Optical Fiber

Whitepaper

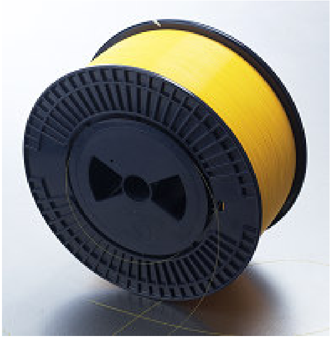
Effect of humidity of drawing environment on dynamic fatigue of polymer coated high strength silica optical fiber

Author
S. Bhaumik

Document: WP0013

Abstract

Dynamic fatigue behavior of high strength silica optical fiber was studied as a function of relative humidity of draw environment. Fibers were drawn with graphite induction heating furnace and controlled temperature, relative humidity and particle count of the draw environment i.e. drawing furnace to coating application point. Dynamic fatigue of the drawn fibers was measured with two different modes of loading, tensile & two-point bending. Draw humidity was found to have a decided impact on dynamic fatigue measured by tensile loading.



Keywords
Strength, Dynamic fatigue

Introduction

Dynamic fatigue behavior of silica optical fiber has been studied for many years. As lifetime of optical fiber used in long-haul telecommunication network can be predicted by dynamic fatigue parameter1,2, this has been a topic of research and interest for optical fiber manufacturers. Dynamic fatigue or stress corrosion, which influences rate of crack growth and delayed failure of silica optical fiber, is known to happen in presence of external stress, flaw/micro-crack and moisture on the surface of fiber. All of these three conditions must be present together for fatigue to occur. So to prevent fatigue, it is necessary to remove any one of these conditions.

The first condition i.e. presence of external stress, can not be avoided completely with existing different types of cable designs like loose tubes, tight buffers and ribbons. In tight buffer and ribbon, fiber can face complex array of external stresses. Even GR-20 (Telcordia) allows fibers to carry 60% of proof-test load (i.e. almost 550gm) inside the cable 3.

The second condition i.e presence of surface flaw/micro-crack, is of great interest to optical fiber manufacturers. Advancement in the quality of raw materials for optical fiber manufacturing and understanding of manufacturing process and controlling instrumentation have made significant improvements in reduction of surface flaws and increase of strength value. Commercially available fibers now have minimum tensile strength value of 4.4 Gpa4 and typical value of 4.8 Gpa measured with 5 percent strain rate against minimum requirement of 3.8 Gpa as per GR-20 (Telcordia). However, the tensile strength value is still much less than the theoretical value of 20Gpa. That means surface flaws/micro-cracks have been reduced but not eliminated completely. Previous studies reveal that mechanisms of fatigue, or absence of fatigue, apparently do not depend on the size of surface flaws and initial strength of fiber 5,6,7. It was also concluded that the fatigue behavior of flaws in optical fiber is relatively independent of origin like abrasion, particle contamination and indentation 7. Thus, reduction of size of surface flaws does not guarantee improvement of dynamic fatigue of silica optical fiber unless until and until flaws are eliminated completely.

Thus the third condition, presence of moisture, becomes the most important criterion and research interest. Stress corrosion in silica glass by water is well known. The reaction between water and strained Si-O-Si bond at the surface crack tip of optical fiber involve three steps 8.

Duncan et al. 9 have studied the behavior of strength and fatigue as a function of both humidity and temperature of test environment and suggested the following equations, which can be used to predict the failure strain ε (or stress) and fatigue parameter (n) as a function of relative humidity (Z) and absolute temperature (T):

