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METHOD FOR OBTAINING LONG-LENGTH STRENGTH DISTRIBUTIONS FOR RELIABILITY PREDICTION

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Abstract. A technique for measuring the fiber strength distribution of many kilometers of fiber was developed. The strength distribution of 100 km can be generated in a week's time by a single operator. A strength distribution for 400 km of fiber is shown to depart from the high-strength region around the 1% failure probability level and the data exhibit the beginnings of the truncated portion of the strength distribution. Such data are believed to be useful in making failure probability predictions, process improvements, and aid in the understanding of crack-growth behavior during proof testing.

Subject terms. optical fiber reliability; strength measurements, reliability predictions; long-length strength distributions.

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CONTENTS

1. INTRODUCTION

Most design methodologies for the mechanical reliability of brittle materials express the allowable in-service stress in terms of either failure probability or a fraction of the minimum strength after proof testing.[1] In the first case, failure probability is incorporated into the design method through knowledge of the strength distribution of flaws governing reliability. In the latter case, materials are treated as though their strength is no greater than the minimum strength. For optical fiber applications, the latter case is the most prevalent in present day cable designs because long-length strength distributions are not readily available. The purpose of this paper is to present an apparatus for strength testing long fiber lengths as well as preliminary strength data.

2. BACKGROUND

The flaws of most concern to the fiber manufacturer, cabler, and end user are the largest ones, since they represent the greatest risk from a mechanical reliability point of view. To limit the size of the flaws, the strength distribution is truncated by proof testing the entire fiber surface to a predetermined stress level. Figure 1 is a 1979 fiber strength distribution of 100-m fiber lengths plotted in Weibull fashion.[2] The vast majority of flaws are below the high-strength region of 500 kpsi (3450 MPa). The lower region of the distribution curves down in classic truncated fashion[3] to the proof stress level of 100 kpsi (690 MPa). Predicting the probability of encountering a flaw at the proof stress for this fiber is simple.

Figure 2 is a schematic of a 1986 strength distribution of fiber proof tested to 50 kpsi (350 MPa) using 20-m gauge lengths. Testing was performed at a strain rate of 4%/min under ambient conditions, and a total of 17 km of fiber were tested. The largest flaw in the 17-km length is shown to be approximately 70 kpsi (480 MPa) in strength.

The curve in Figure 2 does not show the truncated portion of the strength distribution; therefore, the probability of encountering a 55-kpsi (380-MPa) flaw, for example, cannot be predicted accurately. That is to say, this distribution does not contain the data needed to make failure probability predictions for applications involving long fiber lengths. In fact, as fiber manufacturing processes improve, the number of flaws near the proof stress level is expected to decrease even further. Thus, long-length strength distributions are needed to properly assess the distribution of flaw at low levels of failure probability.

To develop a long-length strength distribution, one must first recognize that the flaws in the high-strength region of the fiber

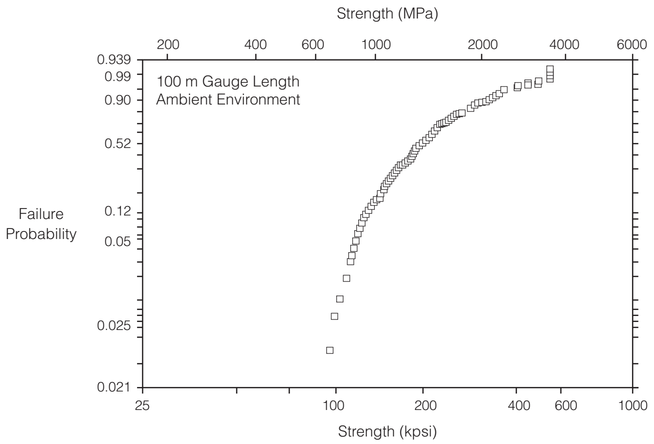

Fig. 1. Strength distribution of optical fiber manufactured in 1979.

