C01-34

Effect of Proof Testing on Optical Fiber Fusion Splices

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Objective: *Determine the effect of proof testing on fusion spliced single mode fiber pull strength under various levels of temperature, humidity and bending stress.*

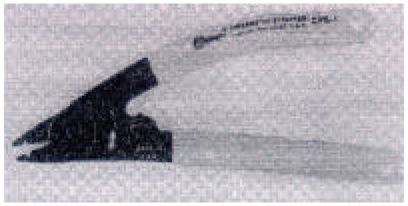
Project Background and Motivation

- Raw optical fiber failure mechanisms have been studied for several decades. The impetus has come from long-haul telecom applications.
- As the technology is adopted by the automotive and aerospace industries, attention is turning to characterizing behavior of splices and bending and handling stresses seen in fiber sensors and back-plane applications.
- From a systems sense, modern fiber splicing optical losses are negligible. Reliability of splices is determined mainly by their mechanical strength degradation.
- Proof testing is used to screen low strength fibers. It has been assumed that the fibers that survive the proof testing have a minimum tensile strength of the proof testing stress level. And the lifetime of fibers is based on this minimum strength value.

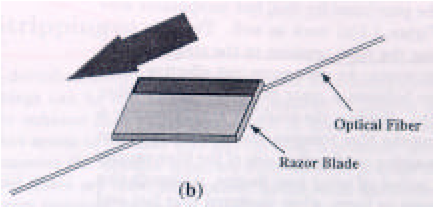
- ***Can proof-testing guarantee the minimum fiber strength?***
- ***Does proof-testing compromises the integrity of the fusion splice?***

Potential Problems Caused by Fusion Splicing

- Handling of the fibers during coating removal, cleaving, splicing compromise the strength of the spliced fiber. Mechanical stripping of the coating reduces strength significantly.

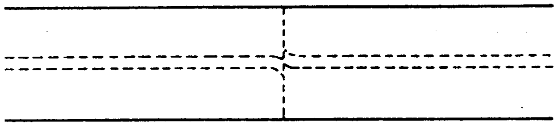


(a) Stripper

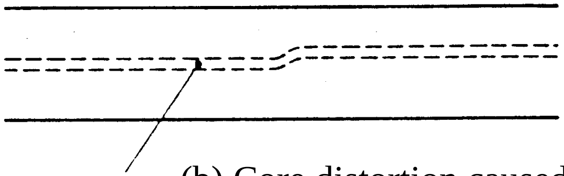


(b) Blade

- Optical loss is mainly caused by core distortion after fusion, because of misalignment, core-cladding nonconcentricity or wrong fusion parameters. But the optical loss is very small, usually order of 0.2dB (modern splicers estimate loss from vision system and amount of core miss-alignment).



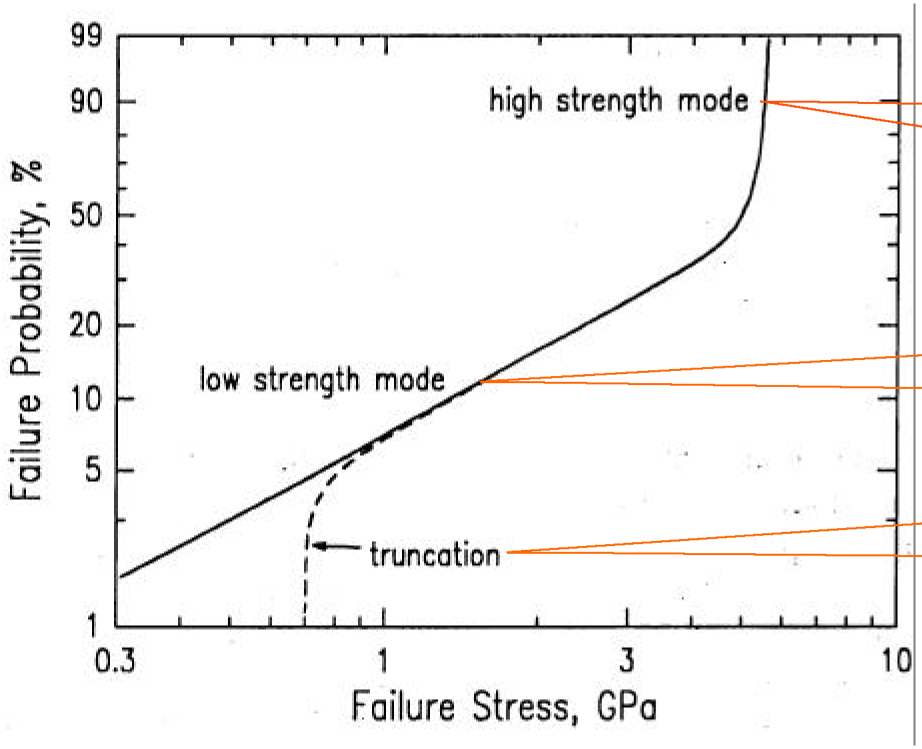
(a) Core distortion
caused by misalignment



(b) Core distortion caused
by nonconcentricity

Fiber Breaking Strength Distribution

Silica fiber can be encountered with a broad range of strengths.



–Very narrow

– Flaw free

– Much broader

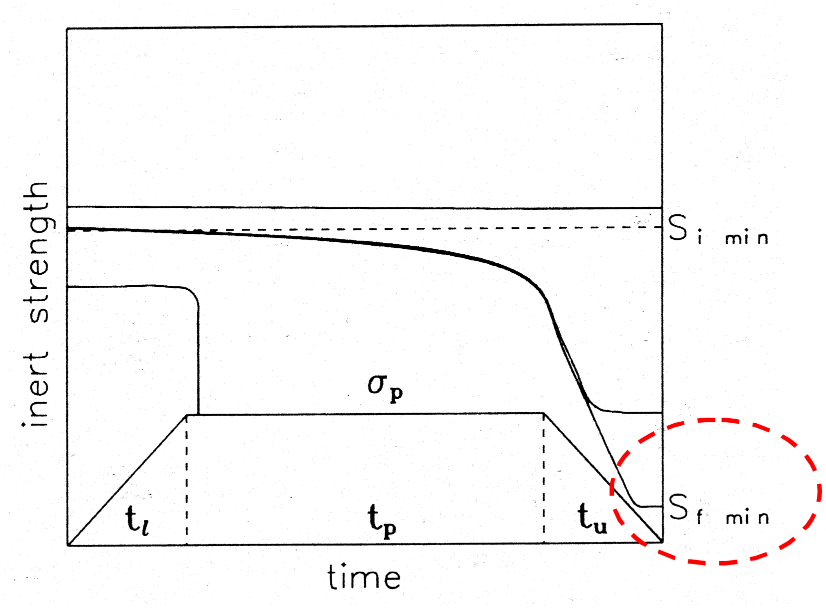
– Flaws (Cracks)

Controlled by the proof testing

Fig.1. Typical Weibull plot for ~1km lengths of fiber [1]

Reference 1: M. John Matthewson, Optical Fiber Reliability Models, *SPIE Fiber Optics Reliability and Testing, Critical Reviews Vol. CR50, 1999*

Problems Proposed in Literature



Fuller and Ritter have shown theoretically:

- the fibers that pass the prooftest could have a strength less than the proofstress!
- the minimal post-proof strength is determined by the unloading rate

But according to Glaesemann [2]

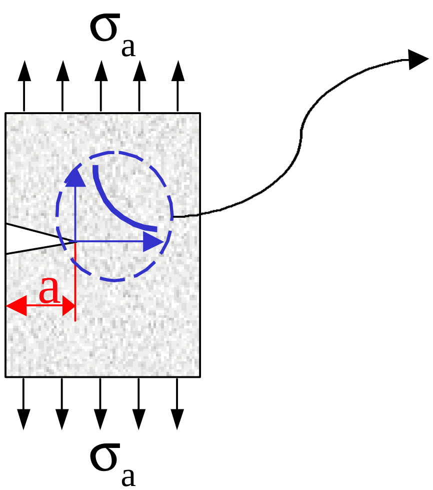
no failures below proof stress were recorded

Does proof-testing compromises the strength of the fiber? What is the effect of unloading rate and dwell time on the strength distribution?

