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Viscoelastic Analysis of Composite Flywheels for Energy Storage

by Jerome T. Tzeng

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Viscoelastic Analysis of Composite Flywheels for Energy Storage

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Abstract

A viscoelastic analysis has been developed to investigate stress relaxation and creep in a multilayered composite cylinder subjected to rotation. The analysis accounts for ply-by-ply variation of material properties, fiber orientations, and density gradients through the thickness of cylinders. A closed form solution based on the corresponding elastic problem is derived for a generalized plane strain state in a thick-walled, multilayered cylinder. Laplace transform is then applied to obtain the numerical solution of the viscoelastic problem. This report illustrates the derivation of the analytical model and solution procedure. A numerical simulation shows substantial creep and stress relaxation in thick-walled cylinders at an elevated temperature. Viscoelastic effects of composite can result in a drastic change of stress and strain profiles in a cylinder over a period of time, which is critical in terms of structural durability for applications such as energy storage flywheels.

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1. Introduction

A composite flywheel is in general operated at high tip speed. Accordingly, centrifugal force resulting from the rotation of the rotors generates very high tensile stresses in the radial and circumferential directions. It is very critical to ensure that the stress profiles and rotor dimensions do not change during the service life of the rotor. However, polymer matrix composites generally creep over a long period of time, especially at an elevated temperature [1]. The associated stress relaxation in the composite will result in the variation of stress profile and dimension, leading to a potential failure. The objective of this investigation is to develop an analytical method to study the viscoelastic behavior of thick-walled composite cylinders subjected to rotation. The analysis can be applied to the design of flywheel machinery constructed from composite materials.

Activities in the research of viscoelasticity have mainly concerned isotropic materials, including the studies in references [2–10]. Schapery [7] investigated the general formulation of linear viscoelastic boundary value problems of composite materials, including the thermal viscoelastic problems for thermorheologically simple materials, and the applications of the correspondence principle. A viscoelastic analysis developed recently by the author [11–13] investigated thick-walled laminated composite cylinders subjected to thermal and mechanical loads. This investigation extends the viscoelastic analysis to model rotating composite cylinders.

In the following research, the linear quasi-static viscoelastic behavior of a thick-laminated composite cylinder is studied. The analysis accounts for ply-by-ply variation of properties and fiber orientations. The thick cylinder is assumed to be in the absence of thermomechanical coupling and in the state of generalized plane strain such that all the stress and strain components are independent of the axial coordinate. Moreover, due to the nature of axisymmetry, all the stress and strain components are also independent of the circumferential coordinate. The mechanical responses of this thick composite cylinder will, therefore, only have to satisfy the governing equation in the radial direction.

Invoking the Boltzmann superposition integral for the complete spectrum of increments of anisotropic material constants with respect to time, the viscoelastic constitutive relations of the anisotropic composite cylinder can be derived in integral forms. Since the thick composite cylinder is maintained at a constant elevated temperature and boundary conditions are all independent of time, formulations of the linear thermal viscoelastic problem can have forms identical to those of the corresponding linear elastic problem by employing the elastic-viscoelastic correspondence principle. In other words, all of these integral constitutive equations reduce to the algebraic relations that are very similar to those developed for elastic media when they are Laplace-transformed by means of the rule for convolution integrals. The elastic analysis can thus be used to derive the transformed viscoelastic solutions in the time domain.

2. Viscoelastic Formulation

The Boltzmann superposition integral of stress σ_{ij} $(i, j = 1, 2, 3)$ and strain ε_{ij} $(i, j = 1, 2, 3)$ relation for an isothermal viscoelastic problem is

$$\sigma_{ij}(t) = \int_0^t C_{ij}^{kl}(t - \tau) \frac{\partial \varepsilon_{kl}(\tau)}{\partial \tau} d\tau \ , \tag{1}$$

where $C_{ij}^{kl}(t)$ is the relaxation modulus dependent on temperature and time, t. The temperature is assumed to be constant in this study. The Laplace transform of a function $f(t)$ is defined as

$$\overline{f} = \overline{f}(s) = \int_0^\infty e^{-st} f(t) dt \ , \tag{2}$$

where s is the Laplace transform variable. Applying equation (2) with the convolution rule to equation (1) reduces the integral constitutive equations to the following algebraic relations:

$$\overline{\sigma}_{ij} = \widetilde{C}_{ij}^{kl} \overline{\varepsilon}_{kl} \ , \tag{3}$$

where

$$\widetilde{C}_{ij}^{kl} = s \overline{C}_{ij}^{kl} . \tag{4}$$

The preceding Laplace transformed constitutive equation (4) is similar to elastic constitutive relation according to the correspondence principle. The transformed stiffness can be obtained from elastic moduli, $\overline{C}_{ij}^{kl}$, multiplied by Laplacian "s".