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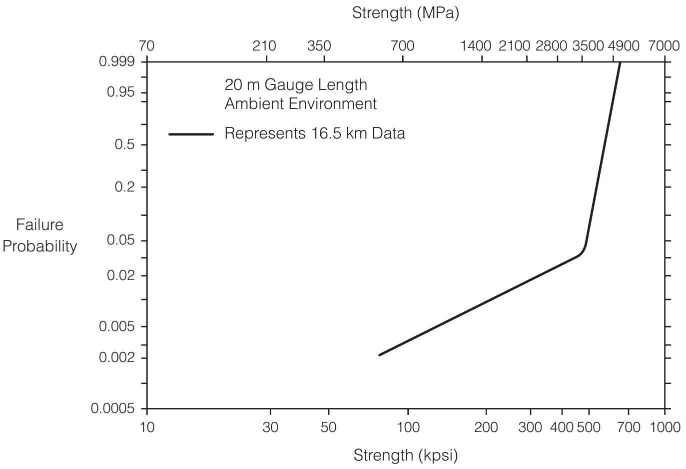

Fig. 2. Strength distribution of standard silica-clad fiber manufactured in 1986.

strength distribution do not pose the greatest risk for long-length applications. However, from Fig. 2 these high-strength flaws demand 95% of the testing time. The approach taken in the long length strength-test development reported here is to avoid testing to failure flaws in the high-strength region, since this region can be easily generated by conventional means.[4] Rather, focus is placed on measuring the strength of larger flaws below the high-strength region.

3. TEST APPARATUS

The apparatus developed for obtaining a long-length strength distribution is shown schematically in Fig. 3. A commercial fiber proof-test machine* was modified to operate as a low-tension payout and take-up device for a predetermined gauge length of fiber. A reel of fiber is attached to the payout spindle, as is normally done, and fiber is threaded partially through the machine, around a pulley approximately 10 m away, back to the machine, and eventually to a take-up reel. This configuration deviates from the conventional proof-test configuration by an increase in the length of fiber in the gauge length portion of the proof tester. This is accomplished by threading the fiber between the tractor pulleys to a remote pulley several meters away. Turning on the proof tester advances fiber from the payout reel through the tractor and pulley assemblies to the take-up reel. For this study, the remote pulley is placed such that the fiber starting at point A in Fig. 3 travels a distance of 20 m to point B.

The remote pulley assembly consists of a 6-in.-diam pulley mounted to a load cell, both of which are attached to a pneumatic slide. Thus, when the slide is activated, the load cell and pulley move horizontally away from the proof tester. Note that the load experienced by the fiber is half that experienced by the load cell. The additional bending stress on the fiber portion bent around the pulley is small due to the large pulley size relative to that of the fiber.

The test sequence is as follows. A 20-m length of fiber is advanced from the payout reel into the gauge length region, between points A and B in Fig. 3, and the proof tester is brought to a stop. Breaks are applied to the tractor assemblies to keep them from rotating. The pneumatic slide is activated such that the fiber in the gauge length is strained at a predetermined rate.

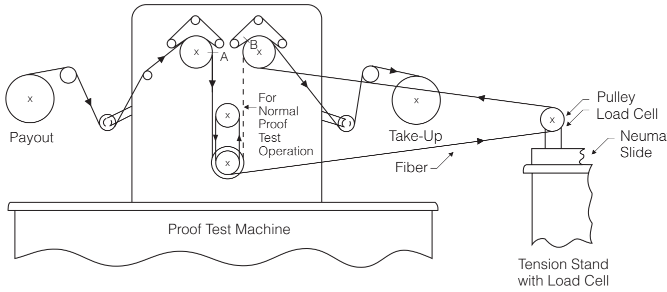

Fig. 3. Schematic of continuous fiber strength-test apparatus.

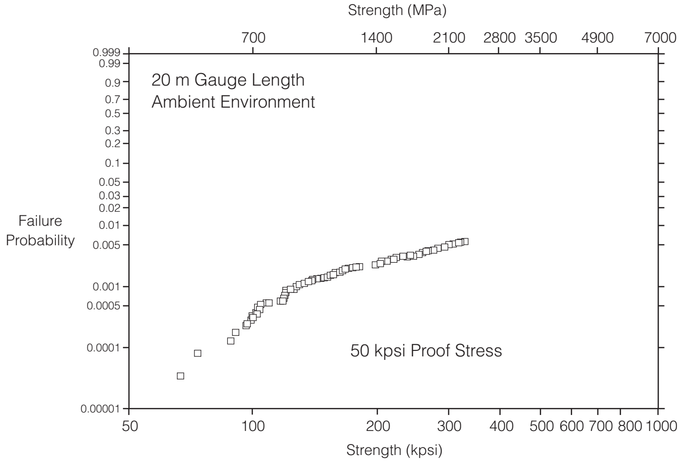

Fig. 4. Strength distribution of 386 km of titania-doped silica-clad fiber.

Fiber loading continues until a preset maximum tensile load level is reached, at which time the slide reverses direction and unloads the fiber. If the fiber passes the load pulse, another 20-m length is advanced by the proof tester into the gauge length region, and the load pulse is repeated. Thus, all fiber passing the load pulse is essentially proof tested to a value equaling half the maximum preset load.

