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The Mechanical Reliability of Corning Optical Fiber in Small Bend Scenarios

White Paper

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Issued: December 2007

Supersedes: October 2007

The purpose of this paper is to provide guidance to network designers on the mechanical reliability of Corning optical fiber for the particular case of very tight bends encountered in fiber-to-the-home (FTTH) and premises networks.

Introduction

As optical fiber is deployed deeper into access networks and ultimately within premises networks, it will be subject to increasingly tighter bends. Examples include distribution cabinets, small footprint modules, storage cassettes, and also in indoor installations such as MDUs (Multi-Dwelling Units) and in-home wiring. Consequently, Corning and others have commercialized new low-bend-loss fiber products with significantly lower optical bending loss in order to accommodate these deployment conditions. However, with this trend towards fiber with tight bends one must consider the implications on fiber mechanical reliability.

In response to the new fiber requirements for fiber-to-the-home and premises networks, a new ITU-T Recommendation (G.657) has been ratified. This standard is devoted to the specific requirements for optical fiber and cable used in the optical access networks to and within buildings and homes. Along with these requirements, the recommendation addresses lifetime expectation in the case of small radius storage of single-mode fiber. It states "Each operator has to determine the accepted failure rate based on more precise data on the outside plant failure rate statistics."

This paper will review fiber mechanical reliability in the context of tight bending FTTH and MDU scenarios. We will also provide guidelines for fiber deployment in tight bending scenarios. A sampling of our fiber reliability publications can be found at:

http://www.corning.com/opticalfiber/technical_library/fiber_mechanical_reliability/basics.aspx

Corning's Approach to Mechanical Reliability

Corning Incorporated has been manufacturing optical glass fiber since the 1970s. Over the past 30 years Corning has developed the tools and models to help customers understand the impact on fiber's mechanical reliability in a wide variety of applications where stress and strain are present. The cornerstone of our mechanical reliability modeling effort is the ability to incorporate tension, bending, various lengths under stress, and multiple stress events into a single model. The present discussion on fiber in tight bends fits well with our prior work in fiber mechanical reliability. In the following sections we present some of the foundational inputs and understanding for reliability modeling.

1. Fiber Strength: Measurements and Predictions

In order to make failure probability predictions, a measured strength distribution is needed. It is important that the length of fiber tested be relevant to the application. In a single FTTH deployment, a single bend involves a relatively short length of fiber, but when considering all the bends in the entire installed base a relevant strength distribution for FTTH should come from kilometers of fiber. Such strength distributions are difficult to obtain because of the level of effort involved. In the early 1990s Corning developed a test method that tests the strength of kilometers of fiber in a short period of time.ⁱ Since then we have strength tested several thousand kilometers of fiber. This machine stretches individual 20 meter lengths in tension to a preset stress level. If a particular 20 meter length is stronger than this preset level, say 600 kpsi (~4200 MPa) the fiber passes the test and a fresh 20 meter length is automatically advanced into the machine and stretched. If a particular 20 meter length has a flaw that is weaker than the preset level, the stress at failure is recorded.

The square symbols in Figure 1 are all the flaws below 560 kpsi on nearly 4000 kilometers of fiber proof tested to 100 kpsi (~700 MPa).ⁱⁱ Now, using established statistical methods one can scale this 20 meter gauge length data, obtained in tension, to various lengths in bending.ⁱⁱⁱ This is shown by the curves in Figure 1. The probability of finding a flaw weaker than, say, 200 kpsi (1400 MPa) on a 1 meter length of this fiber is about 1×10^{-6} . It is interesting that the probability of failure of a 20 meter length of fiber tested in tension, square symbols, is equivalent to testing 100 meters of fiber in bending. Bending exposes fewer flaws to stress because half of the fiber volume is in compression.