Reference 2: G.S.Glaesmann, Method for obtaining long-length strength distributions for reliability prediction, *Optical Engineering*,Vol.30 No.6, June 1991

Crack (flaw) in Fibers Reduce Strength?

The presence of sharp cracks locally amplifies the applied stress at the crack tip.



σ — the actual stress at the crack tip

$$\sigma = \frac{K_I}{\sqrt{2\pi r}}$$

σ_a — the applied stress on the fiber

r — distance From the Crack Tip

a — crack length

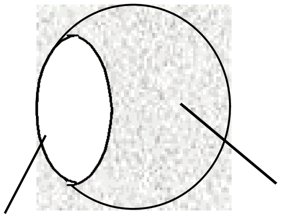
K_I — Stress Intensity Factor

$$K_I = Y \sigma_a \sqrt{a}$$

$$\begin{cases} K_I < K_{Ic}, & \text{Safe} \\ K_I \geq K_{Ic}, & \text{fracture} \end{cases}$$

Y — geometry factor. for a semicircular fiber surface crack, Y = 1.24 [3]

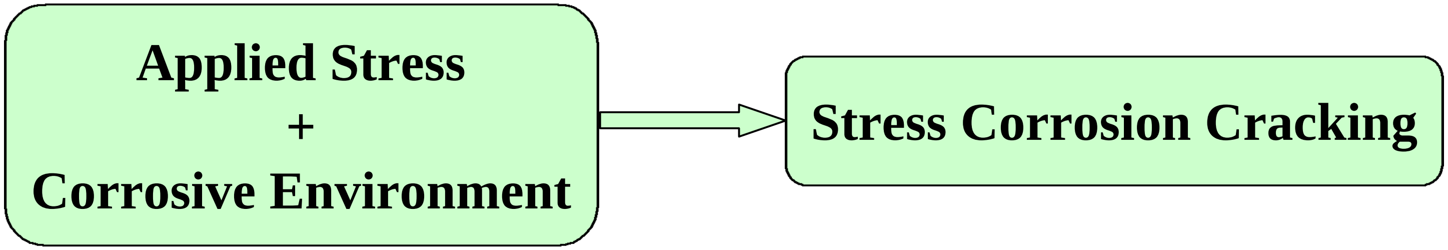
K_{Ic} – Critical value of stress intensity factor, material property known as fracture toughness. K_{Ic} = 0.8 $\text{MPa}\cdot\text{m}^{1/2}$ [3]



Reference 3: W. Griffioen, et.al., COST 218 evaluation of optical fibre lifetime models, *SPIE Vol. 1791, Optical Materials Reliability and Testing, 1992*

Stress Corrosion Cracking

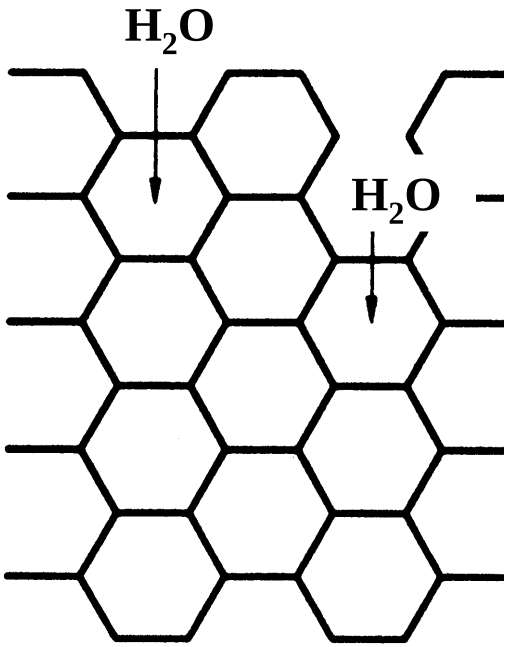
(Static Fatigue when $K_I < K_{Ic}$)



Applied Stress
+
Corrosive Environment

Stress Corrosion Cracking

Subcritical crack growth happens especially in corrosive environment, like water. Water diffuses into glass, break the bond of silica, and create crack.



Subcritical Crack Growth Rate Models

1. Power Law Model

$$\frac{da}{dt} = A_1 \cdot K_I^{\,n_1}$$

- Empirical model
- No humidity, temperature dependence
- Gives a better fit to fatigue life data
- Analytically simple

2. Exponential Model

$$\frac{da}{dt} = A_2 \cdot \exp\left(n_2 \cdot K_I\right)$$

$$A_2 = \nu \cdot RH^m \cdot \exp\left(\frac{-E_0}{kT}\right)$$

- Chemical kinetics model
- Humidity, temperature dependent
- Gives a better description of the humidity data

Reference 4: Janet L. Armstrong and M. John Matthewson, Humidity Dependence of the Fatigue of High-Strength Fused Silica Optical Fibers, *Journal of the American Ceramic Society, Vol 38, No. 12, Dec. 2000.*

Fiber Strength Degradation

Stress Intensity Model + **Crack Growth Model**

$$K_I = Y s_a \sqrt{a}$$

$$\frac{da}{dt} = A \cdot K_I^{\,n}$$

Strength degradation over time

$$S(t)^{n-2} = S_i^{\,n-2} - \frac{1}{B}\int_0^t s(t)^n \, dt$$

$$1/B = (n-2)AY^2 K_{Ic}^{\,n-2}/2$$

Static Fatigue
(long lifetime)

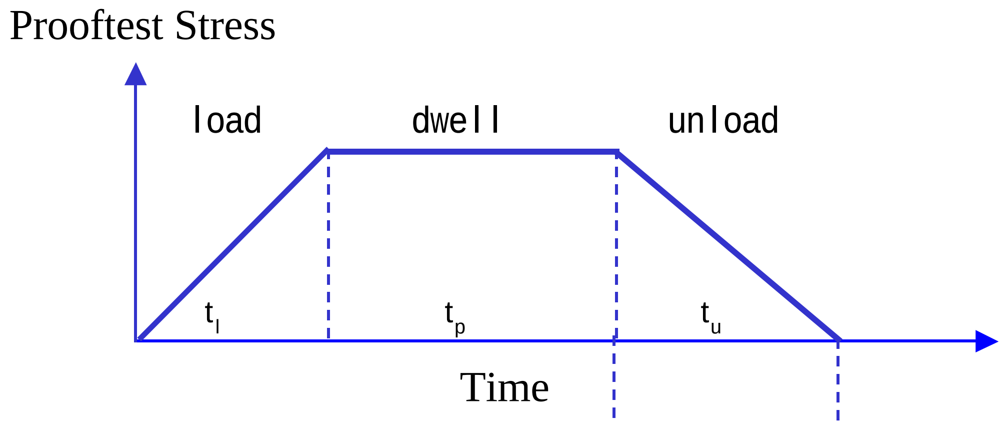
Life Prediction

Static Fatigue
(short lifetime)

Strength Measurement
& Proof Testing

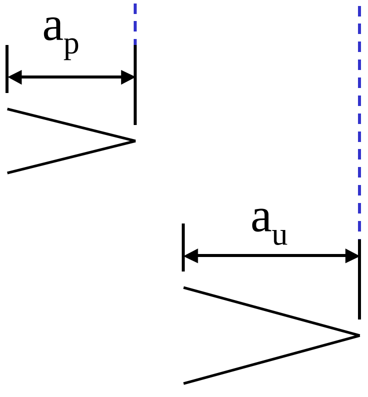
Prooftest Profile

Strength S at any time during prooftest is a function of initial inert strength, provided the applied stress is known as a function of time.