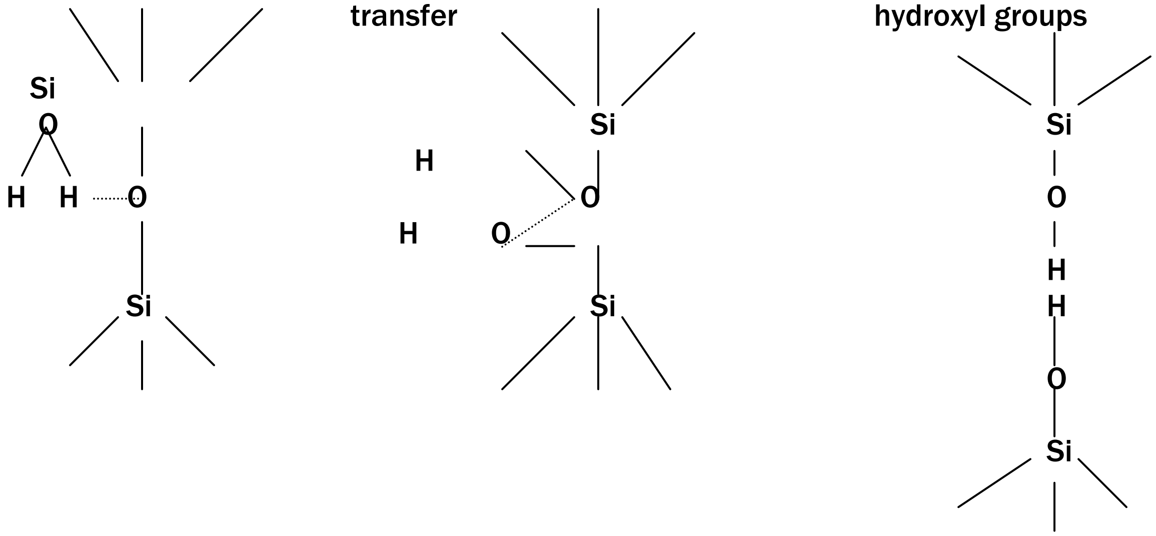
$$\varepsilon = 2.28\, Z-0.093 \;\exp(2400/RT) \quad \text{—————————}(1)$$

$$n-1 = -10 / [-0.9 - 0.093\log Z + (2400/2.3RT)] \text{——————}(2)$$

1.Adsorption of water to Si-O bond at the crack tip

2.Concerted reaction involving simultaneous proton and electron transfer

3.Rupture of hydrogen bond and formation of surface hydroxyl groups



Later these results was reconfirmed by Mrotek J.L. et al., 10 who found the reaction order for fatigue of high strength fused silica fiber to be ~2 at high humidity (20-95% RH) and ~1 in low humidity (0.025-13% RH). Based on an understanding of the detrimental effect of moisture on fatigue, several studies have been done where moisture was prevented from coming in contact with glass surface and to improve fatigue value. The result was the development of a “hermetic” coating that isolated fiber surface from the environment. Application of various hermetic coatings, metals (Aluminum, Nickel, Zirconia), inorganics (SiON, SiC, TiC etc) and carbon on the surface of glass showed substantial improvement of fatigue value. Dynamic fatigue values ranging from 23 to 500 were noted ,11-15 but substantial lowering of the measured strength values(levels of 2.5-3.5 Gpa) were noted for hermetically coated fibers. Tomozawa, et al 16-18 determined that the strength and fatigue behavior of optical fiber is dependent on the fictive temperature of glass. Lower fictive temperature allows more water vapor to enter the glass and thus lowers fatigue resistance parameter. As most of the commercially available fibers are polymer-coated fibers, studies have been done on diffusion of moisture through optical fiber coatings and it has been found that moisture penetrates on a time scale of ~102 to 103 seconds 19. Armstrong, et al.20 had studied dynamic fatigue behavior of silica fibers as a function of humidity of test environment for acrylate, polyamide and silicone coated fibers and compared them with bare fiber. All coated and bare fibers had shown reduction in dynamic fatigue value with an increase in the relative humidity of test environment. The polymer coatings had shown negligible effect on the kinetics of the fatigue as long as the fibers were properly equilibrated in the test environment before testing. Inniss, et al. 21 showed addition of particulate materials (Silica, Alumina, Zirconia, Titania) that are partially soluble in water in the coating increase moisture resistance and thus the fatigue life of optical fiber.

It is clear from the literature that moisture from test environment plays an important role in controlling dynamic fatigue value, particularly the strength value at a slower stress rate where moisture from the test environment gets sufficient time to diffuse through the coating and corrode the glass surface. But the previous studies have ignored the influence of relative humidity of the draw environment, which may be because of the short exposure time of the bare glass before a coating application for high-speed drawing. But direct adsorption of water molecules on the glass surface and cover up by coating during drawing should have more impact compared to water molecules diffused through the coating from test environment. This paper is intended to describe effect of the relative humidity of draw environment on the dynamic fatigue of high strength polymer coated silica optical fiber.

