Mechanical reliability of silica optical fiber: a case study for a biomedical application

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ABSTRACT

The mechanical reliability of optical fiber used in certain biomedical applications is extremely important because failure of the fiber during use might be fatal for the patient. Therefore, prediction of the lifetime of the fiber both in storage and during service is necessary before the fiber can be safely used. In this paper we study two commercially available optical fibers designed specifically for high power laser delivery. The fatigue parameters calculated from static fatigue data are used to estimate the maximum allowed stress that ensures survival for the design life of the fiber. This work properly accounts for uncertainty in the predictions; uncertainty which arises not only from scatter in the experimental data, but also from uncertainty in the form of kinetics model to use for extrapolation (*i.e.* power law, exponential, *etc.*). This paper thus provides an outline for making lifetime predictions for a critical applications involving relatively short lengths of fiber, that does not bind in any questionable assumptions.

Keywords: Optical fiber, strength, fatigue, reliability, biomedical, lifetime prediction.

1. INTRODUCTION

The applications of optical fiber are not restricted to telecommunications, but widely used for different purposes. The polymer coated silica optical fibers studied in this paper are specifically designed for high power laser delivery, which can be used for biomedical or industrial purposes. The proposed usage of the particular fiber discussed here is to be the main component of a 3.5 meters long fiber probe, which is used to perform heart surgery in the human body.

There are two mechanical reliability issues which are of concern for this application of the fiber. The first concern is the short-term reliability. During service, the tip of the fiber will be inserted into a human body and bent through a large angle in order to perform the surgery. The expected service time is less than 5 hours. The fiber therefore has to survive at least 5 hours under a large bending stress in an environment inside a human body which is warmer and wetter than ambient air. The short-term reliability is extremely important because failure of the fiber during surgery might be fatal to the patient.

Another concern is the long-term mechanical reliability of the fiber. After manufacture, the fiber probe is coiled into a radius of ~ 60 mm (or bigger) and stored inside a sterile plastic bag. Since the plastic bag is permeable to water vapor, the fiber is simultaneously exposed to stress and moisture, and so can degrade in strength by fatigue. The expected storage time between manufacture and use is 3 years in this application, and it is therefore necessary to avoid failure on this time scale. Failure during storage, while not dangerous for patients, would not inspire confidence in the surgeon!

In this paper, we compare the mechanical behaviors of two commercial optical fibers that are candidates for use in this application. The short-term reliability of the fibers under a simulated service condition was assessed by performing two-point bending dynamic fatigue experiments. The long-term reliability of the fibers under storage conditions was investigated by performing static fatigue experiments, again in two-point bending. Since it is usually impossible to conduct experiments on a very long time scale to directly assess the long-term reliability, the experiments are usually performed in a harsher environment and the results are then extrapolated to the less severe service conditions. In this study, static fatigue experiments at high stress levels were performed in a liquid environment, which is a more severe environment than the storage condition. The strength degradation and the maximum allowed stress that ensures survival for the design life of the fiber were then estimated by extrapolating the static fatigue data to lower applied stress using several fatigue models.

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The reliability of long lengths (>1 km) of fiber is controlled by occasional weak defects which are extrinsic in nature. In the application of interest here, the lengths involved are comparatively short. Provided a sufficiently high quality fiber is used, the probability of encountering a weak defect is acceptably small, even at the high confidence levels required in this application. With this prevision, the reliability is controlled by the behavior of the intrinsic defects encountered during testing of relatively short lengths of fiber. The methodology of lifetime prediction used in this paper therefore will not take the weak defects into account. Tensile tests on long lengths of fiber could not be performed because of the high loads required to break these thick fibers caused gripping problems. Two-point bending has been used throughout.

What distinguishes this work from previous reliability estimates is that it properly accounts for uncertainty in the predictions; uncertainty which arises from not only scatter in the experimental data, but also due to our uncertainty of which is the correct kinetics model to use.[1] This paper presents an algorithm for making lifetime predictions for a critical but relatively short duration and short fiber length application.