The maximum cracks are those that just survive the prooftest dwell time. The minimum strength of fiber now is equal to the prooftest stress.

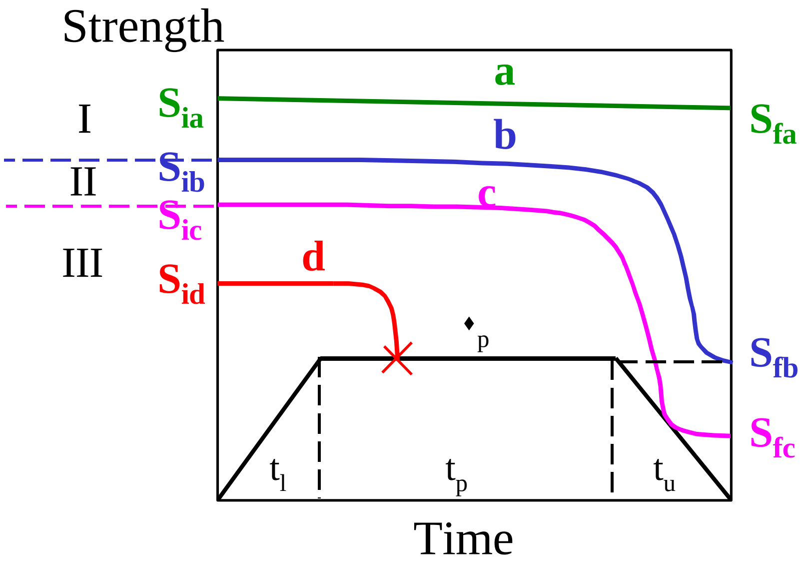
The cracks keep growing during unload. So now the maximum crack length $a_u > a_p$



$$S_p = \frac{1}{\sqrt{a_p}} \cdot \left(\frac{K_{Ic}}{Y}\right)$$

$$S_u = \frac{1}{\sqrt{a_u}} \cdot \left(\frac{K_{Ic}}{Y}\right) < S_p$$

Fiber Strength During Prooftest



$$S_f^{\,n-2} = S_i^{\,n-2} - \frac{1}{B}\cdot s_p^{\,n}\cdot\left(t_p + \frac{t_l + t_u}{n+1}\right)$$

I — passes the proof test, and with higher strength than the proof test stress

II — passes the proof test, but with final strengths less than the proof test stress

III — fails the prooftest

$S_{fc} = S_{fmin}$, the minimal post-proof strength. The higher the unloading rate, the greater S_{fmin} is. [5]

How many fibers pass the proof test, but with final strengths less than the proof test stress ?

Probability{ $S_f < \blacklozenge_p$ } = Probability{ S_i II } = Probability{ S_i (S_{ic}, S_{ib}) }

Reference 5: E. R. Fuller Jr., S. M. Wiederhorn, J. E. Ritter Jr., P. B. Oates, Proof testing of ceramics, Part 2 Theory, *Journal of Materials Science*, 15, p2282-2295, 1980

