White paper

Sterlite Tech

Impact of adverse cable handling on lifetime of optical fiber

Author
Sudipta Bhaumik

Issued
May 2015

Abstract
Optical fiber experiences various stresses during its lifetime starting from proof-testing, cabling, installation and in-service life. For long term reliability prediction, it is required to determine in-service lifetime and in-service failure rate for various fiber stress histories like constant tension in buried cable or sudden jerk during cable installation, and adverse cable handling like accidental cable “dig-ups”. However, a fiber length that is subjected to a constant applied service stress which doesn’t vary with time, is the most common situation for which reliability prediction is made. Thus, there is a need to understand impact on lifetime of fibers exposed to abnormal stress-time profiles such as in cable “digups”.
In this paper various fiber lifetime prediction models are discussed. Fiber lifetime and safe stress are predicted based on stress-time histories and long length (20 m) tensile strength distributions. A set of experiments that can validate the lifetime models, are conducted on fiber with pre-defined testable stress-time exposures. Once validated, these models are used to provide predictions of fiber lifetime of cables exposed to abnormal stress –time profiles.

Keywords
Optical fiber, Optical fiber cable, Fiber reliability, Fiber lifetime.

1. Introduction

Optical fiber is exposed to various stress-time events during manufacture, installation & in-service life.

Typically this includes

a. Optical Fiber manufacture: fiber drawing; proof-testing & rewinding,
b. Optical Fiber Cable manufacture: coloring; tubing; stranding & sheathing,
c. Cable Installation,
d. Long-term field use, and
e. Unscheduled events e.g. accidental cable dig-up

During these events flaws on the optical fiber surface can grow due to the applied stress and moisture in the environment. Consequently the outcome of these events can include a reduction in fiber strength, and associated long term lifetime, or instantaneous fracture & failure. From reliability perspective the growth of these subcritical flaws, or cracks, needs to be controlled to ensure the fiber exceeds the lifetime requirements.

2. Reliability Prediction Models

The flaws on the fiber surface have a range of strengths & are assumed to be randomly distributed along the fiber. The strength of a particular region depends on the weakest flaw present: the low strength (extrinsic) flaws determine lifetime. During subcritical (non-fracture) crack growth the strength decreases and hence so does resistance to future stress-time events. Reliability models need to predict the strength reduction from various stress-time events & estimate fiber lifetime. A possible scenario would be to estimate the lifetime of an installed cable after an unscheduled event e.g. dig-up without breaking: a high stress short time event. The lifetime of the cable needs to be estimated for the combination of the short term high stress event plus the long-term low stress environment. These models need to have extensive validation through controlled experiment to have confidence in these predictions.

The modelling of fiber mechanical strength & lifetime has been considered by many authors using various approaches[1,2] . Many models have been proposed to describe the relationship between crack velocity and stress-intensity factor. The Power Law Theory has gained acceptance for modelling stress driven subcritical crack growth in optical fiber. On application of stress, crack on fiber grew and weakened. When final strength equals to the applied stress instant failure happens. For crack of initial strength S_i subjected to an arbitrary stress-time historyσ (t) to failure, the failure lifetime t_f is implicitly contained in the general lifetime equations 1 & 2[3]. Fracture occurs just when the final strength equals to the applied stress at the instant of failure t_f . However, crack strengths are statistically distributed along the fiber outside surface. This means that the failure times, or the equivalent failure rates, must also be statistically distributed.

$$S^{n-2}(t_f) = S_i^{n-2} - \frac{1}{B}\int_0^{tf} \sigma^n(t).\,dt \text{ -- Eq. (1)}$$

$$\int_0^{tf} \sigma^n(t)\,dt = B\,S_i^{n-2} \text{ -- Eq. (2)}$$

Where,

S_i = Initial Strength
t_f = Failure Lifetime
σ (t) = Stress – Time history
n = Stress corrosion susceptibility constant
B = Crack strength preservation parameter

