AN APPRAISAL OF MECHANICAL RELIABILITY PREDICTIONS FOR OPTICAL FIBERS BASED ON BREAK RATES

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ABSTRACT

This paper examines the use of proof test break rates in estimating lifetime for optical fiber. The statistical basis for models that rely on break rate data is reviewed. The key assumption of the initial strength distribution following the form of Weibull distribution is examined. To test this assumption, the break rate is compared with the strength distribution after proof testing of many kilometers of fiber. Little correlation was found implying that fiber break rate is a poor predictor of the frequency of surviving flaws. This is attributed to the existence of multi-modal flaw populations in the region of proof testing. Alternate approaches that do not necessitate the use of break rate data are, therefore, found to be more appropriate in predicting mechanical fiber reliability.

INTRODUCTION

It is well known that optical fiber strength distributions are multi-modal. For example, Figure 1 shows a schematic of a typical measured strength distribution with the various regions identified. Note that even region 3 in Figure 1 has been shown to have multiple flaw populations.[1] What has received less attention is the nature of fiber strength distributions below the proof stress level. The strength distribution of these flaws are of considerable importance due to the fact that some mechanical reliability models use the failure probability at the proof stress level, i.e., break rate, in making long-term reliability predictions.[2,3,4]

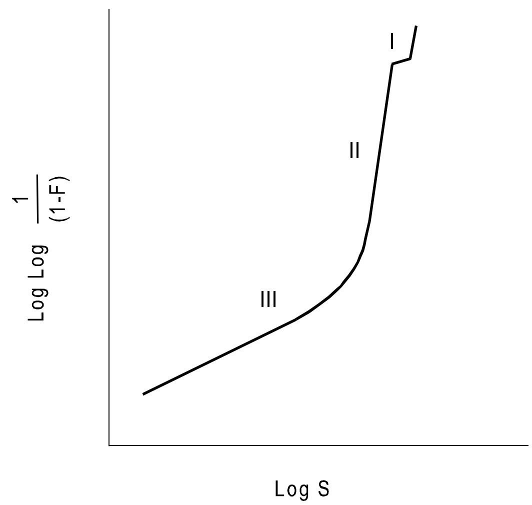

Figure 1. Schematic showing the various regions of a typical 20 meter gauge length optical fiber strength distribution.

The purpose of this research is to explore this region of the fiber strength distribution and to discuss the findings in light of the commonly assumed statistical behavior of the flaw population; namely, that flaws failing proof testing come from the same population as those surviving proof testing.

BACKGROUND

A methodology for incorporating the effect of proof testing on the strength distribution of brittle material has evolved over the years beginning with the work of Evans and Weiderhorn.[5] One begins with the basic statistical expression of the cumulative failure probability, F, of a given length of fiber with strength S,

$$F = 1 - \exp[-N(S)] \tag{1}$$

where $N(S)$ is the cumulative number of flaws per unit length with strength less than

S. It usually is assumed for optical fiber that the initial pre-proof strength distribution follows the Weibull distribution,[6]

$$N(S) = \left(\frac{S_i}{S_o}\right)^m \quad (2)$$

where S_i is the initial strength, m and S_o are the Weibull slope and scaling parameters, respectively, for a given unit length. Therefore, the initial pre-proof test strength distribution of fiber is expressed as,

$$F = 1 - \exp\left[-\left(\frac{S_i}{S_o}\right)^m\right] \quad (3)$$

Using Eq. (3), Figure 2 shows an initial strength distribution of fiber before proof testing as a solid line.[7]

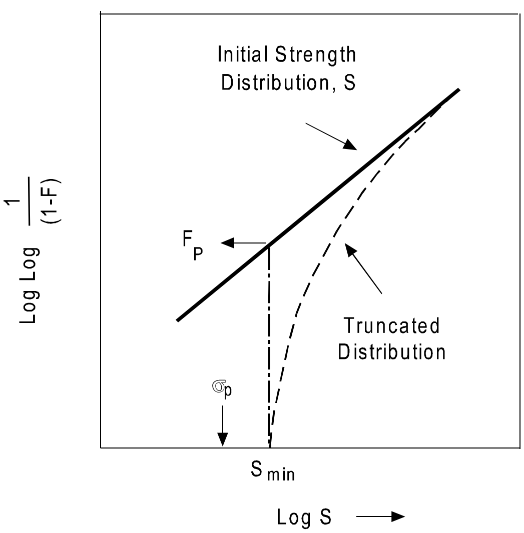

Figure 2. A Weibull strength distribution and the truncation effect of proof testing.[7]

