A Response to Assertions that Fiber Manufactured in a Clean Room is Stronger and Less Susceptible to Fatigue

White Paper

Optical Fiber

CORNING
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WP1280

Issued: February 2007
Supersedes: None
ISO 9001 Registered

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Corning Incorporated has been manufacturing specialty optical glass fiber since the early 1980's. For more than 30 years Corning has been a leader in the research of optical fiber strength and reliability. A sampling of this research can be found at:
http://www.corning.com/opticalfiber/technical_library/fiber_mechanical_reliability/basics.aspx

From time to time it has been asserted that making fiber in an "ultra-clean" environment could improve optical fiber strength and make the optical fiber less susceptible to fatigue failure and subcritical crack growth. In particular, recently a manufacturer has implied that by making fiber in a clean room, strength values close to the theoretical strength of glass can be obtained. Because of the historical importance of this topic to Corning and the inaccuracy of the above claims we felt it necessary to provide a technical response. We will do this by answering four questions:

1. Is a clean room necessary for achieving the theoretical strength of glass?
2. Isn't cleanliness important? If so, when and how is it important?
3. Is the fatigue behavior of optical fiber related to the manufacturing environment?
4. What manufacturing information is needed to design for mechanical reliability?

Is a clean room necessary for achieving the theoretical strength of glass?

As early as the late 1960's researchers at Rolls Royce had already shown that the theoretical strength of silica could be obtained by simply redrawing glass into thin strands using a flame torch.[1] The test was not performed in a laboratory environment, but care was taken to protect the surface from damage before testing. In the early years of optical fiber development several industry labs demonstrated theoretical strength levels. This can be most clearly observed in the work of France et al.[2] Kurkjian and Gupta[3] recently summarized the findings of such experiments. In all these works no mention of a clean room or ultra-clean environment is given. In fact, if one were to redraw an optical fiber preform into fiber in almost any environment, most of the surface will be perfect, without defect, near the theoretical strength of glass. The answer to question 1 is that a clean room is not needed to generate pristine silica-clad optical fiber; that when tested in short lengths yields strength values close to the theoretical limit.

Isn't cleanliness important?

Fiber manufacturers know that there are many factors that go into making sufficiently strong fiber. These factors include the quality of the raw materials like tubing, equipment delivery lines, coating contamination, stray fiber in the furnace, etc. It is quite possible to draw fiber in a clean room and still have surface defects or flaws, e.g. from furnace contamination or contact with stray fiber. While manufacturing in a clean room certainly can't hurt, the mechanical properties of the resultant fiber depend upon far more than the room used for manufacturing. Consequently, in the context of the recent assertions, simply stating that the fiber was manufactured in a clean room is not sufficient. One must demonstrate, through strength testing of a significant number of samples, the distribution and magnitude of strength-limiting flaws produced during manufacture.

The entire manufacturing handling history is imprinted on the fiber and reflected in the strength distribution. When Corning says "strength distribution" we are not referring to the testing of a few 50 cm lengths. Few flaws are ever found on such lengths. Instead, a proper strength distribution should characterize the length of fiber intended for deployment. This will be discussed further below. Cleanliness is important, but the strength distribution, as measured with large scale sampling, is what is most important. Normal factory air-borne contamination is just one of many factors that affect the measured strength distribution.

Is the fatigue behavior of optical fiber related to the manufacturing environment?

Fatigue, or crack growth, of a stressed flaw in glass has to do with glass chemistry and the availability of moisture in the service environment. None of these factors are affected by the cleanliness of the manufacturing process. Review papers on the subject of fiber strength and fatigue find little evidence to suggest that the fatigue is related to flaw size.[4,5] There is, however, evidence that crack growth behavior in silica is independent of both flaw size and flaw source.[6] We are skeptical about claims linking fatigue superiority to the manufacturing environment given the large body of published data, and our own research, on silica-clad fiber.