2. EXPERIMENTAL PROCEDURES

Two silica optical fibers, designated fiber I and fiber II which were obtained from two different manufacturers, were subjected to the same tests. Both fibers have the same glass (cladding) diameter of 400 μm and the polymer coating diameter of 430 μm; they both also have an outer buffer polymer coating, which makes the overall coating diameter 730 μm.

The fibers were broken into ~ 60 mm lengths. Specimens were randomly picked to avoid any effects of systematic variation in strength along the length of the fiber. Testing was performed in two different environments. The first was 37°C standard saline solution (LabChem†), which simulates conditions inside the human body during surgery. The second environment used was 30°C pH 7 buffer solution (Fisher Scientific‡) used to simulate the worst expected storage conditions. The temperature and humidity of the storage conditions for the fiber probe are not known in advance but are very unlikely to exceed 30°C 100% humidity; the 30°C liquid test environment is therefore a worst case – survival here would ensure survival under reasonable storage condition.

3. RESULTS AND DISCUSSION

3.1 Permeation studies

The validity of the dynamic and static fatigue experiments was ensured by performing permeation studies in order to estimate the time needed for the testing liquid to fully penetrate the fiber coating. The specimens were immersed in both of the liquid test environments for various times, and strength was measured at a constant strain rate of 5%/min by a dynamic two-point bend apparatus. Ten specimens were broken for each of seven immersion times which ranged from 10 s to 3 days.

The results of the permeation studies indicate that at least 2 hours is needed for the testing liquid to fully penetrate the coatings. No severe strength degradation was observed for immersion times of up to 3 days, indicating zero stress aging does not happen in such a short time under these testing conditions. Therefore, it was determined that the fibers used for dynamic and static fatigue experiments would be pre-equilibrated with the testing environment overnight before performing the tests.

3.2 Dynamic fatigue

Two-point bending dynamic fatigue experiments[2,3] were performed in both test environments at constant strain rates of 0.005% to 50% per minute. Fifteen specimens were tested under each condition.

The dynamic fatigue experiments tested in 37°C saline solution and 30°C pH 7 buffer solution show very similar results for the two fibers under each testing condition. The fatigue parameters, n, calculated from the dynamic fatigue data, are summarized in table 1 where the errors represent a 95% confidence interval. From the dynamic fatigue results, the fatigue parameters are very similar for both fibers in the two different testing environments. Therefore, it is fair to suggest that both fibers have comparable short-term mechanical reliability for the expected service time of ~5 hours.

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‡ Fisher Scientific International Inc., Pittsburgh, Pennsylvania, USA.

Table 1 Fatigue parameters ($n \pm 95\%$ confidence interval) calculated from the two-point bending dynamic fatigue data.

	37°C saline solution	30°C pH 7 buffer solution
Fiber I	25 ± 4	26 ± 1
Fiber II	27 ± 2	27 ± 2

3.3 Static fatigue

Static fatigue experiments in two-point bending[4] were accomplished in 30°C pH 7 buffer solution at eight applied stresses in the range of 3 to 5 GPa. Fifteen specimens were tested for each stress and the results are shown in figure 1. The static fatigue data in the high stress region (> 4 GPa) give similar times to failure for the two fibers. This again indicates that the short-term mechanical behavior is similar for both fibers, and is consistent with the dynamic fatigue results. However, when the fibers were tested at lower stresses, the failure time for fiber I is shorter than for fiber II. The fatigue parameter, n, obtained from static fatigue data is 22.4 ± 0.7 for fiber I, and 25.4 ± 0.7 for fiber II. This small but statistically significant difference in n means that at low stresses, fiber II has a significantly longer time to failure.

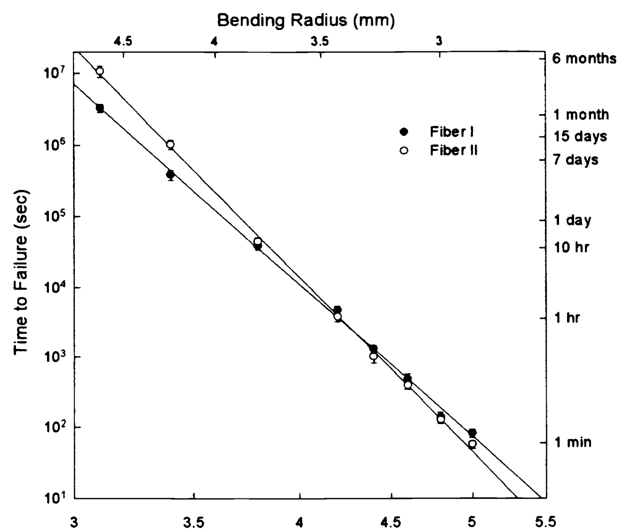

Figure 1. Static fatigue data for fiber I and fiber II measured in 30°C pH7 buffer solution.