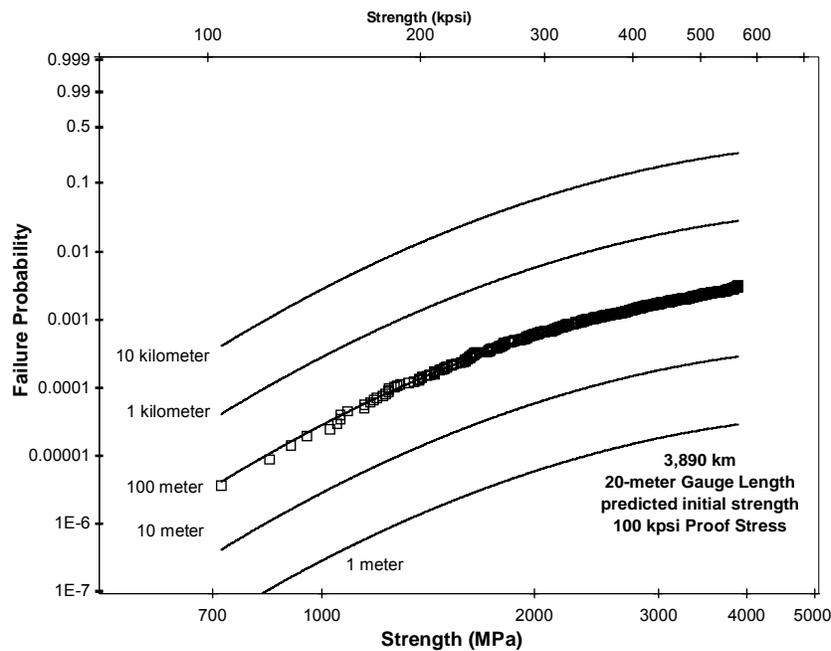


Figure 1. Strength of nearly 4000 km of standard single-mode optical fiber. The lines represent predicted distributions for a wide range of lengths in bending. Note that fatigue during strength testing has been accounted for.²

2. Fiber Fatigue Behavior

The mechanical reliability of silica-based optical fiber is strongly influenced by fatigue. Flaws in glass subjected to a sufficient level of tensile stress in the presence of moisture will grow slowly, i.e., “fatigue”, prior to failure. Michalske and Freiman^{iv} describe this fatigue mechanism as, “the slow extension of a crack due to a specific chemical reaction between strained silica bonds and water.” Ritter describes fatigue in terms of strength degradation when he states that “time-dependent strength behavior (fatigue) of glass is generally believed to be the result of sub critical crack growth of a flaw to a dimension critical for spontaneous failure.”^v The crack growth rate, or fatigue, and respective time-to-failure depend on the initial crack size, applied tensile stress, and environment (temperature, humidity, pH).

The susceptibility of optical fiber glass to fatigue is reflected in the fatigue parameter “n”. The higher the n value the more resistant the glass is to fatigue. The “n” value is most commonly obtained by measuring fiber strength, σ_f , for a range of stressing rates, $\dot{\sigma}$ (the rate of change of the stress during the test). At fast stressing rates there is less time for fatigue and the strength is relatively high. At slow stressing rates there is more time for fatigue and the measured strength is correspondingly lower. The “n” value is obtained from the plot of $\ln \sigma_f$ versus $\ln \dot{\sigma}$ by slope = $1/(n+1)$, and a typical value for silica in fiber form is about 20.

In mechanical reliability models, a high n value leads to a higher allowable stress. However, since all standard optical fiber for telecommunication applications has a silica surface, the basic fatigue behavior for all optical fiber is about the same. Certainly some lab-to-lab differences in measured n values exist due to test method and test environment differences, but the silica is the same for all standard optical fiber. Some key understandings about fiber fatigue are;

- The n value for long-term stress conditions is approximately 20^{vi}
- Fatigue is relatively independent of flaw source and strength. Therefore, the same fatigue model can be used for all the flaws that make up the strength distribution in Figure 1
- Fatigue in fiber is different for short-term events, like fiber proof testing and cabling, than for longer-term stress events like those during installation and long-term life. Thus, the reliability model should account for this behavior.

In the next section we demonstrate how this understanding is used to establish practical guidelines for fiber use in a wide range of applications, especially lengths placed in bending.

3. Design Diagrams

Design Diagram based on Failure Probability

Combining the strength distribution in Figure 1 with Corning’s understanding of fiber fatigue a reliability design diagram for standard optical fiber in bending was created and is shown in Figure 2. With this diagram one can make failure probability predictions for a range of bend radii, load durations, and lengths in bending.

The x-axis in Figure 2 gives the bend condition in terms of bend radius (bottom axis) and maximum bend stress (top axis). With either x-axis one can choose from three deployment durations. A one second stress event is for processes or installations, like travel over a pulley or being pulled around a corner, where the stress is applied momentarily. A 4-hour stress event is meant to represent installations where the fiber might be under stress for some period of time until the installation is complete. The 25-year timeframe is for permanent deployment conditions.

The use of the design diagram can best be explained by considering several examples. The first example is the case where one meter of excess fiber at a termination point is coiled for storage. In most cases the bend radius in a storage tray is typically about 32 millimeters. For this example, let us assume a more extreme case of a permanent bend radius of, say, 20 mm. The maximum bend-induced stress on the glass surface, in this case, is about 275 MPa or 40 kpsi. This is a permanent applied stress, and therefore, the “25-year” life axes in Figure 2 apply. The failure probability is shown to be less than 1×10^{-6} (1 in 1,000,000). The next example is the case where 10 meters of cabled fiber is pulled around a corner during FTTx installation. The duration of the bend at any one location on the fiber is relatively short; and therefore, the “1 second” axes in Figure 2 will be used. For bend radii greater than about 10 mm, the failure probability is on the order of 1×10^{-7} (1 in 10,000,000), i.e., extremely low. For these installation events one is counting on the fact that the probability of encountering a flaw is low. This implies that testing long lengths of fiber is necessary for determining the probability of failure during installation.