The two region power law assigns a B value to Region I (subcritical crack growth) & Region II (high stress short time e.g. proof-testing) as proposed by G.S.Glaesmann et.al[4] . In the Two Region Power Law model, it is proposed to determine two B and n values for two different regions I & II and then consider strength degradation by Eq. 1 with different sets of B & n values.A short-coming with the single region and two region power law is that it requires the calculation of n & B. Values of B depend on the environment & reported values vary widely in the literature. The B value also has to be calculated using inert strength measurements that are most easily performed on short lengths of fiber: results measure only the intrinsic strength of the glass.
An alternative approach is to calculate a safe stress threshold without using B: removing the requirement to measure environment specific B value[5] . It can also incorporate a long-length strength distribution in the threshold calculations. The model derives allowable in-service & short-term stresses as a fraction of the fiber strength for subcritical crack growth.
Eq. 3 is prescribed to calculate safe stress level from a given strength distribution.The equation derived by the authors gives the probability of exceeding a 1% threshold in crack growth over 40years

$$\sigma_s = \exp\left[\frac{1}{m}\ln\ln\frac{1}{1-F} + \ln\sigma'\right] \times \left[\frac{1}{2}\left(\frac{n-2}{n+1}\right)\frac{V}{a}\cdot\frac{\sigma f}{\sigma.}\right]^{1/n} \text{----------------Eq. (3)}$$

Where,
σ_s = Safe stress
m = Shape parameter of the Weibull strength distribution
F = Failure Probability, (should be small, 10^{-3} and 10^{-6})
σ' = Scale parameter of the Weibull strength distribution
n = Stress corrosion susceptibility constant
$\frac{V}{a}$ = Crack growth parameter at n (calculated after considering safe boundary condition with 1% crack growth in 40 years, 7.59 x 10^{-12} at n=18)
σ_f = median strength
$\sigma.$ = Stress rate

There is one more model proposed by Y.Mitsunagaet .al based on single region power law, where failure prediction for long length optical fiber is done based on failure (break) rate during proof testing[6]. In this model some assumptions are made to neglect B parameter. The lifetime model is shown in Eq. 4.

$$\sigma_s / \sigma_p = \left[\frac{n-2}{m}\,\frac{Fs}{LNp}\,\frac{tpe}{ts}\right]^{1/n} \text{-- Eq. (4)}$$

Where,
σ_s = Safe stress
σ_p = Proof test stress
n = Stress corrosion susceptibility constant
m = Shape parameter of the Weibull strength distribution
F_s= Failure Probability with safe stress, (should be small, 10^{-3} and 10^{-6})
L = Fiber Length
N_p = Fiber break rate at proof test level
t_{pe} = Proof test time (loading time + dwell time + unloading time)
t_s= Failure time (expected lifetime, say 40 years)

m-value can be determined by proof-testing at different proof test level and from the break rate by Eq. 5, where p1 and p2 represent two different levels of proof testing. It is counter argued that the assumptions considered in this model results in over conservative estimations of failure probability as actual measurement of strength is superior to proof test break rate information.[7]

$$\frac{n-2}{m} = [\log(1 + \sigma^{n}_{p2}t_{p2} / \sigma^{n}_{p1}t_{p1})] / [\log(1 + N_{p2}/ N_{p1}] \text{ ---------------- Eq. (5)}$$

In our study, Power law theory as mentioned in Eq. 1 is considered for fiber lifetime estimation and experiments.

3. Experimentation

Typical silica glass single mode optical fiber of 245 micron diameter and coated with dual layer polymer coating with substantial homogeneity is considered for this study. Fiber samples having wide range of flaw distribution near prooftesting level were considered for this study. The fiber samples were prooftested with 1% strain (100 kpsi) after fiber drawing. The experiments carried out with the prooftested fiber samples are mentioned below

3.1Post Proof-test Weibull distribution from long length tensile (LLT) strength test