The reader should know that fatigue measurements are highly dependent on test method, test environment, and the coating. The fatigue resistance of silica in fiber form is quite stable and such claims of increased fatigue resistance because of a particular manufacturing environment are misleading. Moreover the claim of "superior" fatigue resistance was based on an "n" value of 22. This is well within the range of typical values for silica-clad optical fiber. Fatigue n values approaching 30 are needed in order to allow higher in-services stress. In order to significantly alter the n value of optical fiber, methods such as coating the cladding surface with hermetic coating must be employed. A typical n value for hermetically coated fiber is 200.

What manufacturing information is needed to design for mechanical reliability?

If the cleanliness of the manufacturing environment or the strength from short length tests do not govern fiber reliability, then what does the customer need to know about fiber manufacturing in order to make an informed decision about fiber reliability?

1) Optical Fiber Reliability Models:
First of all, Corning has developed the tools and models to allow customers to take advantage of our proof test stress and fiber strength distribution. We provide customers with state-of-the-art reliability modeling for a wide range of stresses, lengths and durations. Our modeling capability is well-known through publications, tutorials and direct customer interaction. Our customers, especially those working with Specialty Fiber, have come to rely on the assistance they receive from reliability engineers and scientists when faced with a new or troublesome reliability situation. For example, if a customer has an application where exceedingly high stresses are applied over a long fiber length, our modeling might suggest the need for a high proof stress level or the application of a hermetic coating over the glass cladding. Corning uses hermetic coating for our Erbium-doped fibers that are deployed as tight coils in optical fiber amplifiers.[7]

(2) Understanding of Fiber Mechanical Strength:
Next, one needs to know the minimum strength established by proof testing. Most fiber customers design around the proof stress; and therefore, it is critical that the fiber manufacturer screen out flaws weaker than the proof test stress. Proof testing is conducted after the draw process where the entire fiber length is stressed to a predetermined stress level in order to eliminate the weakest flaws. 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.[8] For example, one can stress optical fiber to 1/5th of its proof stress for a 25 year in-service lifetime. An example of a proof test design diagram is shown in Figure 1 for the particular case of fiber wound on a drum or mandrel under some wind tension. Such a design diagram would be useful for, say, the winding of Erbium-doped fiber on bobbins.

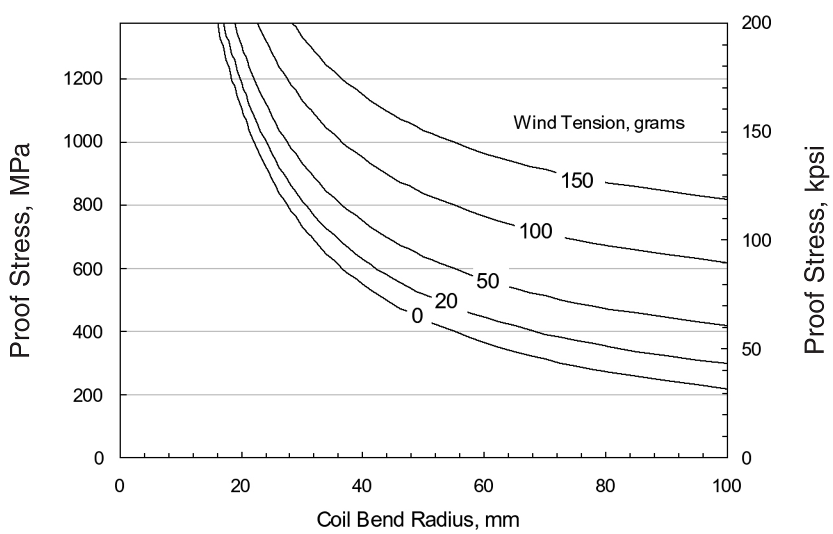

Figure 1. Proof test design diagram for optical fiber permanently wound on bobbins.

(3) Optical Fiber Application Deployment
In some special applications, customers need to stress lengths of fiber in excess of what Corning would advise for proof stress level flaws. These applications typically involve short lengths of fiber placed in small bends, but there are applications with longer lengths under high tensile or bending stress. Here one may exceed the applied stress guidelines for proof stress level flaws if the probability of encountering a flaw that will break during the in-service time is low enough. This means that the manufacturer must have comprehensive knowledge of the post proof test strength distribution. The length tested must be consistent with the application lengths under stress and the probability levels of interest.

