Comparison of Mechanical Reliability Models for Optical Fibers

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Linda K. Baker

Introduction

The design life for optical fiber cables often is in excess of 25 years and it is not practical to conduct experiments to directly assess reliability on such time scales. In order to quantify reliability of the system it is necessary to perform accelerated experiments in the laboratory and extrapolate these results to less severe in-service conditions. The maximum allowed stress that correlates with survival for the design life is then estimated by using an appropriate model for the mechanism that leads to failure. There are many mechanical reliability models available for estimating optical fiber life. This paper reviews the different models, and discusses their advantages and weaknesses. We offer our rationale for endorsing the Two Region Power Law model for estimating optical fiber mechanical reliability.

Flaw Growth

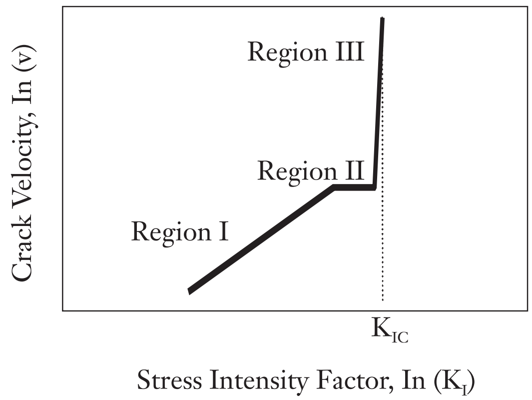
It is well understood that flaws in glass subjected to an applied tensile load in the presence of moisture will experience subcritical growth prior to failure (i.e. fatigue). The crack growth prior to failure can be separated into three distinct regions, which are shown in Figure 1. The stress intensity factor, K_I, in Figure 1 relates the crack depth, a, to the applied stress, σ, through the expression

$$K_I = Y \sigma \sqrt{a} \qquad (1)$$

where Y is a shape factor related to the crack geometry. Region I is the region of stable, or subcritical, crack growth where the crack velocity, V, increases steadily with increasing stress intensity in the presence of an applied load and moisture. Region I of the K_I-V crack growth curve is of significance for long-term loading events when the crack velocity is low. **Fiber deployed in a cable is considered to be a long-term loading event.**

Crack Velocity vs. Stress Intensity Factor

Figure 1



At the critical velocity on the K_I-V curve the limiting rate of water diffusion to the crack tip region results in Region II behavior, where the crack velocity is determined by this diffusion and does not increase further with stress intensity. In other words, in Region II the crack is moving with sufficient speed to "out run" water transport to the crack tip. Region II crack growth is most prominent during short-term loading events, such as proof testing or cabling processes. Region III, just before catastrophic failure at the critical stress intensity (K_{IC}), is the region of unstable crack growth and is independent of environment.

Experimental Data

In order to accurately predict mechanical performance, one first needs to know the strength distribution of the optical fiber. The model of choice then is applied to estimate the crack growth over the design life in order to predict failures. Knowing the strength distribution entails determination of the parameters that describe the Weibull distribution for a fiber. These parameters are the Weibull slope and intercept. In the industry, there are two basic means of obtaining the parameters: determining the failure rate at proof test or performing large scale dynamic strength testing (e.g., continuous rotating capstan fiber tester (CRCFT) testing[1]). The proof test failure rate at one proof test level can provide information only on the intercept. To obtain slope information, either multiple proof stress levels or some dynamic strength testing is required. The CRCFT measures the distribution of the surviving population that represent the flaws being installed, not the flaws that have failed the proof test. The proof test failure rate information could include failures that are not part of the distribution obtained in CRCFT testing. Therefore, we believe that the CRCFT method is superior for determining the strength distribution parameters.

Laboratory testing involves the application of stress to the fiber and measuring the time to failure (static fatigue), or applying stress to the fiber at a constant strain rate and measuring the load at failure (dynamic fatigue). Aging the fiber at extreme conditions prior to testing simulates long-term aging effects. More information on Corning's testing techniques is described in another Corning publication.[2]

Mechanical Reliability Models

The dominant crack growth models are listed below:

Reliability Models
Exponential Model
p-Model
Single Region Power Law Power Law Guideline Mitsunaga
Two Region Power Law

The **exponential model** suggests that the fatigue constant, n, of a silica clad optical fiber should reduce as the applied stress decreases or as the fiber lifetime increases. This is counter to the observations made by many researchers. In addition, some forms of the exponential model predict that many failures already have occurred in the field due to fatigue. This also does not agree with what has been observed in practice. Therefore, the exponential model, though considered to be theoretically more correct by some, is not in agreement with physical data and Corning does not endorse the use of this model for optical fibers.