Flaws of varying strength are distributed along a fiber; for a given stress the probability of failure increases with fiber length. Considering practical networks cover hundreds of kilometres, a representative strength distribution for these is required. A long-length (20 m) sample of fiber flaws is measured to give a representative sample of the low strength extrinsic flaws: typically these have a low probability of occurring and so many 20m gauge lengths of fiber need to be tested to build confidence in the strength distribution particularly at low strength region[8]. Over 100 km optical fiber sample is tested with 10%/min strain rate in standard room environment to generate post-prooftest Weibull strength distribution. General observations on measured Weibull distribution are as follows.

a. No flaw measured below 1% (100 kpsi, 0.69 GPa) Proof Test level: screening truncates strength distribution around 100kpsi.

b. Extrinsic flaw region knee starts around 5% cumulative probability.

c. Approximately 99% of measured breaks are above 2.75 GPa (4 times of proof-test level).

3.2 Stress aging of prooftested fiber

Optical fiber cable is designed to protect fibers from handling damages. Necessary strength members are included in cable to carry external forces applied during cable handling & transportation, cable installation and long –term field use. Most of the outdoor cables are designed such that maximum force experienced by the inside fiber during the rated tensile force (typically 1.5 to 2 times of cable weight/km) on the cable, should not cross 0.3% of fiber strain which is around 1/3 rd of prooftesting strain of 1%. However, during adverse cable handling the force on cable crosses rated tensile force and therefore the force on inside fiber increases as well. In this experiment a prooftest machine is used for stress aging. The fiber samples is passed through various stress-time profile, where applied stress is 200 kpsi (higher than the strength of the weakest flaw found in LLT strength distribution) and variable stress application time which is changed by changing proof-test machine line speed. During the stresstime event, flaws of strength less than 200 kpsi are expected to break the samples. Some flaws of strength just above 200 kpsi are also expected to break during the stress-time event due to weakening.

We expected to see degradation of fiber strength from initial strength due to sub-critical crack growth during stress aging. So to verify actual strength degradation against predicted values, LLT strength testing is conducted with the fiber undergone various stress-time histories.Figure 1 shows the stress-time profile applied on the fiber samples. Both break rates and LLT strength Weibull distributions are predicted from Eq. 1 and experimental results are compared to validate the reliability model. Because anticipated break rates are not large, this cannot be expected to be a definitive validation of the model. This comparison of predicted vs measured breaks provides confidence on the model predictions for lifetime degradation. Once the model is validated, Eq. 1 is used to predict impact on fiber lifetime of cables exposed to adverse stress-time profiles.

4. Results, Analysis and Discussions

200 kpsi constant stress and varying stress application time from 1 sec to 30 sec with an increment of 5 sec are applied on over 750 km of optical fiber samples. Fiber break rate is estimated from Eq.1 assuming n value of 18 as specified in IEC 60793-2-50 and B-value of 6 GPa^2 -ms as mentioned in EIA/TIA FOTP-31 for all the seven stress-time profiles [9,10]. Then estimated vs measured fiber break rates of the seven stress-time profiles are compared and results are shown in Figure 2. Less number of fiber breaks are measured compared to estimated break rate. However, an increasing trend of fiber break rates with increase in stress application time (dwell time) is common in both the cases. The lesser number of measured breaks may be due to conservatively small n and B values assumed during estimation.Typical n value (dynamic tensile) of the fiber samples is 20 as measured by axial tension method by following IEC 60793-1-33[11].B values are back calculated to match measured and estimated break rate. Table 1 shows combination of n and B values to match measured break rates at various stress-time profiles. The calculated B values varies from 10 to 10^3 GPa^2 -ms for different stress-time profiles and distributed in two different ranges. The lower range is 10-20 GPa^2 -ms and the higher range is around 10^3 GPa^2 -ms. B-value is highly dependent on the environment and material and it is also related to the inert strength i.e initial length of crack.