Experimental

Sample

Dual polymer coated high strength silica optical fibers for standard telecommunication networks were used in this study. Silica optical fibers with a glass diameter of 125µm and a coating diameter of 245µm were drawn with a controlled drawing atmosphere in terms of temperature, relative humidity and particle count. The space where bare fiber was exposed to surrounding atmosphere during drawing, the space between the draw furnace and the coating applicator, was maintained to a pre-determined environment. A total of eight samples were drawn with constant temperature of 24±2°C, class-100 (i.e. less than 100 particles of size >=0.5µm per ft^3 volume of air) particle count and varying relative humidity from 40 to 80 percent. The drawn fibers were proof-tested with 1% strain and then proof-tested fibers were tested for dynamic fatigue by different methods. All the samples were aged in laboratory environment (55±5% relative humidity and 23±2°C temperature) for a minimum of 12 hours prior to testing. The tensile strength of all eight fibers are above 4.4 Gpa (Sample length: 0.5 meter and extension rate: 25 mm/min).

Dynamic fatigue by tensile loading

Dynamic fatigue by tensile loading of coated fibers after proof testing was measured as per FOTP-455-28C (EIA/TIA) 22. Four different extension rates were chosen between 0.09, 0.6, 4 & 30 percent/min so that the extension rates are apart by a factor of 7 from each other. The gauge length was 0.58 meter. A sample size of 15 per extension rate for each fiber sample was used. Dynamic fatigue or stress corrosion parameter (Nd) had been calculated from the slope of linear plot of log of failure stress vs. log of the stress rate. As Nd is inversely proportional to the slope, a lesser slope of the linear plot will result in higher Nd. The lesser slope means there is less of a difference between tensile strength measured at four different extension rates.

Dynamic fatigue by two-point bending

Dynamic fatigue of proof-tested coated optical fibers was measured according to the procedure written in Telecommunications System Bulletin no. TSB62-13. In the two-point bend apparatus, the fibers are bent between two faceplates that are brought together until a fiber breaks. An acoustic transducer detects the break. Grooved faceplates are used to locate the fiber accurately. Bending stress develops at the tip of the fiber sample placed in between two faceplates. The length of the region under bending stress is approximately 2 mm. The two-point bend strength of the fiber samples were measured at four different faceplate velocities (1, 10, 100 and 1000 μm/sec). Nd was calculated by the method described earlier.

Result and Discussion

The dynamic fatigue values, both with two-point bending and tensile loading of each fiber along with corresponding draw humidity are shown in Table.1. There is a clear trend of decrease in Nd measured by the tensile loading with the increase in draw humidity. But no such trend exists for Nd measured by two-point bending. Fig.1 shows dynamic fatigue plot of Fiber#1 (highest Nd by tensile loading) and Fiber#8 (lowest Nd by tensile loading). It can be seen that the variation of tensile strength at lowest extension rate (0.09%/min) is much higher in Fiber#8 compare to Fiber#1. The variation in tensile strength resulted in a lower Nd value. For clarity, the Weibull plot of tensile and two-point bend strength values measured at four different speeds of one fiber each from four-draw humidity range were shown in Fig.2 & 3 respectively. From Fig.2, it is clear that as draw humidity increases, the tensile strength measured at its lowest extension rate decreases, but no significant change in values is measured at higher extension rates. Fig.3 suggests that no such change in strength values measured by two-point bending at different speeds for different fibers except for fiber#8, which was drawn in a maximum humid environment.

The effective "tested" length of fiber under load during strength testing is much higher in the case of tensile loading (580 mm) compared to the two-point bending (~2 mm). Breuls 23 & Mattheson, et al., 24 showed that the difference in an effective tested glass area (i.e. length & geometry-bending or tensile) can give a different strength value and also derived a way to predict bending strength from tensile strength. But while comparing predicted & experimental strength values, they found good agreement only for low strength (<0.72Gpa) and high Weibull-modulus fiber. As in this study, high strength fiber was used and at a lower extension rate a bi-modal strength distribution found (see fig.2), the way to predict the bending strength from the tensile strength cannot be applied.