The **p-model** is an adaptation of the exponential model that features multiple crack growth regions. For high speed loading events (e.g. proof testing), Region II crack growth dominates. For moderate speed loading events (e.g. installation), the fatigue constant, n, is the same as that measured by dynamic fatigue tests. For very slow loading events (i.e. installation stresses), the n value will tend to increase. This model is very complex, and Corning does not endorse it due to questions about its underlying physical assumptions.

The Power Law model is the most technologically correct model to date for modeling crack growth in optical fibers. In this model, stress assisted fatigue of optical fibers are characterized by two environment-dependent crack growth parameters: B and n. The B value is the crack strength preservation parameter, and a measure of the weakening effect a particular applied stress history will have on optical fiber strength. The n value is the fatigue constant, also referred to as the stress corrosion susceptibility parameter, and is the measure of how fast a crack grows when exposed to both water and stress.

The values of B and n are necessary when calculating the lifetime of optical fiber under stress from a known initial stress. Two variations of the **Single Region Power Law** model are described below.

The **Power Law Guideline**[3] is a methodology that uses the Single Region Power Law, CRCFT strength distributions, and a low value of B. It also accurately reflects other effects of the proof test. However, it does not accurately estimate effects from higher manufacturing processing rates, and it is overly conservative for making reliability predictions. If one assumes the B value to be low, the calculated minimum surviving strength after proof testing is zero. As should be recognized, this is not true in practice. This is why the value of B becomes so important when modeling the effects of high speed stressing events on the strength of fiber.

The **Mitsunaga Methodology**[4] is based on the Single Region Power Law and makes various assumptions to avoid the use of crack growth parameters, namely the B value. However, in doing so the method suffers serious deficiencies. For one, the method uses failure rate data from proof testing to describe the strength distribution of the surviving flaws (i.e. those that pass proof testing). Given the possibility of multiple modes of failure, this assumption is not valid and results in over conservative estimations of failure probability. As stated previously, an actual measurement of strength is superior to proof test break rate information.

The **Two Region Power Law**[5] includes both low B (which dominates the crack growth outcome for low stress applied over a long time) and a larger value of B (which dominates crack growth due to fast events such as proof tests). The Two Region Power Law is an enhanced Power Law approach and adds a level of elegance that not only links the theory to actual laboratory results, but enables the model to be extended beyond conventional modeling which is based on long term applied stresses alone. The two region approach allows multiple-stress time events, such as short term cascading stresses, to be incorporated to obtain a first order model of crack growth occurring as a result of cabling and installation. The results are more realistic than models that ignore such events. It is hypothesized that most fiber failures occurring during cabling are due to random transient stress events. Depending on the strength of the fiber section to which the random stress was applied the outcome could be fiber failure, a significant reduction in strength, or no substantial strength reduction. None of the other models available today take this effect into account.

Summary

Corning supports the use of the Two Region Power Law as a means of modeling crack growth behavior in optical fibers. This method incorporates the use of an actual strength distribution with the ability to predict the effect of both long and short term stressing events.

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Corning Incorporated
www.corning.com/opticalfiber

One Riverfront Plaza
Corning, NY 14831
U.S.A.

Phone: 800-525-2524 (U.S. and Canada)
607-786-8125 (International)

Fax: 800-539-3632 (U.S. and Canada)
607-786-8344 (International)
Email: info@corningfiber.com

Europe

Berkeley Square House
Berkeley Square
London W1X 5PE
U.K.

Phone: +800 2800 4800 (U.K.*, Ireland, France, Germany, The Netherlands, Spain and Sweden)
*Callers from U.K. dial (00) before the phone number

+800 781 516 (Italy)

+44 7000 280 480 (All other countries)

Fax: +44 7000 250 450

Email: europe@corningfiber.com

Asia Pacific

Australia
Phone:1-800-148-690
Fax: 1-800-148-568

Indonesia
Phone: 001-803-015-721-1261
Fax: 001-803-015-721-1262

Malaysia
Phone: 1-800-80-3156
Fax: 1-800-80-3155

Philippines
Phone: 1-800-1-116-0338
Fax: 1-800-1-116-0339

Singapore
Phone: 800-1300-955
Fax: 800-1300-956

Thailand
Phone: 001-800-1-3-721-1263
Fax: 001-800-1-3-721-1264

Latin America

Brazil
Phone: 000817-762-4732
Fax: 000817-762-4996

Mexico
Phone: 001-800-235-1719
Fax: 001-800-339-1472

Venezuela
Phone: 800-1-4418
Fax: 800-1-4419

Greater China

Beijing
Phone: (86) 10-6505-5066
Fax: (86) 10-6505-5077

Hong Kong
Phone: (852) 2807-2723
Fax: (852) 2807-2152

Shanghai
Phone: (86) 21-6361-0826 ext. 107
Fax: (86) 21-6361-0827

Taiwan
Phone: (886) 2-2716-0338
Fax: (886) 2-2716-0339

E-mail: luyc@corning.com