The bending radius axis shown at the top of figure 1 represents the uniform radius of curvature that would result in a maximum bending stress equal to the corresponding applied stress on the lower axis. This graph can thus be used to indicate what the expected failure time would be for the fiber coiled to that radius. It is readily shown that the bending radius, R, is:

$$R = \frac{E d_f}{2\sigma_a} \tag{1}$$

where σ_a is the applied stress, d_f is the diameter of the glass fiber, and $E = E_0(1 + \alpha\varepsilon)$ is the elastic modulus. Here E_0 is the Young's modulus of the glass in the limit of zero strain, $\alpha = 2.125$ for bending, and ε is the strain.

4. LIFETIME PREDICTION

A short length of the end of the fiber will be heavily bent during surgery; this is one of the reliability concerns. However, the proposed service duration is only ~5 hours, while it is expected to survive for 3 years in storage. Calculations show that failure of the fiber is more likely to happen during storage at 30°C for 3 years, rather than during surgery at 37°C for 5 hours. Therefore, if the fiber survives the storage conditions, it should not fail in service. However, in future work we will explicitly examine reliability under surgical conditions.

In this section, the case of fiber I will be used to demonstrate the estimation of the minimum allowed bend radius in storage for a certain design lifetime. The same method will then be adopted for fiber II to make a lifetime prediction for that fiber.

Any lifetime models need to assume some functional form for the dependence of the slow crack growth velocity, $\dot{c}$, on the applied stress intensity, K_I. Since the predictions are sensitive to the particular kinetics model assumed, we will here consider three different forms. The first model is the widely used empirical power law:[5,6,7]

$$\dot{c} = A_1 K_I^{n_1}\,; \qquad \text{model 1} \tag{2}$$

the second model is based on simple chemical kinetics:[8,9]

$$\dot{c} = A_2 \exp(n_2 K_I)\,; \qquad \text{model 2} \tag{3}$$

and the third model is simplified from a chemical potential model proposed by Lawn:[10,11]

$$\dot{c} = A_3 \exp(n_3 K_I^2)\,. \qquad \text{model 3} \tag{4}$$

The preexponential factors, the A_i, are parameters which depend upon the environments as well as the materials, and the n_i are the fatigue parameters (also known as the stress corrosion susceptibility). The power law has generally been favored because the fatigue equations can not always be solved analytically for the exponential forms. However, solutions for the particular case of static fatigue (σ_a = constant) are presented for the exponential forms by Jakus *et al.*[11] In the following section, the power law will be used to illustrate the fiber lifetime prediction methodology. The lifetime estimated by using the other two models will also be shown and compared.

4.1 Prediction procedures

The requirements of the application are that a minimum bend radius should be found that ensures a better than 99.9% chance of survival, and that this prediction should have 99.9% confidence. The procedures for making a lifetime prediction that satisfy this requirement for the fiber are:

Step 1. Regression fitting to the static fatigue data to find the regression parameters.

Step 2. Finding the median time to failure, t_m, which gives the fiber a 99.9% probability of surviving for a design life, t_s.

Step 3. Finding the 2-point bend stress, σ_0, corresponding to t_m, *i.e.* extrapolating the static fatigue data to t_m.

Step 4. Finding the 2-point bend stress, σ_t, which gives the fiber a 99.9% chance to survive over t_m. That is, finding the stress at the 99.9% lower confidence bound of σ_0.

Step 5. Converting the 2-point bend stress, σ_t, to the uniform bending stress, σ_m, which gives the same lifetime and failure probability.