Most strength distributions reported in the published literature are obtained by testing 50 cm lengths of fiber or by 2-point bending extremely short lengths of fiber. Such testing is necessary for Trade and Commerce, ie: standards compliance, but not sufficient for reliability predictions and design because the total sample size, ie: characterized length, is too small. For decades Corning has been innovating methods for strength testing optical fiber that provide strength distributions relevant to the intended fiber applications.

In the early 1990's Corning developed a machine that automatically strength tests 20 meter lengths of fiber.[9] The sole purpose of this machine is to characterize the strength above the proof stress level on total sample lengths of fiber that are relevant to our customers. Since then we have strength tested 10,000's of kilometers of fiber. Figure 2 shows all the flaws below 600 kpsi on nearly 4000 kilometers of fiber proof tested to 100 kpsi.[10] The probability of finding a flaw weaker than, say, 200 kpsi (1400 MPa) on a 20 meter length of this fiber is about 1 in 10,000. We can then scale this distribution to almost any length for engineering failure probability predictions.

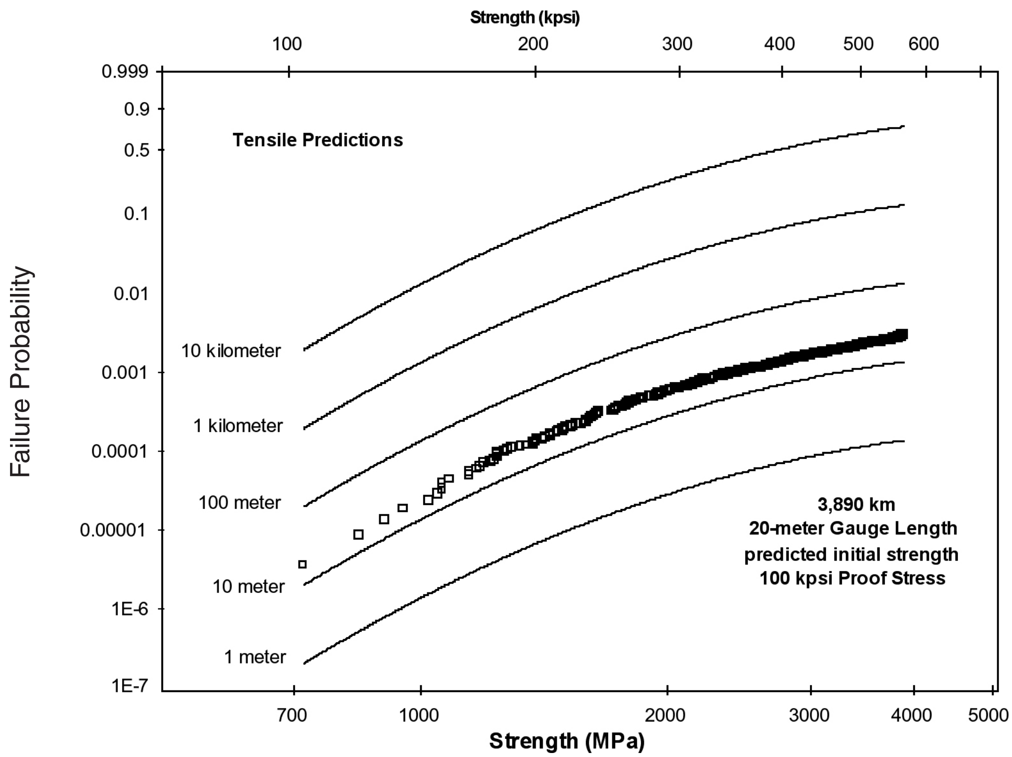

Figure 2. Strength of nearly 4000 km's of standard single-mode optical fiber. The lines represent predicted distributions for lengths other than 20 meters. Note that fatigue during strength testing has been accounted for. This distribution is ready to be incorporated into reliability models.

Combining this strength distribution with Corning's reliability model the following design diagram for single-mode fiber in bending can be created (Figure 3). In this diagram we have included a range of bend radii, load durations, and lengths in bending. Consider the case of a 1 meter length of fiber permanently wound to a bend radius of 8 mm. The failure probability would be approximately 10^{-5}, or 1 in 100,000, which is low for most applications.