Proof testing of fiber is incorporated through the accepted expression where the post-proof test failure probability, F_f, is expressed in terms of the initial failure probability, F_i, and the probability of failure during proof testing, F_p,[5]

$$F_f = \frac{F_i - F_p}{1 - F_p} \quad (4a)$$

or

$$\ln\left(\frac{1}{1-F_f}\right) = \ln\left(\frac{1}{1-F_i}\right) - \ln\left(\frac{1}{1-F_p}\right) \quad (4b)$$

This is a general expression for obtaining the post-proof test failure probability for any distribution. The post proof test failure probability, F_f, for an initial strength distribution, F_i, that is Weibull is obtained simply by substituting Eq. (3) Into Eq, (4),

$$\ln\left(\frac{1}{1-F_f}\right) = \left(\frac{S_i}{S_o}\right)^m - \ln\left(\frac{1}{1-F_p}\right) \quad (5a)$$

or

$$F_f = 1 - \exp\left(-\left[\left(\frac{S_i}{S_o}\right)^m - \ln\left(\frac{1}{1-F_p}\right)\right]\right) \quad (5b)$$

The predicted truncation of an initial Weibull strength distribution as a result of proof testing is shown in Figure 2 as a dashed line.

Proof testing is the process by which flaws below a particular level $S_{\min}$ are eliminated by applying a proof stress, s_p. The probability of a given length failing at $S_{\min}$ during proof testing is taken from Eqs. (2) and (3) where $F_i = F_p$,

$$\ln\left(\frac{1}{1-F_p}\right) = N_p = \left(\frac{S_{\min}}{S_o}\right)^m \quad (6)$$

where $S_i = S_{\min}$ is the initial strength at the proof stress. $\ln(1-F_p)^{-1} = N_p$ is the cumulative number of flaws failing below $S_{\min}$ or simply the break rate for a given length of fiber. The break rate is estimated by counting the number of breaks over a length of processed fiber.

Substituting Eq.(6) into Eq.(5) gives the post-proof test failure probability, F_f, in terms of the initial strength distribution and the break rate, N_p,

$$F_f = 1 - \exp\left(-\left[\left(\frac{S_i}{S_o}\right)^m - N_p\right]\right) \quad (7)$$

It is important to note that by assuming the initial strength distribution to be Weibull the flaws that contribute to break rate, those less than $S_{\min}$, are from the same initial population as those surviving proof testing, $> S_{\min}$. This can be seen in Eq.(6) as well as in Figure 2. If the overall failure probability of the initial strength distribution increases, both the break rate and the over all failure probability of the flaws surviving proof testing increase. This point is illustrated in Figure 3 where two initial strength distributions with the same Weibull slope, m, but different scaling parameters, S_o, are proof tested at the same stress level. The break rate and the post-proof test failure probability increase with a shift to the left in the initial strength distribution.

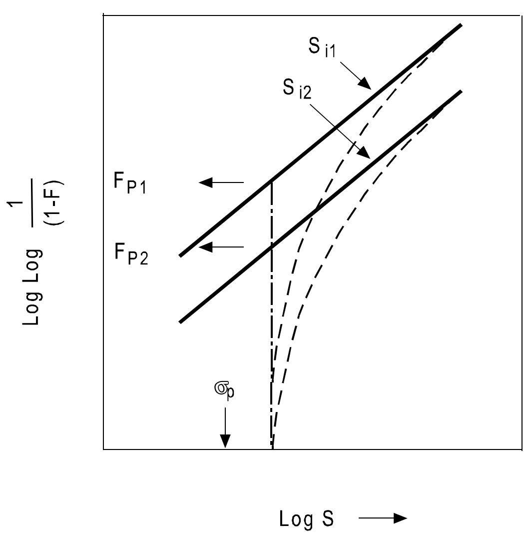

Figure 3. How the initial strength distribution affects the break rate and the post-proof test failure probability.

This is reflected in existing fiber failure probability models based on break rate and can be shown more clearly by substituting Eq.(6) into Eq.(7) and rearranged to give,

$$F_f = 1 - \exp\left(-N_p\left[\left(\frac{S_i}{S_{\min}}\right)^m - 1\right]\right) \quad (8)$$

In practical terms, it follows from Eq. (8) that the fiber with the higher break rate has a poorer post-proof test strength distribution. Furthermore, it is thought that by monitoring the break rate the risk of field failures can be determined for that fiber. Again, this is predicated on the assumption that the initial strength distribution is Weibull.