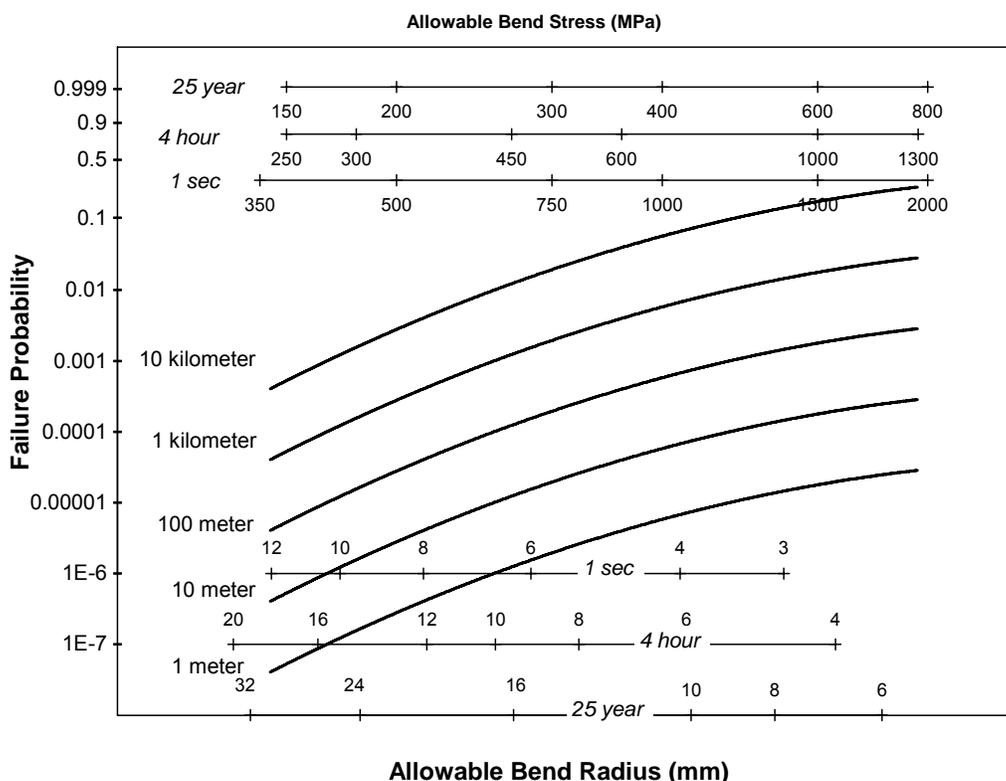


Figure 2. Design diagram for standard optical fiber in bending. The lower axis shows allowable bend radii for three different stress durations. The upper axis is in terms of allowable bend stress in MPa (~7 MPa per kpsi).

Design Diagram based on Proof Stress Level Flaws

If lengths longer than several kilometers are deployed under bending or tensile stress, it is common to design around the weakest possible flaw, one that just passes the proof stress. Proof testing is conducted during fiber manufacturing just after the draw process. The entire fiber length is stressed to a predetermined stress level in order to eliminate the weakest flaws and establish a maximum flaw size. The most common proof stress levels are 100 and 200 kpsi

(700 and 1400 MPa). Corning has well-established guidelines on how much applied stress the fiber can withstand in service over time for a given proof stress.^{vii} For example, one can safely stress optical fiber to 1/5th of its proof stress for a 25 year in-service with no expected breaks for any length. The design guidelines for designing around proof stress are shown in Figure 3 for a range of stress durations. For the most common proof stress of 100 kpsi (700 MPa), long lengths of fiber can be permanently subjected to 20 kpsi stress with minimal risk of fatigue failure. Higher stresses are allowed for shorter durations because there is less time for fatigue to take place. Note that this design methodology is the most conservative as it assumes that the entire length of fiber is no stronger than the lowest possible strength, the proof stress.