As written in IEC 60793-1-33 (Annex H), both the test methods used in this study are measured for the stress corrosion data of the intrinsic strength distribution. But different values of N_d measured by two different methods, particularly for the fibers drawn in higher humid environment (or moisture corroded), were found. The findings suggested that a two-point bend strength method where the effective test length is approximately 2 mm , is measured intrinsic strength distribution and remains unchanged when the extrinsic strength distribution is changed. For the fibers drawn with a drier environment (like fiber #1 to 4), N_d measured with two different methods are closer, compared to those drawn with humid environment (like Fiber# 5 to 8). That means for fibers #1 to 4, there were no big difference between the extrinsic & intrinsic strength distribution but for fibers # 5 to 8, the extrinsic strength distribution differed by moisture corrosion due to the humid draw environment. In the previous studies, stress corrosion parameter of mechanical & particle-abraded fibers was found higher than those of the intrinsic strength distribution [25,26]. But this study found a lower value of stress corrosion parameter of moisture-corroded fibers.

Conclusion

The relative humidity of a fiber drawing environment affects the dynamic fatigue (or stress corrosion parameter, Nd) of high strength polymer coated silica optical fiber. Higher draw humidity decreases strength at the lowest extension rate and subsequently the dynamic fatigue parameter measured by the tensile loading, but Nd measured by two-point bending has little impact except for extremely high relative humidity. Two-point bending measures Nd of intrinsic strength distribution which is unaffected by moisture corrosion due to the humid draw environment. Closer values of Nd are obtained for two different mode of loading (tensile & bending) when the intrinsic & extrinsic strength distributions are same for the fibers drawn with a drier draw environment. Moisture corrosion by a humid draw environment changes extrinsic flaw distribution and decreases Nd measured by tensile loading.

Table.1 Dynamic fatigue values of various fibers drawn with different relative humidity

		Nd-VALUE	
	Draw Relative Humidity (%)	Two-Point bending	Tensile Loading
Fiber#1	40-50	25	25
Fiber#2	40-50	28	25
Fiber#3	50-60	24	25
Fiber#4	50-60	25	22
Fiber#5	60-70	29	21
Fiber#6	60-70	27	22
Fiber#7	70-75	27	19
Fiber#8	75-80	20	16