Consider a filament-wound axisymmetric thick composite cylinder consisting of N layers with the axial coordinate z, the radial coordinate r, and the circumferential coordinate θ, as shown in Figure 1. The composite cylinder has the inner radius a, the outer radius b, and the length L. Accordingly, there is a corresponding elastic problem with the transformed displacement components

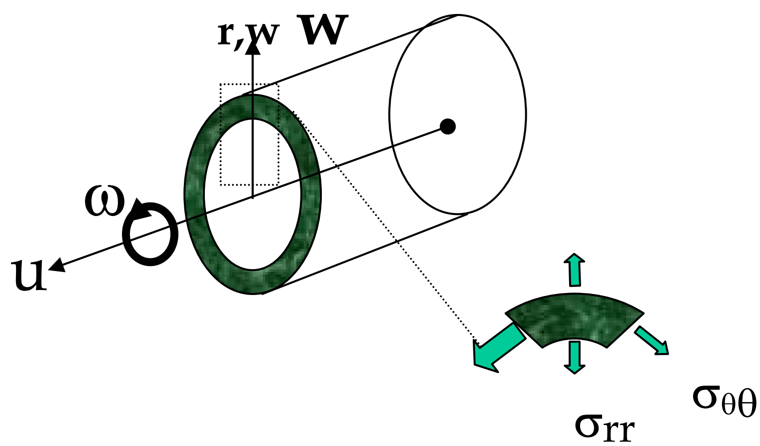

Figure 1. Coordinate system and stress components in a rotating cylinder.

$\bar{u}$, $\bar{v}$, and $\bar{w}$ in the axial direction, the circumferential direction, and the radial direction, respectively, in each layer. The axisymmetric character of the thick composite cylinder, along with the assumption of the state of generalized plane strain, leads to a simplified displacement field, which reflects the circumferential independence and only radial dependence of $\bar{w}$,

$$\bar{u}(r,\theta,z) = \bar{u}(r,z), \bar{v}(r,\theta,z) = \bar{v}(r,z), \text{ and } \bar{w}(r,\theta,z) = \bar{w}(r). \quad (5)$$

Since each layer of the thick laminated cylinder is cylindrically monoclinic in reference to global coordinates, there is no coupling between transverse shears and other deformations. Accordingly, the vanishing shear traction boundary conditions and interface continuity conditions generate zero out-of-plane shear traction and shear strains for each layer. Moreover, owing to the absence of torsional deformation, the transformed displacement components $\bar{u}$ and $\bar{v}$ become

$$\bar{u} = \bar{\varepsilon}^{0} z \quad (6)$$

and

$$\bar{v} = 0, \quad (7)$$

where the constant quantity $\overline{\varepsilon}^{0}$ has the physical interpretation of transformed axial strain of a layer. In fact, $\overline{\varepsilon}^{0}$, according to the present formulation, also represents the transformed axial strain of the entire composite cylinder. The calculation of $\overline{\varepsilon}^{0}$ requires the knowledge of end boundary conditions and will be given later. Likewise, solving for $\overline{w}(r)$ requires the information of transformed strain components, the constitutive equations, as well as the equilibrium equations.

The previously transformed displacement field gives the transformed strain components in cylindrical coordinates

$$\overline{\varepsilon}_{rr}=\frac{d\overline{w}(r)}{dr},\ \overline{\varepsilon}_{\theta\theta}=\frac{\overline{w}(r)}{r},\ \overline{\varepsilon}_{zz}=\frac{d\overline{u}}{dz}=\overline{\varepsilon}^{0},\ and\ \ \overline{\varepsilon}_{\theta r}=\overline{\varepsilon}_{zr}=\overline{\varepsilon}_{z}=0\,. \tag{8}$$

The unabridged form of the constitutive equation (4) for each layer in cylindrical coordinates with the radial coordinate r normal to the plane of symmetry is expressed as