Fiber payout followed by a load pulse continues until the fiber fails during one of the pulsing events. The signal from the load cell is monitored continually to record the load at failure. The strength of the fiber is determined by simply dividing half the failure load, recorded by the load cell, by the cross-sectional area of the fiber. To remain below the high-strength region of the distribution, the maximum preset load is such that the maximum fiber stress is below the high-strength region of approximately 500 kpsi (3450 MPa) shown in Fig. 2.

4. RESULTS AND DISCUSSION

Figure 4 is a strength distribution of 386 km of titania-doped silica-clad fiber proof tested at 50 kpsi (340 MPa) and strength tested with the above apparatus using a 20-m gauge length. The maximum fiber load was chosen to be 350 kpsi (2420 MPa), and loading was performed at a rate of 200%/min in a laboratory ambient environment. A total of 19,300 20-m lengths were tested over a period of four weeks. Figure 4 shows a total of 106 breaks below the 350-kpsi maximum stress level with the weakest flaw being 66 kpsi (460 MPa.)

To generate the distribution in Fig. 4, the data were ranked from weakest to strongest, and cumulative failure probability was assigned using $F = (I - 0.3)/(J + 0.4)$, where I is the rank from 1 to 106 and J is the total number of tests. In this

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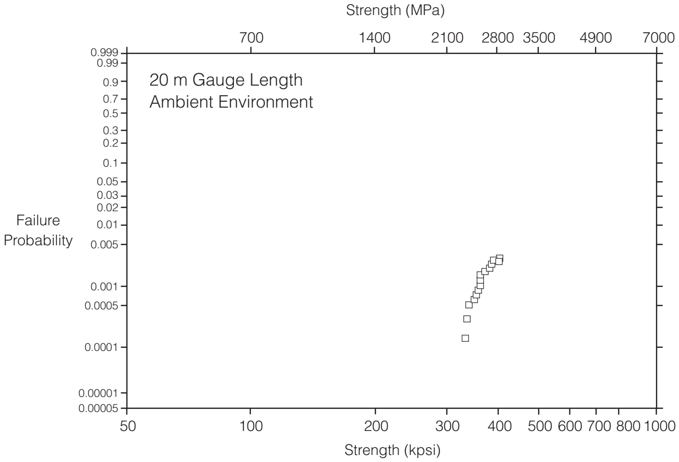

Fig. 5. Strength distribution of 200 km of fiber proof tested at 300 kpsi.

case the value of *J* is 19,300, and the failure probability for the weakest flaw is calculated to be 0.000036. The "knee" in the distribution can be estimated by extending the distribution to the 500-kpsi (3450-MPa) level, whereby a failure probability of 0.01 or 1 % is determined. The data in Fig. 4 also show the beginnings of a truncated distribution although more testing is needed to better establish the shape of the truncated region.

The data in Fig. 4 demonstrate several useful applications for a machine such as this. First, the actual strength distribution of the fiber can be determined for making reliability predictions. Due to the rarity of long-length strength distributions, engineers have been forced to use proof-test theory to extrapolate the truncated portion of the distribution over many orders of magnitude in failure probability. Measuring the strength distribution to very low-failure probabilities, one need only extrapolate over a few orders of magnitude in failure probability. This would greatly reduce the level of uncertainty in failure probability pre dictions.

Second, with this test technique one can better address several areas of proof testing that are not well understood, namely, flaw growth during unloading from proof testing and the effect of dwell time on the strength distribution above the proof stress level. Finally, generating long-length strength distributions in a relatively short period of time would greatly assist in the understanding of fiber manufacturing and cabling processes. For example, it is desirable to know if proof-test machines introduce new flaws when proofing. Figure 5 is a strength distribution of 200 km of fiber proofed at 300 kpsi (2070 MPa). Strength testing was performed under conditions similar to that of the data in Fig. 4 with the exception that the maximum preset fiber stress was 400 kpsi (2760 MPa). Although the number of failures was limited, the fact that no failures below proof stress were recorded suggests that the proof-test machine, as well as the strength-test technique, handled the fiber in an acceptable fashion. This is of particular importance for fiber used in tethered weapons applications where high proof stress and reliability are required.

5. SUMMARY

A technique and apparatus for measuring the fiber strength distribution of many kilometers of fiber was developed, and long length strength distributions from 400- and 200-km lengths of fiber were generated. Such data are useful in making failure probability predictions, process improvements, and in the understanding of crack growth during proof testing.

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G. Scott Glaesemann: Biography and photograph appear with the paper "Design methodology for the mechanical reliability of optical fiber" in this issue.

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