Constitutive Modeling of the Mechanical Properties of Optical Fibers

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ABSTRACT

Micromechanical modeling of the composite mechanical properties of optical fibers was conducted]. Good agreement was obtained between the values of Young's modulus obtained by micromechanics modeling and those determined experimentally for a single mode optical fiber where the wave guide and the jacket are physically coupled. 'l'he modeling was also attempted on a polarization-maintaining optical fiber (PANDA) where the wave guide and the jacket arc physically decoupled, and found not to be applicable since the modeling required perfect bonding at the interface. The modeling utilized constituent physical properties such as the Young's modulus, Poisson's ratio, and shear modulus to establish bounds on the macroscopic behavior of the fiber.

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IN'I'ROIIUCTION

Polarization-maintaining (PM) optical fibers are increasingly being considered for new applications in, for example, advanced space craft inertial reference units as fiberoptic rotation sensors. Applications where volume is a consideration have used PM fibers wound onto small spools'. These new I'M fibers, often referred to as PANDA fibers, are significantly different from commercial optical fibers in two major ways. First, commercial optical fibers generally consist of a wave guide surrounded by an acrylic jacket. In the PANDA fiber, there exists a silicone layer between the wave guide and the jacket. Secondly, the PANDA fiber contains two beryllium oxide stress rods around the wave guide core that produces a stressed wave guide core specific for polarized light.

3'ethnical literature exists on the physical and mechanical properties of commercial optical fibers which can be used for engineering design. Development of theories to predict fiber lifetime for commercial optical fibers using fiber parameters have been established. Literature reports on the temperature-dependent behavior of highly birefringent optical fibers arc available'"'. For the case of PANDA fibers the temperature dependence of fibers wound onto different diameter cylinders has been measured[7]. The modeling and prediction of mechanical properties of optical fibers based on material properties is not available in the open literature. The ability to predict mechanical properties of optical fibers for design applications where testing may not be practical would be of great use.

APPROACH

In this paper, the modeling of the mechanical properties of optical fibers based on micromechanics is presented. The properties predicted by micromechanical modeling are compared to experimental values determined earlier[8].

Micromechanical modeling is often used to quantitatively characterize the effects of constituent properties on the macroscopic behavior of composite materials. The effects of the arrangement of the constituents, as well as the distribution of stresses and deformations among the constituents, can be studied using micromechanical modeling[9]. In the micromechanical self-consistent field methods, approximations of phase geometries are made and a simple representation of the response field is obtained. The phase geometry is represented by one single fiber embedded in a matrix cylinder. This outer cylinder is embedded in an unbounded homogeneous material whose properties are taken to be equivalent to those of the average composite properties. The matrix under a uniform load at infinity introduces a uniform strain field in the fiber. Elastic constants are obtained from this strain field. The results obtained are independent of fiber arrangements in the matrix and are reliable at low fiber volume fractions V_f, reasonable at intermediate V_f, and unreliable at high V_f [10].

RESULTS AND DISCUSSION

In this research, micromechanical analyses was used to estimate the. composite properties of a single mode optical fiber. As in the context of continuum mechanics, it is assumed that the interface between the glass fiber (wave guide) and the polymeric matrix (jacket) is perfect. Therefore throughout the entire loading application, the interface is a mathematical surface across which material properties change discontinuously, while the interfacial traction and displacements are continuous across the interface. When perfect bonding is assumed, the macromechanical properties and strength of the composite (wave guide plus jacket) are determined solely by the properties of the constituent materials. For the control fiber as described earlier, the interface between the wave guide and the jacket can be regarded as being perfect, i.e., physically coupled. in the case of the PANDA fiber, the wave guide and the jacket are physically decoupled.