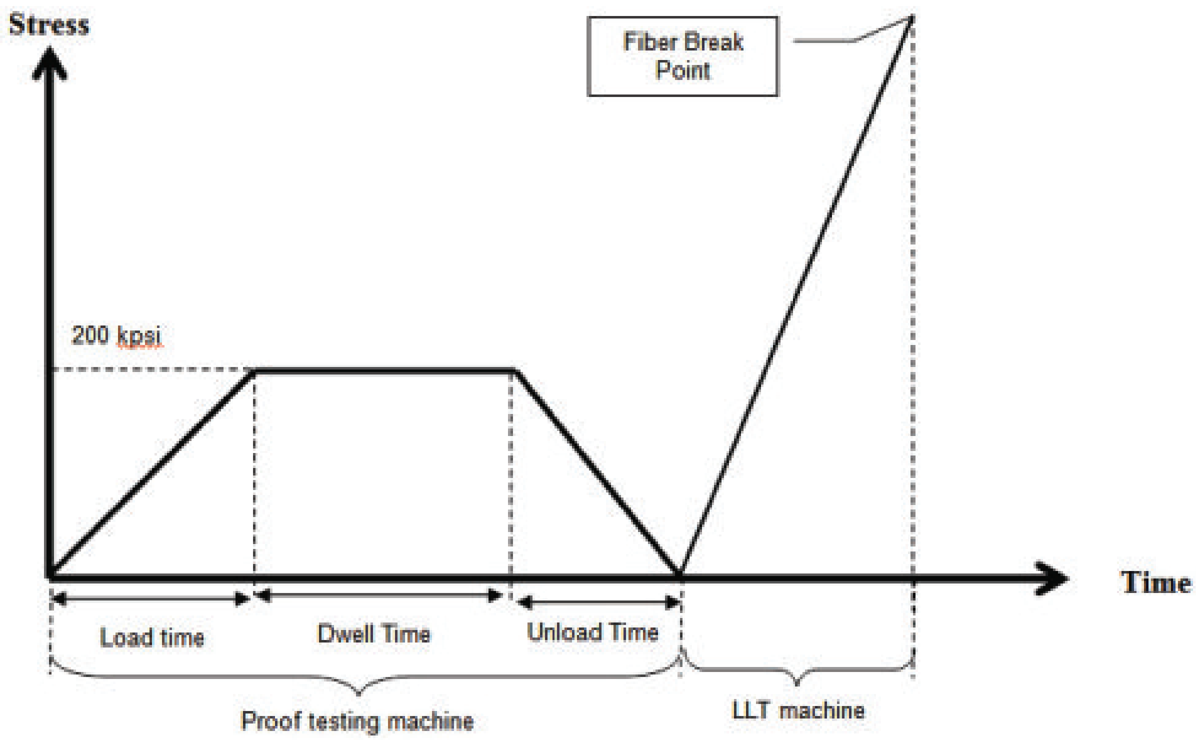

Figure 1 Stress - Time Profile

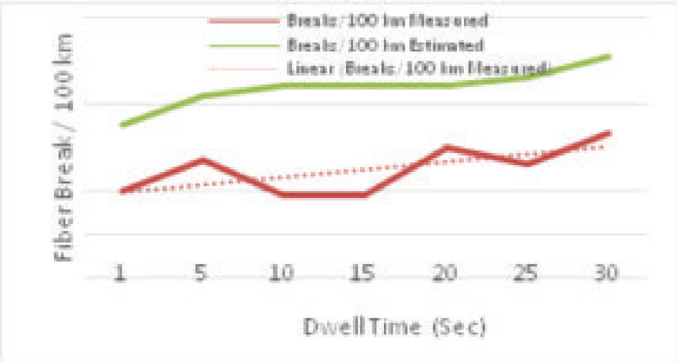

Figure 2 Estimated vs Measured fiber break rate

Stress (kpsi)	Dwell Time (sec)	n value (assumed in estimation)	B value, $GPa^2.ms$ (assumed in estimation)	n value measured	B value, $GPa^2.ms$ (calculated)
200	1	18	6	20	$\sim10^3$
200	5	18	6	20	10-20
200	10	18	6	20	$\sim10^3$
200	15	18	6	20	$\sim10^3$
200	20	18	6	20	10-20
200	25	18	6	20	10-20
200	30	18	6	20	10-20

