White paper

Optical Fiber Composite Young's Modulus: Theoretical Approach, Line Tracking Method, and Finite Element Analysis

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Abstract
Acrylic coated high purity silica glass fibers (optical fibers) are widely used as a transmission medium in fiber optics communication network. These fibers are gaining popularity as remote sensors to aid measurement of strain, temperature, pressure, etc. In sensing applications, these fibers are subjected to a wide range of mechanical, thermal, and environmental stresses. An accurate determination of the physical properties of optical fibers is required to estimate the above stresses. Optical fiber is a composite consisting of high purity amorphous silica fiber protected by multiple layers of acrylic coatings. This article presents an approach to determine the Young's modulus of the optical fiber composite. Experimental data, theoretically predicted values, and Finite Element Analysis (FEA) were found in reasonable agreement.

Key Words
Optical Fiber, Composite, Line tracking method, Iso-stress, Iso-strain, FEA.

1. Introduction

Silica glass optical fibers have several applications such as remote sensing of mechanical distortion, thermal fluctuations, pressure variations etc. besides telecommunications. Commercially available optical fibers are usually protected with double, triple and more layers of epoxy/acrylic polymer coatings. Devices consisting of this type of fibers are mounted on airplane wings as a pressure sensor. These devices are subjected to a highly variable environmental and operating conditions resulting in the introduction of mechanical as well as thermal stresses in the fiber. The resulting stresses cannot be estimated without the accurate material properties of the fiber, for examples, Young's modulus, and Poisson ratio. This paper will only deal with Young's modulus which plays an important role in designing fiber sensor [1,2]. Optical fiber is basically a composite containing two layers of glass i.e. inner core (Germanium doped silica) and outer clad (pure silica) and typically two layers of protective polymer coating: the inner primary coating and outer secondary [3]. Mark tracking method can be used to measure Young's modulus [4] In addition, considering primary coating, secondary coating and the glass assembly as a composite (Fig. 1) instead of individual layers (Fig. 2), will significantly reduce FEA simulation time[5,6].

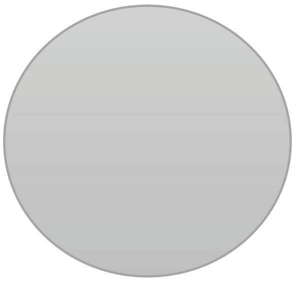

Figure 1: Composite fiber structure

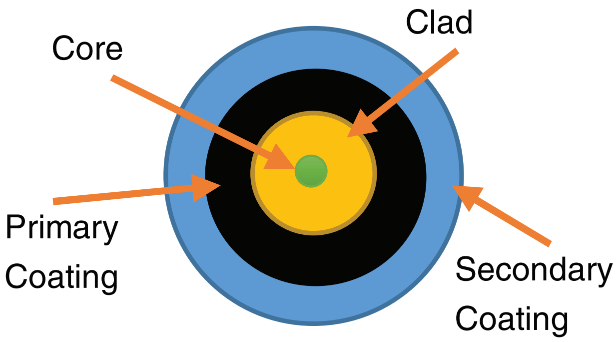

Figure 1: Composite fiber structure **Figure 2: Fiber structure**

This article presents an approach to determine the Young's modulus of the optical fiber composite.

2. Theoretical Approach

Well-known equations have been utilized to calculate the Young's modulus of the composite fiber. These values have been subsequently compared with the experimental data and FEA simulation.

First Approach: Assuming iso-strain condition between the glass fiber and the coating, Voigt proposed [3] a method as shown in equation 1, to calculate the effective Young's modulus (EV) of the composite materials based on the assumption that parallelly arranged composite materials having similar Poisons ratio are subjected to equal strain

$$E_V = E_1 V_1 + E_2 V_2 \text{ and, } V_1 + V_2 = 1, \qquad (1)$$

Where, E1, E2, V1 and V2 are Young's modulus and volume fraction of first and second material respectively.

Second Approach: Assuming iso-stress condition between the glass fiber and the coating, Reuss proposed [3] a method as shown in equation 2, based on the assumptions that composite materials having similar cross-sectional area experience similar level of stress .

$$E_R = (E_1 \times E_2) / (E_1 V_2 + E_2 V_1) \qquad (2)$$

Third Approach: This approach proposes the effective Young's modulus of the composite to be a product of the predicted Young's moduli based on iso-strain and iso-stress. Even though, Eq (1) and Eq (2) are used for calculating effective Young's modulus of two materials, neither iso-strain nor iso-stress assumptions are realistic [3]. Each factor being raised to exponents whose value depend on the geometry of the individual layer of the composite and the nature of the interaction between them. The algebraic expression that may be utilized to correctly estimate the Young's modulus by third approach is given below.

$$E_{oeff} = E_V^{\,n} \text{ X } E_R^{\,n-1} \qquad (3)$$

Where, E_V and E_R are effective Young's modulus per Voigt and Reuss respectively, E_{oeff} is overall effective Young's modulus of composite material and the value of n depends on material properties of fiber and nature of interaction between them.