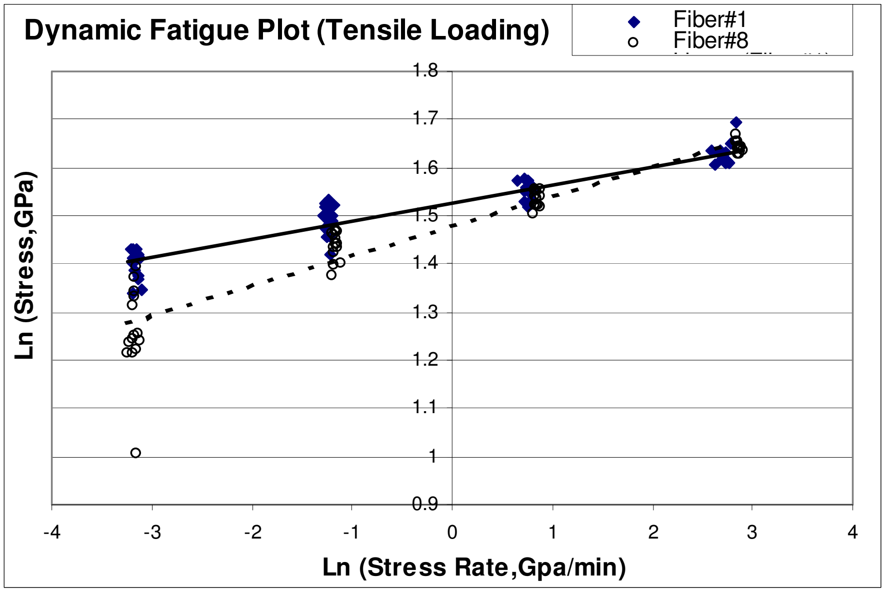


Fig.1 Dynamic Fatigue (tensile loading) plot of Fiber#1 & 8

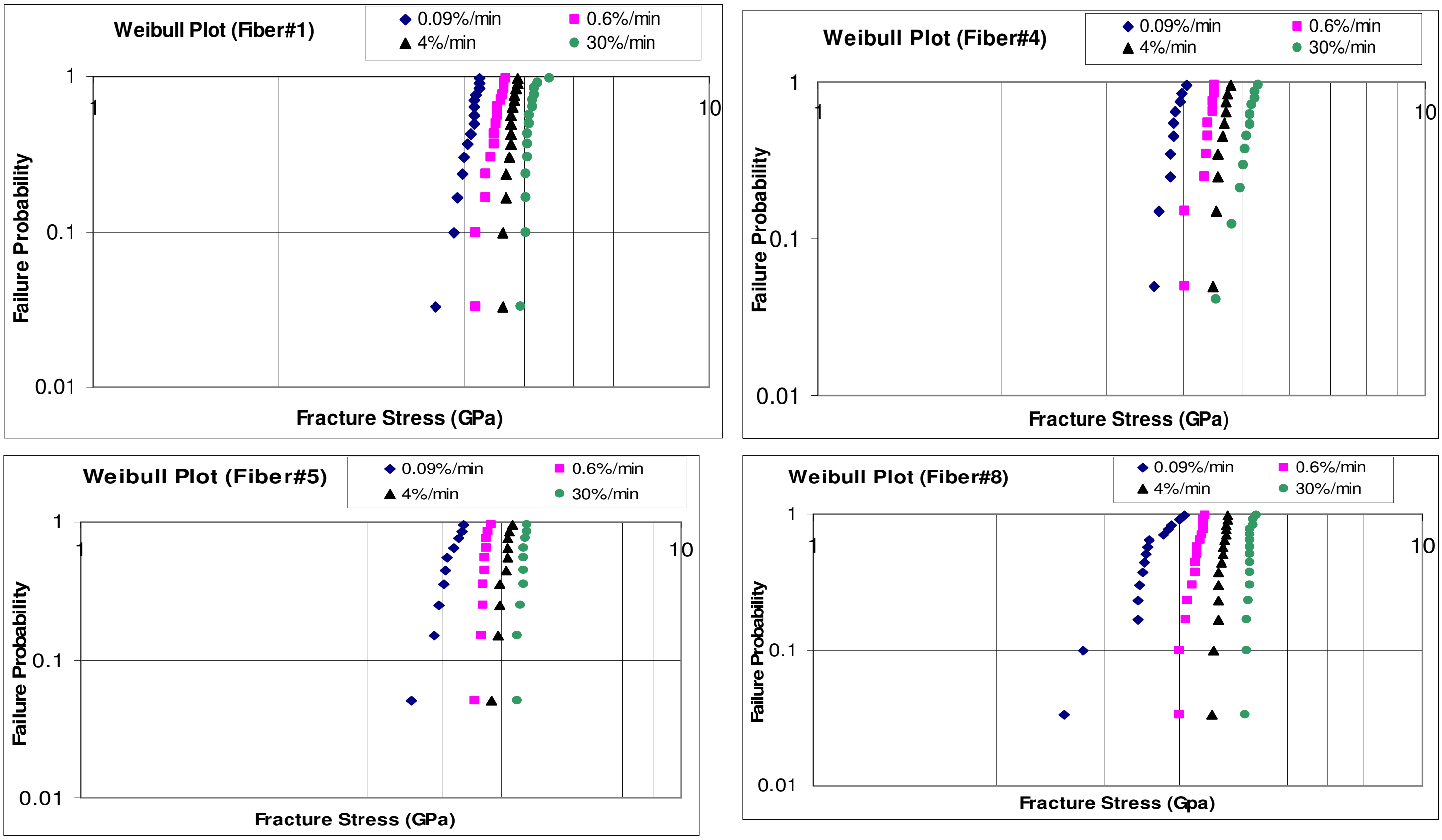


Fig.2 Weibull plot of tensile strength values at four extension rates of Fiber# 1,4,5 & 8