Table 1 n and B values of various stress-time profiles

In a previous study, reported B-value of conventional single-mode fiber vary in the order of magnitude of eight compared to two as found in this study[12]. However, further study is required to understand two different regions of B-value. Figure 3 and Table 2 show a comparison between measured and estimated Weibull LLT strength distributions and related parameters where estimation is done with recalculated B value and measured n parameter for the stress-time profile 200kpsi-10sec. From the comparison results it can be seen that the optical fiber under study reasonably follows Power- Law model of Eq. 1 with n=20 and B value of range $10\text{-}10^3$ GPa^2 .ms. Therefore, power law model can be used along with measured n and calculated B values to predict failure rate of optical fiber during adverse cable handling. Two extreme predictions of lifetime can be made based on two sets of n & B values i.e. n=20 & B=10 GPa^2 .ms for worst case scenario and n=20 & B= 10^3 GPa^2. ms for best case scenario.

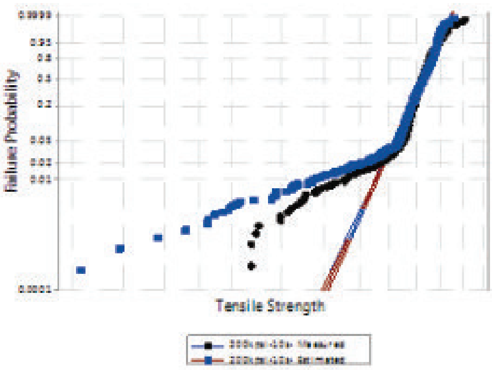

Figure 3 Weibull LLT strength distribution comparison

	Tensile Strength at Failure Probability			Shape Parameter
	0.15	0.50	0.632	
Measured	X.0	X.0 + 0.2	X.0 + 0.2	21
Estimated	X.0	X.0 +0.3	X.0 +0.3	21
% Difference	0%	2%	0%	0%

Table 2

Stress Events	Stress on fiber (kpsi)	Stress Application Time	Worst case (n=20, B=10 GPa^2.ms), Fiber Break / 100 km	Best case (n=20, B= 10^3 GPa^2.ms), Fiber Break / 100 km
Normal Installed fiber	35	40 years	0	0
Adverse Cable handling	300	10 sec	85-95	40-45
		5 sec	70-80	35-40
		1sec	60-70	30-35
	200	10sec	30-35	10-15
		5sec	25-30	10-15
		1 sec	20-25	5-10
	150	10 sec	10-15	0-5
		5 sec	10-15	0
		1sec	5-10	0
	120	10sec	0-5	0
		5sec	0-5	0
		1 sec	0	0
	100	145 sec	0	0

Table 3 Estimated fiber break rates at various stress-time events

If fiber is stressed above the strength of the weakest flaws it is expected that breaks will occur during adverse cable handling. Table 3 shows estimated fiber break rates for two sets of n and B values at various stress-time events according to Eq. 1. Lifetime of normal installed fiber is expected to be above 40 years under 35 kpsi stress. No failure is estimated if 100 kpsi stress is applied for 145 sec duration. Maximum 120 kpsi stress can be applied for 1 sec without any fiber failure.

These results suggest that during adverse cable handling and application of high stress, a proportion of the fiber will break. As most of the low strength flaw broke during cable break event, expected lifetime of the remaining fiber will be much higher.However, the fiber may experience higher static stress during lifetime after cable dig-up event because of inelastic properties of other cable materials. It may take longer time to relax it back to original level of safe stress say 35 kpsi. So lifetime should be re-calculated with higher static stress after an adverse cable handling event. Table 4 shows fiber lifetime (time to failure) at various higher residual static stresses after a cable break event. Fiber strain at cable break point is determined experimentally by stretching a cable till break point. The fiber strain at cable break point is measured 2.7% (270 kpsi, 1.863 GPa) for a buffer tube duct cable. The fiber strain at cable break point will be different for different cable designs. Minimum strength of the residual fiber after cable break event is estimated 2.11 GPa (306 kpsi) from LLT strength Weibull distribution of the fiber samples under study. Thus much higher lifetime is estimated even for higher residual static stress. To ensure minimum40 years fiber lifetime after a cable break event, maximum residual static stress on fiber can be as high as 88 kpsi.