Pre- vs. Post- Prooftest Strength

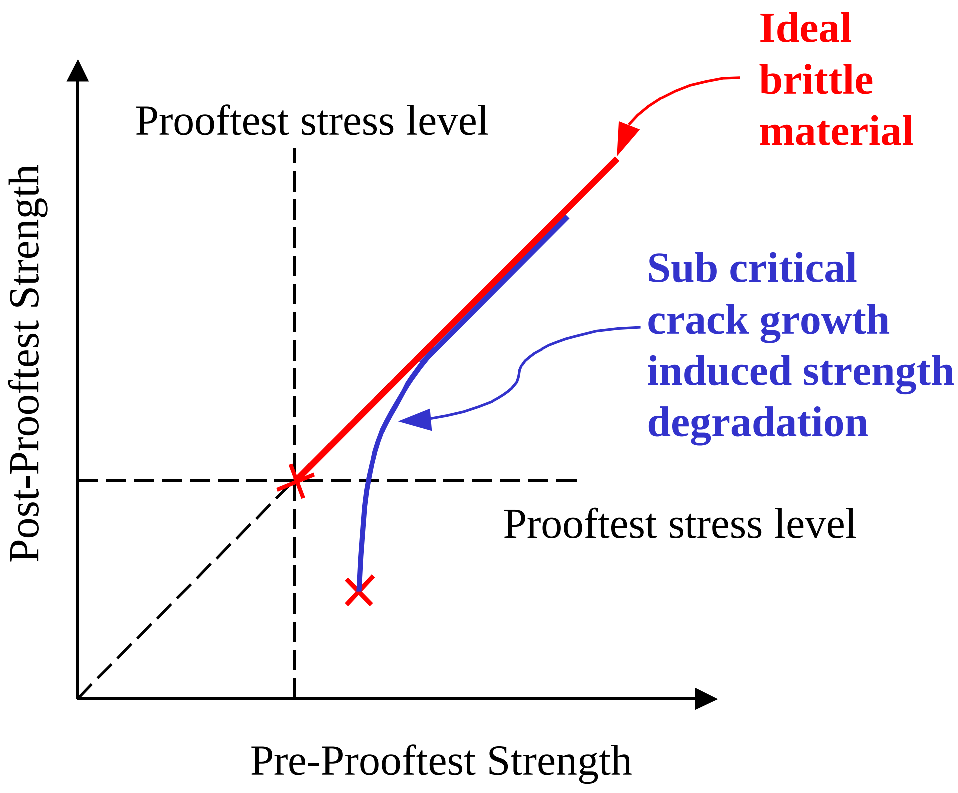


Fig. a Schematic plot

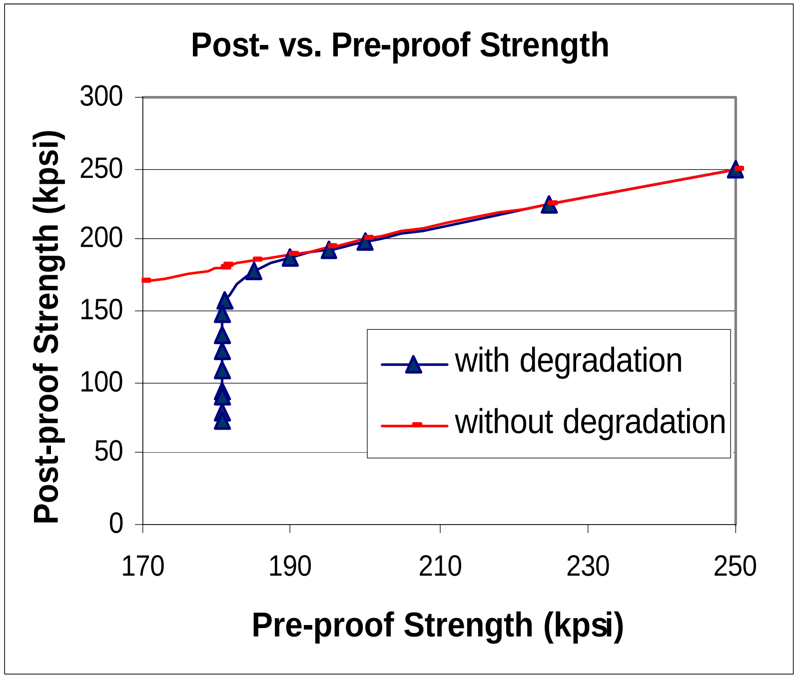


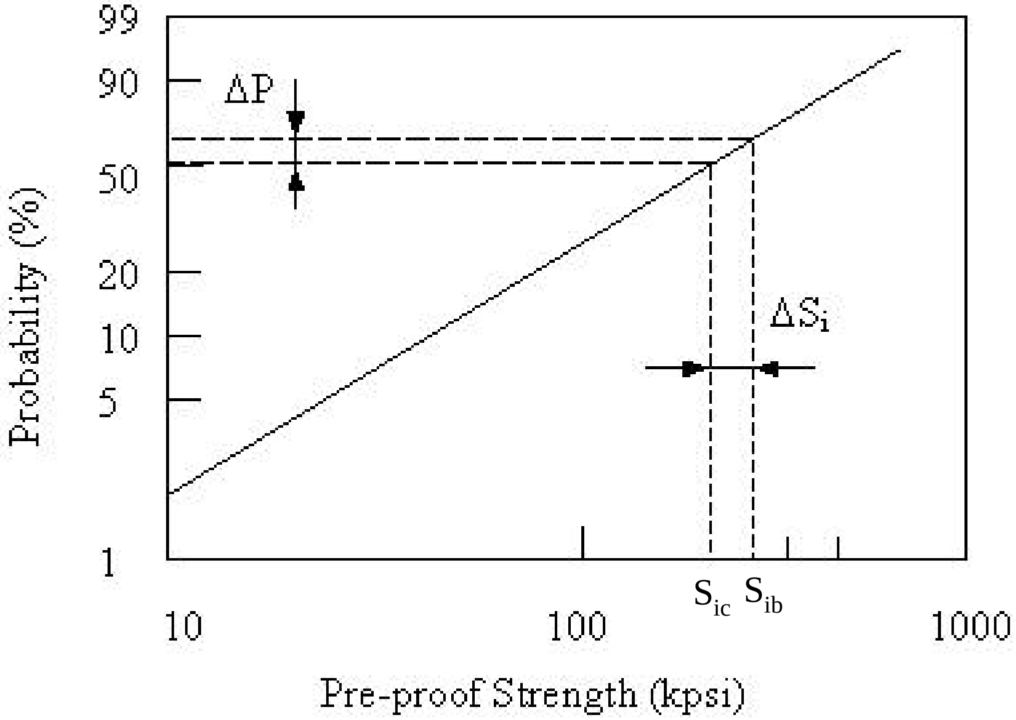
Fig.b Theoretical plot of fiber

Proof test parameters:

♦$_{p}$ = 100kpsi, t_l = 0.1s, t_p = 0.3s,t_u = 0.001s

Weak Strength Probability

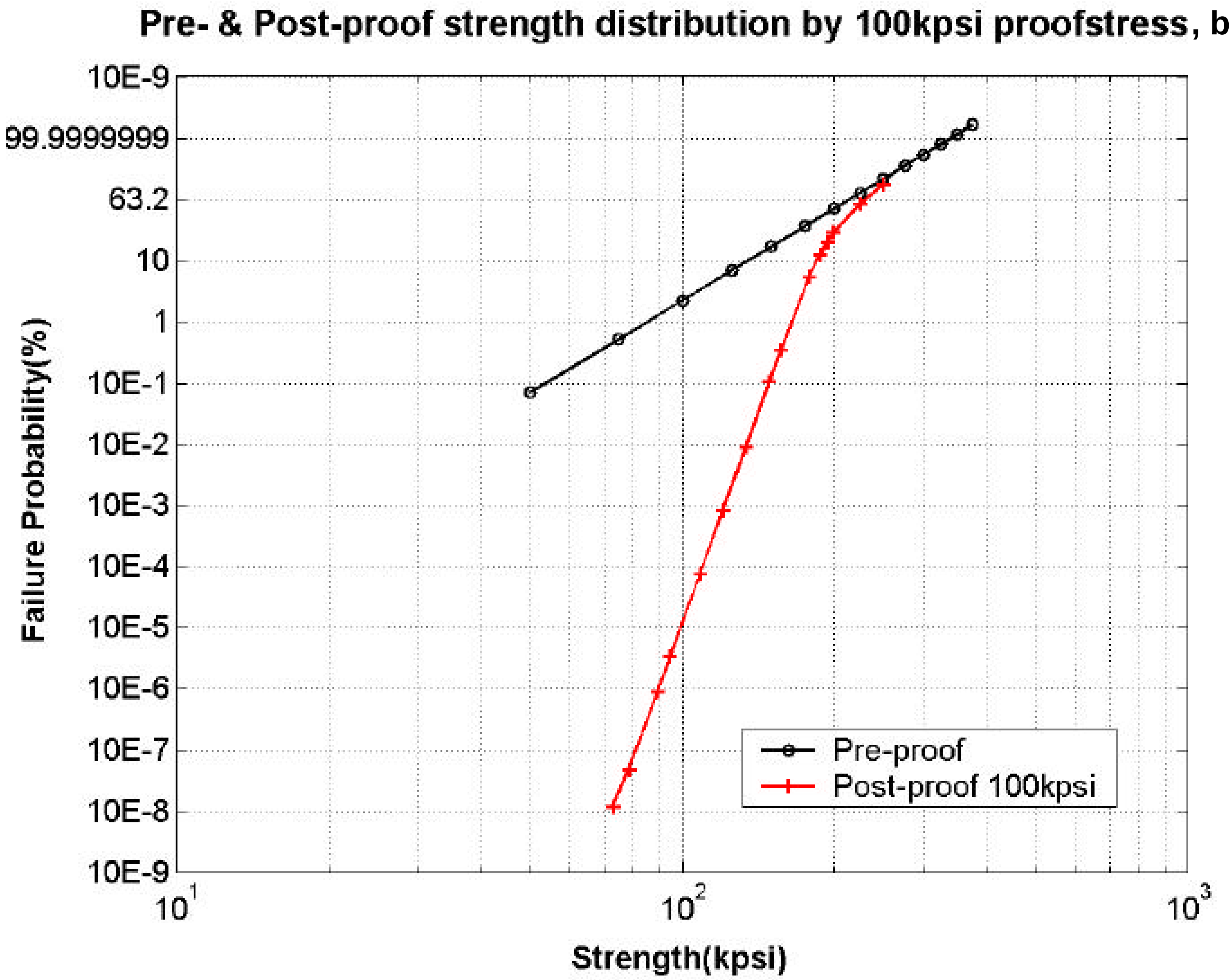
Probability{ S_f <♦$_p$ } = Probability{ S_i (S_{ic},S_{ib}) }



The two parameter Weibull distribution of pre-proof strength: $P(S_i) = 1 - e^{-(\frac{S_i}{S_0})^{b}}$

where β and S_0 are two parameters of Weibull distribution. Typically β=5, and S_0 = 200kpsi.