The micromechanical method used here focuses on the upper and lower bounds on the elastic constants. This method does not predict the properties directly, however, if the upper and lower bounds coincide, then the property is determined exactly. Frequently, the upper and lower bounds arc well separated. When these bounds are close enough they can be used as indicators of the material behavior. This is the case for the longitudinal properties of a unidirectional system as considered here. hill" derived rigorous bounds on the longitudinal Young's modulus, E_{11}, in terms of the hulk modulus in plane strain (kk_p), Poisson's ratio (v), and the shear modulus (G) of the two phases. For the glass wave guide of the optical fiber system, E_f, G, and v_f were 1.04 x 107 Psi, 6.07 x 10^6, and 0.16, respectively which arc known published values for glass. The polymer jacket used on the single mode optical fiber is an acrylic polymer, believed to be similar to polymethyl methacrylate (I'MMA). The published value for the. modulus E_m of PMMA is given as 4.79 x 10^5 Psi, which was used for micrmechanical modeling. The compressibility of PMMA, ξ_m = 0.0355 Psi, was used to derive the shear modulus for the jacket, G_m, as

$$G_m = \frac{3(1-2\nu_m)}{2\xi_m(1+\nu_m)}. \tag{1}$$

The volume fractions for the wave guide. and the jacket, V, and V_m, were 0.25 and 0.75, respectively. Calculations to determine E_{11} of the optical fiber system were made by varying the Poisson's ratio (ν_m) and Young's modulus (E_m) of the jacket, separately. No restrictions were made on the core form or packing geometry. The term k_p is the modulus for lateral dilatation with zero longitudinal strain and is given by

$$k_p = \frac{E}{2(1-2\nu)(1+\nu)}. \tag{2}$$

The bounds on the longitudinal modulus, El, , are

$$\frac{4V_f V_m(\nu_f - \nu_m)^2}{(V_f/k_{pm}) + (V_m/k_{pf}) + 1/G_m} \le E_{11} - E_f V_f - E_m V_m \le \frac{4V_f V_m(\nu_f - \nu_m)^2}{(V_f/k_{pm}) + (V_m/k_{pf}) + 1/G_f} \tag{3}$$

Figure 1 shows the bounds for the longitudinal modulus of the composite. optical fiber, E_{11}, for a Young's modulus (E_m) of the jacket equal to 4.79 x 10^5 Psi, and a range of values of the Poisson's ratio (ν_m) of the jacket. A composite modulus, E_{11}, in the order of 2.96 x 10^6 Psi is estimated from Figure 1, for the single mode optical fiber used in this study. In Figure 2, the bounds for E_{11} is given for Poisson's ratio $\nu_m = 0.37$ and a range of values for E_m. These results show good agreement with the measured values.

in Figure 3, the modulus of the optical fiber determined from static loading is shown. A value of 2.87 x 10^6 Psi for the modulus was obtained which is consistent with the value predicted from micromechanical modeling (2.96 x 10^6 Psi). Good agreement is observed in the values of modulus from micromechanical modeling and static loading, for the single mode optical fiber where the glass wave guide and the polymeric jacket are physically coupled. For the case of the PANDA fiber where the glass wave guide and the polymeric jacket are decoupled, the micromechanical modeling was not applicable.

It should be noted that this type of micromechanical analysis is limited by the assumption of a perfect interface between the wave guide and the jacket. However, the assumption of perfect bonding is sometimes inadequate, as in the case of the PANDA fiber where the wave guide and the jacket are physically decoupled thus providing a distinct interracial zone (interphase) between the core and the jacket. This weak, compliant interphase has lower strength and stiffness than those of the wave guide and the jacket. Recently, Veazie and Qu' obtained micromechanical solutions for the nonlinear inelastic behavior of composites with weak, compliant interphases using the Mori-Tanaka method as a building block. New micromechanical analyses such as these may fine] utility in predicting the macromechanica proper-tics of advanced optical fiber systems such as PANDA fibers.

CONCLUSIONS

Micromechanical modeling was used to predict the composite modulus of a single mode optical fiber. The micromechanical analysis was limited to the case of a perfect interface between the glass wave guide and the polymeric jacket of the optical fibers. The modeling worked well in the case of the single mode optical fiber where the glass wave guide and the polymeric jacket arc physically coupled. The micromechanical modeling did not work for the polarization-maintaining PANDA fiber where the glass wave guide and the polymeric jacket are physically decoupled. Good agreement for the single mode optical fiber was obtained for the modulus predicted by micromechanical modeling and values measured experimentally.