3. Experimental Approach

Line tracking method was employed to determine the tensile strain-to-failure of 200 micron and 250 micron diameter optical fibers both having ~125 micron diameter glass cladding . The Young's modulus was calculated based on measured strain-to-failure and corresponding breaking loads for both the samples. The sample fiber length under tensile testing was 0.5 m, and a relatively small 10 cm section subjected to tensile testing was colored. A digital camera was used to record the elongation of the colored section of the fiber under tensile load till fiber break. Based on the recorded value of elongation of colored section, breaking strain of fiber sample was calculated. The experimental set up of line tracking method is shown in Fig. 3 and color section before and after elongation are shown in Fig. 4.

Figure 3: Short length tensile test set up

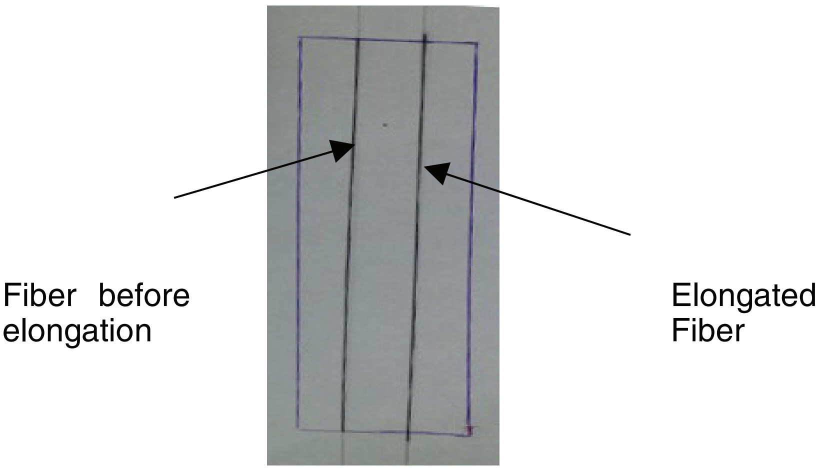

Figure 4: Line-tracking method

The presented method allows one to estimate the Young's modulus based on measured unidirectional elongation and failure load. It is based on colored line of fiber with specified length modulus based on measured unidirectional elongation and failure load. It is based on colored line of fiber with specified length during tensile test. A digital camera can be used to record elongation of colored line on the fiber till fiber breaks during testing. The process is automatically performed either in real time during the test or after video acquisition. This method yielded a true strain value with an accuracy of ± 0.5 % without disturbing tensile testing process.

4. Results

By line tracking method, fiber failure strain and failure load were measured. By equation (4), Young's modulus was calculated by considering total fiber cross-sectional area.

$E = (P) / (\varepsilon \times A)$ (4)

Where,

E= Equivalent Young's modulus of composite fiber (GPa),

P = Breaking Load (N),

ε = Fiber Strain and

A = Total cross sectional area of fiber composite (mm^2).

Therefore, the calculated Young's modulus is the effective Young's modulus of the composite fiber having 3 materials i.e glass cladding, primary coating and secondary coating. Table 1 and Table 2 show results of measured failure strain and calculated Young's modulus of 250 and 200 micron fiber sample respectively.

Table 1: Failure strain and Young's modulus of 250 micron fiber

250 micron fiber			
Sr. No	**Parameters**	**Measured Failure strain (%)**	**Calculated Young's modulus (GPa)**
1	Sample Size	30	30
2	Maximum Value	6.5	23.5
3	Minimum Value	5.5	20.1
4	**Average Value**	**6.0**	**21.7**

Table 2: Failure strain and Young's modulus of 200 Micron Fiber

250 micron fiber			
Sr. No	**Parameters**	**Measured Failure strain (%)**	**Calculated Young's modulus (GPa)**
1	Sample Size	30	30
2	Maximum Value	6.0	37.1
3	Minimum Value	5.0	34.2
4	**Average Value**	**5.6**	**35.8**

fiber were determined to be ~ 21.7 GPa and ~ 35.8 GPa respectively. Failure strain of 250 and 200 micron fibers were 5.5 ~ 6.5 % and 5~ 6% respectively. The difference in effective Young's modulus of 250 and 200 micron fiber is because of difference in coating diameters.