Pre- and Post-proof strength distribution



Proof test truncates strength distribution

Proof test parameters:

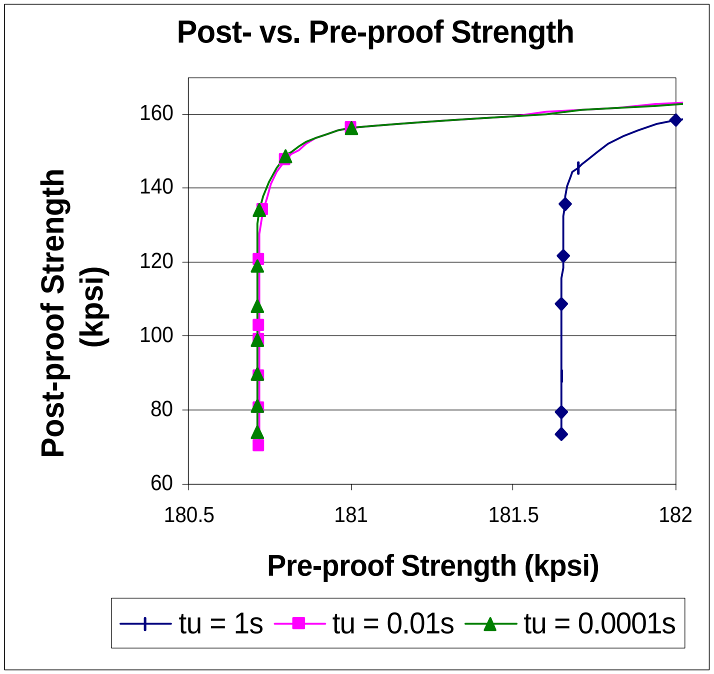
$\blacklozenge_p$ = 100kpsi

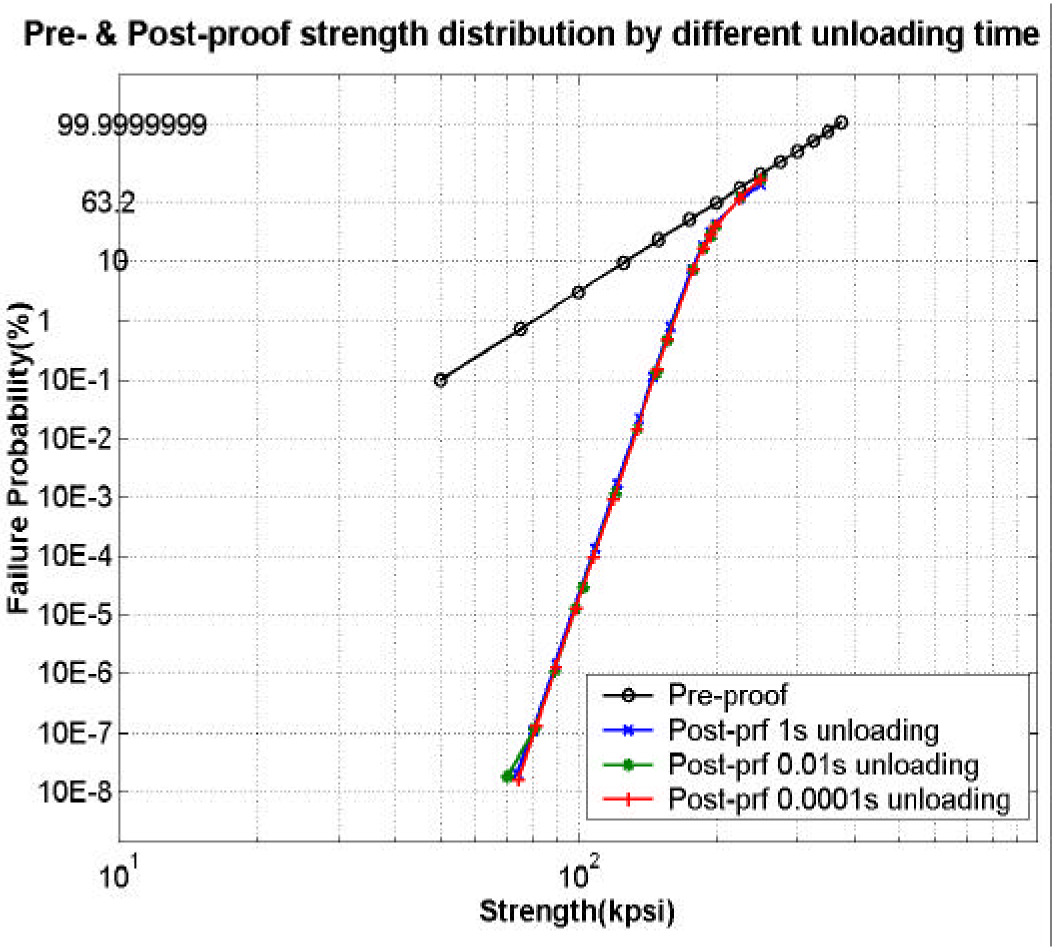
t_l = 0.1s

t_p = 0.3s

t_u = 0.001s

Effect of Unloading Rate



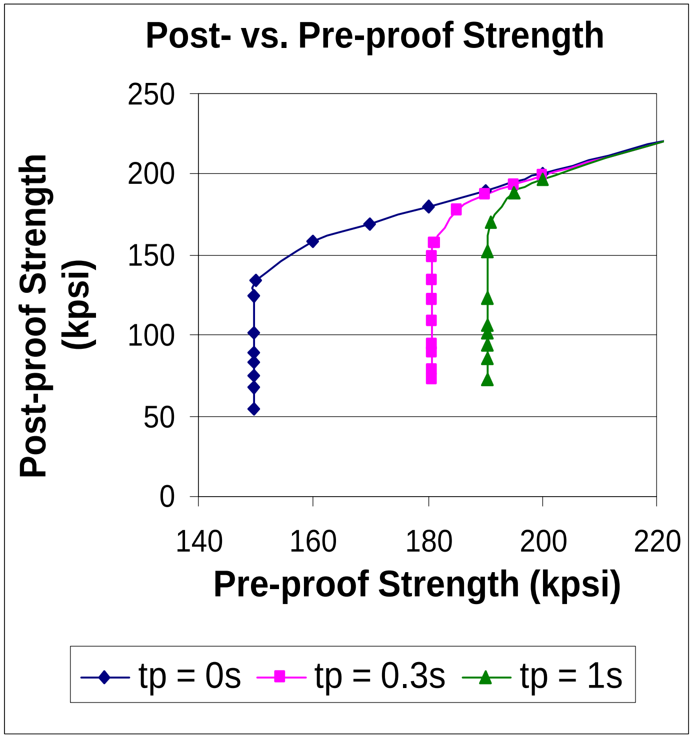


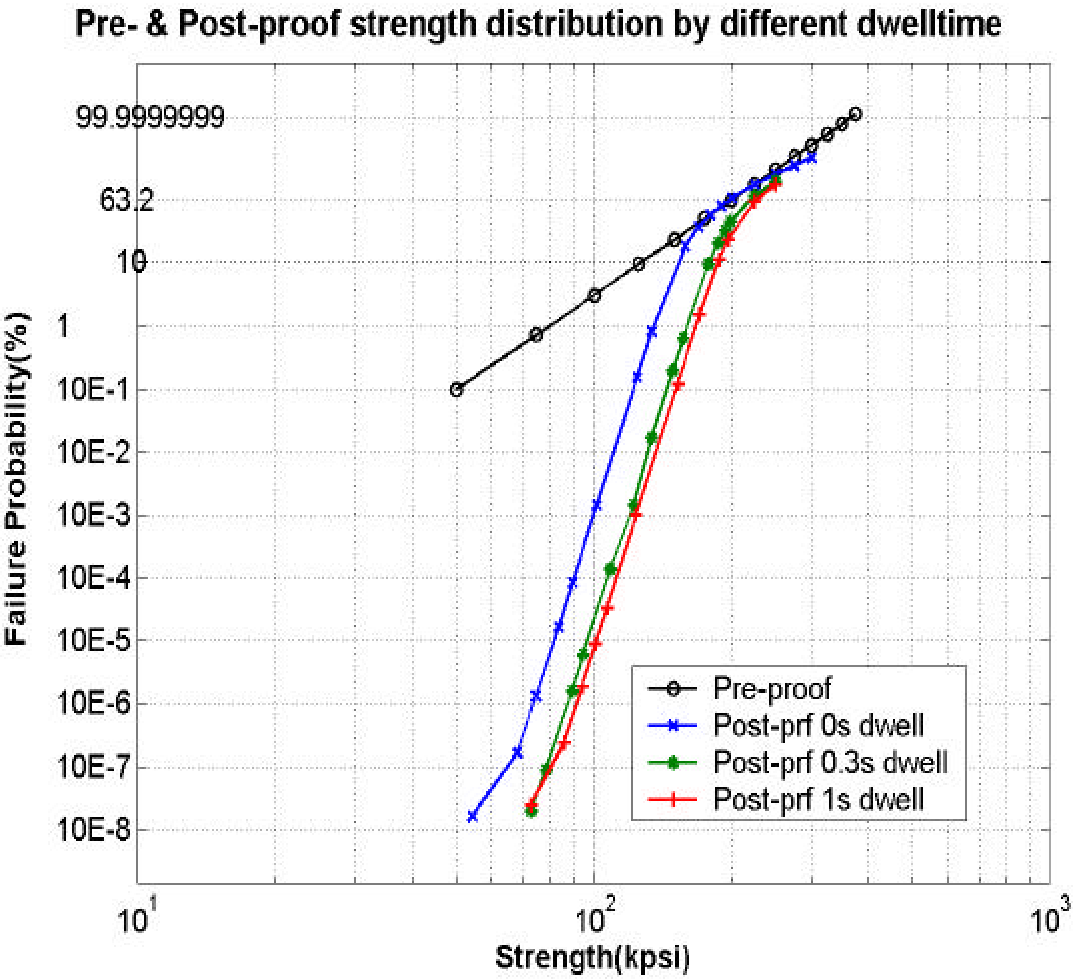
Proof test parameters:

♦$_p$ = 100kpsi, t_l = 0.1s, t_p = 0.3s