Stress Event	static stress on fiber (kpsi)	Fiber lifetime after cable brak event
High Residual stress after cable break evcent	40	> 10^8 years
	80	> 200 years
	88	> 40 years
	100	>4 years
	150	>1 day

Table 4 Fiber lifetime under high residual static stresses

5. Conclusion

Power law model for optical fiber lifetime estimation is verified. Experimental results show that the fiber samples under study reasonably follows Power-Law theory with n=20 and B value of range 10-10^3 GPa^2 .ms, .ms, thus validating its use for life time modelling. As fiber strain at cable break point is higher than the proof-testing strain, before reaching cable break point some fiber break will occur and fiber break rate will depend on the population of low strength flaws (i.e. extrinsic region of Weibull plot). Worst and best case scenarios of fiber break rates are determined for various stress-time events during adverse cable handling. After cable break event, the minimum strength of the survived portion of the fiber is estimated at 306 kpsi (for a buffer tube duct cable sample) which is much higher than the prooftesting stress of 100 kpsi and therefore, higher lifetime of fiber is expected. However, fiber may experience higher static stress during lifetime after a cable dig-up event because of inelastic properties of other cable materials. It may take long time to relax it back to original level of safe stress say 35 kpsi. Lifetime of optical fiber under higher residual stresses after a cable break event is estimated. To achieve at least 40 years of fiber lifetime, maximum allowable static stress is estimated to be 88 kpsi. This study is carried out with the fiber samples containing higher number of low strength flaws at extrinsic region of Weibull plot. The performance of installed fiber optics cables in adverse cable handling events will depend on cable design, cable tensile rating and post-prooftesting fiber strength distribution particularly at the extrinsic region. Environmental aging, however, can change the strength distribution. It can degrade the strength of the weakest flaws or even increase their number significantly. Therefore, a safety margin for strength degradation due to environmental aging need to be considered while determining safe service stress.

Acknowledgement
The author wishes to thank Mr. KapilBatra for organizing testing and analysis.

References

1. R. Castilone, G. Glaesemann, T. Hanson, “Extrinsic Strength Measurement And Associated Mechanical Reliability Modeling of Optical Fiber”, 16th Annual National Fiber Optic Engineers Conference, 2000
2. Glaesemann.G.S., Gulati.S.T., “Design methodology for the mechanical reliability of optical fiber”, Optical Engineering, Vol. 30, No. 6, pp 709-714 (June 1991)
3. IEC TR 62048,Ed.3, Optical Fibers - Reliability- Power law Theory, Jan’2014
4. T.A.Hanson, Glaesemann.G.S, “Incorporating multi-region crack growth into mechanical reliability predictions for optical fibers”, Journal of Materials Science, Vol. 32, pp 5305-5311, 1997
5. Glaesemann.G.S., Gulati.S.T., “Design methodology for the mechanical reliability of optical fiber”, Optical Engineering, Vol. 30, No. 6, pp 709-714 (June 1991)
6. Mitsunaga. Y. et al, “Failure prediction for long length optical fiber based on proof testing”, J. App. Phys., 53 (7), pp 4847-4853, July (1992).
7. Linda K. Baker, “Comparison of Mechanical Reliability Models of optical Fibers” , Corning White paper, WP5049, Issue June’2001
8. TIA/EIA-455-28C, FOTP-31, “Measuring dynamic strength and fatigue parameters of optical fiber by tension”.
9. IEC 60793-2-50, Ed. 4, and Part 2-50: Product specifications –Sectional specification for class B single-mode fibers.
10. TIA/EIA-455-31C, FOTP-31, “Proof Testing Optical Fibers by Tension”, February 1995.
11. IEC 60793-1-33, Ed.1, Measurement methods and test procedures- Stress corrosion susceptibility.
12. T.Volotinen, et al, “Mechanical behavior and B value of an abraded optical fiber”, 47th IWCS, 1998.