Bagley and Torvick [13] and was subsequently applied to unidirectionally reinforced composites by Shan and Bakis [5]. One potential advantage of the fractional derivative model over other models such as the generalized Maxwell model (also known as the Prony series) is a significant reduction in the number of constants needed to describe the viscoelastic response [14]. The fractional derivative viscoelastic model is given by Eq. (2),

$$\sigma[t] + \sum_{k=1}^{n} a_k D^{\beta_k}\sigma[t] = E\varepsilon[t] + E\sum_{k=1}^{n} b_k D^{\beta_k}\varepsilon[t] \tag{2}$$

where σ, ε, and E respectively refer to the stress, engineering strain, and elastic modulus and D^{β_k} are fractional derivatives of order β_k ($0 < \beta_k < 1$), defined as

$$D^{\beta_k}[x[t]] = \frac{1}{\Gamma[1-\beta_k]}\frac{d}{dt}\int_0^t \frac{x[\tau]}{(t-\tau)^{\beta_k}}d\tau \tag{3}$$

where Γ is the gamma function,

$$\Gamma[x] = \int_0^\infty t^{x-1}e^{-t}dt, \quad (x > 0) \tag{4}$$

The constitutive behavior is purely elastic when β_k equals 0 and purely viscous when β_k equals 1. Following Bagley and Torvick [15], the Fourier transform of a time dependent variable $x[t]$ is

$$F[x[t]] = \int_{-\infty}^{\infty} x[t]e^{i\omega t}dt = x^*[if] \tag{5}$$

where $i = \sqrt{-1}$ and the superscript $*$ represents a complex variable which is a function of f—the cyclic frequency in Hz. The fractional derivative operator (Eq. (3)) has a special property in the Fourier domain such that the Fourier transform of the fractional derivative of order β_k of $x[t]$ is given by Eq. (6).

$$F[D^{\beta_k}[x[t]]] = (if)^{\beta_k}F[x[t]] \tag{6}$$

Thus, the Fourier transform of the fractional derivative viscoelastic model (Eq. (2)) is

$$\sigma^*[if] + \sum_{k=1}^{n} a_k(if)^{\beta_k}\sigma^*[if] = E\varepsilon^*[if] + E\sum_{k=1}^{n} b_k(if)^{\beta_k}\varepsilon^*[if] \tag{7}$$

Collecting complex stress, $\sigma^*[if]$, and complex strain, $\varepsilon^*[if]$, terms and rearranging results in

$$\sigma^*[if] = E\varepsilon^*[if]\frac{1+\sum_{k=1}^{n} b_k(if)^{\beta_k}}{1+\sum_{k=1}^{n} a_k(if)^{\beta_k}} \tag{8}$$

The storage modulus, loss modulus, and loss factor are then defined by Eqs. (9)–(11)

$$E' = \mathrm{Re}\left\{\frac{1+\sum_{k=1}^{n} b_k(if)^{\beta_k}}{1+\sum_{k=1}^{n} a_k(if)^{\beta_k}}\right\}E = \frac{AC+BD}{C^2+D^2}E \tag{9}$$

$$E'' = \mathrm{Im}\left\{\frac{1+\sum_{k=1}^{n} b_k(if)^{\beta_k}}{1+\sum_{k=1}^{n} a_k(if)^{\beta_k}}\right\}E = \frac{BC-AD}{C^2+D^2}E \tag{10}$$

$$\eta = \frac{E''}{E'} = \frac{BC-AD}{AC+BD} \tag{11}$$

Previous implementations of Eqs. (9)–(11) with FMCs having low modulus matrix materials (0.10–0.25 GPa) employed two terms ($n = 2$) in the series expansion [5,6]. In the current investigation with a broader range of matrix moduli, however, improved fits were obtained with three terms. Using the identity $i^{\beta_k} = \cos\left(\frac{\pi\beta_k}{2}\right) + i\sin\left(\frac{\pi\beta_k}{2}\right)$, one can express the constants A, B, C, and D as in Eqs. (12)–(15).

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