Theoretically increases minimum possible strength of fiber that can pass proof test, but has negligible practical influence.

Effect of Dwell Time



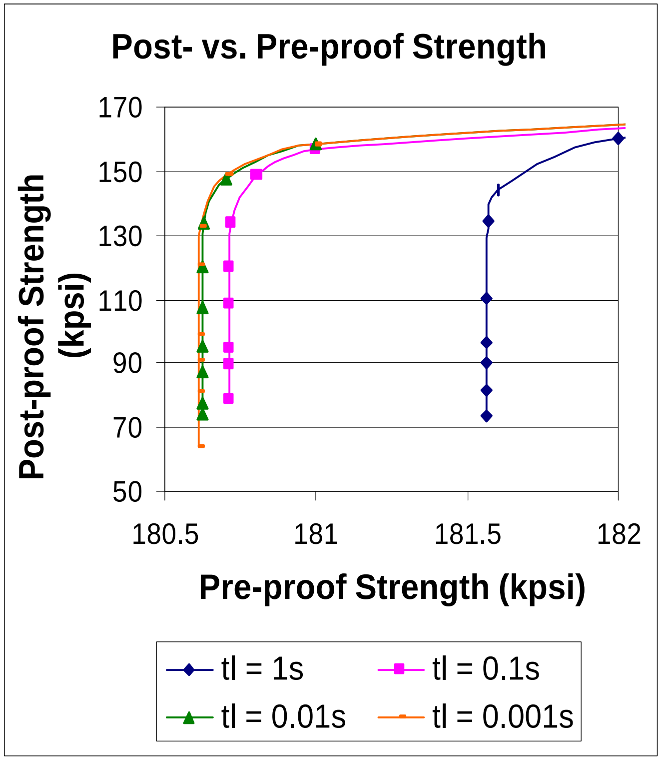


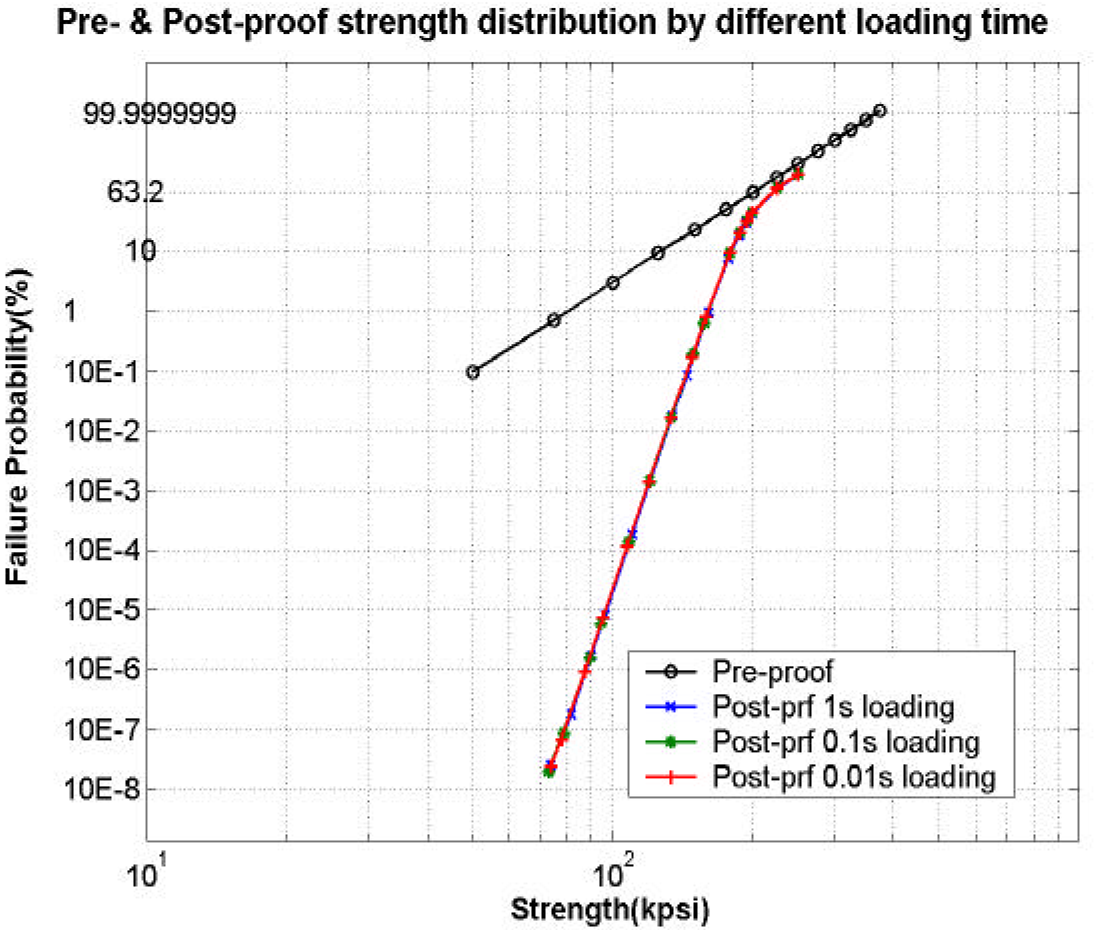
Proof test parameters:

♦$_p$ = 100kpsi, t_l = 0.1s, t_u = 0.001s

Long dwell increases strength of product that passes prooftest, but fails product that could have passed prooftest.