In this paper we examine the basic underlying assumption that the initial strength distribution follows the Weibull distribution and, therefore, that the break rate is a measure of optical fiber reliability.

POST-PROOF TEST STRENGTH DISTRIBUTION AND BREAK RATE DATA

In the previous section it was shown that the number of flaws failing proof testing should correlate with the number surviving assuming the initial pre-proof test strength follows a Weibull distribution. An attempt was made at examining this correlation by comparing the proof test break rate of fibers from individual preforms and the number of flaws surviving the proof test event.

Fiber was generated from 34 preforms manufactured over an 18 month time period. The break rate was estimated by counting the number of flaws that fail during proof testing at 0.7 GPa (100 kpsi) and dividing by the length proof tested. To characterize the post-proof test strength distribution a minimum of 30 kilometers from each preform was strength tested on a continuous fiber strength testing apparatus to 2.45 GPa (350 kpsi). This apparatus has been described in detail elsewhere.[8] Its operation consists of stressing sequential 20 meter sections of a given reel of fiber to a predetermined stress level, such as 2.45 GPa. In this way all the flaws below this stress level are loaded to failure and those surviving are accounted for statistically.

The post-proof failure probability, F_f, was taken from the 1.4 GPa (200 kpsi) strength level on the post-proof Weibull distributions from each fiber. That is to say, the proof test survivors used to represent the post-proof test strength distribution were obtained by simply counting the number of flaws that failed at or below 1.4 GPa (200 kpsi) during post-proof strength testing and dividing that value by the number of kilometers tested for that fiber. The stress level of 1.4 GPa (200 kpsi) was chosen to avoid the interference of other Weibull modes known to exist above this strength level.

RESULTS AND DISCUSSION

Figure 4 is a plot of the 0.7 GPa proof test break rate versus the frequency of flaws below 1.4 GPa after proof testing. Each data point in Figure 4 represents data from a single preform. Note that the proof test break rate has been normalized for proprietary reasons.

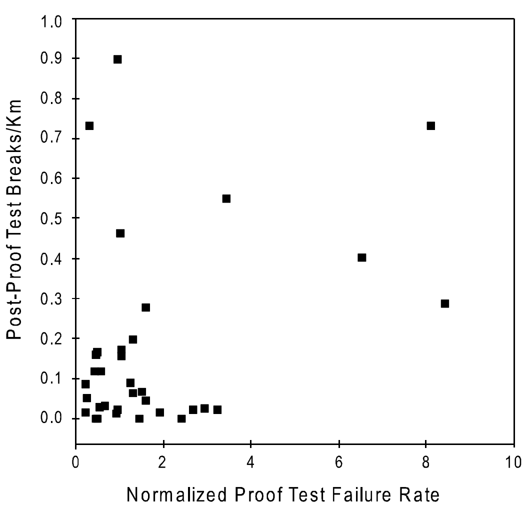

Figure 4. comparison of break rate from proof testing at 0.7 GPa and the frequency of flaws below 1.4 GPa from the post-proof strength distribution.

There is little correlation between the proof test break rate and the frequency of flaws surviving proof testing suggesting that break rate is not a good predictor of the post-proof strength distribution.

It is believed that the lack of correlation observed in Figure 4 is due simply to multiple flaw populations in the region of the strength distribution affected by the proof test. It is quite common for brittle materials to exhibit multi-modal strength distributions. For example, optical fiber is shown in Figure 1 to have several distinct strength distribution regions above the proof stress level. Such regions in the strength distribution also can exist below the proof stress level.

Assuming the initial strength to be a single Weibull distribution when in fact it is multi-modal can cause reliability models based on break rate to either overestimate or underestimate the post-proof test failure probability. Figure 5 shows three distributions, two of which are bi-modal in the region of the proof test stress and one is the usual uni-modal shape.