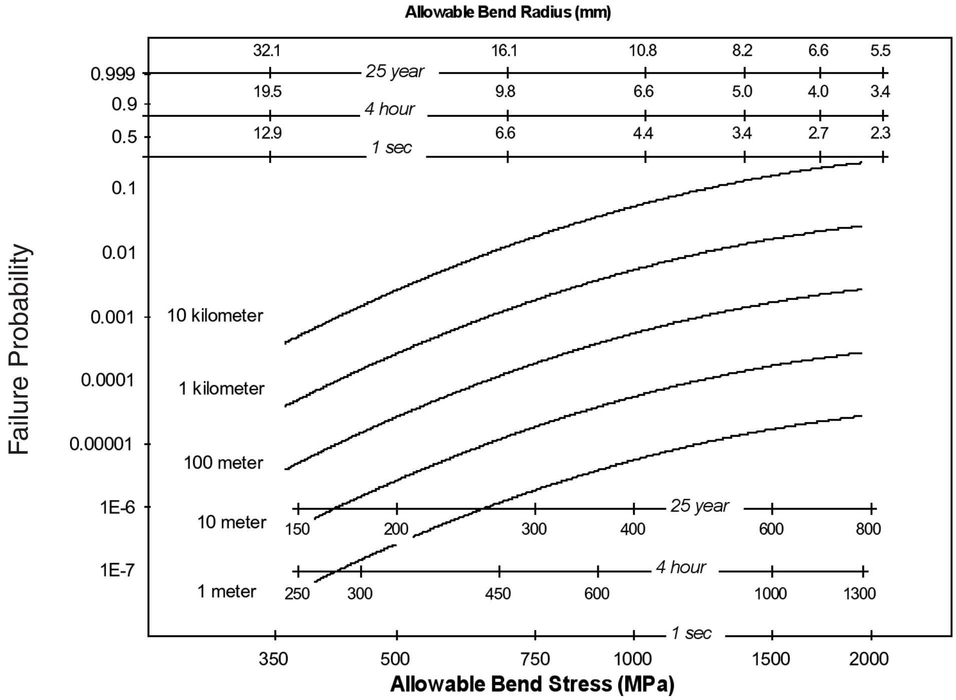

Figure 3. Design diagram for standard single-mode optical fiber in bending.

(4) Determination of Customer Risk Allowance

The ability to bend short fiber lengths tightly when handling fiber during termination, installations and other processing for short time periods. Again, one is counting on the fact that the probability of encountering a flaw is low, implying that large sample lengths are necessary to precisely determine that probability. Consider the case of threading 10 meters of fiber around a tight corner during installation. Using Figure 3 we estimate a failure probability of 1 in 10,000 for a 1 second exposure to a 4 mm bend radius. This is more informative than stating the manufacturing environment or quoting an “n” value.

Summary

Claims of high strength as a result of manufacturing being done in a clean-room environment are a poor substitute for actually measuring and reporting relevant strength distributions and developing models that allow one to make failure probability predictions. There is no published data proving that manufacturing in a clean room creates a superior long-length strength distribution. The manufacturing environment is just one of many factors that can affect the final fiber strength distribution. Although there may be some value to drawing fiber in a clean room environment, it is simply meant to reduce airborne contamination; while it might improve manufacturing yields, it provides no direct benefit to the product or customer. It will not reduce the other sources of contamination or mechanical handling damage that can degrade fiber strength.

There is no evidence to suggest that manufacturing environment affects the fatigue characteristics of silica glass, as some have asserted.

Understanding the strength and fatigue behavior of optical fiber has been a primary focus for Corning as we attempt to anticipate our customer’s diverse fiber applications. Corning has provided extensive strength and fatigue data and associated reliability modeling. The supply of highly reliable fiber utilizing our experienced manufacturing processing continues to be a high priority for Corning.

For more information about Corning's leadership in Specialty Fiber technology or to obtain additional technical information, please contact us:
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