5. Empirical Analysis

The effective Young's modulus also can be estimated empirically as described below. The calculated Young's modulus of the composite fiber by Eq (1), Eq (2) and Eq (4) are different for reasons explained below. Fiber consists of 3 materials i.e. silica glass, primary coating and secondary coating, each having different Poison ratio, Young's modulus and as a result does not meet iso-strain criteria. Further, these 3 materials having dis-similar cross-sectional area and don't experience similar level of stress during tensile loading and as a result does not meet iso-stress criteria. Therefore, neither the Eq (1) and nor the Eq (2) are applicable to the calculation of the Young's modules of the above composite fiber. The overall effective Young's modulus (E_{oeff}) can be estimated by employing Eq (3), provided n – value is known. Since the effective Young's modulus (E_{oeff}) can be determined by utilizing line tracking method, one can estimate n-values for both fibers; by utilizing Eq (4). There are two ways to calculate n-value by using Eq (3).

In one approach, fiber is considered as a composite of 3 materials as shown in Fig. 5.

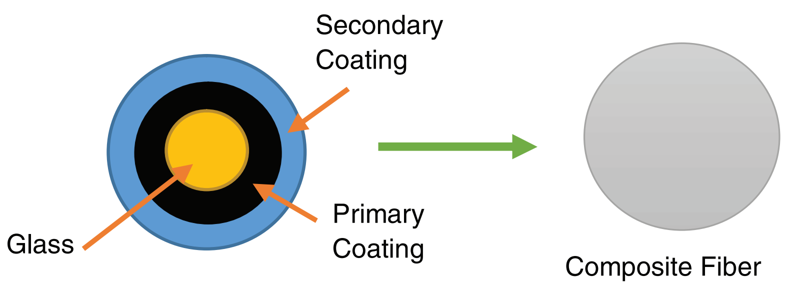

Figure 5: Composite fiber method by first approach

In this approach, we used Eq (3) directly to calculate n-values of 250 and 200 micron fiber. This exercise resulted in average nvalues of 0.67 and 1.42 for 250 and 200 micron fibers respectively based on data set of 30 samples in each case. Note, the n-values are substantially different.
In another approach, for similar coatings and glass materials, we can calculate n-value in such a manner that, by just changing the diameters of different layers of coating, effective Young's modulus of composite fibers can be predicted. The methodology is explained as below. In this approach, we estimated effective Young's modules for coating composite consisting of primary and secondary coating followed by a further estimation of the fiber composite utilizing the coating composite modulus and the modulus of the glass fiber. Fig. 6 explains the procedure to calculate composite fiber Young's modulus.

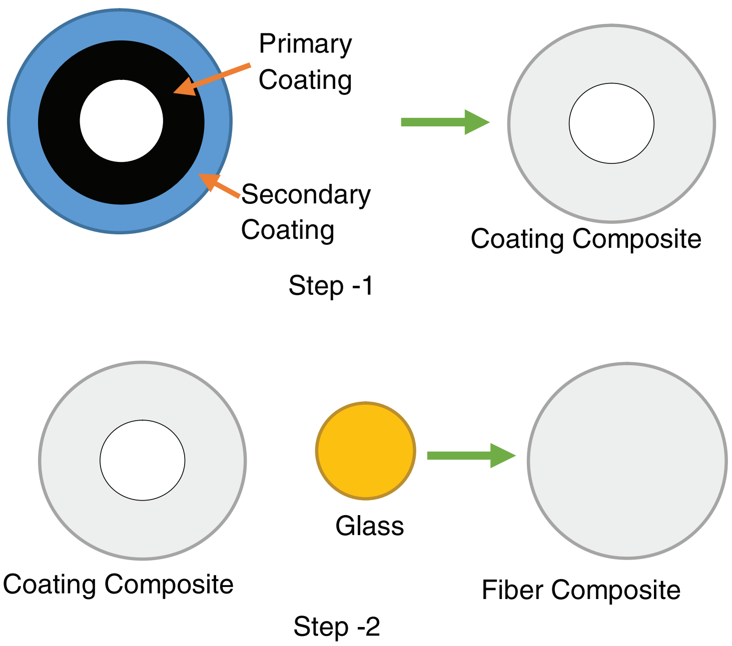

Figure 6: Composite fiber method by second approach

Adopting this procedure allows us to estimate n-values to be 1.066 for either fiber without being committed to a mechanism, the equality of n-values in either fiber composite suggest similar interaction at the glass/polymer interface. Given the circumstances that the n-values are same for two different fibers. The method has potential to be extended to other combination of the similar coatings of other thicknesses and the base glass fiber. The line tracking experimental approach seems to allow one to estimate the effective Young's modulus of the optical fiber composite and a quantitative index (n) of the interaction between the fiber and the coating. However, the n value will depend on different coating material properties, drawing process conditions, aging, etc. FEA analysis as presented in next section also supports the Young's modulus predicted by line tracking method.