$$\begin{Bmatrix}\overline{\sigma}_{zz}\\ \overline{\sigma}_{\theta\theta}\\ \overline{\sigma}_{rr}\\ \overline{\sigma}_{\theta r}\\ \overline{\sigma}_{zr}\\ \overline{\sigma}_{z\theta}\end{Bmatrix}=\begin{bmatrix}\widetilde{C}_{11} & \widetilde{C}_{12} & \widetilde{C}_{13} & 0 & 0 & \widetilde{C}_{16}\\ \widetilde{C}_{12} & \widetilde{C}_{22} & \widetilde{C}_{23} & 0 & 0 & \widetilde{C}_{26}\\ \widetilde{C}_{13} & \widetilde{C}_{23} & \widetilde{C}_{33} & 0 & 0 & \widetilde{C}_{36}\\ 0 & 0 & 0 & \widetilde{C}_{44} & \widetilde{C}_{45} & 0\\ 0 & 0 & 0 & \widetilde{C}_{45} & \widetilde{C}_{55} & 0\\ \widetilde{C}_{16} & \widetilde{C}_{26} & \widetilde{C}_{36} & 0 & 0 & \widetilde{C}_{66}\end{bmatrix}\begin{Bmatrix}\overline{\varepsilon}_{zz}\\ \overline{\varepsilon}_{\theta\theta}\\ \overline{\varepsilon}_{rr}\\ \overline{\varepsilon}_{\theta r}\\ \overline{\varepsilon}_{zr}\\ \overline{\varepsilon}_{z\theta}\end{Bmatrix}\,. \tag{9}$$

Furthermore, from the previous discussions it can be shown that two of the three equilibrium equations are satisfied automatically. The only nontrivial equilibrium equation is the one in the radial direction:

$$\frac{\partial\overline{\sigma}_{rr}}{\partial r}+\frac{\overline{\sigma}_{rr}-\overline{\sigma}_{\theta\theta}}{r}+\frac{\rho\omega^{2}}{s}r=0. \tag{10}$$

Here, ρ is the density of composite and ω is angular velocity of rotation. Substituting equations (6), (7), and (8) into (9), the transformed stress components $\overline{\sigma}_{rr}$ and $\overline{\sigma}_{\theta\theta}$ are obtained in terms of the transformed radial displacement $\overline{w}$. Incorporating the resulting $\overline{\sigma}_{rr}$ and $\overline{\sigma}_{\theta\theta}$ functions with equation (10) gives a nonhomogeneous Euler differential equation of $\overline{w}$ for a layer

$$r^2 \frac{d^2\overline{w}}{dr^2} + r\frac{d\overline{w}}{dr} - \overline{\lambda}^2\overline{w} = \frac{(\widetilde{C}_{13} - \widetilde{C}_{12})}{s\,\widetilde{C}_{33}}\,\overline{\varepsilon}^{o}\,r - \frac{\rho\omega^2}{s\,\widetilde{C}_{33}} r^3, \tag{11}$$

where

$$\overline{\lambda}^2 = \frac{\widetilde{C}_{22}}{\widetilde{C}_{33}} \ . \tag{12}$$

Solving equation (11) for $\overline{w}$ yields to the complete solution as follows:

$$\overline{w} = \overline{A}_1 r^{\overline{\lambda}} + \overline{A}_2 r^{-\overline{\lambda}} + \widetilde{w}_p \,, \tag{13}$$

where $\overline{A}_1$ and $\overline{A}_2$ are coefficients to be determined from boundary and continuity conditions. The particular solution can be obtained in the following expression:

$$\widetilde{w}_p = \frac{\widetilde{C}_{12} - \widetilde{C}_{13}}{\widetilde{C}_{33} - \widetilde{C}_{22}}\overline{\varepsilon}^{o} r - \frac{1}{9-\overline{\lambda}^2}\frac{\rho\omega^2}{\widetilde{C}_{33}} r^3. \tag{14}$$

The governing equation and the solution represents for each single layer in the composite cylinder. For a multilayered composite cylinder, simultaneous equations will need to be solved by applying proper boundary conditions. Finally, it is understood that the initial condition of the original viscoelastic problem is a displacement-free state of rest. The boundary condition is of free traction and, hence, of free transformed traction on both inner and outer circular surfaces:

$$\overline{\sigma}_{rr} = \overline{\sigma}_{\theta r} = \overline{\sigma}_{zr} = 0 \quad \text{at } r = a,\ b\,. \tag{15}$$

On both end surfaces, stress resultants are zero:

$$\sum_{k=1}^{N} \int_{r_i}^{r_o} \overline{\sigma}_{zz}\, r dr = \overline{\sigma}_{zr} = \overline{\sigma}_{z\theta} = 0 \quad \text{at } z = 0, L\,. \tag{16}$$

The r_i and r_o are inner and outer radii, respectively, of an arbitrary layer (the k^{th} layer). The continuity conditions at each interface between two adjacent layers require continuous radial traction and continuous radial displacement at any instant. Thus, when written in the transformed form, they become

$$\overline{\sigma}_{rr,o}^{(k)} - \overline{\sigma}_{rr,i}^{(k+1)} = 0 \tag{17}$$

and

$$\overline{w},_{o}^{(k)} = \overline{w},_{i}^{(k+1)}, \tag{18}$$

where $k = 1,\ldots,N - 1;$ and subscripts i and o denote inner and outer surfaces, respectively.