Effect of Loading Rate



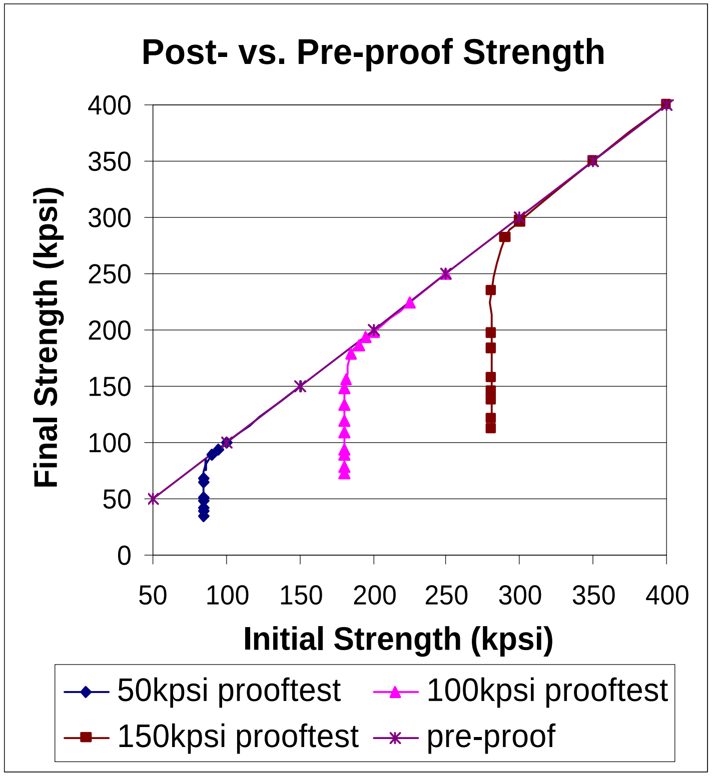


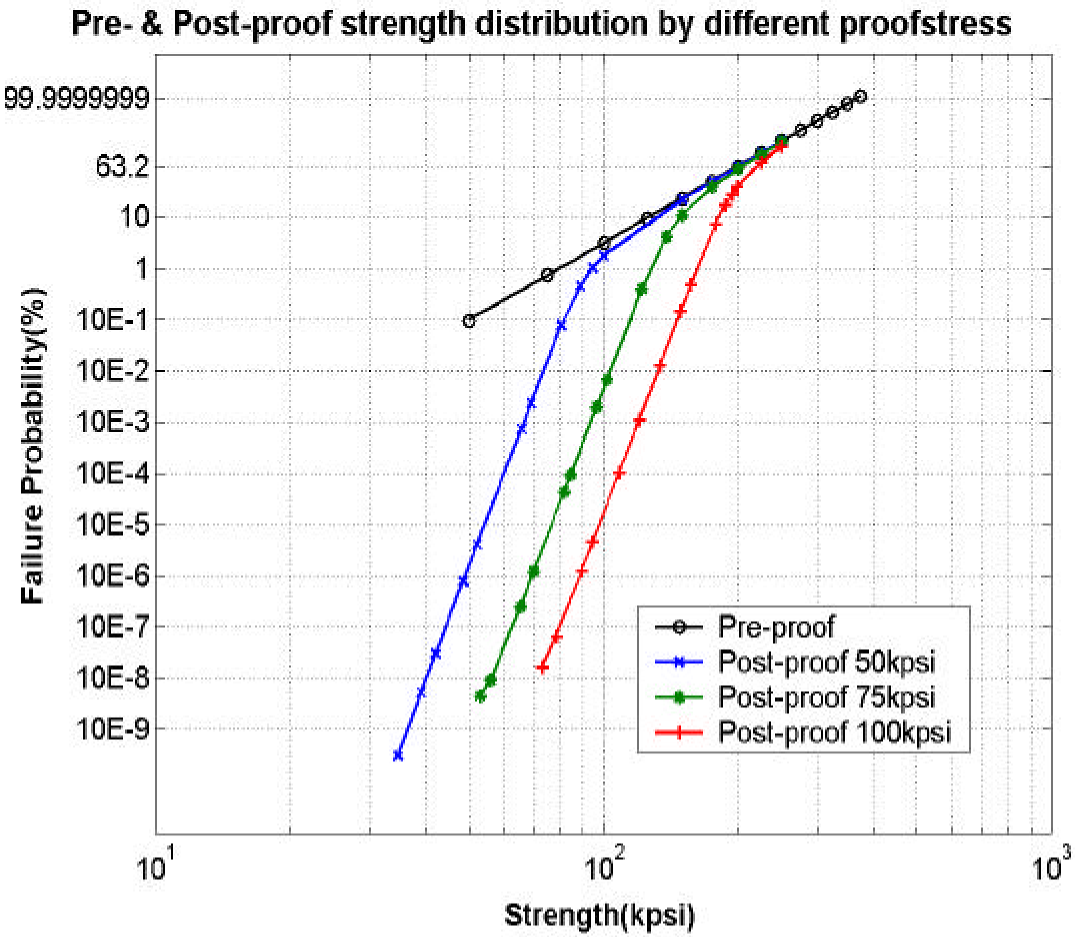
Proof test parameters:

$\blacklozenge_p$ = 100kpsi, t_p = 0.3s, t_u = 0.001s

Slow loading rate can theoretically increase strength of product that passes prooftest, but has negligible practical influence.

Effect of Proof Stress





Proof test parameters:

$t_l = 0.1s$, $t_p = 0.3s$, $t_u = 0.001s$

Proof stress level influences strength truncation.

Spliced Fiber Strength

It is common to find that the strength of a silica glass optical fiber after electric arc-fusion splicing is lower (0.4 ~ 1.5 GPa) than that of a non-spliced fiber (~ 5 GPa).

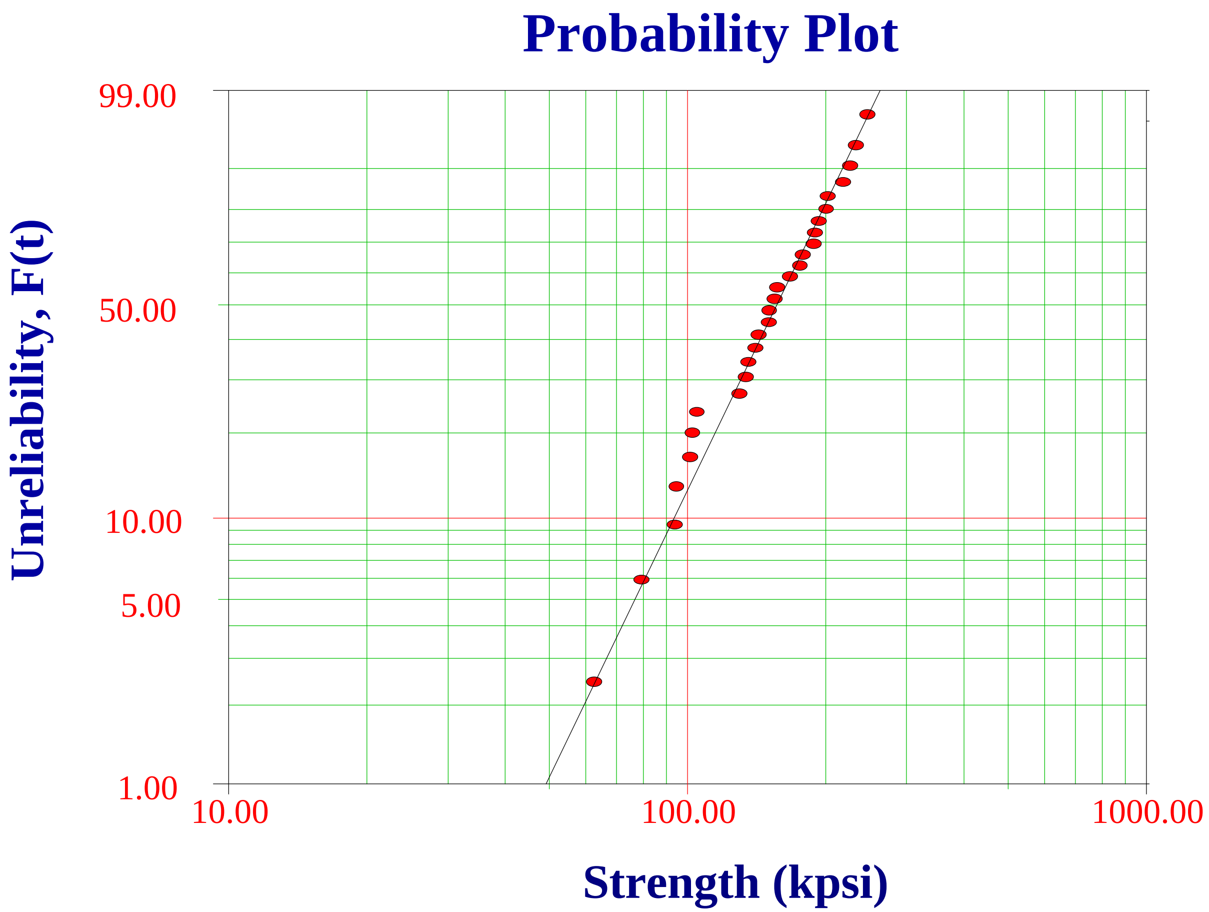
Reason:

1. The extrinsic scratches caused by mechanical stripping methods.
2. An intrinsic change of silica structure, such as the change of fictive temperature (K_{Ic} decreases). Silica glass with a high fictive temperature are stronger and more fatigue resistant. Silica glass can have different structure and properties depending upon its cooling rate.
3. The fibers fractured in tensile test at a 0.5 – 1.5 mm distance from the fusion splice, which is the structure changes zone during fusion.

Reference 6: T. Volotinen, M. Zimnol, et.a., Effect of Mechanical Stripping and Arc-Fusion on the Strength and Aging of a Spliced Recoated Optical Fiber, *Materials Research Society Symposium Proceeding, Vol. 531, 1998*

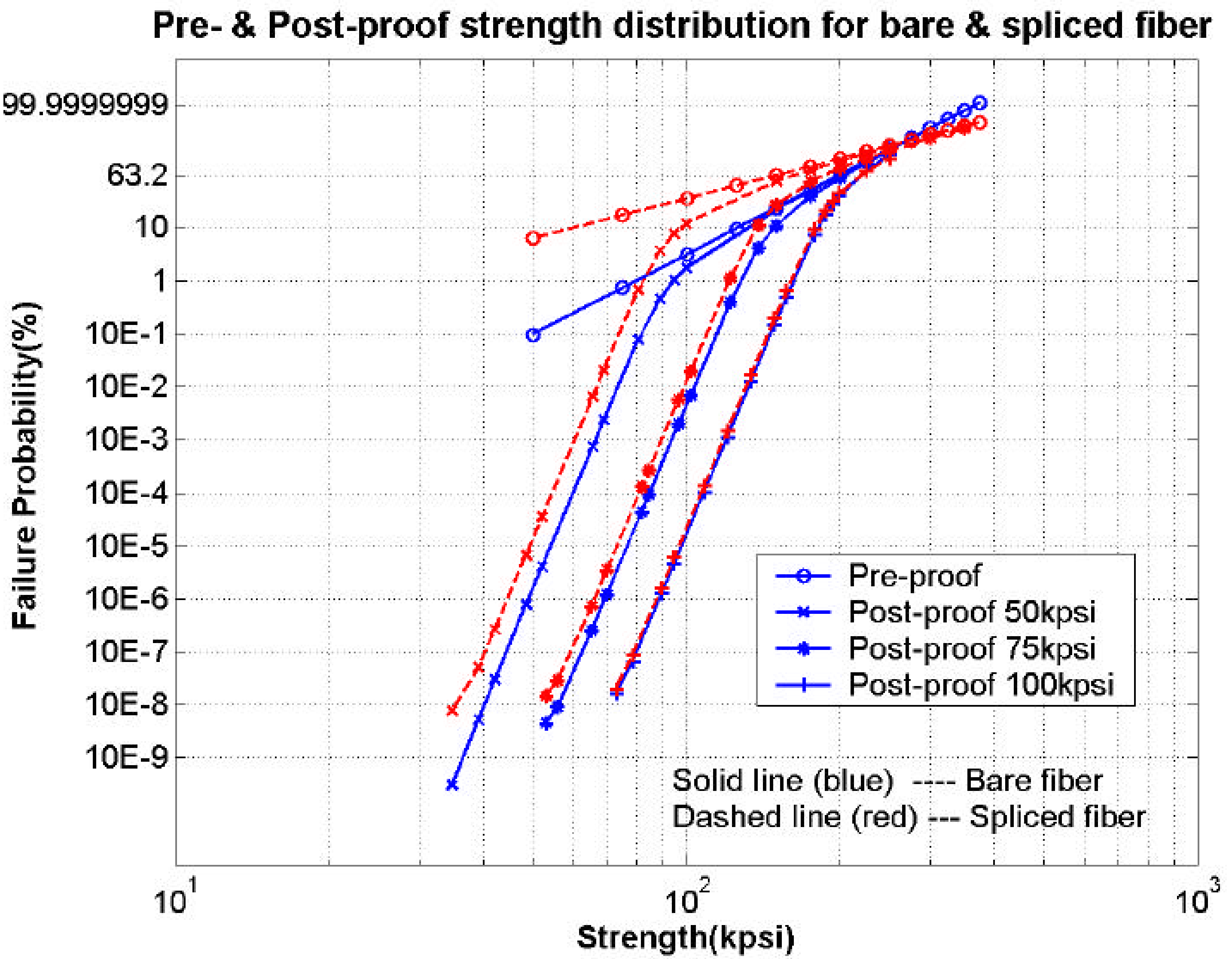
CALCE Weibull Plot of Splice Strength

(Experimental measurements, SMF-28 fiber, Ericsson fusion splicer)



2 parameter Weibull distribution: β=3.65, S_0 = 172.86kpsi, Similar results seen in Volotinen’s paper.[6]

Theoretical Spliced fiber post-proof strength



Conclusions

- Theoretically bare fibers and spliced fibers that pass the prooftest can have a strength less than the proof stress level! But practically this is a small probability event.
- In the strength distribution curve, the proof test does truncate fiber strength well. The truncation strength level is higher than the proof test level, e.g. a 100kpsi proof test on a CALCE SMF-28 fusion fiber splice can guarantee a 150kpsi post-proof strength with a reliability of about 99.9%.
- Unloading rate and loading rate have a negligible effect on post-proof strength distribution.
- Dwell time does have a small effect on post-proof strength distribution. Longer dwell times will cause a higher stress truncation, but fail more product that could pass proof test.
- Proof stress level affects post-proof strength distribution substantially. Higher proof stress level guarantee higher post-proof strength.

Details available in web report under C01-34

Benefit to Members

- Quantified probabilistic strength distribution from proof testing brittle materials that exhibit static fatigue (e.g. bare optical fibers and spliced fibers).
- Laid out mathematical foundation to quantify reliability of optical fibers and spliced fibers that have undergone proof testing and are now subject to field loads (bending, temperature, and humidity).