6. Numerical Analysis

Numerical analysis (FEA) was carried out using Ansys tool to determine the strain of the composite fibers. Fig. 7 and Fig 8 shows the simulation results of the 250 and 200 micron fiber respectively.

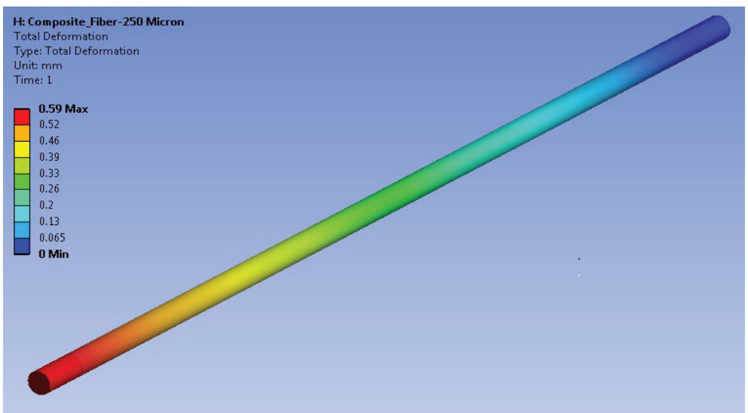

Figure 7 Elongation of 250 micron fiber

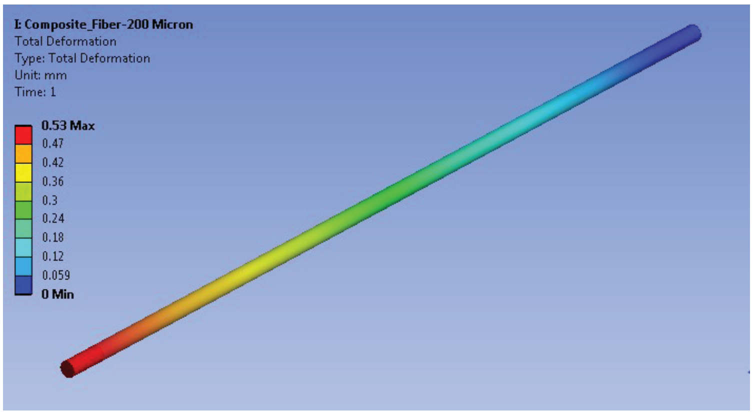

Figure 8: Elongation of 200 micron fiber

purpose. Young's modulus obtained from line tracking method of both the fibers were used as input in simulation. The breaking load was used as pulling force in the simulation. Elongations of 250 and 200 micron fibers were obtained as 0.59 mm and 0.53 mm respectively at the failure load. Conversion of these numbers based on elongations yields a strain value of 5.9 % and 5.3% respectively. Based on line tracking method, the calculated strain values were lied in between 5.5 ~ 6.5 % and 5~ 6% respectively. Thus the line tracking method seems to be potentially a technique for measuring Young's modulus of optical fiber composite. The n values of different diameter fibers were found to be very similar with different Young's modulus. Therefore, the difference in the Young's modulus between two different fibers is a result of coating geometry.

7. Summary and Conclusions

Young's modulus of optical fiber composite. Young's modulus of 250 and 200 micron silica glass optical fibers having 125 micron glass cladding were measured by line-tracking method. Young's modulus and failure strain were found ~ 21.7 GPa and 5.5~ 6.5% for 250 micron fiber and ~ 35.8 GPa and 5~ 6% for 200 micron fiber. Measured modulus did not match with the values calculated using approaches based on iso-stress and iso-strain assumptions. The third approach needed a factor n to determine overall Young's modulus of the composite. The n-values were determined in two ways. First, by considering fiber as a composite of three materials i.e glass, primary and secondary coating and second, by considering two materials i.e glass and two coating layers clubbed into one coating composite layer. Comparable n -values of 250 and 200 micron fibers were found by the second method. It suggests that with known n-value and constant glass & coating characteristics, overall composite Young's modulus of fiber having different coating diameters can be estimated by Eq (3). Predicted Young's modulus by line tracking method was validated by FEA. This fiber can also be treated as composite material in cable numerical simulation for simplification of FEA. We notice that the experimental data, theoretically predicted values, and FEA were in reasonable agreement for Young's modulus. These results show that the fiber coatings are playing a very crucial role in determining Young's modulus of composite fibers having similar glass diameter. Thus, the line-tracking method is a potential technique for optical fiber's Young's modulus measurement.

8. References

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