Accordingly, the formulation accounts for ply-by-ply variations of material properties and temperature change. The matrix form numerical solution procedure with parallel computing techniques resolved the complexity and time-consuming calculation procedures in the Laplace transform of a multilayered composite cylinder.

3. Numerical Results

A numerical simulation is performed using a thick composite cylinder with a 3-in inner diameter and a 6-in outer diameter. The cylinder is subjected to rotation of 50,000 rpm. Two layup constructions, an all-hoop wound $[90]_{30}$, and a cross-ply architecture $[(90)_4(0)_2(90)_4]_3$ are considered. This is an assumed case with ply thickness of 0.1 in. The cylinders are constructed from IM7-graphite/ 8552-epoxy. Creep compliance of the 8552 epoxy neat resin at 75 °C is characterized from DMA measurements, as shown in Figure 2. The time-dependent characteristic of the resin is then used for the creep compliance of the composite. The creep compliance of the composite normalized with time (hour) is listed as follows:

$$S_{tr}(t) = S_{tr}^{0}\left(t\right)^{0.03}, \qquad S_{tr}^{0} = 7.5328 \times 10^{-7} / \text{psi},$$

$$S_{s}(t) = S_{s}^{0}\left(t\right)^{0.03}, \qquad S_{s}^{0} = 1.3834 \times 10^{-6} / \text{psi}. \tag{19}$$

"t" is normalized time in hour. Here, the subscripts "s " and "tr" represent the shear and transverse directions of composite materials, respectively.

The subscript "s" represents shear property. The compliance in the fiber direction, $S_l = 5.9 \times 10^{-8} / \text{psi}$, and Poisson's ratios, $\nu_{12} = \nu_{13} = 0.3,\ \nu_{23} = 0.36$, is assumed to be time independent. Accordingly, the fiber direction properties are assumed to be elastic.

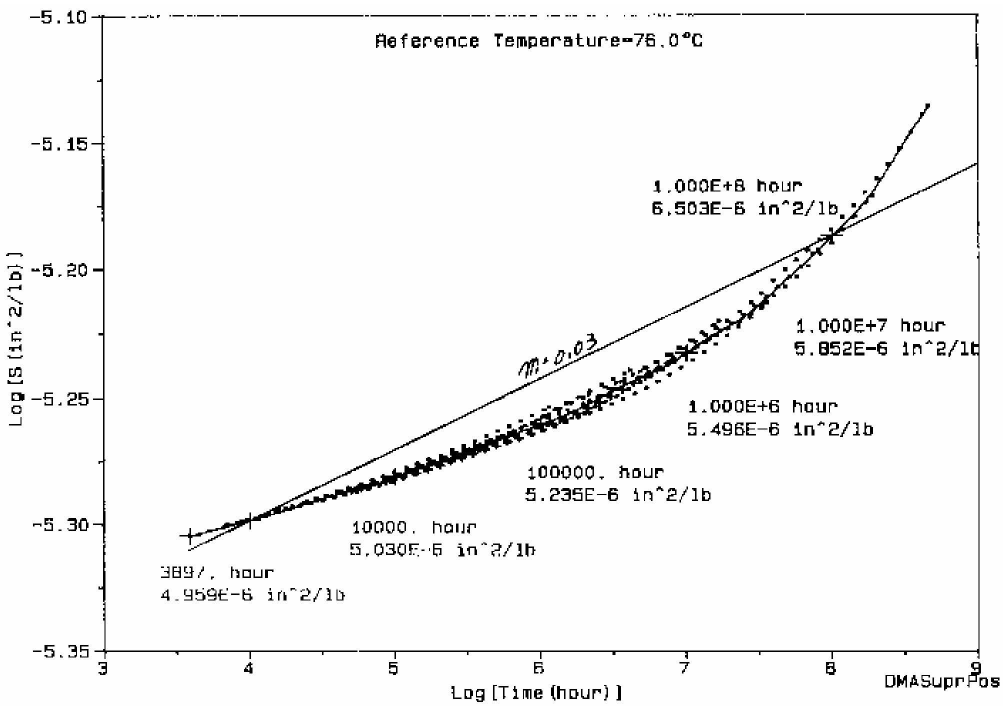

Figure 2. A DMA creep compliance master curve of 8552 epoxy.