The main parameters used to make a fiber lifetime prediction are: E_0 (Young's modulus) = 72 GPa, fiber diameter d_f = 400 μm, design lifetime in storage t_s = 3 years, survival probability at design life p = 99.9% and Weibull modulus for strength m = 25. Further, the overall estimate must have a 99.9% confidence. To ensure that the fiber would survive in the storage environment, the worst cases are assumed in every step of making a lifetime prediction. For example, the Weibull modulus, m, is not a mean value but a rather low estimation from strength data.

4.2 Regression parameters

The regression parameters were obtained by fitting the static fatigue data to the following model, as shown in figure 2:

$$y = m_s(x - x_m) + b_s \tag{5}$$

where $y = \log t_f$ is the time to failure in seconds, $x = \log \sigma_a$ is the applied stress in GPa, m_s is the slope of the linear regression line, x_m is the mean x, *i.e.* mean $\log \sigma_a$, and b_s is the intercept at mean x. For fiber I, $m_s = -22.4$ and the standard error of m_s, Δm_s, is 0.35; $x_m = 0.60$, $b_s = 4.1$ and Δb_s (the standard error of b_s) is 0.02.

The static fatigue parameter, n, for fiber I is equal to $-m_s$, *i.e.*, $n = 22.4$. The Weibull modulus for the time to failure in static fatigue, m_t, can then be calculated from $m_t = m/(n-2)$.[12] In this case, $m = 25$, giving $m_t = 1.225$.

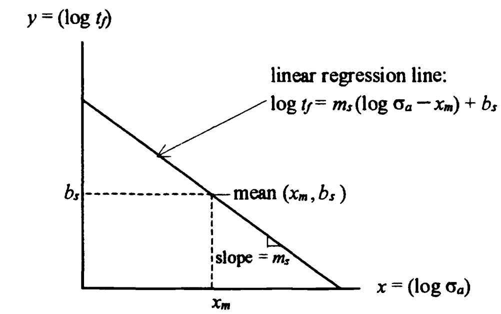

Figure 2. Schematic of linear regression model for fitting static fatigue data.

4.3 The median time to failure

The median time to failure, t_m, which gives the fiber a p% probability of surviving over a design lifetime, t_s, can be calculated from the following equation:[13]

$$\left(\frac{t_m}{t_s}\right)^{m_t} = \frac{\ln(\text{failure probability for } t_s)}{\ln(\text{failure probability for } t_m)} \tag{6}$$

where the failure probability for the median time, t_m, is 50%, and the failure probability for t_s, which has a 99.9% survival probability, is 0.1%. For fiber I, this gives t_m = 19.6 years.

4.4 Extrapolated stress in two-point bending

After finding the median time to failure, t_m, the corresponding applied stress under two-point bending can then be calculated from the following equation by rearranging Eq. (5):

$$\log \sigma_0 = \frac{\log t_m - b_s}{m_s} + x_m . \tag{7}$$

For fiber I, the applied stress, σ_0, which gives the required median lifetime is 2.46 GPa.

This represents extrapolation of the best fit line (solid line in figure 3) to a median life of t_m = 19.6 years. However, there is uncertainty in the extrapolation (the dotted lines). In order to have 99.9% confidence in the predicted stress, we now calculate σ_t, the stress where the lower 99.8% prediction confidence interval intersects t_m = 19.6 years. (The 99.8% confidence means the actual behavior has 0.2% chance of being outside the bound, *i.e.*, 0.1% chance of being below the bound.)

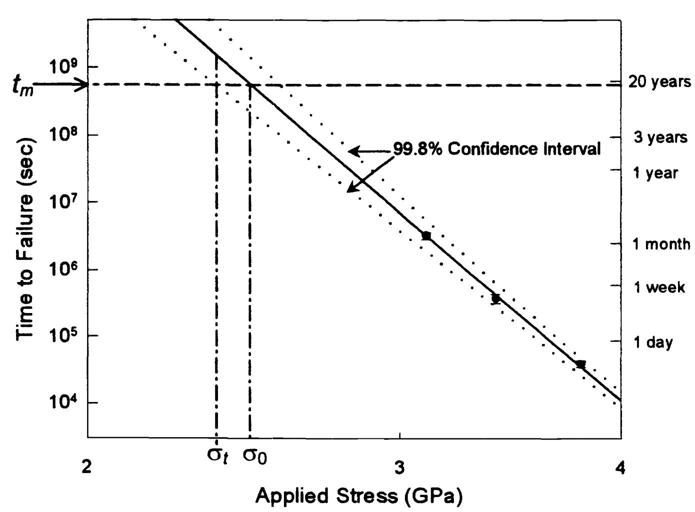

Figure 3. Extrapolation of static fatigue data of fiber I (detailed from figure 1) to the median failure time and the corresponding stress to lower confidence bound.