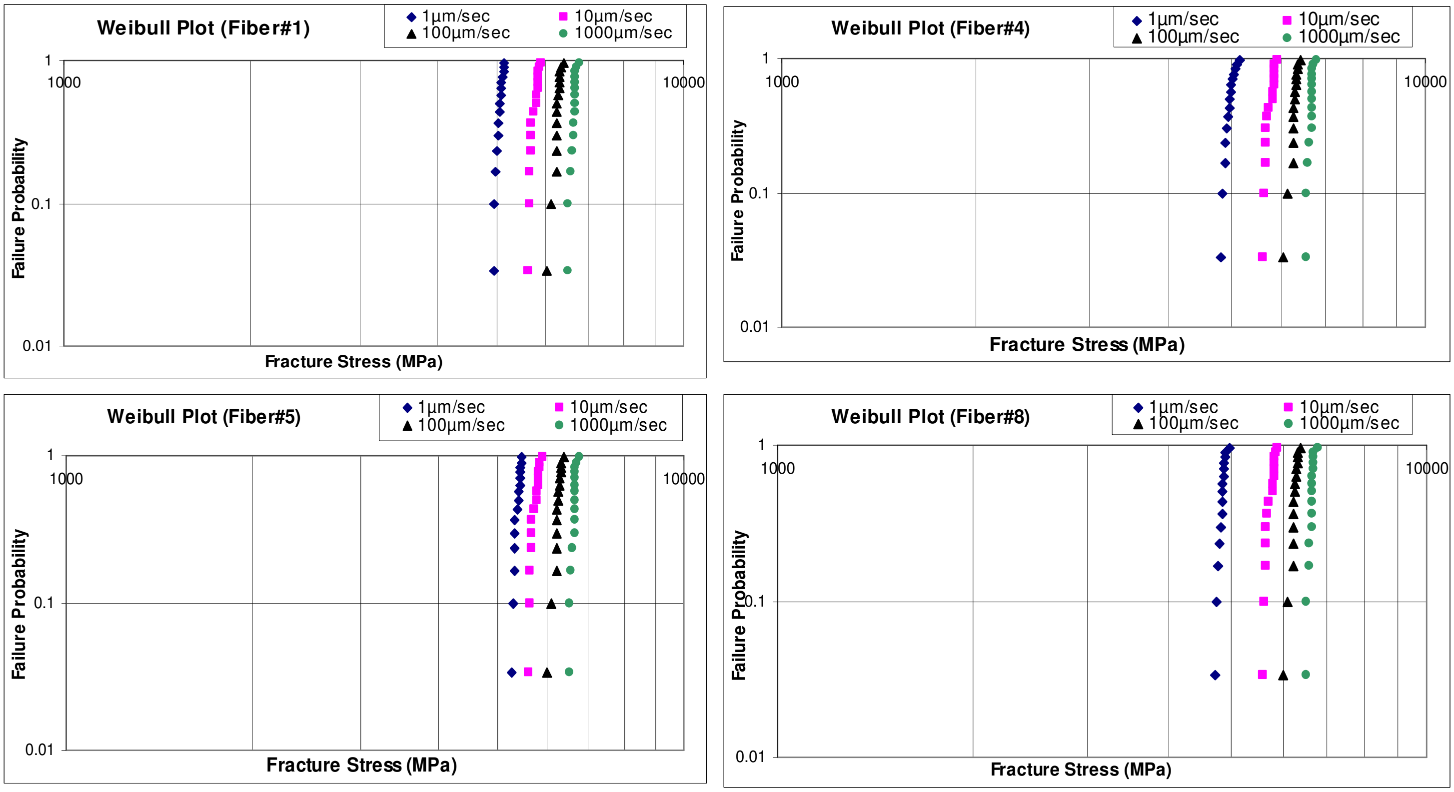


Fig.3 Weibull plot of two-point bend strength values at four extension rates of Fiber# 1,4,5 & 8