Figures 3–5 show the radial displacement, radial stress, and hoop stress distribution in the all-hoop wound thick-walled cylinder at three time instants, respectively. These time instants noted in the figures are initial, 10 years (10^5 hr), and infinite (10^{10} hr). Creep of composite materials over a period of time can result in a significant change in radial displacement and hoop strain. The radial displacement shown in Figure 2 illustrates significant creep over a period of time, which causes an increase of the total radial growth. The radial stress decreases significantly over a period of time due to stress relaxation. Accordingly, a significant redistribution is observed in the hoop stress shown in Figure 4; it is critical from a design point of view. The gradient of hoop stress increases due to viscoelastic response. The hoop stress decreases at the inner radius while it increases at the outer radius over a period of time. Accordingly, a safety margin has to be imposed in the design process.

The results, including the creep of radial displacement and stress relaxation of radial and hoop stresses, are interesting and worth further examination. The viscoelastic behavior of composite results in more compliant radial and axial stiffness in an all-hoop wound cylinder. However, the hoop stiffness remains the same since it is assumed to be elastic. Figure 6 shows a free body diagram analysis of a section of cylinder that is divided into two parts along the circumference (not in ratio). Accordingly, each free body has to be self-balanced among hoop stress, centripetal force, and radial stress. The radial stress, σ_r , is in tension due to rotation, as shown in Figure 4. The free body at the outer radius

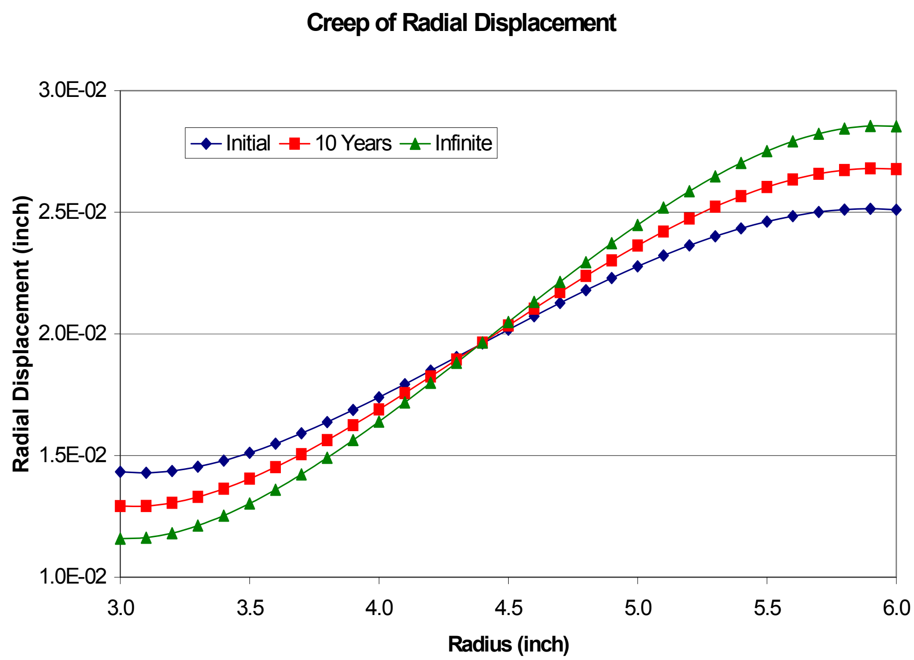

Figure 3. Creep of radial displacement in an all-hoop wound cylinder.

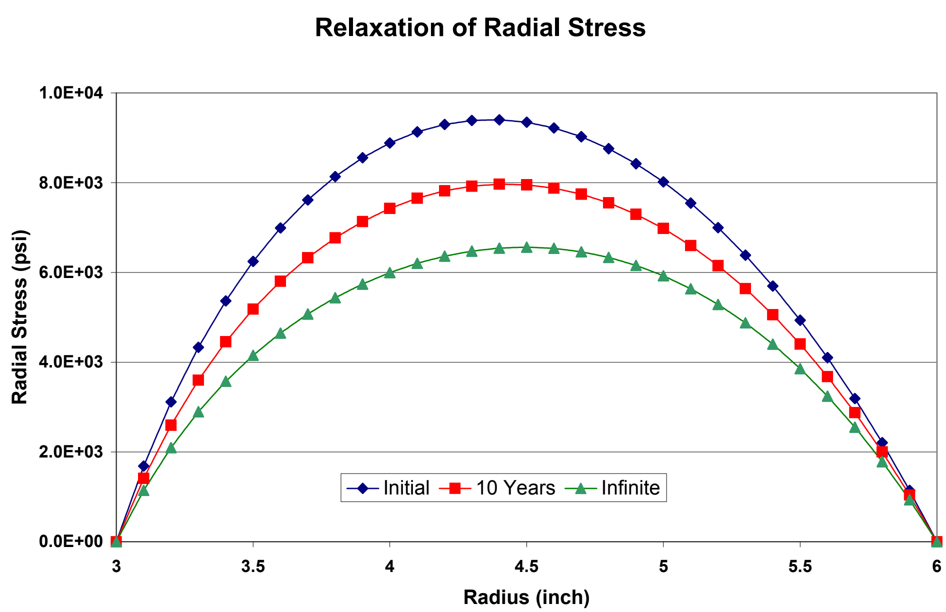

Figure 4. Relaxation of radial stress in an all-hoop wound cylinder.