A 100(1–α)% confidence interval of a simple linear regression line at $x = x_0$ may be computed by standard regression analysis.[14] In most cases, the confidence interval on y in Eq. (5) is found for a known x, while in this case an unknown x is obtained from a known y. Figure 3 shows the extrapolation of the static fatigue data of fiber I to the median failure time (19.6 yr.) and the corresponding stress to lower confidence bound (σ_t). The maximum applied stress, σ_t, shown in figure 3 can be obtained by finding the root of the following equation:[14]

$$\log t_m = m_s(\log \sigma_t - x_m) + b_s - t_p \sqrt{(\Delta b_s)^2 N \left(\frac{1}{N} + \frac{(\log \sigma_t - x_m)^2}{(\Delta b_s / \Delta m_s)^2 N} \right)} \tag{8}$$

where N is the sample size, t_p is the single sided t-statistic for probability p = 99.9%, *i.e.*, α = 0.001. The calculated result of σ_t for fiber I is 2.35 GPa.

4.5 Stress in uniform bending

The applied stresses obtained above were calculated from the experimental data, *i.e.*, assuming two-point bending. However, the fiber is subjected to uniform bending during storage. In contrast to two-point bending, the surface tensile stress in uniform bending is uniform along the length. Matthewson and Kurkjian have compared the fatigue statistics for two-point and mandrel bending (the latter is the same as uniform bending).[12] They find that the mean time to failure under static two-point bending, $\bar{t}_{\text{two-point}}$, is:[12]

$$\bar{t}_{\text{two-point}} = \frac{B\sigma_r^{n-2}}{\sigma_t^n} \left[\frac{A_r \sigma_t}{4Er^2 I((nm_t - 1)/2) I(nm_t)} \right]^{1/m_t} \Gamma(1 + 1/m_t)\,; \tag{9}$$

while the mean time to failure under mandrel bending, $\bar{t}_{\text{mandrel}}$, is:

$$\bar{t}_{\text{mandrel}} = \frac{B\sigma_r^{n-2}}{\sigma_m^n} \left[\frac{A_r}{2rl_m I(nm_t)} \right]^{1/m_t} \Gamma(1 + 1/m_t), \tag{10}$$

where B is a parameter which depends on the environment and the material, σ_r is a reference stress, A_r is a reference area of unity magnitude, σ_m is the mandrel bending stress, r is the radius of the fiber without coating, l_m is the length of fiber wrapped around the mandrel. $I(x)$ is :[12]

$$I(x) = \frac{\sqrt{\pi}}{2} \frac{\Gamma\left(\frac{x+1}{2}\right)}{\Gamma\left(\frac{x}{2} + 1\right)} \tag{11}$$

where Γ is the well-known gamma function. The equivalent mandrel bending stress that gives the same mean time to failure as measured in two-point bending is found by equating the times in Eqs. (9) and (10):

$$\sigma_m = \sigma_t \left[\frac{2Er}{\sigma_t l_m} I\left(\frac{nm_t - 1}{2} \right) \right]^{\frac{1}{nm_t}} \tag{12}$$

Here l_m is 3.5 m and r is 200 μm. Therefore, σ_m for fiber I is 1.84 GPa, and the corresponding bending radius, R_m, is 8.0 mm.

4.6 Comparison of mechanical reliability

The lifetime of fiber II can be estimated by the same methods used for fiber I. Table 2 summarizes the parameters and the calculated results of lifetime predictions for both fibers. On a long time scale, fiber II is more reliable than fiber I, although the short-term strength for both fibers is similar. The two fibers are both capable of being bent to a very small radius (on the order of mm) and still have a 99.9% chance of survival for 3 years in a relatively warm (30°C) and humid storage environment.