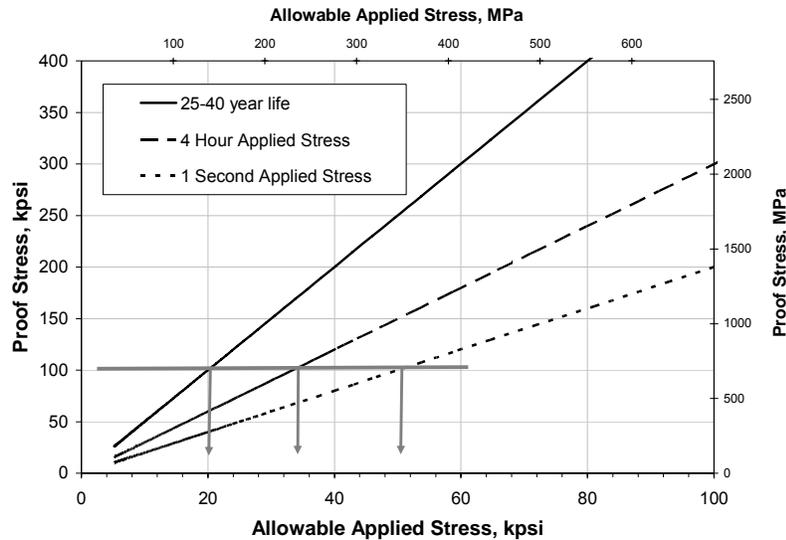


Figure 3. Design diagram for determining the allowable stress for a given proof stress. Arrows illustrate allowable stresses for a typical proof stress of 100 kpsi (700 MPa).

Designing around the proof stress level is not necessarily appropriate for FTTH situations where short lengths of fiber are subjected to high bend-induced stress. Increasing the proof stress to, say, 200 kpsi will have a negligible effect on the predicted failure probability. In other words, if the length under stress is short and the flaws of concern are rare, it is best to use a failure probability design, like that shown in Figure 2.

4. FTTH and Premises Guidelines

In FTTH installations, fiber will be bent around corners and under staples as well as coiled for storage purposes. For these scenarios it is convenient to express fiber bending using a “per turn” basis. Bending about a corner is obviously a single 90° turn. The bending generated by stapling can vary, but will likely be less than a 90° turn. Coiling for storage is best expressed in terms of a complete 360° turn. Using a “per turn” basis can facilitate the assessment of failure probability due to fatigue failures. Table 1 shows the predicted probability of failure for a single 360° turn for several bend radii.

Table 1. Failure probability/turn predictions over a 25 year lifetime.*

Radius (mm)	Probability of Failure/Turn (ppm)
5.0	3
7.5	1
10	0.5
15	0.1

* Failure probabilities are based on the same Corning fiber strength distribution and reliability model used to make Figure 2.

The predictions in Table 1 show that for bends down to 5 mm in radius, the failure probability is still extremely low, below 10 ppm. To obtain an estimate of the overall failure probability for a given installation, one simply adds the number of 90-degree corners, staples, and fiber storage coils and multiplies by the associated failure probability for a complete turn. Consider the following example of an indoor installation with extreme fiber bending due to corners, storage, and staples;

- Twenty permanent 90-degree turns around corners and each bent to a radius of 5 mm. This is equivalent to 5 full 360° turns. Using 3 ppm per turn, the failure probability for corners is 15 ppm.
- Twenty full 360° storage turns at a 15 mm bend radii. This translates to a storage failure probability of 2 ppm (20x0.1).
- Finally, 70 staples causing the equivalent to approximately 3 full turns at 5 mm radius. This translates to a total staple failure probability of 9 ppm (3x3).

The total installed failure probability for this rather severe installation example is less than 30 ppm. One can conclude that risk of fatigue related failures due to bending in FTTH and premises installations is low. Now let us push this example further. Assume an entire hypothetical FTTH network consisting of 100,000 homes installed with the bending scenario described above. The predicted number of fatigue-related breaks is less than 3 for the entire FTTH network over 25 years of operation. This low predicted failure rate is negligible when compared to other sources of fiber failure like excavations.^{viii} When short lengths are subjected to tight bends, the reliability of optical fiber is more than adequate.

Summary

With the trend towards increasingly tighter bend radii in access and FTTH networks it has become increasingly important to understand the reliability performance of optical fiber under tight bend scenarios. Understanding the strength and fatigue behavior of optical fiber and developing the associated lifetime models has been a primary focus for Corning over the past 30 years. Also, supplying reliable fiber and utilizing our world-class manufacturing process continues to be Corning's highest priority. We demonstrate that the reliability of fiber in FTTH installations can be assessed by combining a relevant fiber strength distribution, knowledge of fiber fatigue behavior, and possible bend scenarios into Corning's reliability model. Corning has a proven track record in engineering reliability solutions for optical fiber.

References

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^{vii} R.J. Castilone, "Mechanical Reliability Applied Stress Guidelines,"

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