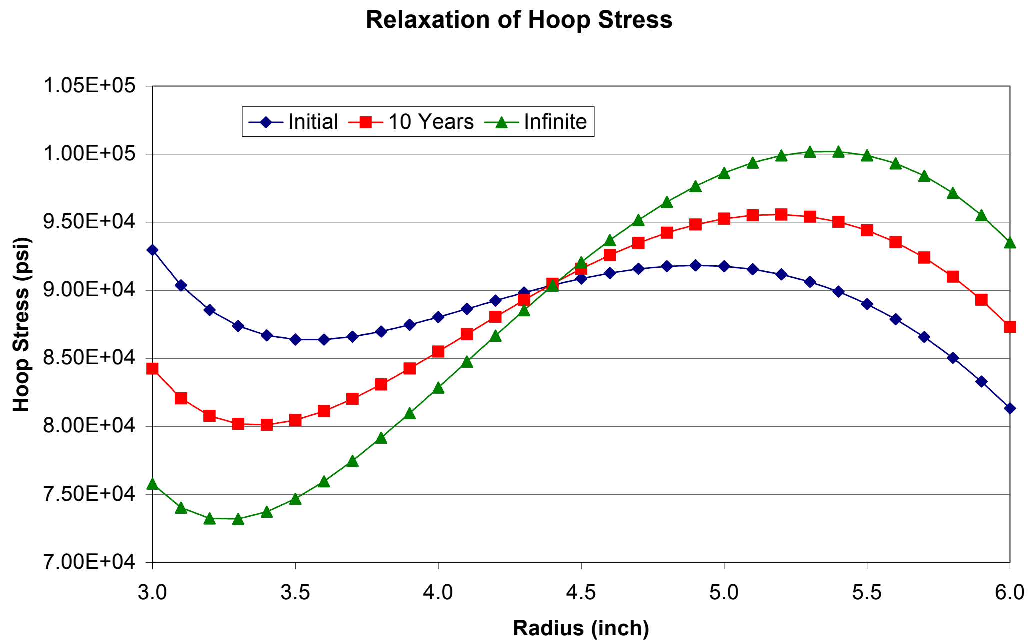

Figure 5. Relaxation of hoop stress in an all-hoop wound cylinder.

must satisfy the force balance as the following equation (conceptually without considering the unit):

$$2\ \sigma^{o}_{\theta}\ \sin\psi + \sigma_r\ = m^{o}\, r^{o}\, \omega^{2}. \tag{20}$$

The radial stress decreases since the radial stiffness decreases over a period of time. The centripetal force (left hand term) remains a constant since the rotation is the same. Accordingly, the hoop stress increases at the outer radius of the cylinder. On the other hand, the free body at the inner radius has to satisfy the force balance as follows:

$$2\ \sigma^{i}_{\ \theta}\ \sin\psi\ = m^{i}\ r^{i}\ \omega^{2} + \sigma_r. \tag{21}$$

The centripetal force remains a constant while the radial stress decreases. Accordingly, it is straightforward that the hoop stress will decrease at the inner radius. Since both the hoop and radial stresses decrease, the radial displacement at the inner radius also decreases. This analysis simply explains the physical meaning of the stress and displacement variation due to viscoelastic behavior. However, an inelastic analysis cannot replace a viscoelastic analysis that involves time dependency.