References

1. Hakan H. and Felix P. Kapron, " Use of Fatigue Measurement for Fiber lifetime prediction", *SPIE*, vol. 1366, pp 144-156 (1990).
2. "Power-Law Theory of Optical Fiber Reliability", *IEC SC 86A/WG 1*, Sept. 1996.
3. Bellcore GR-20-CORE, Issue 2, July 1998.
4. PMD-LITE^{TM} Preform specification, August 2003
5. Torbjorn Svensson, Anton Breuls, "Strength and fatigue of different kind of weak spots from the manufacture of optical glass fibers", *SPIE*, vol.2290, pp 211-220.
6. Sergei L. Semjonov, G.Scott Glaesemann and Mikhail M. Bubnov, "Fatigue behavior of silica fibers of different strength", *SPIE*, vol. 3848, pp 102-107 (1999).
7. Sergei L. Semjonov, G.Scott Glaesemann, Donald A. Clark and Mikhail M. Bubnov, "Fatigue behavior of silica fibers of different defects", *SPIE*, vol. 4215, pp 28-35 (2001).
8. Terry A. Michalske and Stephen W. Freiman, "A Molecular Mechanism for Stress Corrosion in Vitreous Silica", *J. Am Ceramic Soc*., Vol. 66, No. 4, pp 284-288.
9. Duncan W.J., France P.W., and Craig S.P., "The effect of environment on the strength of optical fiber", in *Strength of Inorganic Glass*, C.R.Kurkjian, Ed. New York: Plenum, 1985.
10. Mrotek J.L., Matthewson M.J., Kurkjian C.R., "The fatigue of high-strength fused silica optical fibers in low humidity", J. Non-Crystalline Solids, Vol. 297, pp. 91-95 (2002).
11. Pinnow D.A.,Robertson G.D. and Wysocki J.A., " Reductions in static fatigue of silica fibers by Hermatic Jacketing", Appl. Phys. Lett., vol. 34, p 17 (1979).
12. Hiskes R. et al., "High performance hermetic optical fibers", *OFC*, New Orleans,LA (1983).
13. Hanson E.G., Hisks R. and Shantz C.A., "Optical fiber with hermetic seal and method for making same", *U.S. Patent* 4512629, Apr.23 (1985).
14. Raychaudhuri S. and Schultz P.C., "Hermetic coating on optical fibers", *SPIE,* vol. 717 (1986)
15. Lu K.E., Glaeseman G.S. and Kar G., "Hermetically coated optical fibers", *IWCS*, pp. 241-244 (1987).
16. Tomozawa M., Agarwal A. and Li H., "Effect of temperature on Dynamic Fatigue of Silica and Soda-Lime Glasses", *J.Am.Ceramic Soc*., vol. 78[5], pp. 1393-1396 (1995).
17. Tomozawa M., Agarwal A. and Peng Y.L., "Radial distribution of Fictive Temperatures in Silica Optical Fibers", *J.Non-Cryst. Solids*, Vol. 241, pp. 134-139 (1997).
18. Tomozawa M., Varughese B. and Lee Y.K., "Effect of Fictive Temperature on Mechanical Strength of Soda-Lime Glass", *J.Non-Cryst. Solids*, vol. 241, pp. 134-139 (1998).
19. Mrotek J.L., Matthewson M.J., Kurkjian C.R., "Diffusion of moisture through optical fiber coatings", *J. of Lightwave Tech*., Vol. 19,No. 7, pp. 988-993 (2001).
20. Armstrong J.L. and Matthewson M.J., "Humidity dependence of the fatigue of high-strength fused silica optical fibers", *J. Am. Ceram. Soc*., Vol. 83, No. 12, pp. 3100-108 (2000).
21. Inniss D, Matthewson M.J and Kurkjian C.R, "Optical fiber with improved moisture resistance", *US Patent* 5214734, 25 May (1993).

22. FOTP-455-28C (EIA/TIA), “Measuring Dynamic Strength and Fatigue Parameters of optical fiber by Tension”. April 1999.
23. Breuls A., “A COST 218 comparison of n-values obtained with different techniques”, Proceedings of OFMC’93, 1983, Torino, p. 9-12.
24. Matthewson J., Kurkjian C., Gulati S., “Strength measurement of optical fibers by bending”, J. Am. Cer. Soc. 69, [11], 815-821, 1981.
25. Craig S.P., Duncan W.J., France P.W., Snodgas J.E., “The strength and fatigue of large flaws in silica optical fiber”, ECOC, 1982, p.205-208.
26. Breuls A., and Svensson T., “Strength and fatigue of zirconia induced weak spots in optical fiber”, SPIE, September, 1993, Boston.

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Phone: +91-20-30514000
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