Table 2 Summary of lifetime predictions for fiber I and fiber II using the power law.

Parameters and results	Fiber I	Fiber II
Regression parameters: $m_s \pm \Delta m_s$ $b_s \pm \Delta b_s$ x_m	 -22.4 ± 0.35 4.11 ± 0.02 0.60	 -25.4 ± 0.34 3.39 ± 0.02 0.63
Weibull modulus in static fatigue, m_t	1.225	1.067
Design lifetime in storage, t_s	3 years	3 years
Median failure time, t_m	19.6 years	25.9 years
σ_0 (2-point bend stress corresponds to t_m)	2.46 GPa	2.59 GPa
σ_t (maximum permitted 2-point bend stress)	2.35 GPa	2.49 GPa
σ_m (maximum permitted bend stress in storage) R_m (minimum allowed bend radius in storage)	1.84 GPa 8.0 mm	1.94 GPa 7.6 mm

4.7 Kinetics models

In the above prediction, the power law was used to demonstrate the estimate of minimum allowed bend radius for fiber survival. However, if we want to estimate the fiber lifetime by using the other kinetics models, the prediction procedures described above are still applicable. Identical procedures are used except that the static fatigue equation appropriate for the particular model[11] is used in steps 1 and 3.

To show the effect of using different kinetics models on the lifetime predictions, the static fatigue data of fiber I and fiber II are fitted to the three kinetics models by using the linearized forms described in the paper by Bubel and Matthewson.[15] For long duration, the kinetics models do give quite different predictions, as shown in figure 4.

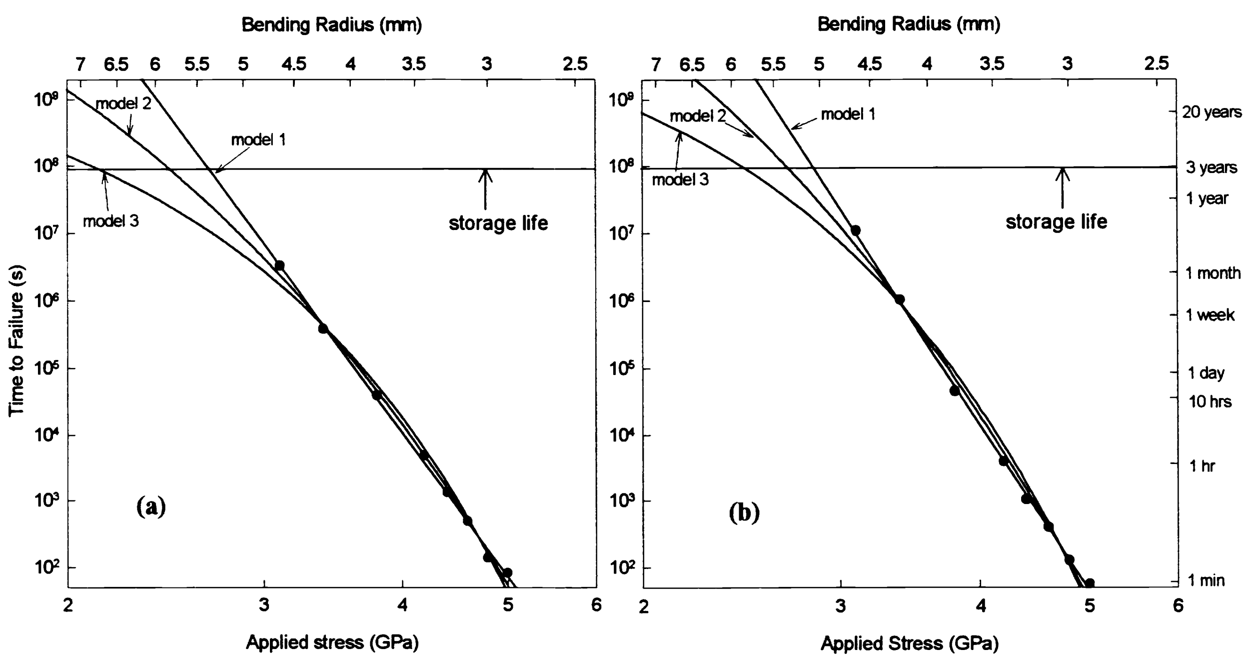

Figure 4. Static fatigue data of (a) fiber I (b) fiber II fitting to various kinetics models.