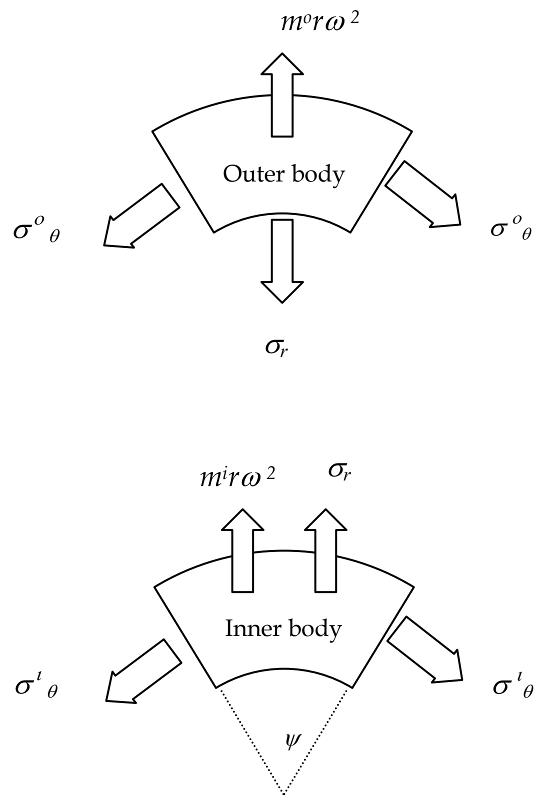

Figure 6. Force balance in the free body diagram of a cylinder.

Figures 7–9 show the radial displacement, radial stress, and hoop stress distribution in a thick-walled cylinder with a layup construction of $[(90)_4(0)_2(90)_4]_3$ at three time instants, respectively. These three instants are defined in the previous section. The radial displacement shows characteristics of creep similar to the all-hoop wound cylinder. However, the deformation profile is not as smooth because of the change of fiber orientation through the thickness. The radial stress also shows significant relaxation over a period of time. The effect of layup construction on the radial stress profile is clearly illustrated in the "zigzag" curves. In Figure 7, the hoop stress profile shows significant variation over a period of time. The hoop stress is low in the 0° plies because of low stiffness in the circumferential direction. The stress gradient also increases significantly in the 90° plies. The stress increases in the outer radius, while it decreases in the inner radius.

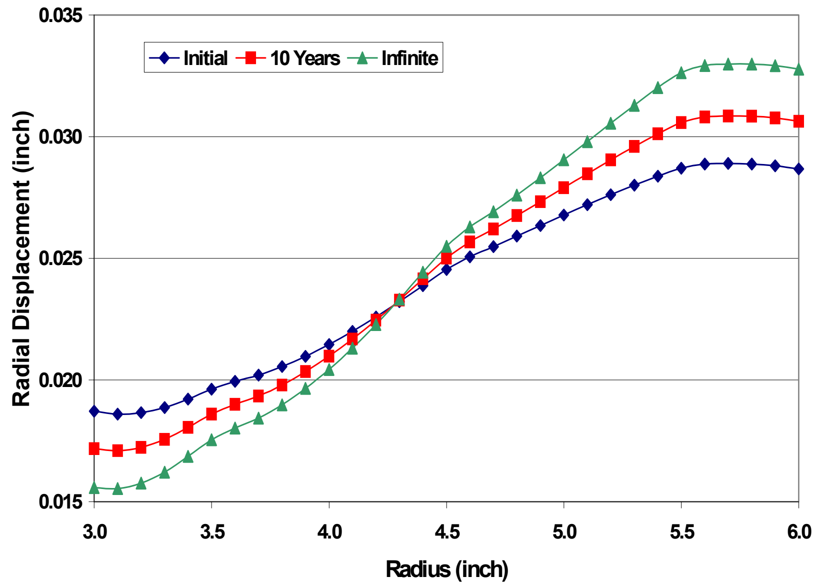

Figure 7. Creep of radial stress in a cross-ply wound cylinder.