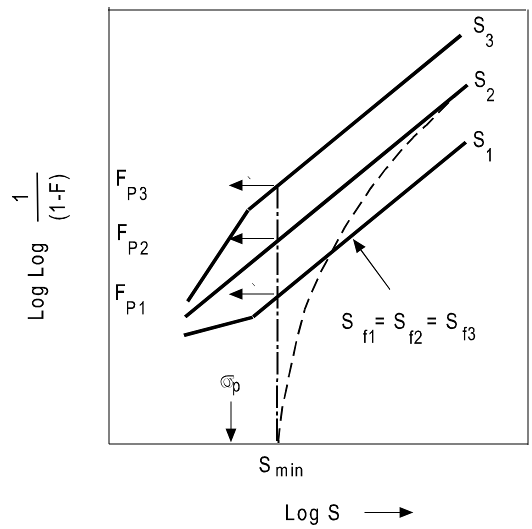

Figure 5. The effect of a multi-modal initial strength distributions on break rate and the post-proof test strength distribution.

With an initial strength distribution S_{i1} there exists a large population of flaws with strengths less than the proof stress level. For optical fiber, these flaws usually result from mechanical abrasion to the fiber surface before the coating is applied, surface contamination, or internal contamination during preform manufacturing. In this case the flaw population above the proof stress level is shown to be the same as that for the uni-modal distribution, S_{i2}. When proof testing fiber with distribution S_{i1} the break rate will be higher than that for S_{i2}, however, the post-proof strength distributions will be the same. Thus, the break rate would predict a poorer post-proof strength distribution than what actually exists after proof testing.

In the case of distribution S_{i3} the situation is reversed from that of S_{i1}. Here the manufacturing process has provided fewer flaw sources that contribute to breaks during proof testing and so the break rate is lowered. However, flaws above the proof stress level are, again, from the same population as the uni-modal distribution and so the post-proof test distribution is identical to that of the uni-modal distribution.

One can see that the effect of multi-modal strength distributions in the range of the proof test stress is to frustrate the convenient assumption of an initial strength distribution that is Weibull.

The question remains, how can one improve the confidence in post-proof test failure probability predictions? The temptation is to assume a conservative break rate, N_p, in Eq. (8). However, one risks the situation where a process consistently produces a particular multi-modal strength distribution. This is especially true in the case where the process produces a distribution similar to S_{i1} in Figure 5. Here one could grossly overestimate the post-proof test failure probability. Basing the reliability model on an actual measured fiber strength distribution, though time consuming, would be the best method for improving confidence in failure probability predictions. However, from the data in Figure 4 one observes some variability here as well. This is mitigated by choosing an overall distribution for modeling purposes that passes through the middle of the data. Where there is wide variability in the post-proof test strength distribution from fiber to fiber, one would choose a more conservative estimate of the overall distribution for modeling purposes.

SUMMARY

Mechanical reliability models employing the fiber break rate as a convenient measure of post-proof test fiber reliability have an implicit assumption that the failure probability of fiber lengths surviving proof testing can be measured by the break rate. Extensive data comparing the post-proof strength to the break rate show a lack of correlation. It is shown that initial strength distributions that are multi-modal in nature give rise to such behavior. Knowledge of the actual post-proof test strength distribution is the best means of reducing uncertainty in fiber failure probability predictions.

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REFERENCES

1. G. S. Glaesemann, "Optical Fiber Failure Probability Predictions from Long-Length Strength Distributions," pp.819-825 in proceedings of the 40th International Wire & Cable Symposium, St. Louis, Mo., 1991.
2. E.R. Fuller, Jr., S.M. Wiederhorn, J.E. Ritter, Jr., P.B. Oats, "Proof Testing of Ceramics, Part 2 Theory," J. Mater. Sci., 15, 2282-2295 (1980).
3. Y. Mitsunaga, Y. Katsuyama, H. Kobayashi, and Y. Ishida, "Failure Prediction for Long-Length Optical Fiber Based on Proof Testing," J. Appl. Phys. 53 (7), 4847-4853 (1982).
4. J.G. Titchmarsh, "Failure Rate as the True Parameter of Optical Fibre Reliability," pp. 441-416 in proceedings of the 41st International Wire & Cable Symposium, Reno, Nevada, 1992.
5. A.G. Evans, and S.M. Wiederhorn, "Proof Testing of Ceramic Materials - an Analytical Basis for Failure Prediction.
6. W. Weibull, "Statistical Distribution Function of Wide Applicability," J. Appl. Mech., 18 (3) 293-297 (1951).
7. A.G. Evans and E.R. Fuller, "Proof Testing - The Effects of Slow Crack Growth," Mat. Sci. and Eng., 19, 69-77 (1975).
8. G.S. Glaesemann and D.J. Walter, "Method for Obtaining Long-Length Strength Distributions for Reliability Prediction," Opt. Eng., 30 (6) 746-748 (1991).

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