The maximum allowed stress and the corresponding bending radius for both fibers estimated by models 2 and 3 are summarized in table 3. In spite of the observation that the experimental data in this study fit model 1 better than the other two models (figure 4), we will consider the worst case, *i.e.*, model 3. Table 3 shows that the critical bending radius estimated by model 3 is still much smaller than the real bending radius for the fiber in storage (> 60 mm). Therefore, taking all the uncertainties in making fiber lifetime predictions into account, the fibers in this study should both be mechanically reliable for at least 3 years under storage conditions.

Table 3 The maximum allowed bending stress and the corresponding bending radius estimated for models 2 and 3.

Bend stress Bend radius	**Model 2**		Bend stress Bend radius	**Model 3**	
	Fiber I	**Fiber II**		**Fiber I**	**Fiber II**
σ_0	2.14 GPa	2.37 GPa	σ_0	1.57 GPa	1.93 GPa
σ_t	1.84 GPa	1.92 GPa	σ_t	0.61 GPa	0.68 GPa
σ_m	1.45 GPa	1.51 GPa	σ_m	0.50 GPa	0.56 GPa
R_m	10.1 mm	9.7 mm	R_m	29.0 mm	25.9 mm

5. IMPACT OF BIMODAL STRENGTH DISTRIBUTIONS

The above analysis assumes that it is valid to extrapolate from the strength distribution of high strength fiber measured in short lengths to low failure probability. However, it is well known that for long tested lengths (equivalent to low failure probability for short lengths) a broad low strength mode is observed due to the presence of occasional extrinsic defects.[16,17] If such weak defects occur with sufficient frequency, they will impact the reliability of the fiber probe even though they were not observed during our experiments.

In order to determine the importance of the weak defects, it is necessary to know the distribution of the low strength mode. Few data have been published on the strength distributions of weak defects. Glaesemann and Walter[18] present a technique for obtaining such data relatively easily. Assuming a worst case Weibull modulus of 2 for the weak defects,[19] the equivalent tensile test length for the fiber probe in storage is calculated to be 0.84 m.[12] 99.9% probability of survival of a 0.84 m fiber corresponds to a 2% failure probability for a 20 m gage length (figure 5 in ref 19), which is in the high strength mode. This calculation shows that the fibers used in our study are still in the high strength mode using the parameters obtained from a particular fiber manufactured in 1986. However, the low strength distribution will vary for different manufacturing runs. Since the low strength distributions are not available for the fibers used in this study, the probability of failure of the probe due to weak defects remains unknown, although it is expected that a well-made modern fiber would have a reliability at least as good as the 1986 fiber. Reliable tensile strength data could not be obtained for these fibers because of the difficulties involves with gripping such thick specimens.

6. SUMMARY

The mechanical reliability of two optical fiber specimens that are candidates for use in a biomedical application were studied by performing dynamic and static fatigue experiments in the simulated service and storage environments. The static fatigue data were used to make lifetime predictions. It has been observed that the two fibers from different manufacturers were comparably reliable for a short service time on the order of hours independently of the kinetics model used. However, fiber II was found to have somewhat better long-term reliability than fiber I.

This paper outlines procedures for making lifetime estimates that take into account statistical variation in the measured parameters. It considers several kinetics models and is not limited to using the ubiquitous power law form. It is found that the models do give quite different predictions and the power law provide the most optimistic predictions. For such a critical biomedical application, it is recommended that an exponential form for the kinetics be used in order to provide a "worst case" analysis.

In this work, we have attempted to make predictions at the 99.9% confidence level. However, the static fatigue data involve breaking only 120 specimens of each fiber. We therefore can not preclude the possibility of the existence of very weak flaws at a low probability level. Such flaws would invalidate our analysis. However, it is still necessary to make a best effort at making a lifetime prediction before using the fiber. The techniques outlined here are valid for any application using short lengths of fiber for which the probability of encountering weak defects is negligible.

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