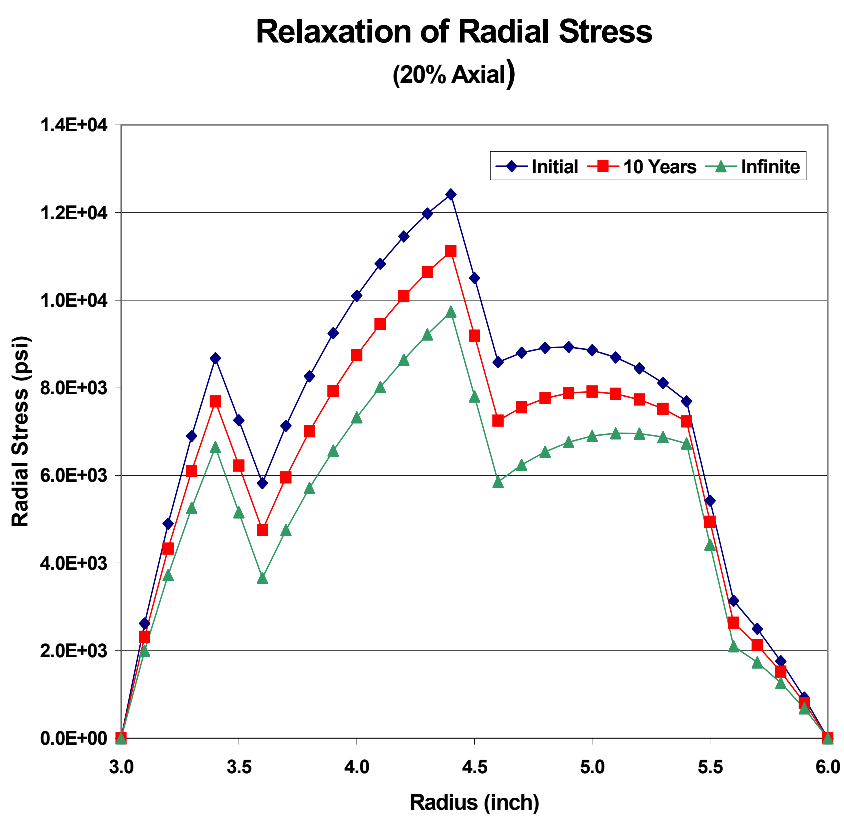

Figure 8. Relaxation of radial stress in a cross-ply wound cylinder.

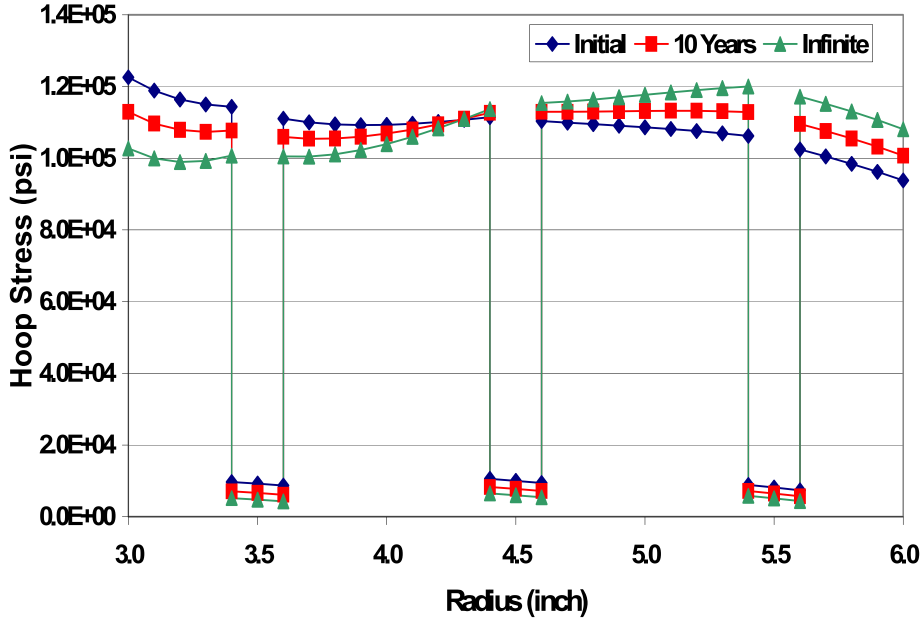

Figure 9. Relaxation of hoop stress in a cross-ply wound cylinder.

4. Conclusions

An analysis has been developed for the viscoelastic behavior of laminated composite rotating cylinders with ply-by-ply variation of anisotropic viscoelastic properties. Stress relaxation and creep are properly calculated in the cylinders with various layup constructions. Creep and stress relaxation exist in the fiber direction even though the fiber dominant properties are elastic. This mainly results from the contribution of the Poisson's effects. Relaxation of radial stress due to the viscoelastic transverse and shear properties of composite changes the hoop stress profile as well as radial displacement.

The results illustrate that the viscoelastic behavior is critical for the composite flywheel design to serve a long lifecycle. The stability of radial dimension is critical for applications such as rotating machines for power generations. The rotor design has to consider the significant change in the hoop stress distribution and radial growth. This investigation provides a theoretic base to predict and understand the time dependent behavior of composite flywheels. An analytical tool is also developed, which can be used for composite rotating machine design.

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13. ABSTRACT *(Maximum 200 words)*

A viscoelastic analysis has been developed to investigate stress relaxation and creep in a multilayered composite cylinder subjected to rotation. The analysis accounts for ply-by-ply variation of material properties, fiber orientations, and density gradients through the thickness of cylinders. A closed form solution based on the corresponding elastic problem is derived for a generalized plane strain state in a thick-walled, multilayered cylinder. Laplace transform is then applied to obtain the numerical solution of the viscoelastic problem. This report illustrates the derivation of the analytical model and solution procedure. A numerical simulation shows substantial creep and stress relaxation in thick-walled cylinders at an elevated temperature. Viscoelastic effects of composite can result in a drastic change of stress and strain profiles in a cylinder over a period of time, which is critical in terms of structural durability for applications such as energy storage flywheels.

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