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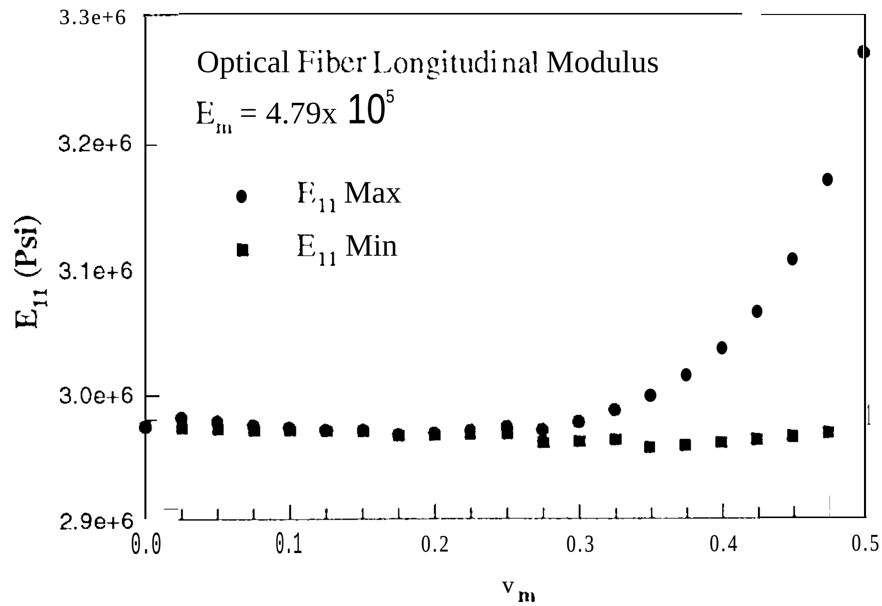

Figure 1. Bounds for the longitudinal modulus, E_{11}, for a Young's modulus (E_m) of the jacket equal to 4.79 x 10^5 psi, and a range of values of the Poisson's ratio (ν_m) of the jacket.

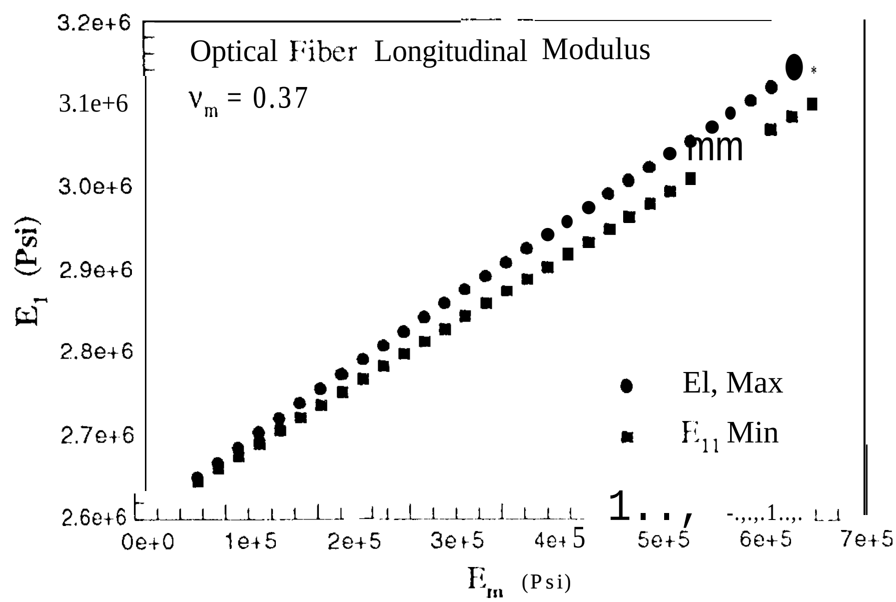

Figure 2. Bounds for the longitudinal modulus, E_{11}, for a Poisson's ratio of the jacket, $\nu_m = 0.37$, and a range of values for the Young's modulus of the jacket (E_m)

FIGURE 3

STATIC LOADING FOR CONTROL FIBER WITH JACKET MEASURED AT ROOM TEMPERATURE